TUGAS AKHIR – MO 184804

ANALISIS *ON-BOTTOM STABILITY* DAN MEKANISME *UPHEAVAL BUCKLING* PADA *SHORE APPROACH PIGGYBACK PIPELINE* DI PERAIRAN UTARA GRESIK, JAWA TIMUR

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ANALYSIS OF ON-BOTTOM STABILITY AND UPHEAVAL BUCKLING MECHANISM OF SHORE APPROACH PIGGYBACK PIPELINE IN NORTHERN COAST OF GRESIK, EAST JAVA

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TUGAS AKHIR

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SURABAYA, JANUARI 2020

ANALISIS *ON-BOTTOM STABILITY* DAN MEKANISME *UPHEAVAL BUCKLING* PADA *SHORE APPROACH PIGGYBACK PIPELINE* DI PERAIRAN UTARA GRESIK, JAWA TIMUR

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ABSTRAK

Piggyback Pipelines adalah suatu bentuk konfigurasi pipa bawah laut yang merepresentasikan perkembangan industri minyak dan gas bumi Indonesia. Dalam pemanfaatannya, pipa bawah laut dirancang sesuai dengan kriteria desain yang telah ditetapkan oleh standard internasional dan juga ketentuan regional pada khususnya. Dalam Tugas Akhir ini dilakukan analisa terhadap stabilitas pipa bawah laut (*exposed and trenched*) yang beroperasi pada lokasi *shore approach* dimana tinggi gelombang akan mengalami peningkatan akibat adanya peristiwa *breaking wave*. Sementara *on-bottom stability* merupakan kemampuan berat terendam pipa bawah laut dalam menahan beban lingkungan (arus dan gelombang perairan) yang bekerja terhadapnya. Melalui penelitian yang dilakukan, dibuktikan bahwa pipa yang beroperasi dekat dengan bibir pantai membutuhkan pemendaman agar mampu stabil di dasar laut. Peletakan pipa di dasar laut tanpa adanya *trenching* akan mengakibatkan meningkatnya kebutuhan lapisan beton pemberat untuk menstabilkan pipa. Dengan menggunakan metode *absolute letaral static stability*, pipa dengan lapisan beton pemberat setebal 40 mm (KP 0+273 – KP 1+393) dan 60 mm (KP 1+393 – KP 5+725) dinyatakan stabil secara horizontal dan vertikal baik pada kondisi instalasi maupun operasi apabila dilakukan aktivitas *trenching*. Sementara pada masa operasionalnya, pipa akan mengalami perubahan tekanan dan temperatur yang dapat mengakibatkan tegangan pada pipa dan terbentuknya *effective axial compressive force*. Pada penelitian ini pipa dinyatakan aman dari *upheaval buckling* dimana berat tanah timbunan memberikan gaya ke bawah lebih besar daripada gaya minimum yang diperlukan untuk menekan *upheaval buckling*.

Kata kunci: *piggyback pipeline, shore approach, pre-trenched, absolute lateral static stability, effective axial compressive force, burried pipeline, upheaval buckling*

ANALYSIS OF ON-BOTTOM STABILITY AND UPHEAVAL BUCKLING MECHANISM OF SHORE APPROACH PIGGYBACK PIPELINE IN NORTHERN COAST OF GRESIK, EAST JAVA

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ABSTRACT

Piggyback Pipelines are a form of underwater pipe configuration that represents the development of the Indonesian oil and gas industry. In its use, the subsea pipeline is designed in accordance with design criteria set by international standards and regional regulations in particular. In this Final Project an analysis of the stability of the underwater pipeline (exposed and trenched) operating at the shore approach location where the wave height will increase due to a breaking wave event. While on-bottom stability is the ability of pipelines submerged weight to withstand environmental loads (currents and waves of water) acting on it. Through research conducted, it is proven that pipes that operate close to the shoreline require burial to be able to stabilize on the seabed. Laying pipes on the seabed without trenching will result in an increase in the need for a concrete weight coating to stabilize the pipe. Using the absolute letaral static stability method, pipes with 40 mm thick concrete weight coating (KP 0 + 273 - KP 1 + 393) and 60 mm thick concrete weight coating (KP 1 + 393 - KP 5 + 725) are declared horizontally and vertically stable both under conditions installation and operation when trenching activities are carried out. While in the operational period, the pipe will experience changes in pressure and temperature that can cause stress on the pipe and the formation of an effective axial compressive force. In this study the pipe was declared safe from upheaval buckling where the weight of the soil cover gave a downward force greater than the minimum force required to prevent upheaval buckling.

Keywords: *piggyback pipeline, shore approach, pre-trenched, absolute lateral static stability, effective axial compressive force, burried pipeline, upheaval buckling*

KATA PENGANTAR

بِسْمِ اللهِ الرَّحْمٰنِ الرَّحِيْمِ

اَلسَّلَامُ عَلَيْكُمْ وَرَحْمَةُ اللهِ وَبَرَكَاتُهُ اَلْحَمْدُ لِلّٰهِ رَبِّ الْعٰلَمِيْنَ

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Surabaya, 1 Januari 2020

Anit Siska Melinda

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DAFTAR NOTASI

LATIN

A_i : *internal area of steel pipe* [m^2]

A_s : *sectional area of pipeline* [m^2]

b : *buoyancy of pipe per unit length* [$N.m^{-1}$]

C_u : *undrained shear strength of soil* [Pa]

C_y^* : *coefficient of horizontal peak loads*

C_z^* : *coefficient of vertical peak loads*

d : *minimum water depth [m]*

D : *overall diameter of pipeline including coating* [m]

E : *young's modulus of steel*

g : *acceleration of gravity* (9,81 m/s^2) [$m.s^{-2}$]

H : *burial depth to top of pipe (TOP) [m]*

I : *moment of inertia [m^4]*

$F_{c,c}$: *vertical contact force of clay [$N.m^{-1}$]*

$F_{R,c}$: *passive soil resistance of clay [$N.m^{-1}$]*

F_y^* : *horizontal peak loads [$N.m^{-1}$]*

F_z^* : *vertical peak loads [$N.m^{-1}$]*

G_c : *clay soil stiffness parameter*

H_s : *significant wave height [m]*

k : *wave number*

K^* : *Keulegan Carpenter number for single design oscillatory*

k_c : *passive resistance factor for clay*

L : *natural half wave length [m]*

M^* : *steady to oscillatory velocity ratio*

q : *uplift resistance [$N.m^{-1}$]*

$r_{perm,z}$: *vertical load reduction due to permeable seabed*

$r_{pen,y}$: *horizontal load reduction factor due to pipe penetration*

$r_{pen,z}$: *vertical load reduction factor due to pipe penetraion*

r_{tot_y} : *horizontal peak load reduction factor*

r_{tot_z} : *vertical peak load reduction factor*

$r_{tr,y}$: *horizontal load reduction factor due to trenching*

$r_{tr,z}$: *vertical load reduction factor due to trenching*

S_u : *undrained shear strength of cover material (clay)*

T^* : *period associated with single design oscillation [s]*

T_{lay} : *lay tension stress [N.m^{-1}]*

U^* : *oscillatory velocity amplitude [m.s^{-1}]*

V^* : *steady current velocity [m.s^{-1}]*

V_c : *mean current velocity over a pipe diameter* [m.s^{-1}]

$V(z)$: *current velocity over a pipe diameter [m.s^{-1}]*

$V(z_r)$: *current velocity at reference height [m.s^{-1}]*

$V_c(z_r)$: *mean current velocity at reference height [m.s^{-1}]*

W_{down} : *available downard force [N.m^{-1}]*

w_s : *pipeline submerged weight based on condition [N.m^{-1}]*

W_{max} : *maximum allowable pipeline submerged weight [N.m^{-1}]*

W_{req} = *required downward force to prevent UHB [N.m^{-1}]*

z : *elevation equals tp pipe diameter [m]*

z_0 : *seabed roughness parameter (lihat Tabel 2.1)*

z_r : *reference height of current velocity measurement [m]*

z : *total penetration depth of pipe [m]*

z_p : *total penetration depth [m]*

z_{pi} : *initial penetration depth [m]*

z_{pl} : *penetration due to dyanamic laying [m]*

z_{pm} : *penetration depth due to movement [m]*

z_{pt} : *total penetration depth of pipe including trenching [m]*

z_t : *trench depth [m]*

GREEK

δ : *imperfection height [m]*

θ_c : *angle between current direction and pipeline [deg]*

$S_{\eta\eta}(\omega)$: *JONSWAP spectrum*

α : *generalized Philips' constant*

ω : *wave frequency [rad/s]*

ω_p : *peak wave frequency [rad/s]*

γ : *peak-enhancement factor*

σ : *spectral width parameter*

$G(\omega)$: *transfer function*

θ_t : *slope angle of trench [m]*

θ_t : *slope angle of trench [deg]*

ρ_w : *density of seawater [kg.m^{-3}]*

γ'_c : *sumberged unit soil weight for clay*

γ_w : *safety factor*

ρ_s : *submerged soil density*

ρ_s : *submerged soil density [kg.m^{-3}]*

γ_{SC} : *safety factor based on condition*

μ : *friction coefficient*

σ_{ax} : *effective axial compressive force [N.m^{-1}]*

DAFTAR LAMPIRAN

LAMPIRAN I PERHITUNGAN *ON-BOTTOM STABILITY* PADA *EXPOSED PIPELINES* UNTUK KONDISI INSTALASI

LAMPIRAN II PERHITUNGAN *ON-BOTTOM STABILITY* PADA *EXPOSED PIPELINES* UNTUK KONDISI OPERASI

LAMPIRAN III PERHITUNGAN *ON-BOTTOM STABILITY* PADA *TRENCHED PIPELINES* UNTUK KONDISI INSTALASI

LAMPIRAN IV PERHITUNGAN *ON-BOTTOM STABILITY* PADA *TRENCHED PIPELINES* UNTUK KONDISI OPERASI

LAMPIRAN V PERHITUNGAN *UPHEAVAL BUCKLING* PADA PIPA (*CORRODED CASE*)

LAMPIRAN VI AUTOPIPE *MODELLING REPORT*

BAB I

PENDAHULUAN

1.1. Latar Belakang

Ketertarikan industri terhadap eksplorasi lepas pantai nampak mengalami peningkatan seiring dengan pemahaman terkait menurunnya cadangan migas di darat. Namun, ditinjau dari kondisi yang terjadi di lapangan perindustrian, Indonesia mengalami kemunduran dalam produktivitas minyak dan gas bumi dikarenakan rendahnya tingkat temuan cadangan baru.

Dalam Instruksi Presiden Republik Indonesia Nomor 2 Tahun 2012 tentang Peningkatan Produksi Minyak Bumi Nasional, Presiden Republik Indonesia menetapkan kebijakan terhadap Kepala Badan Pelaksana Kegiatan Usaha Hulu Minyak dan Gas Bumi untuk melakukan peningkatkan efisiensi operasi dan optimasi fasilitas produksi dalam rangka pencapaian produksi minyak bumi nasional dengan rata rata minimum sebesar 1,01 juta barrel per hari. Hal tersebut didasari dengan pemahaman terhadap potensi yang dimiliki oleh negara Indonesia dalam menghasilkan sumber energi bahan bakar bagi kehidupan dan perekonomian nasional.

PT.X yang berperan sebagai salah satu pemegang kepentingan dalam industri ini, turut melakukan pengembangan lapangan produksi melalui pembangunan infrastruktur yang menunjang proses eksplorasi hingga proses distribusi. Pipa bawah laut dipilih sebagai moda transportasi yang digunakan berdasarkan pertimbangan lokasi keberlangsungan proyek yang berlokasi pada perairan dengan kedalaman relatif dangkal sehingga penggunaan kapal seperti *tanker* dianggap kurang tepat untuk beroperasi. Pipa bawah laut kerap menjadi pilihan utama dalam industri ini di samping karena mampu bekerja tanpa dipengaruhi cuaca, pipa bawah laut juga memberikan efisiensi dan efektivitas yang lebih dibandingkan moda transportasi lain.

Salah satunya adalah dengan digunakannya konfigurasi pipa yang dirancang agar mampu melakukan pekerjaan secara bersamaan dan mendukung keoptimalan jadwal proyek. Piggyback pipelines menjadi salah satu konfigurasi yang sedang berkembang di Indonesia dan termasuk ke dalam salah satu lingkup pekerjaan dalam proyek miliki PT.X. Umumnya, pipa bawah laut yang memiliki perbedaan diameter dikaitkan satu dengan lainnya dengan menggunakan suatu pengait (*clamp*) membentuk suatu konfigurasi yang dianggap memberikan efektivitas berdasarkan pertimbangan teknis dan ekonomis[1]. Melalui pipa tumpuk ini, hasil produksi minyak diangkut oleh *16" Production Pipeline* dan produksi gas oleh *6" Gas Lift Pipeline.*

Pipa tumpuk ini membentang sepanjang ± 5.8 km menghubungkan *Wellhead Platform* (WHP) dengan sebuah *onshore Wellsite.* Dengan jarak yang relatif dekat dengan bibir pantai, lokasi ini termasuk ke dalam wilayah *shore approach*. Pendangkalan kedalaman yang terjadi dapat mengakibatkan peristiwa gelombang pecah dimana tinggi gelombang yang terjadi akan relatif lebih besar daripada tinggi gelombang signifikannya. Hal tersebut yang akan memngakibatakan tingginya beban hidrodinamis yang bekerja terhadap pipa. Pengaruh beban hidrodinamis yang besar dapat mengakibatkan ketidaksatabilan pipa di dasar laut. Sementara perancangan terhadap pemafaatan sttuktur harus memastikan bahwa struktur akan aman selama masa operasionalnya

On-bottom stability adalah kemampuan berat terendam pipa bawah laut dalam melawan pembebanan lingkungan yang diterimanya. Pipa pada umumnya meletak di dasar laut, namun dengan dikeluarkannya perautran pemerintah, Regulasi Indonesia telah menyebutkan bahwa melalui pertimbangan keamanan serta keselamatan operasional, seluruh pipa bawah laut yang beroperasi pada kedalaman perairan kurang dari 13 m, diperlukan pemendaman pipa sekurang-kurangnya 2 m terhitung dari ujung terluarnya (*top of steel*). Peraturan ini didasari oleh banyaknya kepentingan yang berlangsung pada wilayah *shore approach* seperti kegiatan pelayaran, *trawling*, *anchoring* maupun aktivitas pancing yang dapat membahayakan masa operasional pipa. Namun Pemendaman pipa sbenarnya berefek pada mahalnya biaya konstruksi serta kesulitan yang dihadapi dalam inspeksi dan perawatan pipa. Sedangkan penambahan berat terendam menggunakan lapisan beton pemberat maupun penambahan ketebalan dinding pipa akan sangat berefek secara ekonomikal. Untuk itu perancangan yang ideal dibutuhkan untuk mendapatakan hasil yang sesuai pada lokasi tersebut.

Dalam tugas akhir ini dilakukan peninjauan terhadap stabilitas pipa bawah laut yang berlokasi di daerah *shore approach* dengan variasi kondisi pipa yaitu *exposed* dan *trench* untuk melihat perbandingan angka kestabilan pipa bawah laut dengan mempertimbangkan ketebalan optimum oleh lapisan beton pemberat.

Selain itu, dengan mempertimbangkan masa operasional pipa, dimana pada saat pipa beroperasi, pipa akan menerima beban tekanan internal dan beban termal fluida yang dialirkan oleh jaringan pipa tersebut. Beban yang ditanggung oleh suatu sistem *pipeline* akan menyebabkan pipa berada dalam kondisi tegang (Rizal, 2014).

Kontur dasar laut yang beragama menjadi variabel yang tidak mudah untuk dikontrol sehingga *imperfection height* menjadi hal yang umum untuk terjadi. Kondisi dimana pipa akan meletak di atas struktur tanah yang memiliki ketidakmerataan serta mengalami pembebanan melalui tekanan dan temperature oleh fluida nya, akan menyebabkan pipa mengalami gaya aksial efektif yang menyebabkan pipa berekspansi dalam bentuk elongasi pipa. Burried pipelines didefinisikan sebagai struktur yang berada dalam kondisi tertahan (*restrained*) akibat adanya tanah timbunan yang mengalangi pemanjangan tersebut.

Tertahannya deformasi pipa tersebut akan menyebabkan gaya aksial efektif berubah menjadi gaya aksial yang bersifat tekan terhadap struktur pipa sebagai bentuk respon dari elongasi yang tertahan. Dengan adanya imperfection height di awal, pipa telah memiliki kecendrungan lengkung awal yang memberikan dukungan terhadap defleksi pipa secara vertikal akibat gaya tekan aksial efektif tersebut.

Dalam hal ini, tahanan tanah berperan penting sebagai beban yang melawan pergerakan pipa ke atas akibat ekspansi termal yang terjadi dan mencegah terjadinya *upheaval buckling.*

Pipeline yang mengalami deformasi akan mengalami penurunan kekuatan. Walaupun dalam tahap desain faktor *buckling* ini sudah dipertimbangkan dengan memberikan batas umur operasi, namun akibat sulitnya mengontrol dan tidak seragamnya daya dukung tanah di setiap lokasi, maka kegagalan *pipeline* yang diakibat oleh *buckling* masih sering terjadi. Melalui pemahaman terkait faktor-faktor kegagalan pada struktur Penulis pada akhirnya mengangkat judul ini untuk sekiranya layak dibahas dan diharapkan dapat menjadi kontribusi keilmuan yang berguna untuk perkembangan edukasi.

1.2. Perumusan Masalah

Melalui penelitian Tugas Akhir ini dirumuskan permasalahan yang menjadi pokok bahasan dan terjabarkan sebagai berikut:

1. Bagaimana hasil perbandingan stabilitas pipa *exposed* dengan pipa *pre-trenched* pada pipa yang beroperasi di daerah *shore approach*?
2. Bagaimana pengaruh intervensi *seabed* (*trenching*) terhadap beban hidrodinamis yang bekerja pada pipa?
3. Bagaimana analisis mekanisme *upheaval buckling* untuk setiap *imperfection height* yang terjadi di sepanjang jalur pipa?

1.3. Tujuan Penelitian

Adapun tujuan yang menjadi pencapaian dalam penelitian Tugas Akhir ini adalah sebagai berikut:

1. Memahami hasil perbandingan stabilitas pipa *exposed* dengan pipa *pre-trenched* pada pipa yang beroperasi di daerah *shore approach*.
2. Memahami pengaruh intervensi *seabed* (*trenching*) terhadap beban hidrodinamis yang bekerja pada pipa.
3. Memahami mekanisme *upheaval buckling* untuk setiap *imperfection height* yang terjadi di sepanjang jalur pipa.

1.4. Manfaat Penelitian

Penelitian ini memberikan gambaran terhadap suatu studi mengenai stabilitas pipa bawah laut (*on-bottom stability*) yang beroperasi pada daerah *shore approach,* dimana pada lokasi tersebut terdapat potensi terjadinya peristiwa *breaking wave.*

Penelitian ini juga memberikan suatu gambaran dari mekanisme penekukan pipa bawah laut (*upheaval buckling*) yang disebabkan oleh pembebanan temperatur serta tekanan pada saat operasi.

Dengan dilakukannya penelitian ini diharapkan mampu menyajikan pemahaman kepada penulis maupun mahasiswa sebagai peneliti selanjutnya dalam menganalisis parameter yang mempengaruhi perancangan pipa.

1.5. Batasan Masalah

Beberapa batasan yang ditentukan dalam penelitian Tugas Akhir ini adalah sebagai berikut:

1. Material pipa adalah API 5L X65 dan mengacu pada API Spec 5L.
2. Pipa didefinisikan sebagai silinder lurus tanpa adanya pembelokan rute.
3. Perhitungan *pipeline on-bottom stability* mengacu pada DNVGL-OS-F101, DNVGL-RP-F109, dan DNVGL-RP-C205.
4. Tinjauan stabilitas dalam penelitian ini adalah stabilitas terhadap pengapungan, penenggelaman dan pergeseran pipa secara lateral.
5. Metode yang digunakan dalam analisis *on-bottom stability* adalah *absolute lateral static stability*.
6. Perhitungan dan penentuan batas ijin tegangan pipa mengacu pada ASME B31.4 dan ASME B31.8.
7. Analisa mekanisme terjadinya *upheaval buckling* mengacu pada DNV-RP-F110, DNVGL-RP-F114 dan Jurnal OTC 6335.
8. Pipa sekunder hanya memberikan pengaruh dalam berat terendam pipa.
9. Kondisi arus perairan diasumsikan sebagai *steady flow.*
10. Jenis tanah di sepanjang jalur pipa dianggap homogen yaitu *clay*.
11. Pengaruh *scouring* dan likuifaksi tanah diabaikan karena pipa berada dalam kondisi *trenching.*
12. Kemungkinan dan pengaruh beban gempa diabaikan.

13. Untuk menyamaratakan parameter dalam perhitungan berat pipa, pengaruh *marine growth* diabaikan.
14. Tidak melakukan peninjauan terhadap pipa darat (KP 0+000 – KP 0+273).
15. Tidak melakukan perhitungan terhadap proteksi katodik sehingga berat anoda tidak dipertimbangkan dalam perhitungan.
16. Tidak melakukan analisa perlindungan pipa e.g. *trawling, anchoring,* ataupun *dropped objects*.
17. Tidak melakukan analisis biaya dan resiko.
18. Tidak melakukan analisis keandalan dan kelelahan struktur.

1.6. Sistematika Penulisan

Penyusunan Laporan Tugas Akhir ini ditulis sesuai dengan sistematika penulisan sebagai berikut:

Bab I – Pendahuluan, menjelaskan kronologis yang menjadi latar belakang dalam penyusunan Tugas Akhir ini sehingga didapatkan perumusan masalah yang akan menjadi topik bahasan penelitian. Dengan tujuan dan manfaat yang menjadi pondasi laporan ini diharapkan mampu memberikan kontribusi pada bidang keilmuan.

Bab II – Tinjauan Pustaka dan Dasar Teori, merupakan peninjauan terhadap penelitian serupa yang telah dilakukan sebelumnya serta pemaparan terhadap dasar-dasar teori pendukung yang bersumber dari standar ketentuan nasional maupun internasional.

Bab III – Metodologi Penelitian, berisi metodologi pengerjaan yang disajikan dalam bentuk diagram alir serta dilengkapi dengan penjelasan terperinci terhadap setiap langkah yang tersusun secara sistematis.

Bab IV – Analisis, Pembahasan dan Pemodelan menampilkan perhitungan dari hasil olah data yang dilakukan serta analisa terhadap *shore approach pipeline on-bottom stability* dan *pipeline upheaval buckling mechanism*. Menyertakan pula hasil pemodelan yang dilakukan menggunakan *software* AutoPIPE *by* Bentley.

Bab V – Penutup, berisi kesimpulan yang menjadi jawaban atas perumusan masalah sekaligus menjadi konklusi dalam penelitian ini. Pada bab ini pula penulis menyertakan saran sebagai bentuk tindak lanjut yang diharapkan dapat bermanfaat terhadap penelitian selanjutnya.

Daftar Pustaka, berisi daftar referensi pendukung baik dalam bentuk jurnal, buku, thesis, *rules* maupun pustaka lainnya yang telah menjadi acuan dan inspirasi penulis dalam penyusunan Tugas Akhir ini.

Lampiran, memuat semua langkah-langkah perhitungan dan hasil *running* pada *software* yang digunakan.

(Halaman sengaja dikosongkan)

BAB II

TINJAUAN PUSTAKA DAN DASAR TEORI

2.1. Tinjauan Pustaka

Kemasivan pemanfaatan pipa bawah laut yang terjadi di lapangan perindustrian nampak menjadi suatu ketertarikan bagi *pipeline engineer* untuk terus melakukan dan mengembangkan suatu kajian terkait kemampuan operabilitas pipa dalam menyalurkan hasil eksplorasi.Konsep stabilitas pipa bawah laut pun hingga kini masih menjadi bahasan yang cukup menarik dikarenakan persyaratan operasional pipa.

Sibuea (2016) melakukan penelitian mengenai stabilitas pipa penyalur minyak dan gas dengan diameter luar 323 mm yang membentang sepanjang 6.1 km dari platform ULA menuju platform UW. Dalam penelitian ini didapatkan bahwa pipa berada dalam kondisi yang tidak stabil secara lateral baik saat proses instalasi maupun operasi. Sehingga asumsi tebal concrete yang digunakan di awal memerlukan penambahan ketebalan agar memberikan berat terendam pada pipa lebih besar dari sebelumnya dan mampu menstabilkan pipa tersebut. Dilakukan pula analisis terhadap terjadinya local buckling yang menghasilkan panjang allowable free span agar menghindari kemungkinan terjadinya kegagala local buckling pada struktut.

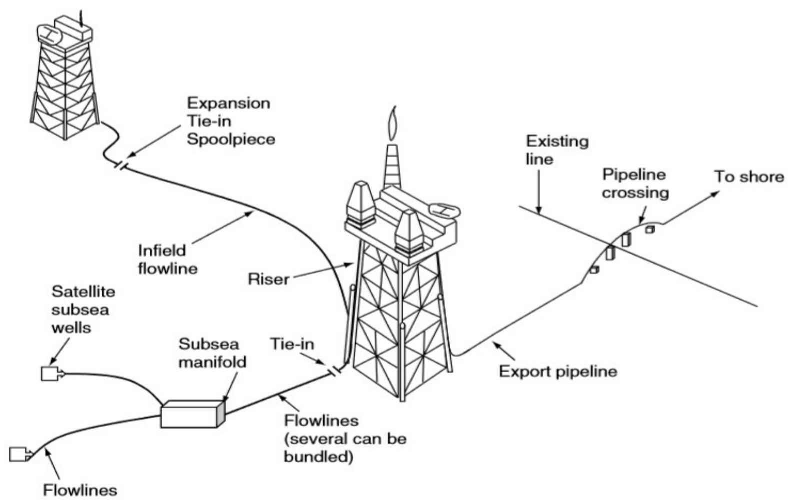
Danendra (2018) juga menganalisis stabilitas pipa bawah laut dengan diameter luar 16 inch dan beroperasi di MMF – LPRO field sepanjang 13,2 m milik PT. Pertamina. Dalam penelitian didapatkan hasil bahwa pipa tidak stabil secara lateral. Makadari itu pipa direkomendasikan untuk dipendam (burried) sesuai dengan ketetuan pemerintah yang termuat dalam Peraturan Pemerintah No 300.K/38/M.Pe/1997 Pasal 13 ayat 3

Hamzah (2018) juga melakukan penelitian serupa dengan memvariasikan kedalaman perairan dan menganalisis pengaruhnya terhadap stabilitas pipa. Hasil yang didapatkan adalah pipa tetap stabil dengan variasi kedalaman yang dilakukan serta tidak membutuhkan penambahan tebal concrete weight coating yaitu tetap pada ketebalan 40 mm, namun terjadi perubahan safety factor dimana semakain tinggi kedalaman perairan maka akan memberikan safety factor atau keamanan (stabilitas) yang lebih tinggi pula.

2.2. Dasar Teori

Dalam melaksanakan studi dilakukan pengkajian terhadap teori-teori mendasar yang mendukung metode analisis pada penelitian ini:

2.2.1. Gambaran Umum



Gambar 2. 1 Gambaran Umum (Guo et al, 2014)

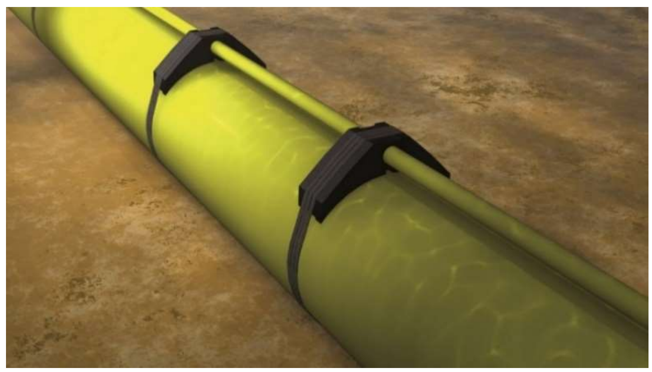
Gambar 2.1 merupakan skema gambaran umum sistem perpipaan di lapangan perindustrian. Pipa bawah laut dapat diklasifikasikan menjadi (Guo et al, 2014):

a. *Flowlines* yang mentransmisikan minyak dan/atau gas dari *satellite subsea wells* ke *subsea manifolds*
b. *Flowlines* yang mentransmisikan minyak dan/atau gas dari *subsea manifolds* ke *platform* fasilitas produksi
c. *Infield Flowlines* yang mentransmisikan minyak dan/atau gas di antara *platform* fasilitas produksi
d. *Export Flowlines* yang mentransmisikan minyak dan/atau gas dari *platform* fasilitas produksi ke darat.

e. *Flowlines* yang mentransmisikan air atau bahan kimia dari *platform* fasilitas produksi melalui subsea injection manifolds ke *injection wellheads.*

2.2.2. Pipa Bawah Laut: *Piggyback Pipelines*

Di lapangan telah berkembang suatu konfigurasi pipa bawah laut yang yang didasari oleh pertimbangan teknis dan ekonomis. *Piggyback pipeline* adalah salah satu bentuk konfigurasi dimana pipa-pipa dengan diameter yang berbeda diikat dalam kesatuan bundel dan tersusun secara tumpuk (Cheng et al, 2012) walau terkadang dapat disusun sejajar berdampingan.

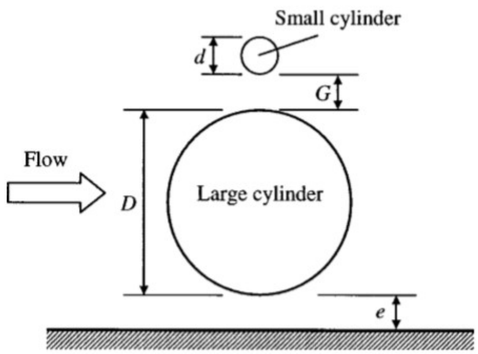


Gambar 2. 2 Ilustrasi *Piggybacked Pipeline* (BASF, 2019)

Konfigurasi seperti pada Gambar 2.2 mulai digunakan karena memberikan efisiensi dan efektivitas dalam aplikasinya i.e. optimalisasi biaya konstruksi dan perawatan; peningkatan angka stabilitas; serta pemanfaatan lahan (Zhao, Cheng, & Teng, 2007). Dengan *piggyback pipeline* operasional pendistribusian hasil produksi menjadi lebih cepat dikarenakan dapat berlangsung secara bersamaan.

Pada tahap instalasi, pipa sekunder dikaitkan di atas pipa utama dengan bantuan *clamp* agar tidak mudah terlepas akibat pengaruh gelombang dan arus perairan. Penentuan spesfikasi terkait *clamp* dapat disesuaikan dengan kebutuhan dan dapat dianalisa mendalam melalui perancangan lebih lanjut.

Gambar 2.3 menunjukkan parameter pipa tumpuk terhadap kondisi di bawah laur. Dalam proses fabrikasi, dilakukan pelapisan *concrete weight coating* pada pipa utama sebagai pemberat tambahan juga sebagai pelindung pipa terhadap aktivitaseksternal yang berpotensi bahaya. Ketebalan lapisan ini selanjutnya akan diuraikan lebih mendalam pada konsep stabilitas pipa bawah laut. Sementara itu pada pipa sekunder tidak diberikan lapisan beton pemberat melainkan hanya lapisan anti korosi.



Gambar 2. 3 Parameter Piggyback Pipeline di Dasar Laut (Zhao, 2007)

Pada umumnya rasio antara diameter pipa kecil *(d)* dengan diameter pipa besar *(D)* berkisar antara 0.1 – 0.5. Sedangkan untuk jarak antara keduanya *(G)* dapat disesuaikan pada tahap perancangan.

2.2.3. Perancangan Sistem Perpipaan: Basic Requirements

Perancangan pipa adalah tentang memprediksi beban maksimum yang mungkin terjadi terhadap pipa dengan tahanan minimum yang dapat diusahakan oleh pipa tersebut. Tujuan utama dari perancangan pipa adalah untuk meminimalisir resiko yang secara langsung berdampak pada lingkungan juga ekonomi. Dalam bukunya: *Design and Installation of Marine Pipelines* **Invalid source specified.** menguraikan persyaratan yang harus dipertimbangkan dalam sistem perancangan pipa bawah laut, diantaranya adalah:

a. Persyaratan Fungsi

Secara fungsi, pemanfaatan pipa bawah laut adalah untuk mendistribusikan hasil produksi minyak dan gas bumi dalam kondisi aman dan andal selama masa operasionalnya. Persyaratan fungsi ini mencakup pemantauan, perawatan serta akses inspeksi terhadap kemampuan operasional pipa sebagai rangkaian dalam penilaian keselamatan kerja pipa.

b. Persyaratan Otoritas

Dalam menyusun parameter perancangan, penting untuk mengevaluasi dengan cermat organisasi dan ruang lingkup otoritas rekayasa. Kompleksitas prosedur persetujuan menjadi hal yang harus dipertimbangkan saat berhubungan dengan pihak ketiga (*third party*) i.e. organisasi perikanan yang sangat melindungi kepentingannya.

Proses konstruksi pipa bawah laut yang terjadi di lapangan mempengaruhi kegiatan yang telah lama berlangsung pada lokasi tersebut i.e. kemunduran aktivitas oleh pihak ketiga yang kemudian memberikan dampak pada penurunan pendapatan.

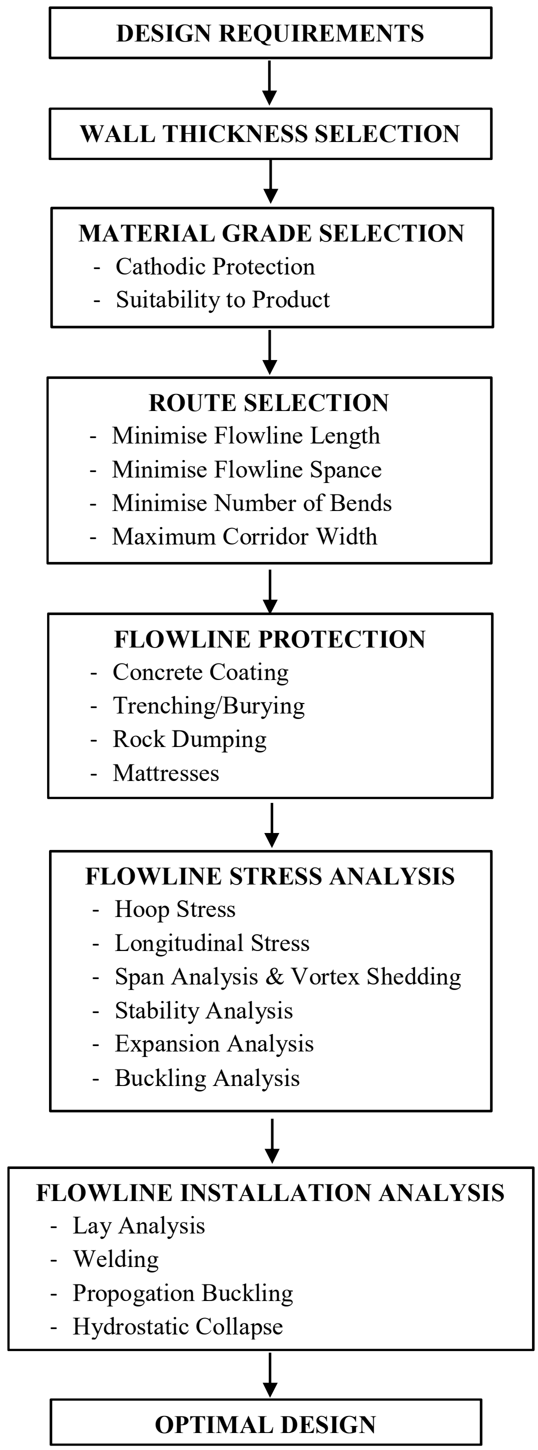
Untuk itu perlu untuk dipertimbangkan bagi pemilik kepentingan agar memiliki suatu agensi terstruktur yang bertugas khsuus menangani persoalan terkait perijinan penggunaan wilayah.

Rekomendasi ini agar harap dipertimbangkan dengan tujuan memberikan waktu dan sumber daya yang memadai dalam menjalankan perancangan.

c. Dampak Lingkungan

Belakangan aktivitas dalam bidang maritim khususnya pipa bawah laut telah terlindungi oleh badan otoritas nasional melalui penilaian dampak lingkungan/environmental impact assesment (EIA). Walaupun EIA tidak secara khusus mengkaji persoalan terkait pipa lepas pantai (offshore interfield pipelines) namun pada pipa yang melewati garis pantai akan sangat memberikan dampak lingkungan mengingat wilayah tersebut sebagai lokasi aktivitas manusia.

Pertimbangan-pertimbangan diatas dapat diperjelas menjadi kriteria-keriteria perancangan sistem perpipaan yang dipresentasikan melalui Gambar 2.4 di bawah ini:



Gambar 2. 4 Kriteria Perancangan Sistem Perpipaan (Bai and Bai, 2005)

2.2.4. Beban pada Sistem Perpipaan

Dalam bukunya: *Design and Installation of Marine Pipelines*, **Invalid source specified.** menguraikan jenis pembebanan yang harus dipertimbangkan dalam sistem perancangan pipa bawah laut, diantaranya adalah:

a. Beban Fungsional

Beban fungsional didefiniskan sebagai beban yang terjadi akibat dari beroperasinya pipa bawah laut. Beban fungsional mencakup seluruh efek yang ditimbulkan dari tekanan internal dan lonjakan tekanan pada pipa, serta temperatur operasi yang mampu mengakibatkan pembebanan dalam bentuk tegangan pada sistem perpipaan.

b. Beban Lingkungan

Beban lingkungan didefinisikan sebagai respon yang ditimbulkan oleh interaksi pipa dengan lingkungannya. Pada pipa bawah laut, beban lingkungan yang bekerja terhadapnya adalah gelombang dan arus perairan (*hydrodinamic loads*) yang mana dapat mempengaruhi tekanan & temperatur eksternal pipa.

c. Beban Kecelakaan

Beban kecelakaan didefinisikan sebagai beban yang memiliki kemungkinan untuk terjadi. Bahaya pada sistem perpipaan dapat dikategorikan menjadi bahaya alami (e.g. gempa bumi, tanah longsor, erosi gunung es, *etc*) dan bahaya pihak ketiga (e.g. kejatuhan benda anjungan, aktivitas pancing, pelepasan jangkar kapal, persenjatan dan pengeboman)

d. Beban Instalasi

Aktivitas teknis selama masa konstruksi harus dievaluasi dengan cermat untuk menghindari pembebanan yang berlebihan pada pipa, e.g. transportasi pipa sambungan; pemasangan tali untuk proses *laying*, *reeling*, *towing*, dan *pulling*; pengikatan pipa, aktivitas penggalian dan penimbunan pipa; *hydrostatic testing*, *etc*

2.2.5. Kondisi Pembebanan

Pipa yang telah melalui proses fabrikasi dan dinyatakan lolos sesuai persyaratan Berikut adalah kondisi pembebanan yang dialami oleh pipa:

a. Installation: Air-filled

Adalah kondisi dimana pipa dalam keadaan kosong (*empty*) dan belum terisi oleh fluida apapun. Pada saat instalasi pipa terkena beban dari metode instalasi itu sendiri dan beban lingkungan yang mempengaruhi kondisi instalasi.

b. Hydrotest*: *Water-filled

Adalah kondisi dimana pipa dialiri oleh fluida air laut untuk dilakukan pengujian terhadap ketahanan struktur pipa. Densitas air laut memiliki nilai yang paling besar dari konten apapun yang diangkut oleh pipa, sehingga pada kondisi pembebanan ini pipa akan memiliki berat maksimum.

c. *Operation: Pipeline Content*

Adalah kondisi dimana pipa mulai beroperasi dan mengangkut fluida yang sebenarnya. Pada kondisi ini pipa akan menerima beban dari peningkatan suhu yang drastis sebagai hasil dari aliran fluida di dalamnya. Perancangan sistem perpipaan harus memperhitungkan segala parameter yang dipengaruhi oleh kondisi operasi. Hal ini dikarenakan kondisi operasi merupakan kondisi terpanjang yang akan dialami sistem tersebut.

2.2.6. Kombinasi Pembebanan

Kombinasi pembebanan terhadap gelombang dan arus harus mampu merefleksikan kemungkinan respon paling ekstrim oleh pipa selama periode desainnya. Berikut adalah kondisi pembebanan yang bekerja pada pipa beserta pendekatan yang digunakan (DNVGL RP F109, 2017):

a. Kondisi Sementara (Instalasi)

Untuk kondisi instalasi yang berdurasi kurang dari 3 hari digunakan data harian cuaca yang telah terverifikasi secara resmi. Untuk kondisi instalasi yang berdurasi lebih dari 3 hari dan kurang dari 12 bulan digunakan periode ulang 10 tahunan.

Pendekatan kondisi instalasi menggunakan beban paling ekstrim diantara dua kondisi berikut:

- Periode ulang 10 tahun gelombang dikombinasikan dengan periode ulang 1 tahun arus.
- Periode ulang 1 tahun gelombang dikombinasikan dengan periode ulang 10 tahun arus.

Untuk kondisi instalasi yang berdurasi lebih dari 12 bulan digunakan kondisi pembebanan operasi.

b. Kondisi Permanen (Operasi):

Untuk kondisi operasi maupun instalasi yang berdurasi lebih dari 12 bulan digunakan periode ulang 100 tahunan.

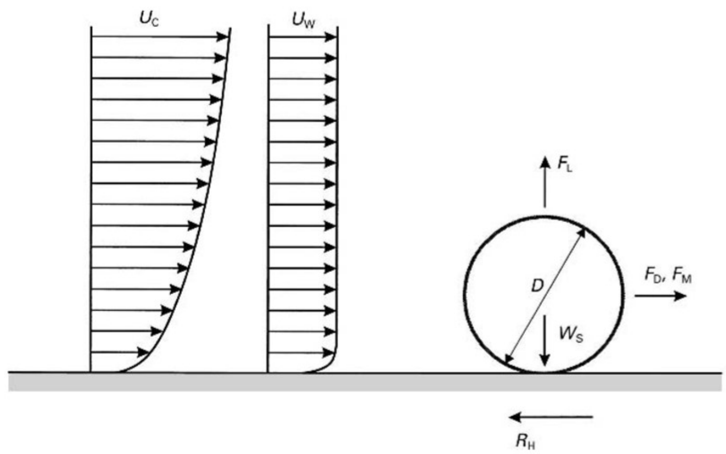
Pendekatan kondisi permanen menggunakan beban paling ekstrim diantara dua kondisi berikut:

- Periode ulang 100 tahun gelombang dikombinasikan dengan periode ulang 10 tahun arus.
- Periode ulang 10 tahun gelombang dikombinasikan dengan periode ulang 100 tahun arus.

2.2.7. Pendahuluan: Pipeline On-Bottom Stability

Struktur pipa apabila ditinjau secara satuan merupakan sebuah silinder kaku yang memiliki ketahanan sesuai kategori material penyusunnya. Namun, penyambungan pipa yang membentuk suatu bentang sistem memanjang, mengakibatkan pipa memiliki kelenturan struktur yang kemudian dapat berpotensi kegagalan pada pipa. Hal tersebut sudah harus menjadi pertimbangan mendasar dalam perancangan sistem perpipaan.

Pipa yang meletak bebas di dasar laut akan terkena pengaruh dari beban lingkungan yang bekerja terhadapnya i.e. gelombang dan arus perairan sebagai beban hidrodinamis. Apabila secara secara statis pipa tidak mampu menahan gaya tersebut, maka pipa akan terseret bersama dengan perpindahan energi yang terbawa oleh kecepatan aliran. Skema kondisi pipa di bawah laut terhadap beban arus dan beban gelombang (beserta gaya-gaya lain yang dihasilkan) dapat dilihat pada Gambar 2.5 di bawah ini:



Gambar 2. 5 Parameter *Pipeline On-Bottom Stability*
(Braestrup, et al., 2015)

On-bottom stability analysis adalah suatu perancangan terhadap berat terendam minimum yang dibutuhkan pipa agar mampu menahan beban lingkungan dan memastikan bahwa pipa dalam kondisi stabil di dasar laut.

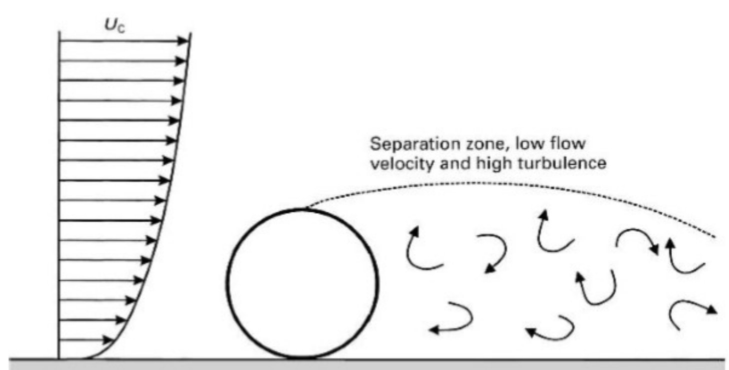
Menurut Bai et al (2015), pendekatan yang paling umum digunakan dalam industri untuk menilai suatu stabilitas pipa adalah dengan membuat asumsi konservatif berdasarkan pembebanan hidrodinamik dan ketahanan tanah.

Det Norske Veritas mengungkapkan dalam edisi DNVGL-RP-F109: *On-Bottom Stability Design of Submarine Pipelines*, untuk pipa dapat dinyatakan stabil di dasar laut harus memenuhi persyaratan stabilitas dimana beban hidrodinamis yang bekerja tidak lebih besar daripada tahanan tanah pada kondisi laut ekstrim (*ensuring absolute stability*); pergeseran pipa tidak lebih dari 1.5 diameternya (*ensuring no-break out*); pergeseran pipa maksimum yang boleh terjadi harus diakumulasikan secara detail terhadap waktu dimana mempertimbangkan jumlah gelombang yang terjadi (*allowing accumulated displacement*).

Sehingga dengan kriteria yang telah terumuskan, metode analitis yang dapat diterapkan dalam perhitungan stabilitas pipa adalah: [1] *Absolute Lateral Static Stability*, [2] *Generalised Lateral Stability* dan [3] *Dynamic Lateral Stability.*

2.2.8. Kecepatan Arus *Steady*

Pada umumnya, arus yang terjadi di lepas pantai diasumsikan sebagai aliran tenang (*steady current flow*) yang disebabkan oleh arus pasang surut (*tide*), arus akibat angin (*wind*) dan arus akibat gelombang badai (*storm surge)* yang tejadi di perairan tersebut. Sederhananya, arus dapat didefinisikan sebagai massa air yang terbawa per satuan volumenya (*density driven*).



Gambar 2. 6 Skema Arus Tenang terhadap Pipa
(Braestrup, et al., 2015)

Dari Gambar 2.6 di atas, diilustrasikan rasio kecepatan arus yang bekerja pada pipa terhadap kedalaman perairan, dimana arus akan semakin kecil seiring dengan peningkatan kedalaman perairan.

Pipa bawah laut terkena beban arus yang arah datangnya dipresentasikan sebagai θ_c. Arus diasumsikan tegak lurus dengan pipa atau $\theta_c = 90°$ apabila tidak terdapat informasi terkait besar sudut datang arus yang digunakan. Hal ini didasari oleh pertimbangan bahwasanya pipa akan terkena beban maksimum dari arus yang bekerja secara perpendicular terhadap pipa.

Secara umum, kecepatan arus yang mempertimbangkan efek lapisan batas bawah (*bottom boundary layer*) dirumuskan melalui persamaan berikut (DNVGL RP F109, 2017):

$$V(z) = V(z_r) . \left(\frac{ln(z+z_0)-ln\ _0}{ln(z_r+z_0)-ln\ _0}\right) . sin\theta_c \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(2.1)}$$

dimana *bottom boundary layer* didefinisikan sebagai parameter kekasaran dasar laut yang nilainya diberikan dalam Tabel 2.1 di bawah ini:

Tabel 2. 1 Parameter Kekasaran *Seabed* (DNVGL RP F109, 2017)

Seabed	*Grain size* d_{50} *[mm]*	*Roughness* z_0 *[m]*
Silt and clay	0.0625	$\approx 5\cdot10^{-6}$
Fine sand	0.25	$\approx 1\cdot10^{-5}$
Medium sand	0.5	$\approx 4\cdot10^{-5}$
Coarse sand	1.0	$\approx 1\cdot10^{-4}$
Gravel	4.0	$\approx 3\cdot10^{-4}$
Pebble	25	$\approx 2\cdot10^{-3}$
Cobble	125	$\approx 1\cdot10^{-2}$
Boulder	500	$\approx 4\cdot10^{-2}$

Sementara itu, kecepatan rata-rata arus yang tegak lurus terhadap pipa dan ditinjau terhadap diameter keseluruhan pipa dirumuskan sebagai (DNVGL RP F109, 2017):

$$V_c = V_c(z_r) . \left(\frac{\left(1+\frac{z_0}{D}\right).ln\left(\frac{D}{z_0}+1\right)-1}{ln\left(\frac{z}{z_0}+1\right)}\right) . sin\theta_c \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(2.2)}$$

dimana,

$V(z)$: *current velocity over a pipe diameter* [m.s^{-1}]

$V(z_r)$: *current velocity at reference height* [m.s^{-1}]

V_c : *mean current velocity over a pipe diameter* [m.s^{-1}]

$V_c(z_r)$: *mean current velocity at reference height* [m.s^{-1}]

z : *elevation equals to pipe diameter* [m]

z_0 : *seabed roughness parameter* (lihat Tabel 2.1)

z_r : *reference height of current velocity measurement* [m]

D : *overall diameter including coating of pipeline* [m]

θ_c : *angle between current direction and pipeline* [deg]

Kecepatan arus elevasi untuk sebaiknya diukur pada kedalaman dimana kecepatan arus rata-rata hanya memiliki perbedaan kecil dalam arah horizontalnya. Untuk arus yang bersifat non-linier perlu untuk modifikasi lanjutan dari profil *steady current*.

2.2.9. Transformasi Gelombang: Peristiwa Gelombang Pecah

Ketika suatu deretan gelombang bergerak menuju pantai, gelombang tersebut akan mengalami perubahan bentuk yang disebabkan oleh proses refraksi dan pendangkalan gelombang, difraksi, refleksi, dan gelombang pecah (Triatmodjo, 1999).

Teori gelombang yang digunakan pada perairan dengan kedalaman relatif konstan dapat digunakan untuk memprediksi transformasi dari karakteristik gelombang yang terjadi pada perairan dengan kedalaman yang cenderung bervariasi ketika gelombang merambat menuju pantai dari laut dalam menuju laut dangkal (DNV RP C205, 2010).

Refraksi terjadi karena adanya pengaruh perubahan kedalaman laut. Di daerah dimana kedalaman air lebih besar daripada setengah panjang gelombang, gelombang akan menjalar tanpa dipengaruhi dasar laut. Tetapi di laut transisi dan dangkal, penjalaran gelombang tersebut akan sangat dipengaruhi oleh dasar laut dikarenakan kedalaman yang relatif minimum.

Di daerah ini, apabila ditinjau suatu garis puncak gelombang, bagian puncak gelombang yang berada di air yang lebih dangkal akan menjalar dengan kecepatan yang lebih kecil daripada bagian di air yang lebih dalam. Akibatnya garis puncak gelombang akan membelok dan berusaha sejajar dengan garis kontur dasar laut.

Difraksi terjadi apabila tinggi gelombang di suatu titik pada garis puncak gelombang lebih besar daripada titik di dekatnya, yang menyebabkan perpindahan energi sepanjang puncak gelombang ke arah tinggi gelombang yang lebih kecil. Difraksi terjadi apabila suatu deretan gelombang terhalang oleh rintangan seperti pemecah gelombang atau suatu pulau.

Gelombang yang menjalar dari laut dalam menuju pantai akan mengalami perubahan bentuk. Di laut dalam bentuk gelombang adalah sinusoidal, sementara di laut transisi atau dangkal puncak gelombang akan semakin tajam sementara lembah gelombang akan semakin landai. Pada suatu kedalaman tertentu puncak gelombang akan mengalami ketajaman maksimum sehingga tidak stabil dan pecah. Setelah pecah, gelombang terus menjalar ke pantai, dan semakin dekat dengan pantai tinggi gelombang semakin berkurang.

Dalam hal ini, periode gelombang, T, akan bernilai konstan sementara kecepatan rambat gelombang, c, dan panjang gelombang, λ, akan menurun sedangkan tinggi gelombang, H, dan ketajamannya, S, akan meningkat.

Refraksi dan pengaruh penangkalan, difraksi, refleksi gelombang dan gelombang pecah akan menentukan tinggi gelombang dan pola (bentuk) garis puncak gelombang di suatu tempat di daerah pantai. Dalam analisis stabilitas pipa bawah laut, ketinggian gelombang menentukan besar pembebanan yang akan bekerja terhadap pipa.

a. *Shoaling*

Untuk gerakan dua dimensional, ketinggian gelombang meningkat sesuai dengan rumus:

$$\frac{H}{H_0} = K_S = \sqrt{\frac{C_{g.0}}{C_g}} \quad \text{..} \quad \textbf{(2.3)}$$

Kecepatan rambat gelombang dalam kedalaman tertentu:

$$C_{go}(d) = \frac{1}{2} \cdot \left[1 + \frac{\left(\frac{4\pi d}{L_{ref}(d)} \right)}{sinh\left(\frac{4\pi d}{L_{ref}(d)} \right)} \right] \cdot \left(\frac{gT_p}{2\pi} tanh\left(\frac{2\pi d}{L_{ref}(d)} \right) \right) \text{.... } \mathbf{(2.4)}$$

b. *Refraction*

Perubahan tinggi gelombang dirumuskan dalam:

$$\frac{H}{H_0} = K_s \cdot K_r \text{ .... } \mathbf{(2.5)}$$

Koefisien refraksi dirumuskan sebagai:

$$K_r(d) = \frac{1}{2} \cdot \left[\frac{1 - (\sin(\theta_0)^2 \left(tanh\left(\frac{2\pi d}{L_{ref}(d)} \right) \right)^2}{(cos(\theta_0))^2} \right]^{-\frac{1}{4}} \text{ .... } \mathbf{(2.6)}$$

2.2.10. *Wave Induced Parameter*: JONSWAP (*Short Term Wave*)

Dalam kenyataannya karakteristik gelombang di laut memiliki pola acak dimana elevasi maupun propagasinya tidak pernah berulang urutan kejadiannya (Djatmiko, 2012). Gelombang laut dapat terinduksi oleh berbagai macam sebab namun umumnya terjadi akibat pengaruh angin di perairan tersebut. Dimana mekanisme terjadinya gelombang tersebut karena adanya tekanan dan tahanan gesek antara angin dengan permukaan laut, yang diikuti oleh pemindahan energi dari angin ke laut (Philips, 1957 dan Miles 1956 dalam Djatmiko, 2012). Angin menyebabkan permukaan air mengalami osilasi yang terlihat dalam bentuk puncak atau lembah (Djatmiko, 2012).

Analisis gelombang acak dapat dilakukan dengan menggunakan perhitungan teori gelombang secara numerik maupun analitis, yang mana pada dasarnya diawali dengan mengevaluasi satu rekaman gelombang, yang disebut dengan analisis gelombang kurun waktu pendek (*short term wave analysis).* Metode ini dilakukan untuk mendapatkan informasi mengenai distribusi tinggi gelombang.

Teori gelombang yang digunakan harus mampu mempresentasikan kondisi perairan tersebut termasuk efek dari perairan dangkal jika dibutuhkan. JONSWAP (*Joint North Sea Wave Project*) adalah suatu teori gelombang yang digunakan pada perairan tertutup untuk mendapatkan susunan gelombang yang teratur dari sebuah gelombang irregular agar memudahkan dalam analisa. Persamaan matematis yang digunakan untuk menghitung parameter gelombang diberikan dalam DNVGL RP F109 (2017).

$$S_{\eta\eta}(\omega) = \alpha . g^2 . \omega^{-5} . exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right) . \gamma^{exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma.\omega_p}\right)^2\right)} \text{ .... } \textbf{(2.7)}$$

dimana,

$S_{\eta\eta}(\omega)$: *JONSWAP spectrum*

α : *generalized Philips' constant*

g : *acceleration of gravity* (9,81 m/s^2) [m.s^{-2}]

ω : *wave frequency* [rad/s]

ω_p : *peak wave frequency* [rad/s]

γ : *peak-enhancement factor*

σ : *spectral width parameter*

dengan konstanta Generalised Philips' yang dirumuskan dalam persamaan berikut:

$$\alpha = \frac{5}{16}\frac{{H_s}^2{\omega_p}^2}{g^2} . (1 - 0{,}287 . ln\gamma) \text{.................................. } \textbf{(2.8)}$$

dimana,

H_s : *significant wave height* [m]

dan parameter lebar spektra dengan ketentuan berikut:

$$\sigma = \begin{cases} 0.07 & \text{untuk } \omega \leq \omega_p \\ 0.09 & \omega > \omega_p \end{cases} \text{ .... } \textbf{(2.9)}$$

serta *peak-enhancement factor* yang diberikan sebagai:

$$\gamma = \begin{cases} 5{,}0 & \varphi \leq 3{,}6 \\ \exp(5.75 - 1.15\varphi) \quad \text{untuk} & 3{,}6 \leq \varphi \leq 5.0 \\ 1{,}0 & \varphi \geq 5.0 \end{cases} \quad \varphi = \frac{T_p}{\sqrt{H_s}} \ldots\ldots \quad \textbf{(2.10)}$$

Setelah itu, gelombang yang diinduksi oleh spektrum kecepatan (*wave induced velocity spectrum*) pada dasar laut didapat dari transformasi spektral gelombang di permukaan laut dengan teori geolombang orde 1 melalui persamaan berikut:

$$S_{UU}(\omega) = G^2(\omega) \, . S_{\eta\eta}(\omega) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(2.11)}$$

Fungsi tranfer G mentransformasikan elevasi permukaan laut menjadi gelombang yang diinduksi oleh kecepatan aliran di dasar laut melalui persamaan berikut:

$$G(\omega) = \frac{\omega}{\sinh(\mathrm{k.d})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(2.12)}$$

dimana,

$G(\omega)$: *transfer function*

k : *wave number*

d : *minimum water depth* [m]

dengan nilai k dan d didapatkan melalui iterasi dari persamaan transcendental berikut:

$$\frac{\omega^2}{g} = k. \tanh(k.d) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(2.13)}$$

Selanjutnya momen spektra gelombang pada orde-n didefinisikan melalui persamaan berikut:

$$M_n = \int_0^\infty \omega^n \, S_{UU}(\omega) d\omega \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(2.14)}$$

dan amplitudo kecepatan aliran signifikan yang melewati pipa dirumuskan dengan persamaan:

$$U_s = 2\sqrt{M_0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(2.15)}$$

Tidak direkomendasikan untuk mempertimbangkan karakteristik dasar laut dalam perhitungan kecepatan paertikel air akibat gelombang.

Sementara itu, *mean zero up-crossing period* akibat aliran yang berosilasi terhadap pipa dicari menggunakan persamaan:

$$T_u = 2\pi\sqrt{\frac{M_0}{M_2}} \quad \dots\dots \textbf{(2.16)}$$

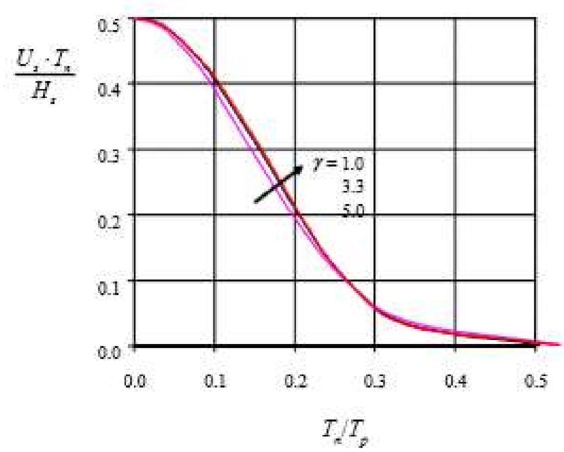
dimana,

M_0 : *zeroth order spectral moment*

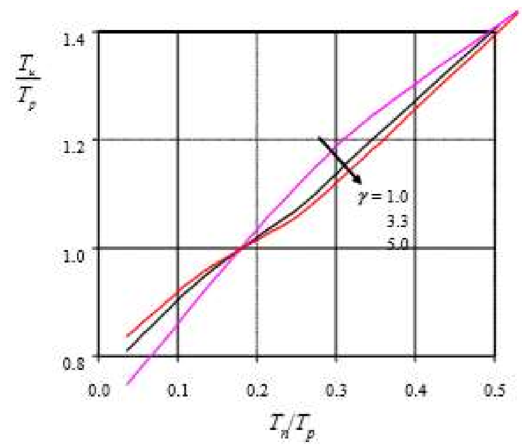
M_2 : *second order spectral moment*

Dengan mengasumsikan teori gelombang linier, U_s dapat ditentukan melalui grafik pada Gambar 2.7 dan T_u pada Gambar 2.8 berikut ini, dimana:

$$T_n = \sqrt{\frac{d}{g}} \quad \dots\dots \textbf{(2.17)}$$



Gambar 2. 7 Grafik Amplitudo Kecepatan Signifikan, U_s, di Dasar Laut (DNVGL RP F109, 2017)



Gambar 2. 8 Grafik *Mean Zero Up-Crossing*, T_u
di dasar Laut (DNVGL RP F109, 2017)

Rasio antara amplitudo kecepatan osilasi desain tunggal dan amplitudo kecepatan desain spektral untuk τ osilasi adalah:

$$k_U = \frac{U^*}{U_S} = \frac{1}{2} \cdot \left(\sqrt{2. ln\tau} + \frac{0.5772}{\sqrt{2..ln\tau}}\right) \text{..............................} \textbf{(2.18)}$$

dan rasio antara periode kecepatan osilasi desain tunggal dan periode *zero up-crossing* rata-rata adalah:

$$k_T = \frac{T^*}{T_S} = \begin{cases} k_t - 5 \cdot (k_T - 1). {}^{T_n}/_{T_u} & \text{untuk } {}^{T_n}/_{T_u} \leq 0.2 \\ 1 & {}^{T_n}/_{T_u} > 0.2 \end{cases} \text{.........} \textbf{(2.19)}$$

dengan,

$$k_t = \begin{cases} 1{,}25 & untuk\ \gamma = 1.0 \\ 1{,}21 & untuk\ \gamma = 3.3 \\ 1{,}17 & untuk\ \gamma = 5.0 \end{cases} \text{..} \textbf{(2.20)}$$

dimana,

τ : *number of oscillations*

k_U : *ratio between the design single oscillation velocity amplitude and the design spectral velocity amplitude*

k_T *: ratio between the design single oscillation period and the average zero-up crossing period*

k_t : *parameter of wave period*

2.2.11. Penetrasi Total Pipa

Penetrasi total merupakan kombinasi dari penetrasi awal pipa, penetrasi akibat pergerakan pipa di bawah laut, serta penetrasi akibat proses instalasi. Penetrasi yang disebabkan oleh *trenching* juga harus dipertimbangkan apabila kegiatan tersebut dilakukan. Penetrasi total yang terjadi dirumuskan sebagai (DNVGL RP F109. 2017):

$$Z_p = Z_{pi} + Z_{pm} + Z_{pl} \quad \text{(2.21)}$$

dengan penetrasi awal untuk tanah lempung (*clay*) dirumuskan sebagai (DNVGL RP F109, 2017):

$$Z_{pi} = 0.0071 \cdot \left(\frac{G_c{}^{0.3}}{k_c}\right)^{3.2} + 0.062 \cdot \left(\frac{G_c{}^{0.3}}{k_c}\right)^{0.7} \quad \text{(2.22)}$$

dimana,

Z_p : *total penetration depth of pipe* [m]

Z_{pi} : *initial penetration depth* [m]

Z_{pm} : *penetration depth due to movement* [m]

Z_{pl} : *penetration due to dyanamic laying* [m]

*catatan: nilai dari kedalaman penetrasi akibat pergerakan pipa dan akibat instalasi disesuaikan pada asumsi yang ditentukan pada saat perancangan.

Sementara penetrasi yang terjadi akibat aktivitas *trenching* dirumuskan sebagai (DNVGL RP F109. 2017):

$$\frac{Z_{pt}}{D} = \frac{1}{2} tan\theta_t \qquad \text{however} \qquad \leq \frac{Z_t}{2} \quad \text{(2.23)}$$

dimana,

Z_{pt} : *total penetration depth of pipe including trenching* [m]

θ_t : *slope angle of trench* [m]

Z_t : *trench depth* [m]

2.2.12. Reduksi Beban

Pergelaran pipa di dasar laut menimbulkan adanya interaksi antara pipa dengan permukaan tanah (*pipe-soil interaction*) yang mana mampu mereduksi besar beban lingkungan e.g. gelombang dan arus yang bekerja terhadap pipa. Reduksi beban total dirumuskan sebagai (DNVGL RP F109, 2017):

$$r_{tot,y} = r_{pen,y} \cdot r_{tr,y} \quad \text{.......} \quad \textbf{(2.24)}$$

$$r_{tot,z} = r_{perm,z} \cdot r_{pen,z} \cdot r_{tr,z} \quad \text{.......} \quad \textbf{(2.25)}$$

Melalui rumus diatas, dapat diuraikan bahwa reduksi beban dapat terjadi akibat adanya pengaruh dari kemampuan permeabilitas tanah, kedalaman penetrasi yang terjadi akibat berat terendam pipa terhadap parameter kekakuan tanahnya, serta aktivitas *trenching* yang mampu memberikan tahanan tanah terhadap pembebanan hidrodinamis oleh lingkungan.

a. Reduksi Beban Akibat *Permeable Seabed*

Tanah pada umumnya terdiri atas partikel-partikel yang tersusun dengan kerapatan tertentu sehingga membentuk ruang dan disebut sebagai pori-pori i.e. pipa dengan kemampuannya yang dapat tertembus oleh suatu zat (*permeability*). Pada tanah berpori, air dapat mengalir melalui bagian bawah pipa dan mengakibatkan berkurangnya beban vertikal atau gaya angkat (*lift force*) yang bekerja terhdapnya. *Clay* didefinisikan sebagai tanah dengan kemampuan tembus yang rendah dan tingkat kohesif yang tinggi. Sehingga, faktor reduksi beban untuk tanah *clay* berdasarkan permeabilitasnya dapat diasumsikan sebagai:

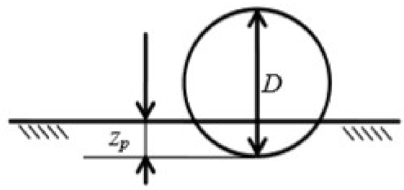
$$r_{perm,z} = 1 \quad \text{.......} \quad \textbf{(2.26)}$$

dimana,

$r_{perm,z}$: *vertical load reduction due to permeable seabed*

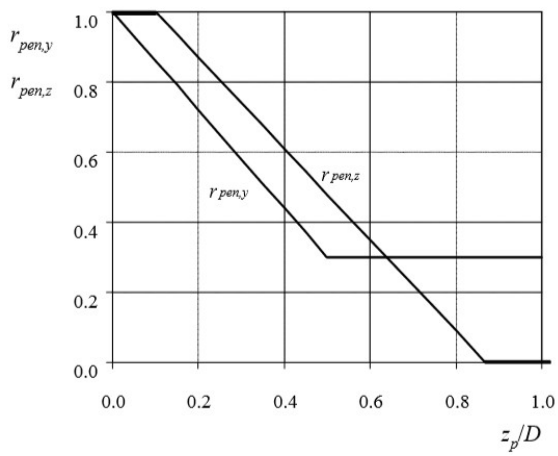
b. Reduksi Beban Akibat Penetrasi Pipa

Penetrasi pipa dapat terjadi apabila daya dukung tanah lebih kecil dibandingkan dengan tekanan efektif pipa akibat berat terendam pipa di bawah air. Penetrasi pipa yang terjadi dapat dilihat pada ilustrasi Gambar 2.9 di bawah ini:



Gambar 2. 9 Parameter Penetrasi Pipa Bawah Laut (DNVGL-RP-F109, 2017)

Reduksi beban akibat penetrasi pipa dapat ditentukan melalui grafik kurva pada Gambar 2.10 di bawah ini:



Gambar 2. 10 Grafik Faktor Reduksi Beban Akibat Penetrasi Pipa (DNVGL-RP-F109, 2017)

atau secara matematis dirumuskan melalui persamaan sederhana berikut ini (DNVGL RP F109, 2017):

$$r_{pen,y} = 1.0 - 1.4 \, . \frac{z_p}{D} \qquad \textit{however} \quad \geq 0.3 \; \ldots \; \textbf{(2.27)}$$

$$r_{pen,z} = 1.0 - 1.3 \, . \left(\frac{z_p}{D} - 0.1\right) \qquad \textit{however} \quad \geq 0.0 \; \ldots. \; \textbf{(2.28)}$$

dimana,

$r_{pen,y}$: *horizontal load reduction factor due to pipe penetration*

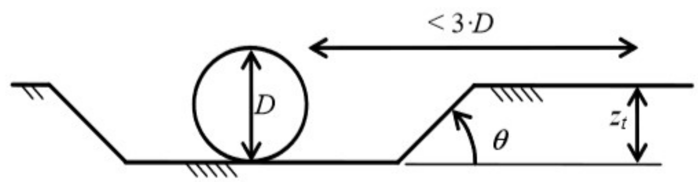
$r_{pen,z}$: *vertical load reduction factor due to pipe penetraion*

z_p : *total penetration depth* [m]

c. **Reduksi Beban Akibat Aktivitas *Trenching***

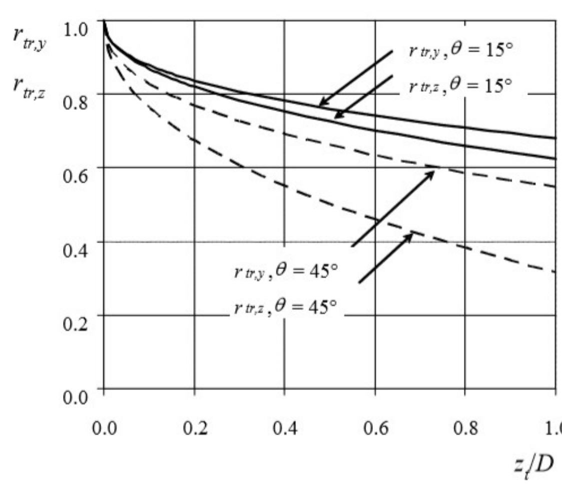
Pada dasarnya aktivitas penggalian tanah ini merupakan tahap awal dari proses pemendaman pipa yang telah ditetapkan dalam regulasi kementrian Republik Indonesia

Pemaritan di sepanjang sisi pipa dimaksudkan untuk menjaga kestabilan pipa di bawah air terhadap beban lingkungan dimana parameter *trenching* diilustrasikan dalam Gambar 2.11 di bawah ini:



Gambar 2. 11 Parameter *Trenching* pada Pipa Bawah Laut (DNVGL-RP-F109, 2017)

Reduksi beban dari aktivitas *trenching* dapat ditentukan melalui grafik kurva pada Gambar 2.12 di bawah ini:



Gambar 2. 12 Grafik Faktor Reduksi Beban Akibat *Trenching* (DNVGL-RP-F109, 2017)

atau secara matematis dirumuskan melalui persamaan sederhana berikut ini (DNVGL RP F109, 2017)::

$r_{tr,y} = 1.0 - 0.18 \, . \, (\theta_t - 5)^{0.25} \, . \left(\frac{z_t}{D}\right)^{0.42}$ jika $0.5 \leq \theta_t \leq 45$…**(2.29)**

$r_{tr,z} = 1.0 - 0.14 \, . \, (\theta - 5)^{0.43} \, . \left(\frac{z_t}{D}\right)^{0.46}$ jika $0.5 \leq \theta_t \leq 45$…**(2.30)**

dimana,

$r_{tr,y}$: *horizontal load reduction factor due to trenching*

$r_{tr,z}$: *vertical load reduction factor due to trenching*

θ_t : *slope angle of trench* [deg]

z_t : *trench depth* [m]

2.2.13. Beban Hidrodinamis: *Peak Loads*

$F_y^* = r_{tot\_y} \cdot \frac{1}{2} . \rho_w . D . C_y^* . (U^* + V^*)^2$ .... **(2.31)**

$F_z^* = r_{tot\_z} \cdot \frac{1}{2} . \rho_w . D . \boldsymbol{C_z^*} . (U^* + V^*)^2$ .... **(2.32)**

dengan,

F_y^* : *horizontal peak loads* [N.m^{-1}]

F_z^* : *vertical peak loads* [N.m^{-1}]

r_{tot_y} : *horizontal load reduction factor*

r_{tot_z} : *vertical load reduction factor*

ρ_w : *density of seawater* [kg.m^{-3}]

D : *total diameter of pipeline including coating* [m]

C_y^* : *horizontal peak loads coefficient*

C_z^* : *vertical peak loads coefficient*

U^* : *oscillatory velocity amplitude* [m.s^{-1}]

V^* : *steady current velocity* [m.s^{-1}]

Tabel 2.2 dan Tabel 2.3 berikut ini merupakan tabel acuan yang digunakan untuk menentukan koefisien beban puncak hidrodinamis yang bekerja pada pipa pada arah horizontal maupun vertikal,

Tabel 2. 2 Koefisien Beban Puncak Horizontal (DNVGL-RP-F109, 2010)

Table 3-9 Peak horizontal load coefficients

C_Y^*		K^*										
		2.5	*5*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*100*	*≥140*
M^*	0.0	13.0	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.7	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.09
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.05
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00
	5.0	1.11	1.10	1.07	1.06	1.04	1.01	1.00	1.00	1.00	1.00	1.00
	10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Tabel 2. 3 Koefisien Beban Puncak Vertikal (DNVGL-RP-F109, 2010)

Table 3-10 Peak vertical load coefficients

C_Z^*		K^*										
		≤2.5	*5*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*100*	*≥140*
M^*	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	5.0	0.91	0.92	0.93	0.91	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	10	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Untuk mendapatkan nilai dari C_y^* dan C_z^* pada tabel koefisien beban puncak diatas, terlebih dahulu mencari nilai K^* dan M^* melalui persamaan berikut:

$$K^* = \frac{U^*.T^*}{D} \qquad \textbf{(2.33)}$$

$$M^* = \frac{V^*}{U} \qquad \textbf{(2.34)}$$

dengan,

K^* : *significant Keulegan Carpenter Number*

M^* : *steady to oscillatory velocity amplitude ratio*

T^* : *single oscillation velocity period* [s]

D : *total diameter of pipeline including coating* [m]

2.2.14. *Pipe-Soil Interaction*: Tahanan Pasif Tanah

Tahanan tanah dapat disebabkan oleh pengaruh gesekan Coulumb murni (*Coulumb's friction*) serta tahanan pasif tanah, F_R yang diakibatkan dari penetrasi tanah pada saat pipa bergerak secara lateral (i.e. sejajar dengan sisinya) sehingga menimbulkan tumpukan tanah di sekitarnya.

Pasir (*sand*) didefinisikan sebagai tanah yang memiliki kemampuan tembus (*permeable*) dan efek kohesif i.e. partikel penyusun saling melekat satu dengan yang lain. Parameter terpenting dalam menjelaskan pipe-sand interaction adalah dengan memperhitungkan koefisien gesek dan berat terendam pasir. Pertimbangan khusus diperlukan jika tanah berpasir mengandung Kalsium Karbonanat dengan fraksi tinggi.

Lempung (*clay*) didefinisikan sebagai tanah yang tidak dapat tertembus dikarenakan efek kohesif yang siginifikan.

Batuan (*rock*) didefinisikan sebagai tanah berkerikil dengan 50% diameternya batuannya lebih besar dari 50 mm.

Tahanan pasif tanah pada tanah lempung dirumuskan melalui persamaan berikut (DNVGL RP F109, 2017):

$$\frac{F_{R,c}}{F_{C,c}} = \frac{4.1k_c}{{G_c}^{0.39}} \cdot \left(\frac{z_p}{D}\right)^{1.31} \quad \textbf{(2.35)}$$

dengan,

$$G_c = \frac{S_u}{D.\gamma_s} \quad \textbf{(2.36)}$$

dan,

$$k_c = \frac{S_u.D}{F_c} \quad \textbf{(2.37)}$$

dimana,

$F_{R,c}$: *passive soil resistance of clay* [N.m^{-1}]

$F_{c,c}$: *vertical contact force of clay* [N.m^{-1}]

k_c : *passive resistance factor for clay*

z_p : *penetration depth* [m]

D : *overall diameter including coating of pipeline* [m]

G_c : *clay soil stiffness parameter*

S_u : *clay undrained shear strength*

γ'_c : *sumberged unit soil weight for clay*

2.2.15. Analisis: *Vertical Stability Criteria*

2.2.15.1. Stabilitas di Air: Pengapungan (*Floatation*)

Pengapungan terjadi apabila berat terendam minimum pipa di bawah air tidak lebih besar daripada kemampuan apungnya akibat massa jenis air laut i.e. *pipeline with air-filled*. Untuk menghindari pengapungan tersebut, berat terendam minimum pipa harus memenuhi kriteria di bawah ini (DNVGL-RP-F109, 2017):

$$\gamma_w \cdot \frac{b}{w_s + b} = \frac{\gamma_w}{S_g} \leq 1.00 \qquad \text{……..…………………..…(2.38)}$$

dimana,

γ_w : *safety factor*

b : *pipeline buoyancy* [N.m^{-1}]

w_s : *pipeline submerged weight* [N.m^{-1}]

Apabila tidak dilakukan pertimbangan atas daya apung dalam arah negatif maka dapat diasumsikan bahwa $\gamma_w = 1.1$

2.2.15.2. Stabilitas di Tanah: Penenggelaman (*Sinking*)

Perancangan pada pipa yang dipendam harus mempertimbangkan kemungkinan terjadinya penggelaman pipa akibat berat terendam pipa yang melebihi kriteria ijin. Pada analisis stabilitas ini diperhitungan berat terendam maksimum pipa i.e. *pipeline with water-filled*.

Apabila berat spesifik pipa (termasuk muatan air) tidak lebih besar dari berat spesifik tanah maka tidak dibutuhkan analisis lanjutan terhadap penenggelaman pipa. Sementara pipa yang yang diletakkan pada tanah dengan kemampuan geser yang kecil, maka perhitungan terhadap tegangan tanah diperlukan

Untuk pipa yang dipendam dalam *soft cohesive soil*, analisa stabilitas menggunakan persamaan Terzaghi yang dirumuskan melalui persamaan berikut:

$$W_{max} \leq D \cdot (3.3 \cdot C_u + \rho_s \cdot (H + D)) \quad \textbf{(2.39)}$$

dimana,

W_{max} : *maximum allowable pipeline submerged weight*

D : *overal diameter of pipeline* [m]

C_u : *undrained shear strength of soil*

ρ_s : *submerged soil density*

H : *burial depth to top of pipe* (TOP) [m]

2.2.16. Analisis: *Absolute Lateral Static Stability Criteria*

Pipa dikatakan stabil secara lateral apabila terjadi keseimbangan statis antara tahanan pipa dengan beban maksimum hidrodinamis yang dapat mempengaruhi pergerakan pipa selama *sea-states.* Kriteria yang harus dipenuhi agar pipa mampu stabil secara lateral telah dirumuskan dalam DNVGL-RP-F109 (2017) sebagai berikut:

$$\gamma_{SC} \cdot \frac{F_y^* + \mu \,.\, F_Z^*}{\mu \,.\, w_s + F_R} \leq 1.0 \quad \textbf{(2.40)}$$

$$\gamma_{SC} \cdot \frac{F_Z^*}{w_s} \leq 1.0 \quad \textbf{(2.41)}$$

dimana,

γ_{SC} : *safety factor based on condition*

F_y^* : *horizontal peak load* [N.m^{-1}]

F_z^* : *vertical peak load* [N.m^{-1}]

μ : *friction coefficient*

w_s : *submerged weight of pipeline* [N.m^{-1}]

F_R : *passive soil resistance* [N.m^{-1}]

Safety factor yang digunakan dalam perancangan stabilitas pipa bawah laut dapat mengacu pada Tabel 2.4 – Tabel 2.7 di bawah ini:

Tabel 2. 4 *Safety Factor* untuk Kondisi *Cyclonic* di *Gulf of Mexico* (DNV RP F109, 2010)

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Tabel 2. 5 *Safety Factor* untuk Kondisi *Cyclonic* di *North West Shelf* (DNV RP F109, 2010)

Table 3-7 Safety factors, cyclonic conditions North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Tabel 2. 6 *Safety Factor* untuk Kondisi Badai Salju di *Gulf of Mexico* (DNV RP F109, 2010)

Table 3-6 Safety factors, winter storms in Gulf of Mexico and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Tabel 2. 7 *Safety Factor* untuk Kondisi Badai Salju di *North Sea* (DNV RP F109, 2010)

Table 3-5 Safety factors, winter storms in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

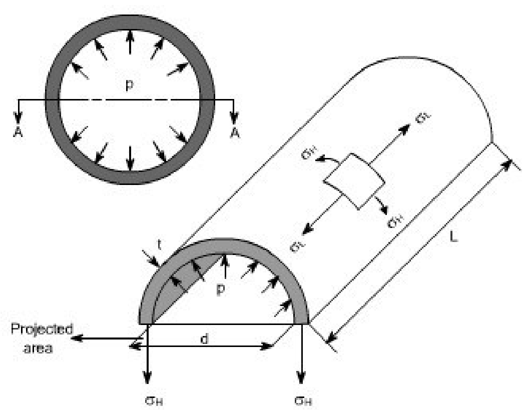
2.2.17. Teori Tegangan pada Sistem Perpipaan: Kriteria Ijin

Untuk memastikan kelayakan operasional pipa, perlu untuk dilakukan verifikasi terhadap kemungkinan tegangan maksimum yang dapat terjadi pada pipa. Apabila didapatkan hasil yang melebihi kriteria ijinnya, maka perancangan ulang diperlukan agar mendapatkan hasil yang optimum.

Tabel 2. 8 Kriteria Tegangan Ijin pada Pipa
(ASME B31.8, 2003, Table A842.22)

Design Condition	Allowable Criteria		
	Hoop Stress	**Longitudinal Stress**	**Von Mises Stress**
Installation	72% SMYS	80% SMYS	90% SMYS
Hydrotest	90% SMYS	-	96% SMYS
Operation	72% SMYS	80% SMYS	90% SMYS

Tegangan yang terjadi pada pipa umumnya disebabkan oleh perubahan tekanan maupun temperatur yang kemudian menghasilkan tarikan dalam arah tangensial maupun longitudinalnya.



Gambar 2. 13 Tegangan pada Sistem Perpipaan
(SemanticScholar, 2019)

2.2.17.1. Tegangan Gelung: *Hoop Stress*

Adanya fluida yang mulai dialirkan pada kondisi operasi mengakibatkan perubahan tekanan internal yang kemudian menginisiasi terjadinya tegangan gelung (*hoop stress*) di sepanjang lingkaran dinding pipa, dimana arah gayanya tegak lurus terhadap sumbu longitudinalnya. *Hoop stress* ditentukan melalui persamaan Barlow di bawah ini (ASME B31.8, 2003):

$$\sigma_H = \frac{\Delta P \cdot D}{2 \cdot t} \quad \text{.......................................} \quad \textbf{(2.42)}$$

dimana,

σ_H : *hoop stress* [MPa]

ΔP : *pressure difference* [MPa]

D : *nominal outside diameter of steel pipe* [m]

t : *nominal wall thickness of steel pipe* [m]

2.2.17.2. Tegangan Memanjang: *Longitudinal Stress*

Tegangan pada arah longitudinal pipa diakibatkan oleh pengaruh ekspansi termal dan faktor Poisson terhadap tegangan gelungnya.

$$\sigma_L = \sigma_T + \sigma_P \quad \text{.......................................} \quad \textbf{(2.43)}$$

Selengkapnya akan diuraikan melalui penjelasan di bawah ini:

a. Longitudinal Stress due to Thermal Expansion

Perubahan temperatur oleh muatan fluida mengakibatkan pipa mengalami ekspansi termal (pemuaian) pada arah longitudinalnya. Namun, pada pipa tertahan (*restrained*) e.g. *burried pipelines,* ekspansi terhambat oleh timbunan tanah di sekelilingnya sehingga berubah menjadi tegangan termal yang bersifat tekan (*compressive*). *Thermal expansion stress* pada pipa tertahan dirumuskan melalui persamaan berikut (ASME B31.8, 2003):

$$\sigma_T = E.\alpha.(T_1 - T_2) \quad \text{...............................} \quad \textbf{(2.44)}$$

dimana,

σ_T : *thermal expansion stress* [MPa]

E : *young's modulus of steel*

α : *thermal expansion coefficient*

T_1 : *installation temperature* [°C]

T_2 : *internal temperature (during operation)* [°C]

b. Longitudinal Stress due to Internal Pressure

Pada pipa yang tertahan akan timbul reaksi tegangan yang berifat tarik akibat pengaruh *Poisson* dari tegangan gelung. Sebagaimana diketahui bahwa pengaruh *Poisson* menggambarkan rasio regangan yang terjadi pada arah melintang terhadap regangan pada arah longitudinal. Dengan kata lain, tegangan gelung akan menimbulkan pengaruh tegangan tarik *poisson* pada arah longitudinal. Secara matematis, tegangan tarik longitudinal akibat pengaruh Poisson pada pipa tertahan dirumuskan melalui (ASME B31.8, 2003):

$$\sigma_P = v.\sigma_H \quad \text{.. } \mathbf{(2.45)}$$

dimana,

σ_P : *internal pressure force* [MPa]

v : *Poisson's factor*

2.2.17.3. Tegangan Kombinasi: *Von Mises Stress*

Tegangan ekuivalen *Von Mises* merupakan resultan dari seluruh komponen tegangan yang bekerja pada pipa, yang mana besarnya dapat ditentukan melalui persamaan berikut (ASME B31.8, 2003):

$$\sigma_v = \sqrt{(\sigma_H{}^2 + \sigma_L{}^2) - (\sigma_H.\sigma_L)} \quad \text{........................} \mathbf{(2.46)}$$

dimana,

σ_v : *von mises stress* [MPa]

2.2.18. *Effective Axial Compressive Force*

Gaya aksial efektif adalah gaya yang bekerja pada sumbu aksial pipa. karena pipa diletakann secara memanjang maka gaya aksial yang bekerja pada pipa adalah tegangan longitudinalnya. Dimana tegangan longitudinal diakibatkan oleh tegangan termal dan tegangan tarik akibat poisson.

Pada pipa tertahan gaya aksial efektif berubah menjadi gaya aksial kompresif dimana akibat penekanan ini, pipa terdorong untuk menekuk. Dikarenakan pipa tidak mampu untuk bergerak secara lateral diakibatkan oleh adanya tanah disekelilingnya, pipa mencuat ke atas dan menembus tanah timbunan yang kemudian disebut dengan peristiwa *upheaval buckling*. gaya akssial efektif dirmuskan melalui persamaan berikut:

$$\sigma_{ax} = T_{lay} - [\Delta P. A_i. (1 - 2v)] - [A_s. E. \alpha. \Delta T] \quad \text{........... (2.47)}$$

dimana,

σ_{ax} = *effective axial compressive force* [N.m^{-1}]

T_{lay} = *lay tension stress* [N.m^{-1}]

A_i = *internal area of steel pipe* [m^2]

A_s = *sectional area of pipeline* [m^2]

2.2.19. Available Downward Force

Available downward force adalah gaya vertikal ke bawah yang ditimbulkan oleh berat terendam pipa dan berat timbunan tanah diatasnya. Available d*ownward force* dirumuskan sebagai berikut (Palmer, 1990):

$$W_{down} = W_s + q \quad \text{.. (2.48)}$$

dengan,

$$q = S_u \cdot D \cdot min\left(3, \frac{H}{D}\right) \quad \text{...................................... (2.49)}$$

dimana,

W_{down} : *available downard force* [N.m^{-1}]

W_s : *submerged weight of pipeline based on condition* [N.m^{-1}]

q : *uplift resistance* [N.m^{-1}]

S_u : *undrained shear strength of cover material*

H : *burial depth above top of pipe* [m]

D : *overall external diameter of pipe* [m]

2.2.20. *Required Downward Force*

Required downward force adalah gaya minimum yang dibutuhkan untuk mencegah terjadinya *upheaval buckling* i.e. penekukan pipa ke atas akibat dari elongasi pipa yang tertahan. Oleh karena itu dibutuhkan tahanan yang cukup untuk melawan gaya aksial efektif pada pipa sehingga mampu menekan deformasi pipa untuk menekuk ke atas.

Besar *required downward force* bervariasi terhadap *imperfection height* yang diukur atau diasumsikan dalam perancangan. Hal ini dikarenakan perbedaan volume tanah timbunan akan menghasilkan gaya tahanan yang berbeda pula.

Required downward force dapat dihitung dengan menggunakan beberapa persamaan di bawah ini (Palmer, 1990):

$$L = \sqrt[4]{\frac{72 \cdot \delta \cdot E \cdot I}{W_s}} \qquad \text{……………………..…………………}\mathbf{(2.50)}$$

dimana,

L : *imperfection length* [m]

δ : *imperfection height* [m]

E : *young's modulus of steel*

I : *moment of inertia* [m^4]

W_s : *submerged weight of pipeline* [N.m^{-1}]

$$\phi_L = L \cdot \left(\frac{P}{E \cdot I}\right)^{\frac{1}{2}} \quad \text{...} \textbf{(2.51)}$$

dimana,

ϕ_L : *dimensionless imperfection length*

P : *effective axial force in operation* [MPa]

$\phi_L < 4.49$ $\phi_w = 0.0646$ .... **(2.52a)**

$4.49 < \phi_L < 8.06$ $\phi_w = \frac{5.68}{{\phi_L}^2} - \frac{88.35}{{\phi_L}^4}$ .... **(2.52b)**

$\phi_L > 8.06$ $\phi_w = \frac{9.6}{{\phi_L}^2} - \frac{343}{{\phi_L}^4}$ .... **(2.52c)**

dimana,

ϕ_w = *dimensionless maximum download parameter*

$$W_{req} = \frac{\phi_w \cdot \delta \cdot P^2}{W_S \cdot E \cdot I} \quad \text{...} \textbf{(2.53)}$$

dimana,

W_{req} = *required downward force to prevent UHB* [N.m^{-1}]

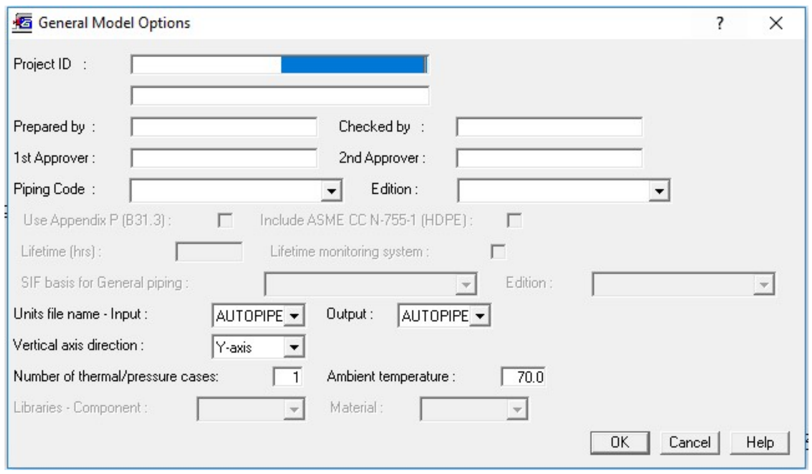
2.2.21. Analisis: *Pipeline Upheaval Buckling*

Sesuai konsep yang sebelumnya telah disebutkan bahwa mekanisme terjadinya *upheaval buckling* pada pipa adalah apabila gaya tahanan tanah tidak dapat menahan ekspansi pipa dalam bentuk gaya aksial efektifnya. Sehingga dapat dirumuskan bahwa angka keamanan pipa dari salah satu kegagalan struktur ini adalah sebagai berikut:

$$SF = \frac{W_{down}}{W_{req}} > 1.2 \quad \text{...} \textbf{(2.54)}$$

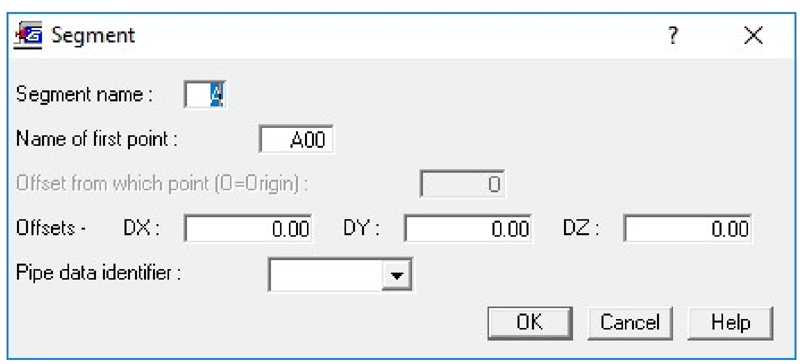
2.2.22. *Numerical Modelling*: AutoPipe by Bentley

Tahap pertama pemodelan pipa menggunakan *software* AutoPipe by Bentley adalah pendefinisian *codes and rules* yang digunakan pada pemodelan ini. *Codes* dan *rules* yang digunakan sebaiknya sesuai dengan acuan yang dipakai saat perhitungan manual agar didapatkan hasil yang sesuai. Didefiniskan pula sumbu pipa untuk menentukan arah horizontal dan vertikalnya. Satuan (units) juga dapat ditentukan sesuai kategori aturan satuan yang berlaku.



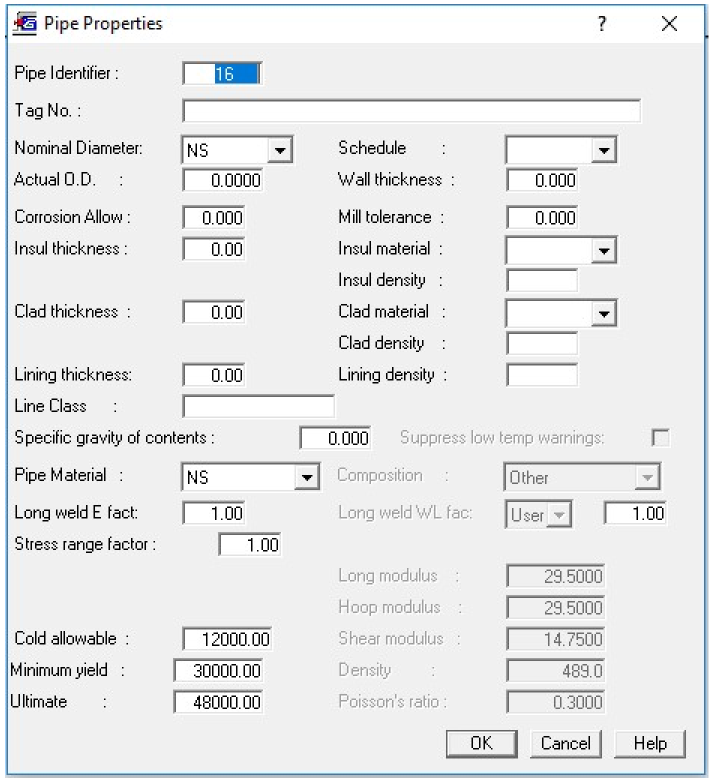
Gambar 2. 14 *Input AutoPipe: General Model Options* (AutoPipe, 2019)

Selanjutnya dilakukan pemodelan pipa berdasarkan koordinat pipa, yaitu x (arah memanjang), y (arah vertikal), z (arah melintang).



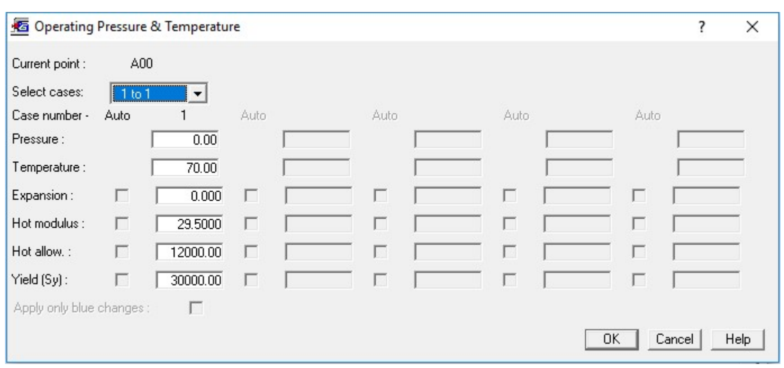
Gambar 2. 15 *Input AutoPipe: Segment Modelling* (AutoPipe, 2019)

Selanjutnya dilakukan pendefinisian material pipa sesuai dengan data pipa yang diperoleh. Dalam hal hal terpenting yang harus didefiniskan adalah diameter pipa, ketebalan dinding pipa, tebal lapisan luar dan dalam (jika ada).



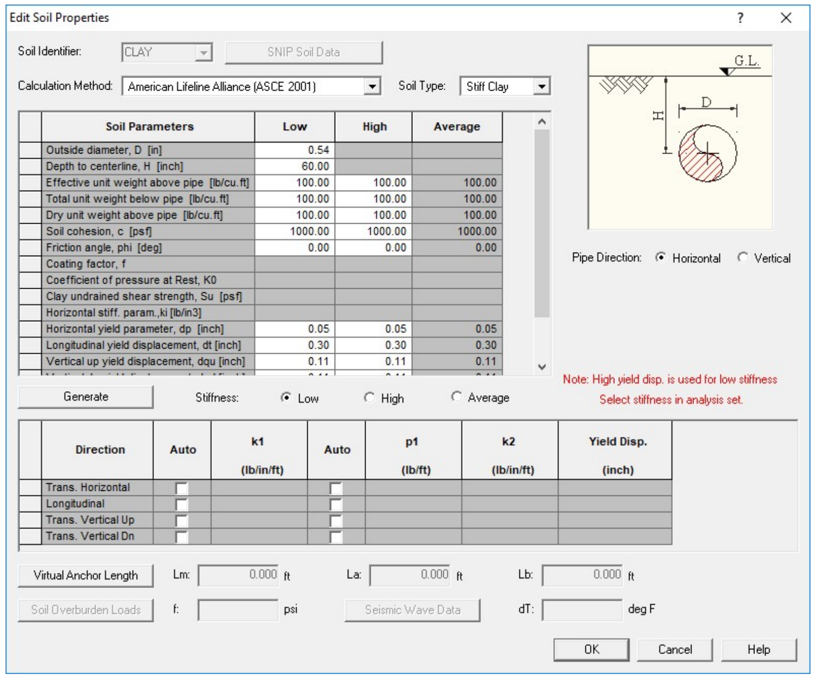
Gambar 2. 16 *Input AutoPipe: Pipe Properties* (AutoPipe, 2019)

Pembebanan yang dilakukan adalah pembebanan terhadap tekanan dan temperature yang bekerja terhadap pipa dikarenakan adanya fluida yang mengalir di dalamnya.



Gambar 2. 17 *Input AutoPipe: Operating Pressure & Temperature* (AutoPipe, 2019)

Tanah didefinisikan melalui *Soil Properties*. Dalam hal ini tanah dapat didefinisikan sebagai clay, sand dsb dan dapat dikategorikan sebagai soft, stiff, dsb seperti pada gambar di bawah ini:



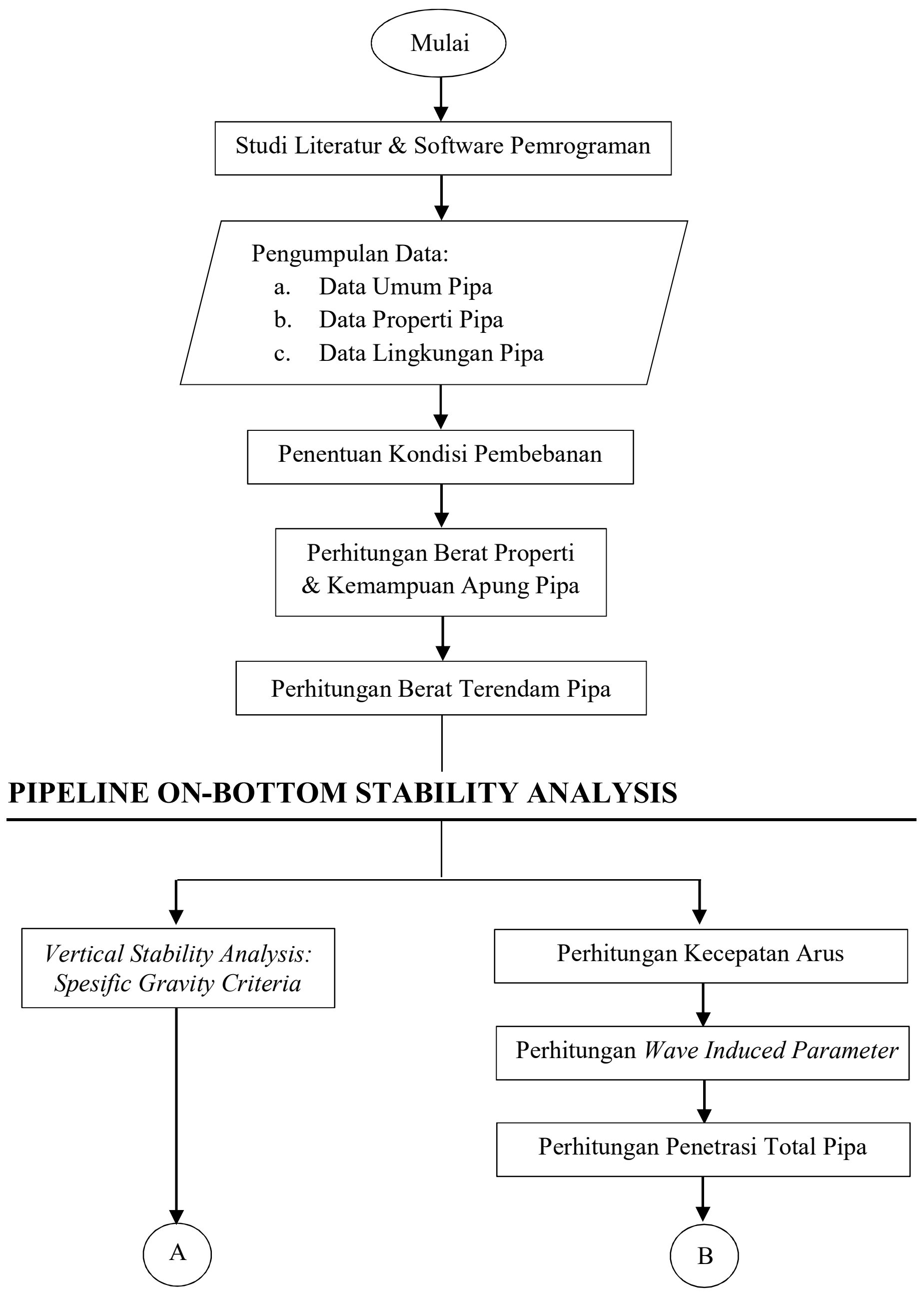
Gambar 2. 18 *Input AutoPipe: Soil Properties* (AutoPipe, 2019)

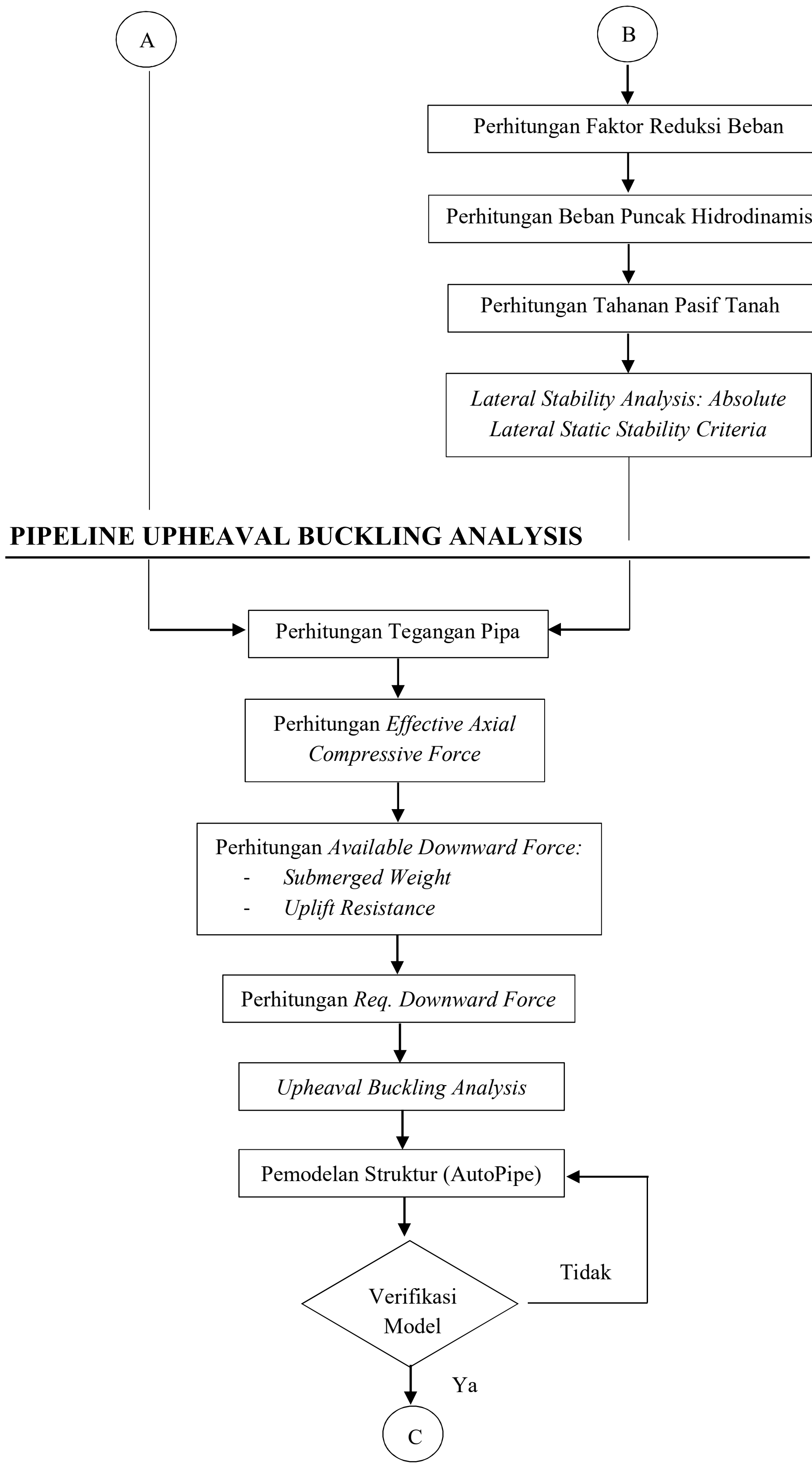
Setelah semua didefinisikan, dapat dilakukan *running*. *Running* dilakukan untuk mendapatkan nilai tegangan dan *displacement* yang terjadi terhadap pipa.

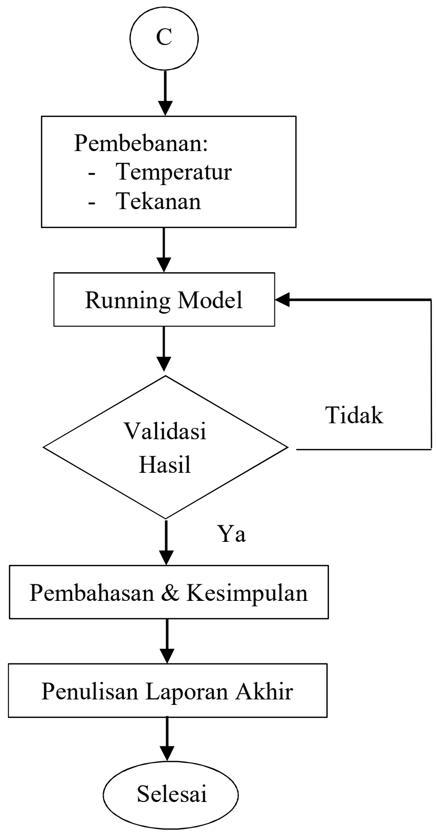
BAB III
METODOLOGI PENELITIAN

3.1. Diagram Alir Penelitian

Berikut adalah diagram alir yang digunakan dalam penelitian ini, terbagi menjadi *Pipeline On-Bottom Stability Analysis* dan *Pipeline Upheaval Buckling Analysis*:




A
B
Perhitungan Faktor Reduksi Beban
Perhitungan Beban Puncak Hidrodinamis
Perhitungan Tahanan Pasif Tanah
Lateral Stability Analysis: Absolute Lateral Static Stability Criteria
PIPELINE UPHEAVAL BUCKLING ANALYSIS
Perhitungan Tegangan Pipa
Perhitungan Effective Axial Compressive Force
Perhitungan Available Downward Force:
- Submerged Weight
- Uplift Resistance
Perhitungan Req. Downward Force
Upheaval Buckling Analysis
Pemodelan Struktur (AutoPipe)
Verifikasi Model
Tidak
Ya
C



Gambar 3. 1 Diagram Alir Penelitian

3.2. Deskripsi Prosedur Penelitian

Perumusan masalah yang telah dirangkum sebelumnya diselesaikan dengan mengacu pada alur penelitian. Diagram alir diatas adalah bentuk prosedur penelitian yang tersusun secara sistematis mengurutkan langkah-langkah dalam proses penelitian Tugas Akhir ini. Adapun deskripsi dari langkah-langkah umum tersebut adalah sebagai berikut:

A. GENERAL

1. **Studi Literatur dan Tinjauan Pustaka**

   Dilakukan peninjauan terhadap penelitian serupa sebagai pembanding dalam penyusunan metodologi penelitian Tugas Akhir ini. Studi literatur yang bersumber dari buku, jurnal penelitian, thesis, regulasi pemerintah, juga *codes and standards* menjadi pustaka yang memberikan pengetahuan dasar dalam menjalankan penelitian. Mempelajari pula *software* pemodelan yang mampu memvisualisasikan hasil analisis secara numerik

2. Pengumpulan Data

Penelitian ini menggunakan data milik PT. X dengan mengangkat studi kasus proyek pengembangan lapangan melalui pemanfaatan pipa bawah laut sebagai moda transportasi hasil produksi yang terkonfigurasi secara tumpuk: *16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline.* Pengumpulan data meliputi data umum pipa, data properti pipa, parameter desain dan operasi serta data lingkungan sebagai lokasi operasional pipa. Selengkapnya akan terlampir pada [Bab IV – Analisis, Pembahasan dan Pemodelan].

3. Penentuan Kondisi Pembebanan

Dalam penelitian ini dilakukan analisa terhadap tiga kondisi pembebanan: instalasi, *hydrotest* dan operasi. Selengkapnya akan dipaparkan pada [Bab IV – Analisa, Pembahasan dan Pemodelan].

4. Perhitungan Berat Properti & Buoyancy Pipa

Properti yang menyusun struktur pipa bawah laut diantaranya: pipa baja (*steel pipe*), lapisan anti korosi (*anti-corrosion coating*), lapisan beton pemberat (*concrete weight coating*), lapisan sambungan (*field joint coating*), dan material pengisi (*infill material*). Sedangkan *buoyancy* adalah kemampuan pengapungan oleh pipa akibat adanya respon dari massa tercelup pipa dengan massa jenis air laut.

5. Perhitungan Berat Terendam Pipa

Berat terendam pipa adalah berat struktur pipa dan pengaruh *buoyancy*nya di bawah air. Konten pipa dipengaruhi oleh kondisi pembebanan yang ditentukan. Selengkapnya akan diuraikan pada [Bab IV – Analisa, Pembahasan dan Pemodelan].

6. ***Vertical Stability Analysis: Spesific Gravity Criteria***

Dilakukan analisis stabilitas vertikal untuk mengetahui kestabilan pipa terhadap pengapungan. Apabila kemampuan apung pipa lebih besar daripada berat terendamnya, maka kemungkinan besar pipa akan mengalami pengapungan dan terjadi ketidakstabilan pipa. Untuk itu dilakukan analisis untuk membuktikan stabilitas vertikal pipa berdasarkan kriteria *spesific gravity.*

7. **Perhitungan Kecepatan Arus**

Melakukan perhitungan terhadap arus yang melewati pipa dengan menggunakan kecepatana arus referensi yang diukur pada ketinggian referensi. Perhitungan arus *steady* menggunakan pers 2.1 yang termuat dalam [Bab II – Tinjauan Pustaka & Dasar Teori].

8. **Perhitungan *Wave Induced Parameters***

Beban hidrodinamis yang bekerja terhadap pipa merupakan pengaruh dari arus dan gelombang perairan. Untuk menentukan karakteristik gelombang perairan digunakan parameter spektrum JONSWAP yang mampu merepresntasikan rekam gelombang kurun waktu pendek yang terjadi pada lokasi perairan tertutup. Dengan spektrum JONSWAP akan didapatkan kecepatan partikel air dan periode osilasinya terhadap pipa. Persamaan yang digunakan pada tahap ini diuraikan dalam [Bab II – Tinjauan Pustaka & Dasar Teori].

9. **Perhitungan Penetrasi Total Pipa**

Pentrasi pipa yang terjadi diakibatkan oleh penetrasi awal pipa, penetrasi akibat pegerakan pipa, penetrasi akibat instalasi serta penetrasi akibat *trenching.* Penetrasi total merupakan kombinasi dari pertimbangan-pertimbangan tersebut.

10. **Perhitungan Faktor Reduksi Beban**

Beban hidrodinamis yang dipengaruhi oleh gelombang serta arus perairan dapat tereduksi akibat adanya interaksi antara pipa dengan tanah (*pipe-soil interaction*) yang disebabkan oleh sifat permeablitas dari tanah, penetrasi tanah, serta aktivitas *trenching*. Reduksi beban total yang bekerja pada pipa dalam horizontal dan vertikal sesuai dengan pers. 2.16 dan pers. 2.17 pada [Bab II – Tinjauan Pustaka & Dasar Teori].

11. Perhitungan Beban Puncak Hidrodinamis

Dengan menggunakan koefisien beban puncak yang didapatkan melalui interpolasi nilai M dan KC pada Tabel 2.2 dan Tabel 2.3 di [Bab II – Tinjauan Pustaka & Dasar Teori], akan didapatkan besar beban puncak hidrodinamis yang tejadi pada pipa dimana beban puncak ini adalah beban maksimum yang bekerja pada pipa dengan mempertimbangkan faktor reduksi yang terjadi akibat penetrasi pipa. Beban puncak hidrodinamis terjadi dalam arah horizontal dan vertikal terhadap pipa dan besarnya dapat ditentukan melalui pers. 2.28 dan 2.29 pada [Bab II – Tinjauan Pustaka & Dasar Teori].

12. Perhitungan Tahanan Pasif Tanah

Akibat yang ditimbulkan dari adanya penumpukan tanah di sekitar pipa menimbulkan gaya tahanan yang bersifat pasif terhadap stabilitas pipa di bawah laut. Gaya tahanan ini akan mencapai nilai konstan apabila telah terjadi kedalaman penetrasi maksimum yang dapat terjadi. Peninjauan lanjutan akan dipaparkan pada [Bab IV – Analisa, Pembahasan dan Pemodelan].

13. *Absolute Lateral Static Stability Analysis*

Absolute lateral static stability adalah kriteria stabilitas pipa bawah laut dimana tidak mengizinkan adanya pergeseran pipa secara lateral sehingga pipa dapat dikatakan stabil. Dalam analisis stabilitas mutlak, berat terendam, beban hidrodinamis, dan tahanan tanah menentukan tingkat stabilitas pipa. Pipa dapat dikatakan stabil apabila memenuhi kriteria yang telah dirumuskan dalam pers. 2.xx

C. PIPELINE UPHEAVAL BUCKLING ANALYSIS

14. Perhitungan Tegangan Pipa

Dilakukan pengecekan tegangan yang bekerja pada pipa akibat pengaruh dari perbedaan temperatur dan tekanan yang terjadi pada kondisi instalasi menuju operasi dengan kriteria tegangan maksimum yang diperbolehkan sesuai dengan material pipa.

15. Perhitungan Gaya Aksial Effektif

Gaya aksial yang terjadi pada pipa adalah gaya yang diakibatkan oleh tegangan longitudinalnya dikarenakan pipa meletak secara memanjang di dasar laut. Dengan kata lain, gaya aksial tersebut terbentuk karena adanya ekspansi yang disebabkan oleh perubahan temperatur dan tekanan.

16. Perhitungsn *Available Downward Force*

Available downward force adalah gaya vertikal ke bawah yang dihasilkan oleh kombinasi antara berat terendam pipa bawah laut dengan resistensi tanah timbunan (*uplift resistance*).

17. Perhitungan Required Downward Force

Required downward force adalah suatu gaya minimum yang dibutuhkan oleh pipa untuk menekan gaya angkat (*uplift force*) akibat elongasi pipa yang tertahan. Nilai dari *downward force* akan bervariasi sesuai dengan *imperfection height* dimana ketidakmerataan kontur dasar laut tersebut akan semakin memeperbesar kemungkinan terjadinya *upheaval buckling*.

18. *Upheaval Buckling Analysis*

Analisis dilakukan pada sepanjang jalur pipa dengan kondisi fully corroded case sebagai kondisi real operasional.

19. Pemodelan Struktur: AutoPipe

Struktur dimodelkan menggunakan *software* AutoPIPE oleh Bentley sepanjang ±5 km dengan mempertimbangkan karakteristik material pipa yang termuat dalam pengumpulan data.

20. Pembebanan

Selanjutnya dilakukan pembebanan terhadap pipa yaitu temperatur dan tekanan operasi. Dimasukkan pula parameter lingkungan e.g. gelombang dan tanah sebagai pembebanan terhadap model struktur.

21. Running Model

Dilakukan *running model* dengan mengkombinasikan model struktur yang telah dibuat dengan pembebanan yang sesuai dengan tinjauan analisa penelitian.

22. Verifikasi Hasil

Dilakukan perbandingan terhadap hasil perhitungan manual dengan hasil pemodelan numerik dan meminimalisir nilai error yang terjadi.

23. Kesimpulan & Saran

Melakukan pembahasan terhadap penelitian yang dilakukan serta menarik kesimpulan terkait faktor-faktor yang mempengaruhi penekukan pipa secara vertikal.

24. Pembahasan & Kesimpulan

Melakukan pembahasan terhadap penelitian yang dilakukan serta menarik kesimpulan terkait faktor-faktor yang mempengaruhi stabilitas pipa baik secara vertikal maupun lateral.

25. Penulisan Laporan Tugas Akhir

Dilakukan dokumentasi terhadap penelitian yang telah dilakukan melalui format laporan Tugas Akhir. Hal-hal yang termuat dalam pendokumentasian adalah pendahuluan, tinjauan pustaka dan dasar teori, metodologi penelitian, analisis dan pemodelan, kesimpulan & saran serta lampiran yang memuat perhitungan selama pernelitian berlangsung.

BAB IV
ANALISIS, PEMBAHASAN DAN PEMODELAN

4.1. Lokasi Pengamatan

Penelitian ini dilakukan terhadap pipa bawah laut yang beroperasi sepanjang ±5 km menghubungkan *Wellhead Platform* dengan *onshore Wellsite* yang berada di utara Gresik, Jawa Timur, Indonesia. *Wellhead Platform-X* melakukan produksi gas alam dan minyak mentah yang kemudian disalurkan ke sebuah CPP (*Compression & Processing Platform*) untuk dipisah dan dikompresi melewati proses pemompaan. Hasil dari proses ini akan diangkut oleh pipa produksi 16 inch yang terkonfigurasi secara tumpuk dengan pipa gas 6 inch. Proyek ini merupakan suatu pengembangan lahan dengan memanfaatkan penggunanan pipa bawah laut untuk mentransmisikan hasil produksi oleh sumur eksploitasi dikarenakan kedalaman perairan yang sangat minimum sehingga penggunaan *tanker* dianggap kurang relevan berdasarkan kondisi yang ada.

Gambar 4. 1 Peta Lokasi Penelitian (*Google Earth*, 2019)

Tabel 4. 1 Lokasi Fasilitas *(X, 2018)*

Structure	Grid Coordinates	
	Easting (m)	**Northing (m)**
Onshore Wellsite	670 308.74	9 241 915.46
WHP-X	673 460.00	9 245 660.00

4.2. Pengumpulan Data

4.2.1. Parameter Desain dan Operasi

Berikut adalah parameter desain dan operasi dari *16" Production Pipeline* dan *6" Gas Lift Pipeline* yang disajikan dalam Tabel 4.2 di bawah ini:

Tabel 4. 2 Parameter Desain dan Operasi (X, 2018)

Description	Units	Value	
		16" Production Pipeline	6" Gas Lift Pipeline
Design Pressure	MPa	13.8	13.8
Design Temperature (Min./Max.)	°C	-29/90	-29/65
Maximum Operating Pressure	Mpa	1.92	9.51
Maximum Operating Temperature	°C	69.34	35.00
Hydrotest Pressure	MPa	20.7	20.7
Hydrotest Temperature	°C	25	25

4.2.2. Parameter Umum dan Properti Pipa

Berikut adalah parameter umum dan properti pipa dari *16" Production Pipeline* dan *6" Gas Lift Pipeline* yang disajikan dalam Tabel 4.3 di bawah ini:

Tabel 4. 3 Parameter Umum Pipa (X, 2018)

Parameter	Unit	Value	
		16" Production Pipeline	6" Gas Lift Pipeline
Nominal Pipe Size	-	16	6
Nominal Outside Diameter	mm	406.4	168.3
Manufacturing Process	-	ERW/HFW	SMLS
Material Type and Grade	-	API 5L X65 PSL2 NACE	
SMYS	MPa	450 (65300 psi)	
SMTS	MPa	535 (77600 psi)	
Steel Density	kg/m^3	7850	
Poisson's Ratio of Steel	-	0.3	

Young's Modulus of Steel	MPa	207000
Shear Modulus of Steel	MPa	79300
Thermal Expansion Coefficient	1/ºC	1.17 x 10^{5}
Pipe Joint Length	m	12.2

Untuk melindungi pipa dari lingkungan yang bersifat korosif, pipa dilapisi oleh lapisan anti korosi yang mana parameter lapisan ini disajikan dalam Tabel 4.4:

Tabel 4. 4 Parameter Lapisan Anti-Korosi Pipa (X, 2018)

Parameter	Unit	Value	
		16" Production Pipeline	6" Gas Lift Pipeline
Anti-Corrosion Coating Type	-	3LPE	
Anti-Corrosion Coating Thickness	mm	3.5	
Anti-Corrosion Coating Density	kg/m^3	940	
Anti-Corrosion C. Cutback Length	mm	150	

Pipa harus dapat dipastikan stabil secara vertikal maupun lateral selama kondisi instalasi, *hydrotest* dan operasi. Penambahan berat terendam pipa dapat menggunakan lapisan beton pemberat, yang mana parameter lapisan beton pemberat dari *16" Production Pipeline* disajikan dalam Tabel 4.5 berikut ini:

Tabel 4. 5 Parameter Lapisan Beton Pemberat (X, 2018)

Parameter		Unit	Value
Concrete Coating Thickness	KP 0+000 – KP 0+273	mm	0
	KP 0+273 – KP 1+393	mm	40
	KP 1+393 – KP 5+725	mm	60
Concrete Weight Coating Density		kg/m^3	3040
Concrete Weight Coating Cutback Length		mm	200
Maximum Water Absorption		%	5

*Catatan:

1. Pada 6" Gas Lift Pipeline tidak diberikan lapisan beton pemberat.

Pada segmen sambungan pipa, diberikan properti dengan parameter yang disajikan dalam Tabel 4.6 di bawah ini:

Tabel 4. 6 Parameter Lapisan Sambungan Pipa (X, 2018)

Parameter	Unit	Value	
		16" Production Pipeline	6" Gas Lift Pipeline
Field Joint Coating Type	-	HSS	
Field Joint Coating Density	kg/m^3	930	
Infill Material Type	-	HDPU	N/A
Infill Material Density	kg/m^3	1025	N/A

4.2.3. Parameter Muatan Pipa

Berikut adalah Tabel 4.7 yang menyajikan parameter dari muatan yang diangkut oleh *16" Production Pipeline* dan *6" Gas Lift Pipeline*:

Tabel 4. 7 Parameter Muatan Pipa (X, 2018)

Parameter	Unit	Value	
		16" Production Pipeline	6" Gas Lift Pipeline
Minimum Content Density	kg/m^3	73.83	109.85
Maximum Content Density	kg/m^3	126.58	111.88

4.2.4. Parameter Lingkungan

Parameter lingkungan sebagai lokasi pergelaran pipa bawah laut (*piggyback pipeline*) disajikan dalam Tabel 4.8, Tabel 4.9, Tabel 4.10, Tabel 4.11, Tabel 4.12, dan Tabel 4.13 di bawah ini:

Tabel 4. 8 Parameter Kedalaman Perairan (X, 2018)

Parameter	Units	Value
Maximum Water Depth along the Route	m	4.5
Minimum Water Depth along the Route	m	0.0

Tabel 4. 9 Parameter Gelombang Perairan (X, 2018)

Parameter	Unit	Value	
		1-yr RP	**100-yr RP**
Significant Wave Height	m	0.79	0.93
Peak Period of Wave	s	7.72	10.13
Zero-Up Crossing Period	s	4.86	5.89
Maximum Wave Height	m	1.46	1.73
Wave Period of Maximum Wave	s	5.89	7.16

Tabel 4. 10 Parameter Arus Perairan (X, 2018)

Parameter	Unit	Value	
		1-yr RP	**100-yr RP**
Current Velocity at 1 m above Seabed	m/s	0.31	0.35

Tabel 4. 11 Parameter Pasang Surut Perairan (X, 2018)

Parameter	Units	Elevation	Elevation (MSL)
Highest Astronomical Tide (HAT)	m	2.79	1.4
Mean Sea Level (MSL)	m	1.4	0
Lowest Astronomical Tide (LAT)	m	-0.07	-1.4

Tabel 4. 12 Parameter Air laut (X, 2018)

Parameter	Units	Value
Seawater Density	kg/m^3	1025
Minimum Seawater Temperature	°C	25.00
Average Seawater Temperature	°C	28.70
Maximum Seawater Temperature	°C	31.00
Kinematics Viscocity of Seawater	m^2/s	0.96×10^{-6}

Tabel 4. 13 Parameter Tanah Dasar Laut (X, 2018)

Parameter	Units	Value
Soil Type	-	Clay
Undrained Shear Strength	kPa	2
Submerged Unit Weight	N/m^3	8090
Depth of Measurement	m	2.0 - 3.0

4.2.5. Parameter *Trenching*

Berikut adalah Tabel 4.14 berisi parameter kedalaman *trenching* yang digunakan dalam analisis perbandingan pipa *exposed* dengan pipa *trenched* yang berlokasi di area *shore approach*. Kedalaman *trenching* diukur dari *bottom of pipe* hingga permukaan dasar laut aktual atau sama dengan total diameter luar pipa (pipa 16 inch dan pipa 6 inch serta *gap* di antara keduanya) ditambah dengan ketinggian tanah timbun.

Tabel 4. 14 Parameter Aktivitas *Trenching* (X, 2018)

Parameter		Unit	Value
Trenching Depth	KP 0+273 – KP 1+393	m	2.749
	KP 1+393 – KP 5+725	m	2.789
Trenching Slope		deg	> 45

PIPELINE ON-BOTTOM STABILITY ANALYSIS

4.3. Penentuan Kondisi Pembebanan

Dalam melakukan analisis stabilitas pipa, perlu untuk kita menentukan terlebih dahulu kondisi pembebanan yang akan ditinjau dalam penelitian. Hal ini menjadi pertimbangan penting dikarenakan angka stabilitas pipa akan bergantung pada kondisi yang terjadi pada pipa.

Sebagai contoh adalah parameter lingkungan yang menggunakan periode ulang 1 tahunan untuk kondisi instalasi dan 100 tahunan untuk kondisi operasi. Disamping parameter lingkungan, berikut adalah beberapa parameter yang mempengaruhi properti pipa berdasarkan kondisi pembebanan terangkum dalam Tabel 4.15 di bawah ini:

Tabel 4. 15 Parameter Pipa Berdasarkan Kondisi Pembebanan

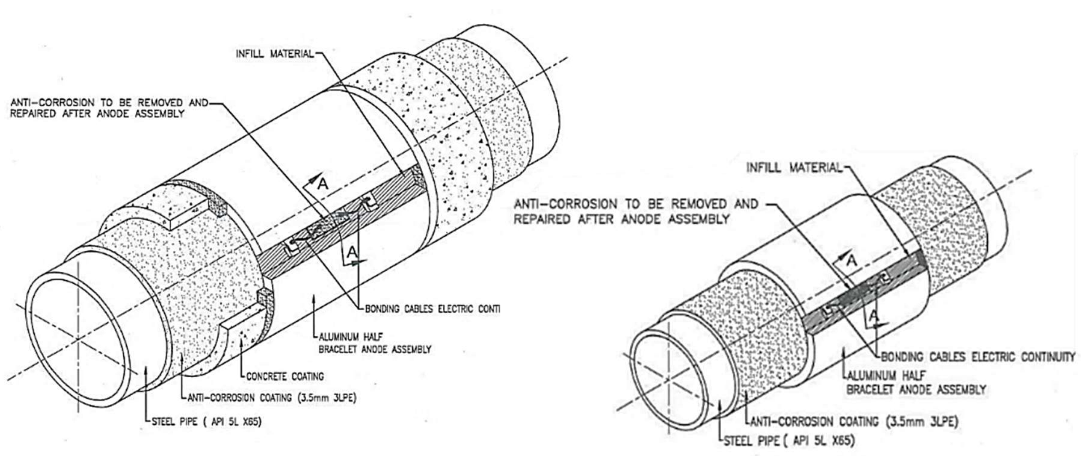
Parameter		Installation	Hydrotest	Operation
Corrosion Allowance		0%	0%	100%
Water Absorption		0%	0%	5%
Density of Content	16” Pipeline	0 $kg.m^{-3}$	1025 $kg.m^{-3}$	73.83 $kg.m^{-3}$
	6” Pipeline	0 $kg.m^{-3}$	1025 $kg.m^{-3}$	109.85 $kg.m^{-3}$

Untuk kondisi instalasi dan *hydrotest* diasumsikan belum terjadi korosi dan penyerapan air oleh lapisan beton pemberat, sedangkan pada saat kondisi operasi pipa diasumsikan telah terokorosi penuh (*fully corroded case*) dan terjadi penyerapan air sebanyak 5% dari diameter total pipa.

Untuk kondisi instalasi, pipa diasumsikan berada dalam kondisi kosong tanpa muatan (*air-filled*) sedangkan pada kondisi *hydrotest* pipa mengalami uji coba operasional dengan mengalirkan fluida berupa air laut di dalamnya (*water filled*). Sementara pada kondisi operasi pipa mulai dialiri oleh konten yang sebenarnya. Massa jenis konten bergantung pada masing-masing pipa: *16" Production Pipeline* dan *6" Gas Lift Pipeline*.

4.4. Berat Properti & *Buoyancy* Pipa

Pada dasarnya, stabilitas pipa bawah laut dipengaruhi oleh berat pipa yang terendam di bawah permukaan air laut. Pipa secara struktural terususun dari berbagai macam lapisan yang diperlukan sebagai penunjang operabilitas pipa dalam proses pendistribusian migas. Untuk lebih mudahnya, Gambar 4.2 di bawah ini merupakan ilustrasi penampang melintang untuk pipa utama dan pipa sekunder yang ditinjau.



[a] [b]

Gambar 4. 2 Penampang Melintang *Piggyback Pipeline* (X, 2018)
[a] *16" Production Pipeline*
[b] *6" Gas Lift Pipeline*

Dari Gambar 4.2, dapat dilihat bahwa properti yang menyusun struktur pipa bawah laut diantaranya: pipa baja (*steel pipe*), lapisan anti korosi (*anti-corrosion coating*), lapisan beton pemberat (*concrete weight coating*), lapisan sambungan (*field joint coating*), dan material pengisi (*infill material*).

Sedangkan untuk parameter tambahan yang sifatnya bergantung pada kondisi pembebanan adalah berat penyerapan air oleh lapisan beton pemberat (*water absorption*) dan berat fluida yang diangkut oleh pipa (*content*).

Dalam kasus ini, khusus *16" Production Pipeline* dilakukan peninjauan terhadap dua *pipeline section* dimana untuk masing-masing section pipa memiliki parameter ukuran properti yang berbeda. Untuk KP 0+273 – KP 1+393 ketebalan lapisan beton pemberat pipa sebesar 40 mm sedangkan untuk KP 1+393 – KP 5+725 ketebalan lapisan beton pemberat pipa sebesar 60 mm. Perlu diperhatikan bahwa dalam penelitian ini tidak dilakukan analisa terhadap pipa darat (*onshore pipeline*) yang membentang dari KP 0+000 – KP 0+273.

Tabel 4.16, Tabel 4.17, dan Tabel 4.18 berikut ini merangkum hasil perhitungan terhadap parameter ukuran, berat properti penyusun serta daya apung pada masing-masing pipa yang terkonfigurasi secara tumpuk untuk setiap kondisi pembebanan:

Tabel 4. 16 Parameter Ukuran dan Berat Properti:
16" Production Pipeline (KP 0+273 - KP 1+393)

Parameter of 16" Production Pipeline	Sym	Condition			Units
		Installation	Hydrotest	Operation	
Outside Diameter of Steel Pipe	D_{o16}	0.4064			m
Nominal Wall Thickness	t_{s16}	0.0127	0.0127	0.0097	m
Inside Diameter of Steel Pipe	D_{i16}	0.3810	0.3810	0.3870	m
Anti-Corrosion Coating Diameter	D_{acc16}	0.4134			m
Concrete Coating Diameter	D_{conc16}	0.4934			m
Total Outside Diameter	D_{top16}	0.4934			m

Weight of Steel Pipe	Wt_{s16}	1209.23	1209.23	930.62	N.m^{-1}
Weight of Anti-Corrosion Coating	Wt_{acc16}	40.53			N.m^{-1}
Weight of Concrete Weight Coating	Wt_{conc16}	1642.89			N.m^{-1}
Weight of Field Joint Coating	Wt_{fjc16}	1.01			N.m^{-1}
Weight of Infill Material	Wt_{im16}	14.08			N.m^{-1}
Weight of Water Absorption	Wt_{wab16}	0.00	0.00	82.14	N.m^{-1}
Weight of Content	Wt_{cont16}	0.00	1146	85.17	N.m^{-1}
Total Weight of Pipeline	Wt_{tot16}	2907.74	4053.74	2796.44	N.m^{-1}
Buoyancy of Pipeline	W_{b16}	1921.91			N.m^{-1}
Submerged Weight of Pipeline	W_{sub16}	985.83	2131.83	874.53	N.m^{-1}

Tabel 4. 17 Perhitungan Parameter Ukuran dan Berat Properti:
16" Production Pipeline (KP 1+393 – KP 5+725)

Parameter of 16" Production Pipeline	Sym	Condition			Units
		Installation	Hydrotest	Operation	
Outside Diameter of Steel Pipe	D_{o16}	0.4064			m
Nominal Wall Thickness	t_{s16}	0.0127	0.0127	0.0097	m
Inside Diameter of Steel Pipe	D_{i16}	0.3810	0.3810	0.3870	m
Anti-Corrosion Coating Diameter	D_{acc16}	0.4134			m
Concrete Coating Diameter	D_{conc16}	0.5334			m
Total Outside Diameter	D_{top16}	0.5334			m
Weight of Steel Pipe	Wt_{s16}	1209.23	1209.23	930.62	N.m^{-1}
Weight of Anti-Corrosion Coating	Wt_{acc16}	40.53			N.m^{-1}
Weight of Concrete Weight Coating	Wt_{conc16}	2573.04			N.m^{-1}
Weight of Field Joint Coating	Wt_{fjc16}	1.01			N.m^{-1}
Weight of Infill Material	Wt_{im16}	22.06			N.m^{-1}
Weight of Water Absorption	Wt_{wab16}	0.00	0.00	128.65	N.m^{-1}
Weight of Content	Wt_{cont16}	0.00	1146	85.17	N.m^{-1}
Total Weight of Pipeline	Wt_{tot16}	3845.87	4991.87	3781.07	N.m^{-1}
Buoyancy of Pipeline	W_{b16}	2246.16			N.m^{-1}
Submerged Weight of Pipeline	W_{sub16}	1599.70	2745.70	1534.91	N.m^{-1}

Tabel 4. 18 Perhitungan Parameter Ukuran dan Berat Properti:
6" Gas Lift Pipeline (KP 0+273 - KP 5+725)

Parameter of 6" Gas Lift Pipeline	**Sym**	**Condition**			**Units**
		Installation	**Hydrotest**	**Operation**	
Outside Diameter of Steel Pipe	D_{o6}	0.1683			m
Nominal Wall Thickness	t_{s6}	0.0095	0.0095	0.0065	m
Inside Diameter of Steel Pipe	D_{i6}	0.1493	0.1493	0.1553	m
Anti-Corrosion Coating Diameter	D_{acc6}	0.1753			m
Concrete Coating Diameter	D_{conc6}	0.1753			m
Total Outside Diameter	D_{top6}	0.1753			m
Weight of Steel Pipe	Wt_{s6}	364.85	364.85	254.35	$N.m^{-1}$
Weight of Anti-Corrosion Coating	Wt_{acc6}	16.99			$N.m^{-1}$
Weight of Concrete Weight Coating	Wt_{conc6}	0.00			$N.m^{-1}$
Weight of Field Joint Coating	Wt_{fjc6}	0.42			$N.m^{-1}$
Weight of Infill Material	Wt_{im6}	0.00			$N.m^{-1}$
Weight of Content	Wt_{cont6}	0.00	175.98	20.41	$N.m^{-1}$
Total Weight of Pipeline	Wt_{tot6}	382.26	558.24	292.17	$N.m^{-1}$
Buoyancy of Pipeline	W_{b6}	242.60			$N.m^{-1}$
Submerged Weight of Pipeline	W_{sub6}	139.66	315.63	49.56	$N.m^{-1}$

Dari ketiga tabel diatas dapat dilihat bahwa kondisi pembebanan mempengaruhi berat properti penyusun pipa dengan perubahan parameter ukuran akibat dari adanya %*corrosion allowance* yang mana umumnya diasumsikan sebesesar 100% sebagai antisipasi terhadap kondisi terburuk. Pipa pun akan semakin berat dengan adanya *water absorption* pada saat kondisi operasi. Namun, massa konten terbesar terjadi pada saat kondisi *hydrotest* dikarenakan massa jenis air laut memiliki nilai yang paling tinggi dibandingkan dengan massa jenis fluida untuk kondisi operasi.

4.5. Berat Terendam *Piggyback Pipeline*

Sebagai parameter yang akan digunakan pada perhitungan selanjutnya, Tabel 4.19 berikut ini adalah total berat terendam dari struktur pipa bawah laut (*configurated as a piggyback pipeline*) untuk masing-

masing kondisi pembebanan dimana berat terendam pipa tumpuk adalah penjumlahan dari *16" Production Pipeline* dan *6" Gas Lift Pipeline*:

Tabel 4. 19 Berat Terendam *Piggyback Pipeline*

Pipeline	Section		Submerged Weight [N.m^{-1}]		
	From	To	Installation	Hydrotest	Operation
16" Prodcution Pipeline Piggyback with 6" Gas Lift Pipeline	0+273	1+393	1125.49	2447.46	924.09
	1+393	5+725	1739.36	3061.33	1584.47

Analisa stabilitas pipa bawah laut adalah analisa terhadap kemampuan berat terendam pipa di bawah air dalam menahan beban-beban hidrodinamis yang bekerja terhadapnya agar pipa tetap dalam kondisi stabil dan tidak mengalami kegagalan operasional. Dalam penelitian ini digunakan dua variasi tebal beton pemberat (KP 0+273 – KP 1+393: 40 mm dan KP 1+393 – KP 5+725: 60 mm).

4.6. Stability in Water: Spesific Gravity Criteria

Pengapungan terjadi apabila berat terendam minimum pipa tidak lebih besar dari daya apungnya akibat massa jenis air laut. Untuk itu dalam perancangan pipa perlu untuk dipastikan bahwa pipa stabil secara vertikal dalam artian tidak terjadi pengapungan pipa. Kriteria stabilitas pipa terhadap pengapungan menggunakan pers. 2.38 dan Tabel 4.20 berikut ini adalah hasil analisa yang dilakukan terhadap *piggyback pipeline*:

Tabel 4. 20 Stabilitas Vertikal Pipa terhadap Pengapungan

Condition	Pipeline Section		Submerged Weight	Buoyancy	Safety Factor for Weight	SG	Remark
	From	To	[N.m^{-1}]	[N.m^{-1}]			
Installation	0+273	1+393	1125.49	2165	1.1	0.724	Stable
	1+393	5+725	1739.36	2489	1.1	0.647	Stable
Hydrotest	0+273	1+393	2447.46	2165	1.1	0.516	Stable
	1+393	5+725	3061.33	2489	1.1	0.493	Stable
Operation	0+273	1+393	924.09	2165	1.1	0.771	Stable
	1+393	5+725	1584.47	2489	1.1	0.672	Stable

Dari Tabel 4.20 diatas, terlihat bahwa kondisi kestabilan pipa pada KP 1+393 – KP 5+725 memiliki *safety factor* yang lebih baik dikarenakan pada *section* tersebut pipa memiliki berat terendam paling besar disebabkan penggunaan *concrete weight coating* setebal 60 mm oleh *16" Production Pipeline.*

4.7. Stability in/on Soil: Against Sinking

Penenggelaman terjadi apabila berat terendam minimum pipa lebih besar dari kemampuan tanah untuk menahan berat pipa. Untuk itu dalam perancangan pipa perlu untuk dipastikan juga bahwa pipa stabil secara vertikal terhadap penenggelaman. Kriteria stabilitas pipa terhadap penenggelaman menggunakan pers. 2.39 dan Tabel 4.21 berikut ini adalah hasil analisa yang dilakukan terhadap *piggyback pipeline*:

Tabel 4. 21 Stabilitas Vertikal Pipa terhadap Penenggelaman

Pipeline	**Section**		**Submerged Weight**	**Max. Allowable Submerged Weight**	**Safety Factor**	**Remark**
	From	**To**	**[N.m^{-1}]**	**[N.m^{-1}]**		
Piggyback Pipeline Condition: Hydrotest	0+273	1+373	2495.10	3256.44	0.766	Stable
	1+373	5+375	3108.97	3520.44	0.833	Stable

Analisis tidak dilakukan terhadap masing-masing kondisi pembebanan dikarenakan yang hanya berkemungkinan untuk tenggelam adalah pipa dalam kondisi hydortest yang memiliki berat terendam maksimum.

4.8. Kecepatan Arus Laut

Untuk menghitung kecepatan arus rata-rata yang melewati pipa digunakan arus acuan, $V_c(z_r)$, yang diukur pada kedalaman dimana variasi kecepatan arus pada arah horizontal kecil (DNVGL RP F109, 2017). Pengukuran arus acuan umumnya mampu dilakukan hingga kedalaman 1 m diukur dari *seabed*. Pada dasar laut yang relatif datar, tinggi acuan dapat lebih besar dari 1 m tergantung pada parameter kekasaran dasar laut.

Untuk kasus ini, jenis tanah diasumsikan sebagai *clay* sehingga digunakan parameter kekasaran dasar laut sebesar $5 \cdot 10^{-6}$ m (Lihat Tabel 2.1). Dengan menggunakan pers. 2.1 berikut adalah Tabel 4.22 yang merangkum hasil perhitungan kecepatan arus terhadap *16" Production Pipeline* untuk setiap *pipeline section*:

Tabel 4. 22 Kecepatan Arus terhadap *16" Production Pipeline*

Pipeline	Section	Overall Diameter	Current Velocity [$m.s^{-1}$]	
		[m]	Installation	Operation
16" Production Pipeline	KP 0+273 – KP 1+393	0.4934	0.267	0.301
	KP 1+393 – KP 5+725	0.5334	0.269	0.303

Pada Tabel 4.22 diatas, kecepatan arus yang melewati *16" Production Pipeline* dengan diameter luar sebesar 0.4934 m memiliki nilai lebih kecil daripada arus yang melewati *16" Production Pipeline* dengan diameter luar sebesar 0.5334 m. Hal ini sesuai dengan skema karakteristik arus pada Gambar 2.5, dimana semakin mendekati dasar laut, maka kecepatan arus yang terjadi akan semakin kecil. Sedangkan perbandingan antara besar kecepatan arus pada saat instalasi dan operasi akan memiliki harga yang lebih besar pada kondisi operasi dikarenakan perhitungan arus kondisi operasi menggunakan data 100 tahunan.

4.9. Transformasi Gelombang: *Shore Approach Design*

Pada pipa yang beroperasi pada lokasi *shore approach*, hal utama yang akan menjadi pertimbangan dalam perancangan adalah kejadian gelombang pecah yang disebabkan oleh adanya *shoaling* (pendangkalan) dan *refraction* (pembelokan) dari gelombang laut.

Kejadian gelombang pecah akan menyebabkan kenaikan tinggi gelombang dimana akan mempengaruhi besar beban lingkungan yang akan bekerja terhadap pipa. Untuk itu dilakukan analisis perubahan gelombang (*wave transform analysis*) untuk mendapatkan tinggi gelombang sesungguhnya yang terjadi akibat penurunan kedalaman perairan. Berikut adalah Tabel 4.22 sebagai hasil perhitungan terhadap kejadian gelombang pecah yang terjadi pada lokasi operasional *piggyback pipeline:*

Tabel 4. 23 Transformasi Gelombang: Kejadian Gelombang Pecah

Significant Wave Height [m]	**Wave Breaking Depth [m]**	**Height of Breaking Wave [m]**	**Water Depth [m]**	**KP**
0.79	1.311	1.022	1.31	1+393
0.93	1.449	1.132	1.45	1+393

Dari hasil yang didapatkan terjadi gelombang pecah dengan ketinggian gelombang setinggi 1.022 m (1 yr RP) dan 1.132 (100 yr RP). Gelombang pecah tersebut diperkirakan akan terjadi pada KP 1+393 dimana pada KP 1+393 – KP 5+725 pipa tepat untuk dirancang dengan lapisan beton pemberat yang lebih tebal dengan tujuan agar tetap mampu stabil terhadap pembebanan energi gelombang pecah yang terjadi.

Ketinggian gelombang setelah gelombang pecah terjadi akan menurun seiring mendekati garis pantai (*shoreline*). Sehingga pada KP 0+273 – KP 1+393 digunakan ketinggian gelombang sesuai dengan kedalaman perairan agar didapatkan hasil yang konservatif.

4.10. *Short Term Wave* (JONSWAP): *Wave Induced Parameter*

Kecepatan partikel air di dasar laut dipengaruhi oleh gelombang permukaan. Untuk mendefinisikan karakteristik gelombang acak digunakan parameter spektrum JONSWAP yang mampu merepresentasikan gelombang kurun waktu pendek (DNVGL-RP-F109, 2017). Persamaan spektrum JONSWAP telah disebutkan dalam pers. 2.7. Berikut adalah hasil yang didapatkan dari perhitungan yang dilakukan terhadap spektrum gelombang, terangkum dalam Tabel 4.24 – Tabel 4.28 di bawah ini.

Tabel 4. 24 Parameter Spektrum JONSWAP

Parameter (KP 0+273 – KP 1+393)	Sym	Condition		Unit
		Installation	Operation	
Peak Wave Frequency	ω_p	0.814	0.620	rad/s
Peak Enchancement Parameter	ϕ	24.413	32.034	-
Peak Enhcancement Factor	γ	1	1	-
Generalised Philips' Constant	α	$1.426 \cdot 10^{-5}$	$4.809 \cdot 10^{-6}$	-
Parameter (KP 1+393 – KP 5+725)	**Sym**	**Condition**		**Unit**
		Installation	**Operation**	
Peak Wave Frequency	ω_p	0.814	0.620	rad/s
Peak Enchancement Parameter	ϕ	7.636	9.521	-
Peak Enhcancement Factor	γ	1	1	-
Generalised Philips' Constant	α	$1.489 \cdot 10^{-3}$	$6.163 \cdot 10^{-4}$	-

Tabel 4. 25 Momen Spektra Gelombang

Parameter (KP 0+273 – KP 1+393)	Sym	Value		Unit
		Installation	Operation	
Zeroth Order Spectral Moment	M_0	0.061	0.061	-
First Order Spectral Moment	M_1	0.064	0.049	-
Second Order Spectral Moment	M_2	0.078	0.046	-
Fourth Order Spectral Moment	M_4	0.284	0.108	-
Parameter (KP 1+393 – KP 5+725)	**Sym**	**Value**		**Unit**
		Installation	**Operation**	
Zeroth Order Spectral Moment	M_0	0.436	0.561	-
First Order Spectral Moment	M_1	0.439	0.437	-
Second Order Spectral Moment	M_2	0.491	0.384	-
Fourth Order Spectral Moment	M_4	0.938	0.499	-

Tabel 4. 26 Periode dan Kecepatan Partikel Air di Dasar Laut untuk Desain Spektrum

Parameter (KP 0+273 – KP 1+393)	Sym	Value		Unit
		Installation	Operation	
Design Spectral Velocity Amplitude	U_s	0.493	0.494	m.s^{-1}
Mean Zero Up-Crossing Period	T_u	5.550	7.253	s
Reference Period	T_n	0.101	0.101	s
Parameter (KP 1+393 – KP 5+725)	**Sym**	**Value**		**Unit**
		Installation	**Operation**	
Design Spectral Velocity Amplitude	U_s	1.321	1.498	m.s^{-1}
Mean Zero Up-Crossing Period	T_u	5.923	7.592	s
Reference Period	T_n	0.365	0.365	s

Tabel 4. 27 Periode dan Kecepatan Partikel Air di Dasar laut untuk Osilasi Desain Tunggal

Parameter (KP 0+273 – KP 1+393)	Sym	Value		Unit
		Installation	Operation	
Number of Oscillations in Spectrum	τ	1946	1489	-
Ratio of Velocity Amplitude	k_U	2.02	1.987	-
Parameter of Wave Period	k_t	1.25	1.25	
Ratio of Period	k_T	1.227	1.233	-
Single Oscillation Vel. Amplitude	U'	0.996	0.981	m.s^{-1}
Single Oscillation Velocity Period	T'	6.812	8.940	s
Parameter (KP 1+393 – KP 5+725)	**Sym**	**Value**		**Unit**
		Installation	**Operation**	
Number of Oscillations in Spectrum	τ	1823	1423	-
Ratio of Velocity Amplitude	k_U	2.012	1.981	-
Parameter of Wave Period	k_t	1.25	1.25	
Ratio of Period	k_T	1.173	1.190	-
Single Oscillation Vel. Amplitude	U'	2.658	2.967	m.s^{-1}
Single Oscillation Velocity Period	T'	6.947	9.033	s

Tabel 4. 28 Kecepatan Partikel Air yang Tereduksi oleh Arah dan Persebaran Gelombang

Parameter (KP 0+273 – KP 1+393)	Sym	Value		Unit
		Installation	Operation	
Spectral Spreading Exponent	S_p	8		-
Reduction Factor	R_D	0.949		-
Design Spectral Velocity Amplitude with Wave Spreading Effect	$U_{s.w}$	0.468	0.469	$m.s^{-1}$
Single Oscillation Velocity Amplitude with Wave Spreading Effect	U'_w	0.945	0.931	$m.s^{-1}$
Parameter (KP 1+393 – KP 5+725)	**Sym**	**Value**		**Unit**
		Installation	**Operation**	
Spectral Spreading Exponent	S_p	8		-
Reduction Factor	R_D	0.949		-
Design Spectral Velocity Amplitude with Wave Spreading Effect	$U_{s.w}$	1.253	1.421	$m.s^{-1}$
Single Oscillation Velocity Amplitude with Wave Spreading Effect	U'_w	2.521	2.815	$m.s^{-1}$

4.11. Koefisien Beban Puncak Hidrodinamis:

Untuk mendapatkan koefisien beban puncak hidrodinamis horizontal maupun vertikal dilakukan interpolasi terhadap nilai M' dan KC' pada Tabel 2.2 dan Tabel 2.3, dimana M' adalah rasio perbandingan antara kecepatan arus *steady* dengan kecepatan arus osilasi akibat gelombang dan KC' adalah *Significant Keulegan Carpenter Number*.

Tabel 4. 29 Parameter Spektrum Desain dan Osilasi Desain Tunggal

Parameter (KP 0+273 – KP 1+393)	Sym	Value	
		Installation	Operation
Design Spectrum			
Steady to Oscillatory Velocity Ratio	M	0.625	0.704
Significant Keulegan-Carpenter Number	KC	5.261	6.887
Single Design Oscillation			
Steady to Oscillatory Velocity Ratio	M'	0.282	0.323
Significant Keulegan-Carpenter Number	KC'	13.043	16.865

Parameter (KP 0+273 – KP 1+393)	Sym	Value	
		Installation	Operation
Design Spectrum			
Steady to Oscillatory Velocity Ratio	M	0.235	0.234
Significant Keulegan-Carpenter Number	KC	13.916	20.227
Single Design Oscillation			
Steady to Oscillatory Velocity Ratio	M'	0.107	0.108
Significant Keulegan-Carpenter Number	KC'	32.84	47.677

Tabel 4. 30 Koefisien Beban Hidrodinamis Puncak

Parameter (KP 0+273 – KP 1+393)	Sym	Value	
		Instalasi	Operasi
Horizontal Peak Load Coefficient	C_y	2.613	2.197
Vertical Peak Load Coefficient	C_z	3.158	2.511
Parameter (KP 1+393 – KP 5+725)	**Sym**	**Value**	
		Instalasi	**Operasi**
Horizontal Peak Load Coefficient	C_y	2.092	1.731
Vertical Peak Load Coefficient	C_z	2.023	1.578

Melalui Tabel 4.29 didapatkan koefisien beban puncak hidrodinamis untuk masing-masing kondisi pembebanan (instalasi dan operasi) serta untuk masing-masing *pipeline section* (KP 0+273 – KP 1+373 dan KP 1+373 – KP 5+725) yang disajikan dalam Tabel 4.30 di atas.

4.12. Penetrasi Total Pipa

Interaksi yang terjadi antara pipa dengan tanah (*pipe-soil interaction*) menyebabkan pipa mengalami penetrasi. Kedalaman penetrasi umumnya dipengaruhi oleh berat terendam pipa di bawah air serta karakteristik tanah yang didefinisikan melalui parameter kekakuan tanah dan faktor tahanan pasif tanah. Penetrasi total merupakan kombinasi dari penetrasi awal pipa, penetrasi akibat pergerakan pipa, penetrasi akibat proses instalasi serta penetrasi akibat *trenching* apabila dilakukan.

Dalam penelitian ini, dilakukan perbandingan terhadap stabilitas pipa bawah laut dalam kondisi *exposed* dan juga *trenched*. Aktivitas penggalian (*trenching*) terhadap pipa sebagai bentuk pertimbangan teknis terhadap Peraturan Pemerintah 300.K/38/M.PE/1997 Pasal 13 Ayat 3 yang menyebutkan bahwasanya pipa yang beroperasi pada kedalaman laut kurang dari 13 m wajib untuk dilakukan pemendaman pipa sekurang-kurangnya 2 m diukur dari ujung teratas pipa (*top of steel*).

Trenching dapat dikatakan sebagai metode awal yang digunakan untuk melakukan penguburan pipa bawah laut. Dalam aplikasinya aktivitas ini dibagi menjadi dua kondisi: *pre-trenched* dan *post-trenched* yang mana pemanfaatannya didasari oleh pertimbangan pada saat tahap perancangan.

Dengan menggunakan persamaan pada sect 2.2.11, berikut adalah Tabel 4.31 dan Tabel 4.32 sebagai tabulasi hasil perhitungan penetrasi total yang terjadi:

Tabel 4. 31 Penetrasi Total Pipa (*Exposed*)

Parameter Condition: Installation (exposed pipeline on seabed)	**Sym**	**Value**				**Unit**
		0+273	**1+393**	**1+393**	**5+725**	
Passive Resistance Factor	k_{ci}	0.877		0.613		-
Soil Stiffness Parameter	G_{ci}	0.223		0.207		-
Initial Penetration of Pipe	z_{pi}	0.026		0.037		m
Penetration due to Movement	z_{pm}	0.000		0.000		m
Penetration due to Laying	z_{pl}	0.025		0.027		m
Total Penetration	z_p	0.050		0.064		m
Parameter Condition: Operation (exposed pipeline on seabed)	**Sym**	**Value**				**Unit**
		0+273	**1+393**	**1+393**	**5+725**	
Passive Resistance Factor	k_{ci}	1.068		0.673		-
Soil Stiffness Parameter	G_{ci}	0.223		0.207		-
Initial Penetration of Pipe	z_{pi}	0.022		0.034		m
Penetration due to Movement	z_{pm}	0.000		0.000		m
Penetration due to Laying	z_{pl}	0.025		0.027		m
Total Penetration	z_p	0.047		0.061		m

Tabel 4. 32 Penetrasi Total Pipa (*Ttrenched*)

Parameter Condition: Installation (pre-trenched pipeline)	Sym	Value				Unit
		0+273	1+393	1+393	5+725	
Passive Resistance Factor	k_{ci}	0.877		0.613		-
Soil Stiffness Parameter	G_{ci}	0.223		0.207		-
Initial Penetration of Pipe	z_{pi}	0.026		0.037		m
Penetration due to Movement	z_{pm}	0.000		0.000		m
Penetration due to Laying	z_{pl}	0.025		0.027		m
Total Penetration	z_p	0.050		0.064		m
Total Penetration (with Trenching)	z_{tp}	0.297		0.331		m
Parameter Condition: Operation (pre-trenched pipeline)	**Sym**	**Value**				**Unit**
		0+273	**1+393**	**1+393**	**5+725**	
Passive Resistance Factor	k_{ci}	1.068		0.673		-
Soil Stiffness Parameter	G_{ci}	0.223		0.207		-
Initial Penetration of Pipe	z_{pi}	0.022		0.034		m
Penetration due to Movement	z_{pm}	0.000		0.000		m
Penetration due to Laying	z_{pl}	0.025		0.027		m
Total Penetration	z_p	0.047		0.061		m
Total Penetration (Trenching)	z_{tp}	0.293		0.328		m

Dikarenakan dalam penelitian ini mengggunakan analisa *absolute lateral static stability*, maka penetrasi yang diakibatkan oleh pergeseran pipa diasumsikan sebesar 0% dari diameternya. Sedangkan, penetrasi yang diakibatkan oleh proses instalasi pipa diasumsikan sebesar 5% dari total diameter pipa termasuk seluruh lapisan pelindungnya.

Dari Tabel 4.31 dan Tabel 4.32 di atas dapat diketahui bahwa kedalaman penetrasi yang terjadi pada pipa *trench* memiliki nilai yang lebih besar daripada penetrasi yang terjadi pada pipa *exposed*. Hal ini dikarenakan walaupun kedalaman penetrasi yang terjadi dipengaruhi oleh berat terendam pipa di bawah air, dimana semakin berat pipa maka akan semakin dalam penetrasi yang terjadi, namun pada pipa yang di-*trench*, kedalaman penetrasi juga dipengaruhi oleh kedalaman *trenching* yang dilakukan serta sudut kemiringan (*slope angle*) dari *trench* tersebut

4.13. Reduksi Beban

Interaksi antara pipa bawah laut dengan permukaan tanah juga akan mengakibatkan adanya reduksi beban seperti yang telah dijelaskan pada sect. 2.2.12. Harga reduksi beban yang dihasilkan dipengaruhi oleh sifat permeabilitas tanah, penetrasi yang terjadi oleh pipa, serta aktivitas trenching yang dilakukan. Tabel 4.33 dan Tabel 4.34 berikut ini merangkum hasil perhitungan faktor reduksi beban dari *Piggyback Configurated Pipeline* untuk KP 0+273 – KP 1+373 dan KP 1+373 – KP 5+375 dengan sudut *trenching* (θ_t) sebesar 45° untuk pipa *trenched*:

Tabel 4. 33 Angka Reduksi Beban (*Exposed*)

Condition: Installation (exposed)	Section	Overall Diameter [m]	Trench Depth [m]	Horizontal Reduction Factor	Vertical Reduction Factor
16” Production Pipeline Piggyback with 6” Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	0.00	0.857	0.997
	KP 1+393 – KP 5+375	0.5334	0.00	0.832	0.974
Condition: Operation (exposed)	**Section**	**Overall Diameter [m]**	**Trench Depth [m]**	**Horizontal Reduction Factor**	**Vertical Reduction Factor**
16” Production Pipeline Piggyback with 6” Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	0.000	0.868	1.000
	KP 1+393 – KP 5+375	0.5334	0.000	0.840	0.981

Tabel 4. 34 Angka Reduksi Beban (*Trenched*)

Condition: Installation (pre-trenched)	Section	Overall Diameter [m]	Trench Depth [m]	Horizontal Reduction Factor	Vertical Reduction Factor
16” Production Pipeline Piggyback with 6” Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	2.749	0.059	0.000
	KP 1+393 – KP 5+375	0.5334	2.789	0.078	0.000
Condition: Operation (pre-trenched)	**Section**	**Overall Diameter [m]**	**Trench Depth [m]**	**Horizontal Reduction Factor**	**Vertical Reduction Factor**
16” Production Pipeline Piggyback with 6” Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	2.749	0.060	0.000
	KP 1+393 – KP 5+375	0.5334	2.789	0.078	0.000

Dengan membandingkan hasil pada Tabel 4.33 dan Tabel 4.34, dapat dilihat bahwa aktivitas *trenching* akan menghasilkan angka reduksi beban yang sangat kecil hingga mendekati 0 (nol) sedangkan pada pipa *exposed* harga reduksi beban masih tergolong cukup tinggi dengan angka reduksi yang melebihi 0.5. Hal ini kemudian membuktikan bahwa dengan dilakukannya *trenching,* akan tercipta suatu mekanisme pereduksian beban hidrodinamis yang bekerja pada pipa melalui interaksi yang terjadi antara pipa dengan tanah.

4.14. Beban Puncak Hidrodinamis

Beban hidrodinamis terdiri dari gaya seret, gaya inersia dan gaya angkat yang bekerja terhadap pipa secara horizontal dan vertikal. Beban hidrodinamis arah horizontal adalah kombinasi antara gaya seret dan gaya inersia yang terjadi. Sedangkan beban hidrodinamis arah vertikal adalah nilai dari gaya angkatnya. Beban hidrodinamis yang bekerja pada pipa sangat berpengaruh terhadap stabilitas pipa di dasar laut, terutama pada lokasi *shore approach* dimana ketinggian gelombang cenderung mengalami peningkatan akibat adanya peristiwa *refraction* dan *shoaling* yang memicu terjadinya gelombang pecah. Dengan menggunakan pers. 2.31 dan pers. 2.32, berikut adalah Tabel 4.35 dan Tabel 4.36 sebagai hasil perhitungan beban puncak hidrodinamis yang bekerja terhadap pipa:

Tabel 4. 35 Beban Puncak Hidrodinamis (*Exposed*)

Condition: Installation (exposed)	Section	Overall Diameter [m]	Trench Depth [m]	Horizontal Peak Load [$N.m^{-1}$]	Vertical Peak Load [$N.m^{-1}$]
16" Production Pipeline Piggyback with 6" Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	0.00	830.782	1168
	KP 1+393 – KP 5+375	0.5334	0.00	3704	4191
Condition: Operation (exposed)	**Section**	**Overall Diameter [m]**	**Trench Depth [m]**	**Horizontal Peak Load [$N.m^{-1}$]**	**Vertical Peak Load [$N.m^{-1}$]**
16" Production Pipeline Piggyback with 6" Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	0.00	731.435	963.613
	KP 1+393 – KP 5+375	0.5334	0.00	3312	3568

Tabel 4. 36 Beban Puncak Hidrodinamis (*Trenched*)

Condition: Installation (pre-trenched)	Section	Overall Diameter [m]	Trench Depth [m]	Horizontal Peak Load [$N.m^{-1}$]	Vertical Peak Load [$N.m^{-1}$]
16" Production Pipeline Piggyback with 6" Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	2.749	57.061	0.00
	KP 1+393 – KP 5+375	0.5334	2.789	345.153	0.00
Condition: Operation (pre-trenched)	**Section**	**Overall Diameter [m]**	**Trench Depth [m]**	**Horizontal Peak Load [$N.m^{-1}$]**	**Vertical Peak Load [$N.m^{-1}$]**
16" Production Pipeline Piggyback with 6" Gas Lift Pipeline	KP 0+273 – KP 1+393	0.4934	2.749	50.238	0.00
	KP 1+393 – KP 5+375	0.5334	2.789	360.291	0.00

Dari Tabel 4.35 dan Tabel 4.36 diatas dapat dilihat bahwa pipa *trenched* akan mengalami beban hidrodinamis yang lebih kecil daripada pipa *exposed* dikarenakan adanya faktor reduksi akibat *pipe-soil interaction.* Dari tabel-tabel di atas pula, dapat dilihat bahwa pada KP 1+393 – KP 5+725 mengalami beban hidrodinamis yang lebih besar daripada yang terjadi di KP 0+273 – KP 1+393 dikarenakan gelombang pecah terjadi pada KP 1+393 yang menyebabkan gelombang akan mengalami penurunan ketinggian seiring mendekati *shoreline* (KP 0+273 – KP 1+393)

4.15. Tahanan Pasif Tanah

Tahanan pasif tanah (*passive soil resistance*) adalah suatu gaya pasif yang terbentuk dari adanya timbunan tanah di sekitar pipa akibat penetrasi pipa oleh berat terendam pipa itu sendiri. persamaan matematis dari tahanan pasif tanah dirumuskan melalui pers. 2.35:

Tabel 4. 37 Tahanan Pasif Tanah (*Exposed*)

Pipeline (exposed pipeline)	Section	Installation Condition [$N.m^{-1}$]	Operation Condition [$N.m^{-1}$]
16" Production Pipeline Piggyback with 6" Gas Lift Pipeline	KP 0+273 – KP 1+393	0.00	0.00
	KP 1+393 – KP 5+375	0.00	0.00

Tabel 4. 38 Tahanan Pasif Tanah (*Trenched*)

Pipeline (pre-trenched pipeline)	Section	Installation Condition [N.m^{-1}]	Operation Condition [N.m^{-1}]
16" Production Pipeline Piggyback with 6" Gas Lift Pipeline	KP 0+273 – KP 1+393	3735	3673
	KP 1+393 – KP 5+375	4326	4272

Pipa *exposed* memiliki tahanan pasif yang sangat kecil dikarenakan berat terendam pipa tidak lebih besar daripada gaya angkat yang bekerja terhadapnya. Sedangkan pada pipa *trenched* tercipta gaya tahanan pasif tanah dengan nilai maksimum akibat dari kedalaman penetrasi maksimum yang disebabkan oleh *trenching.*

4.16. Absolute Lateral Static Stability Analysis

Dalam penelitian ini dilakukan analisa terhadap stabilitas pipa bawah laut dalam kondisi *exposed* dan *trenched* yang beroperasi pada lokasi *shore approach* dimana pada lokasi tersebut, gelombang perairan cenderung mengalami peningkatan dikarenakan adanya peristiwa gelombang pecah yang diinduksi oleh refraksi dan pendangkalan gelombang.

Analisa dilakukan dengan metode *absolute lateral static stability* untuk mendapatkan angka stabilitas pipa sehingga dapat dilakukan analisa apakah pipa mampu stabil pada lokasi *shore approach* tanpa adanya intervensi tanah sebelumnya. Hal ini kemudian dibandingkan pada stabilitas pipa trenched untuk mendukung ketetapan regional yaitu Peraturan Pemerintah 300.K/38/M.PE/1997 Pasal 13 Ayat 3 yang menyebutkan pemendaman pipa pada lokasi pantai akibat banyaknya kepentingan eksternal yang berlangsung pada lokasi tersebut e.g. kegiatan pelayaran, *trawling*, *anchoring*, aktivitas pancing.

Dalam metode analisis ini, pipa dinyatakan stabil apabila tidak terjadi pepindahan pipa (*no displacement*) secara lateral akibat pengaruh gelombang estimasi maksimum. Kriteria stabilitas lateral dirumuskan dalam pers. 2.40 dan pers. 2.41 dengan *safety factor* yang diasumsikan 1.1 untuk kondisi instalasi dan 1.4 untuk kondisi operasi. Angka ini diperoleh berdasarkan analisa yang dilakukan terhadap Tabel 2.4 – Tabel 4.7. Berikut adalah hasil perhitungan stabilitas statis mutlak pada sumbu lateral pipa:

Tabel 4. 39 Stabilitas Lateral Pipa (*Exposed*)

Condition: Installation (exposed)	**Minimum Water Depth [m]**	**Concrete Coating Thickness [mm]**	**Submerged Weight [N.m^{-1}]**	**Absolute Stability Criteria**		**Remark**
				SF Lateral	**SF Vertical**	
Piggyback Configurated Pipeline	0.100	40	1125	4.729	1.038	Unstable
	1.311	60	1739	13.056	2.41	Unstable
Condition: Operation (exposed)	**Minimum Water Depth [m]**	**Concrete Coating Thickness [mm]**	**Submerged Weight [N.m^{-1}]**	**Absolute Stability Criteria**		**Remark**
				SF Lateral	**SF Vertical**	
Piggyback Configurated Pipeline	0.100	40	924	9.151	1.908	Unstable
	1.311	60	1584	12.703	2.252	Unstable

Tabel 4. 40 Stabilitas Lateral Pipa (*Trenched*)

Condition: Installation (pre-trenched)	**Minimum Water Depth [m]**	**Concrete Coating Thickness [mm]**	**Submerged Weight [N.m^{-1}]**	**Absolute Stability Criteria**		**Remark**
				SF Lateral	**SF Vertical**	
Piggyback Configurated Pipeline	0.100	40	1125	0.133	0.324	Stable
	1.311	60	1739	0.536	0.810	Stable
Condition: Operation (pre-trenched)	**Minimum Water Depth [m]**	**Concrete Coating Thickness [mm]**	**Submerged Weight [N.m^{-1}]**	**Absolute Stability Criteria**		**Remark**
				SF Lateral	**SF Vertical**	
Piggyback Configurated Pipeline	0.100	40	924	0.024	0.00	Stable
	1.311	60	1584	0.079	0.00	Stable

Dari Tabel 4.38, dapat dilihat bahwa pipa *exposed* dinyatakan tidak stabil di dasar laut dalam artian bahwasanya berat terendam pipa tidak mampu menahan beban hidrodinamis yang bekerja terhadapnya sehingga pipa mengalami pergeseran yang dalam metode ini dinyatakan sebagai ketidakstabilan. Sedangkan pada Tabel 4.39 pipa *trenched* dinyatakan stabil di dasar laut. Hal ini dikarenakan adanya gaya yang dihasilkan oleh interaksi pipa dengan tanah yang membantu dalam menahan beban hidrodinamis.

PIPELINE UPHEAVAL BUCKLING ANALYSIS ANALYSIS

4.17. Tegangan Kritis pada Pipa: Kriteria Ijin

Selama beroperasi pipa akan mengalami tegangan yang disebabkan oleh perbedaan temperatur dan tekanan antara kondisi instalasi dengan kondisi operasi. Melakukan perhitungan tegangan kritis bertujuan untuk memastikan bahwa pipa tidak mengalami *overstress*. Apabila tegangan yang terjadi melebihi SMYS (*Specified Minimum Yoield Strength*) maka pipa akan mengalami deformasi plastis i.e. perubahan bentuk permanen pada material. Berikut adalah hasil analisis tegangan yang bekerja pada pipa dan rasionya terhadap tegangan ijin maksimum:

Tabel 4. 41 Tegangan Kritis pada Pipa (*Corroded*)

Parameter	Case	Value [MPa]	Allowable Stress [MPa]	SF	Remark
Hoop Stress (72% SMSYS)	6” Gas Lift	123.12	324	0.38	Qualified
	16” Production	40.22		0.12	Qualified
Longitudinal Stress (82% SMSYS)	6” Gas Lift	36.94	360	0.17	Qualified
	16” Production	119.45		0.32	Qualified
Von Mises Stress (90% SMSYS)	6” Gas Lift	145.15	405	0.40	Qualified
	16” Production	143.84		0.36	Qualified

Dari hasil Tabel 4.35 dan Tabel 4.36 di atas, dapat dikonfirmasi bahwa tegangan yang terjadi pada pipa e.g. *hoop, longitudinal* dan *combined stress* tidak melebihi batas ijin yang ditentukan berdasarkan kekuatan struktur material tersebut. Melalui analisa ini, dapat dikatakan bahwa *6" Gas Lift Pipeline* dan *16" Production Pipeline* aman dari terjadinya deformasi plastis secara perancangan.

4.18. Effective Axial Compressive Force

Perubahan tekanan dan temperatur yang dialami oleh pipa juga menyebabkan terbentuknya gaya aksial efektif yang bekerja terhadap luasannya. Dikarenakan pipa memiliki struktur horizontal memanjang, maka gaya yang bekerja merupakan gaya pada arah longitudinalnya.

Pada pipa yang tertahan (*restrained*), gaya ini bernilai negatif disebabkan oleh tahanan tanah timbunan yang mengubah gaya tersebut menjadi gaya aksial tekan. Dengan adanya tahanan pada ujung-ujung pipa, elongasi sebagai akibat dari ekspansi termal tidak dapat terjadi sehingga menyebabkan kecendrungan pipa untuk menekuk (*buckling*). Berikut adalah besar gaya aksial effektif yang terjadi pada masing-masing pipa sesuai dengan tekanan dan temperatur operasionalnya:

Tabel 4. 42 *Effective Axial Compressive Force*

Pipeline	Maximum Operating Pressure [MPa]	Maximum Operating Temperature (°C)	Effective Axial Compressive Force [kN]
16" Production Pipeline	1.92	69.34	-1387.82

4.19. Total Available Downward Force

Pengaruh gravitasi bumi mengakibatkan pipa secara natural memiliki arah gaya vertikal ke bawah oleh beratnya. Pada pipa yang terpendam, berat tanah timbunan di atasnya akan memberikan gaya tahanan yang bersifat menekan deformasi pipa. Oleh karena besar gaya dorong total yang dihasilkan adalah penjumlahan dari berat terendam pipa beserta gaya yang dihasilkan dari berat tanah timbunan. Untuk perhitungan berat terendam pipa telah dirangkum dalam Tabel 4.2, Tabel 4.3 serta Tabel 4.4. Sedangkan untuk menghitung besar tahanan tanah dapat menggunakan pers

2.49 (Lihat sect 2.2.19). Berikut adalah hasil perhitungan gaya total vertikal ke bawah untuk masing-masing *pipeline section*.

Tabel 4. 43 *Available Downward Force*

Pipeline Section		Overall Diameter	Pipeline Submerged Weight	Burial Depth	Undrained Shear Strength	Uplift Force	Available Downward Force
From	**To**	**[m]**	**[N.m^{-1}]**	**[m]**	**[kPa]**	**[N.m^{-1}]**	**[N.m^{-1}]**
0+273	1+393	0.4934	874.53	2	2	2960.4	3834.93
1+393	5+725	0.5334	1534.91			3200.4	4735.31

4.20. Required Downward Force

Untuk menekan deformasi pipa yang bergerak ke atas, dibutuhkan suatu berat yang mampu memberikan gaya dorong ke bawah agar *upheaval buckling* dapat dihindari. *Required downward force* adalah gaya minimum yang dibutuhkan oleh pipa untuk menahan kecendrungan tekuknya yang disebabkan oleh gaya aksial tekan efektif. Besar *required downward force* akan bervariasi sesuai dengan ketinggian amplitudo yang dihasilkan dari ketidakmerataan tanah dasar laut. Berikut adalah tabulasi yang merangkum hasil perhitungan *required downward force* untuk masing-masing *imperfection height* yang terjadi di sepanjang jalur pipa:

Tabel 4. 44 *Required Downward Force*

Pipeline Section	Effective Axial Compressive Force [kPa]	Imperfection Height [m]	Required Downward Force [N.m^{-1}]
16" Production Pipeline From: 0+273 To: 1+393	-1387.82	0.6	199.56
		1.2	482.87
		1.9	884.79
		2.6	1217.24
		3.4	1546.01
		4	1767.72

16" Production Pipeline From: 1+393 To: 5+725	-1387.82	1.1	230.29
		2.2	460.58
		3.4	869.43
		4.6	1318.59
		5.8	1712.07
		7	2066.55

Semakin tinggi *imperfection height* yang terjadi maka gaya minimum yang dibutuhkan untuk mencegah *upheaval buckling* juga semakin tinggi sedangkan gaya yang tersedia konstan. Jika i*mperfection height* semakin besar nilainya maka *upheaval buckling* dapat memungkinkan untuk terjadi.

4.21. Upheaval Buckling Analysis

Penentuan nilai Safety Factor bertujuan untuk mengetahui segmen pipa mana yang paling rawan terhadap terjadinya upheaval buckling dan/atau segmen pipa mana yang sudah terjadi upheaval buckling. Perhitungan Safety Factor ini diperoleh dari perbandingan antara total downward force dengan required downward force. Yong Bai dalam bukunya "Subsea Pipeline and Risers" menyatakan bahwa nilai *Safety Facto*r yang paling umum digunakan adalah 1.2, yang berarti bahwa segmen pipa yang mempunyai nilai Safety Factor di bawah angka 1.2 akan mengalami *upheaval buckling*.

Tabel 4. 45 *Safety Factor for Upheaval Buckling Analysis*

Pipeline Section	KP	Imperfection Height [m]	Available Downward Force [N.m^{-1}]	Required Downward Force [N.m^{-1}]	Safety Factor	Remarked
16" Production Pipeline From: 0+273 To: 1+393	KP 0+34	0.6	3834.93	199.56	19.22	Not occurred
	KP 0+52	1.2		482.87	7.94	Not occurred
	KP 0+68	1.9		884.79	4.33	Not occurred
	KP 0+85	2.6		1217.24	3.15	Not occurred
	KP 1+02	3.4		1546.01	2.48	Not occurred
	KP 1+17	4		1767.72	2.17	Not occured

16” Production Pipeline From: 0+273 To: 1+393	KP1+46	1.1	4735.31	230.29	20.56	Not occurred
	KP 1+61	2.2		460.58	10.28	Not occurred
	KP 1+78	3.4		869.43	5.45	Not occurred
	KP 1+95	4.6		1318.59	3.59	Not occurred
	KP 2+11	5.8		1712.07	2.77	Not occurred
	KP 2+16	7		2066.55	2.29	Not occurred

Dalam perhitungan yang disajikan dalam Tabel 4.45 di atas, nilai *Safety Factor* yang paling kecil ada di *imperfection height* 4 m dengan harga 2.17. Sehingga bisa disimpulkan bahwa sistem pipa masih cukup aman dalam menghadapi ancaman terjadinya upheaval buckling.

4.22. Pemodelan Struktur: AutoPIPE by Bentley

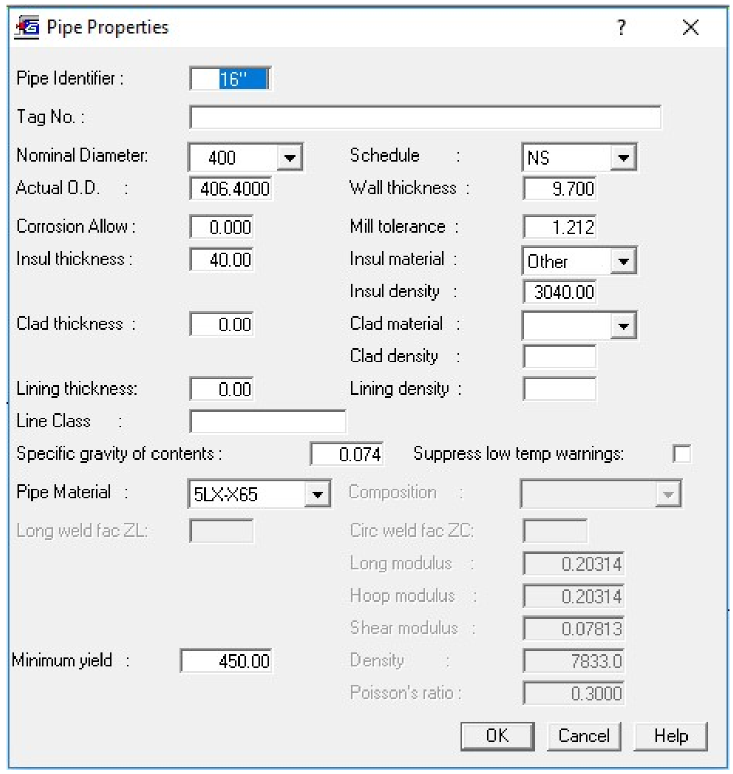
Pemodelan dilakukan untuk memvisualisasikan bentuk deformasi pipa yang terjadi akibat pembebanan yang diberikan yaitu tekanan dan temperature. Melalui pemodelan oleh software AutoPipe, diharapkan dapat memberikan hasil yang sesuai dengan kalkukasi manual yang telah dilakukan. Namun, tidak menutup kemungkinan bahwa hasil yang didapatkan akan memiliki nilai yang berbeda dikarenakan adanya variabel yang mampu diolah oleh pemrograman sementara keterbatasan perhitungan manual

dengan memasukkan seluruh data-data yang telah diberikan sebelumnya. Pemodelan ini juga bertujuan untuk validasi perhitungan manual yang telah dilakukan sebelumnya, dimana tidak terjadi tegangan berlebih (overstress) pada pipa yang dianalisa. Dengan dilakukan pemodelan, nantinya kita akan mendapatkan besar tegangan yang terjadi pada pipa serta perubahan displacement dari pipa akibat tegangan yang terjadi. Berikut langkah-langkah dalam melakukan pemodelan:

4.22.1. Pendefinisian Properti Pipa

Pipa dimodelkan sesuai dengan data pipa yang didapatkan yaitu pipa 16” dengan diameter sebesar 406.4 mm dan tebal dinding pipa sebesar 12.7 mm sesuai dengan schedule pipa yaitu 40. Material pipa adalah API 5L X65 sehingga SMYS pipa adalah

450 MPa. Dimodelkan juga concrete weight coating sebagai lapisan luar dengan tebal 40 mm dan massa jenis lapisan sebesar 3040 kg/m3. Spesific gravity dari konten adalah 0.074.

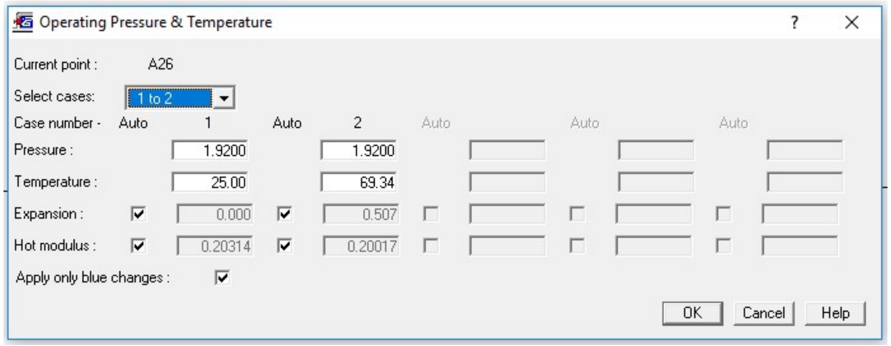


Gambar 4. 3 Input AutoPipe: Properti Pipa

Gambar 4.3 di atas merupakan gambaran input yang dilakukan terhadap properti pipa. Pada pemodelan ini dilakukan juga pemodelan terhadap pipa dengan tebal concrete weigth coating setebal 60 mm.

4.22.2. Pembebanan: Temperature dan Tekanan

Temperatur dan tekanan termasuk input yang akan menjadi pembebanan dalam pemodelan. Untuk tekanan maksimum operasional pada pipa 16” adalah 1.92 MPa dan terjadi perubahan temperatur antara kondisi instalasi dan operasi yaitu 25C (instalasi, diasumsikan sebagai temperatur minimum lingkungan yaitu air laut) menjadi 69.34C (temperatur maksimum operasi).



Gambar 4. 4 Input AutoPipe: Pembebanan

Gambar 4.4 di atas merupakan gambaran input yang dilakukan terhadap tekanan dan temperature pipa. Pada pemodelan ini dilakukan pemodelan terhadap pipa 16 inch sebagai pipa utama yang menjadi pokok bahasan terhadap kemungkinan terjadinya *upheaval buckling.*

4.22.3. Pemodelan Koordinat Pipa

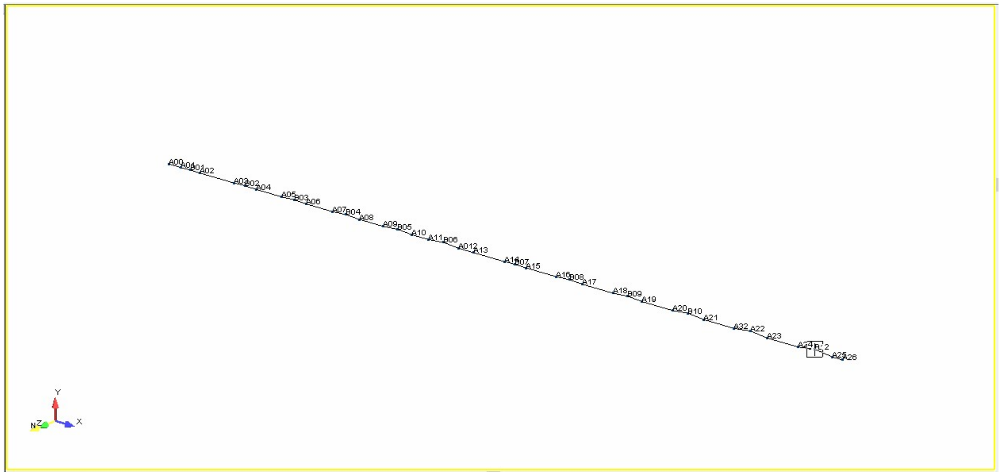
Selanjutnya memodelkan pipa sesuai dengan point-point yang ingin ditinjau. Dalam hal ini pipa dimodelkan sepanjang 1120 m atau sekitar 1 km untuk peninjauan KP 0+273 – KP 1+393. Dimodelkan pula imperfection height yang terjadi pada lokasi seperti pada Gambar 4.5 dan Gambar 4.6 di bawah ini:

Review Component Data

From	To	Comp.	Nominal mm	Length mm	Segment	Offset DX mm	Offset DY mm	Offset DZ mm	Global X mm	Global Y mm	Global Z mm
Origin	A00	Point	400.0		A	99999.99			99999.99		
A00	A01	Run	400.0	60000.00	A	60000.00			160000.0		
A01	B01	Bend	400.0	30876.82	A	30870.99	600.00		190871.0	600.00	
B01	A02	Run	400.0	30875.84	A	30870.02	-600.00		221741.0		
A02	A03	Run	400.0	69999.99	A	69999.99			291741.0		
A03	B02	Bend	400.0	36731.61	A	36712.00	1200.00		328453.0	1200.00	
B02	A04	Run	400.0	36730.59	A	36710.98	-1200.00		365164.0		
A04	A05	Run	400.0	69962.61	A	69962.61			435126.5		
A05	B03	Bend	400.0	41224.80	A	41180.99	1900.00		476307.5	1900.00	
B03	A06	Run	400.0	41224.80	A	41180.99	-1900.00		517488.5		
A06	A07	Run	400.0	79914.99	A	79914.99			597403.6		
A07	B04	Bend	400.0	44615.81	A	44539.99	2600.00		641943.6	2600.00	
B04	A08	Run	400.0	44625.82	A	44550.01	-2600.00		686493.6		
A08	A09	Run	400.0	99830.13	A	99830.13			786323.6		
A09	B05	Bend	400.0	47724.39	A	47630.01	3000.00		833953.6	3000.00	
B05	A10	Run	400.0	47724.34	A	47629.96	-3000.00		881583.6		
A10	A11	Run	400.0	99802.25	A	99802.25			981385.8		
A11	B06	Bend	400.0	49766.02	A	49605.00	4000.00		1030991.	4000.00	
B06	A012	Run	400.0	49766.02	A	49605.00	-4000.00		1080596.		
A012	A13	Run	400.0	99676.44	A	99676.44			1180272.		

Pres/Temp/PipeID | Pipe Properties | Segment | Point | Anchor | Support | Tee | Bend | Valve | Flange | Fl

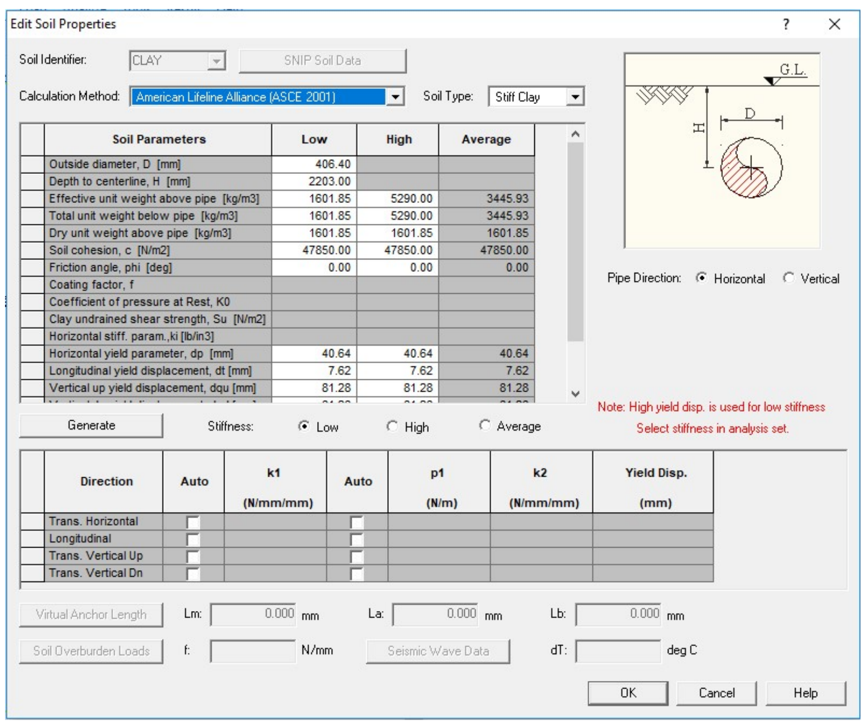
Gambar 4. 5 Input AutoPipe: Koordinat Pipa



Gambar 4. 6 Hasil Pemodelan Struktur Memanjang Pipa

4.22.4. Pendefinisian Karakteristik Tanah

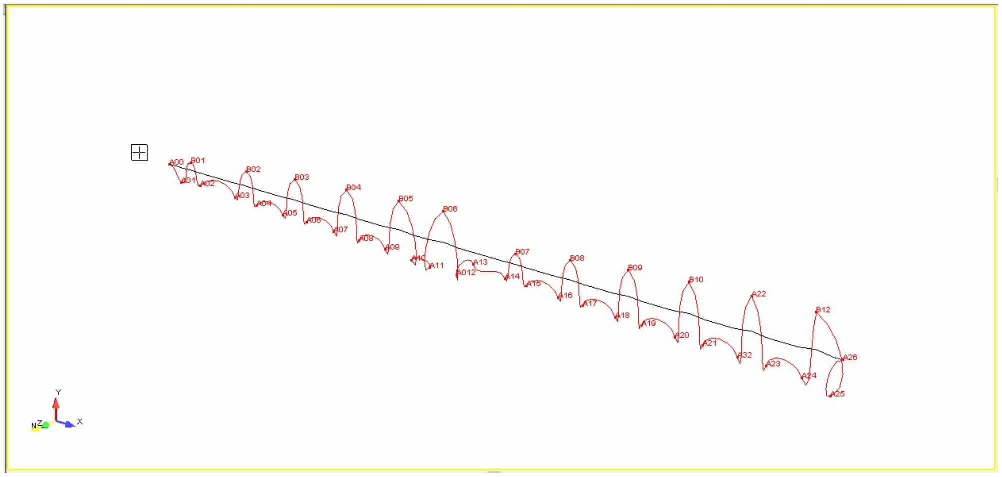
Pada kasus ini tanah adalah *clay* dan dimodelkan dengan pengaturan autopipe dimana dilakukan dengan memasukkan parameter-parameter yang menjadi input nya seperti pada Gambar 4.7 di bawah ini:



Gambar 4. 7 Input AutoPipe: Karakteristik Tanah

4.22.5. Running Model

Berikut adalah hasil *running* pada software AutoPipe. Dari Gambar 4.8 dapat dilihat terjadi *displacement* yang cenderung mengarah ke atas (vertikal) dikarenakan pipa pada awalnya telah dimodelkan untuk memiliki kecendrungan menekuk ke atas karena adanya *imperfection height:*



Gambar 4. 8 Hasil Running Model

Setelah membuat model yang sesuai dengan data yang telah diberikan, maka kita dapat melakukan analisa sesuai dengan apa yang kita inginkan. Dalam pemodelan kali ini dilakukan analisa statis sehingga menghasilkan output berupa *displacement* dan besar tegangan pada masing-masing segmen pipa.

4.23. Validasi Hasil Pemodelan: Tegangan Pipa

Validasi dilakukan dengan menggunakan hasil perhitungan antara perhitungan manual dan hasil perhitungan pada software. Pada pemodelan software beban internal yang terjadi pada pipa berupa internal pressure menyebabkan adanya hoop stress yang bekerja pada pipa. Pada pemodelan pipa menggunakan software AutoPIPE menghasilkan hoop stress sebesar 40.22 N/mm2 seperti yang ditunjukkan dalam Gambar Sedangkan dalam perhitungan manual, didapatkan hasil hoop stress sebesar 40.22 N/mm2. Sehingga dapat disimpulkan bahwa validasi model dari AutoPIPE dengan perhitungan manual sebesar 0.00 %. Tabel 4.46 berikut ini adalah hasil tegangan yang dihasilkan dari pemodelan untuk setiap titik yang menjadi titik kritis dari pemodelan ini.

Tabel 4. 46 Hasil Tegangan (AutoPipe)

Pipeline Section	δ [m]	Hoop [MPa]	Ratio	Long. [MPa]	Ratio	Combined [MPa]	Ratio
KP 0+34	0.6	40.22	0.15	116.90	0.32	139.18	0.34
KP 0+52	1.2	40.22	0.15	116.76	0.32	138.47	0.34
KP 0+68	1.9	40.22	0.15	114.14	0.32	136.77	0.34
KP 0+85	2.6	40.22	0.15	114.48	0.31	134.92	0.33
KP 1+02	3.4	40.22	0.15	107.15	0.30	132.32	0.33
KP 1+17	4	40.22	0.15	105.39	0.29	131.81	0.33
KP 1+46	1.1	40.22	0.15	116.75	0.33	138.30	0.34
KP 1+61	2.2	40.22	0.15	114.15	0.32	136.51	0.34
KP 1+78	3.4	40.22	0.15	110.36	0.31	133.90	0.33
KP 1+95	4.6	40.22	0.15	106.39	0.30	131.19	0.33
KP 2+11	5.8	40.22	0.15	102.38	0.29	128.44	0.32
KP 2+16	7	40.22	0.15	94.82	0.26	129.91	0.31

Tegangan longitudinal dan tegangan von mises akan cenderung mengalami perbedaan dengan perhitungan manual dikarenakan adanya kemampuan *software* untuk memodelkan perubahan temperatur sesuai jarak dan pembelokan pipa sementara pada perhitungan manual hal tersebut tidak dapat dilakukan kecuali dengan adanya data tambahan dari lapangan. Untuk itu, adanya keterbatasan dalam perhitungan manual. Namun, rasio yang didapatkan dari perhitungan manual dengan pemodelan AutoPipe dapat diterima karena memiliki hasil yang tidak jauh berbeda dengan perhitungan manual dimana tegangan longitudinal memiliki rasio sebesar 0.32 sedangkan tegangan von mises memiliki rasio sebesar 0.36.

4.24. Analisis *Displacement*

Tabel dibawah ini menunjukkan bahwa pipa mengalami defleksi. Titik yang mengalami defleksi paling besar terletak pada KP 2+160 yaitu pada saat *imperfection height* 7 m sebesar 24.30 mm ke arah Y (sumbu vertikal), 0.66 mm ke arah X, 0.0 mm ke arah Z, dan jumlah total defleksi sebesar 24.31 mm. Adapun titik-titik yang mengalami defleksi terbesar ditunjukkan dalam Tabel 4.47 berikut ini:

Tabel 4. 47 Hasil *Displacement* Pipa (AutoPipe)

Pipeline Section	δ [m]	Dx [mm]	Dy [mm]	Dz [mm]	Total [mm]	Disp.Total / Diameter Pipa [%]
KP 0+34	0.6	0.02	4.96	0	4.96	0.01
KP 0+52	1.2	0.21	9.52	0	9.52	0.02
KP 0+68	1.9	0.21	13.18	0	13.18	0.03
KP 0+85	2.6	0.27	16.01	0	16.02	0.03
KP 1+02	3.4	0.36	18.48	0	18.48	0.04
KP 1+17	4	-0.47	20.23	0	20.24	0.04
KP 1+46	1.1	-0.02	6.96	0	6.96	0.01
KP 1+61	2.2	0.22	12.75	0	12.75	0.02
KP 1+78	3.4	0.25	17.08	0	17.09	0.03
KP 1+95	4.6	0.24	20.34	0	20.34	0.04
KP 2+11	5.8	0.25	22.90	0	22.90	0.05
KP 2+16	7	0.66	24.30	0	24.31	0.05

Defleksi maksimum yang terjadi ini relatif kecil jika dibandingkan dengan diameter pipa yang mencapai 406.4 mm. Hal ini berarti bahwa sistem pipa masih cukup aman dalam menghadapi ancaman *upheaval buckling*.

BAB V
PENUTUP

5.1. Kesimpulan

Dari penelitian Tugas Akhir yang telah dilakukan, diperoleh kesimpulan sebagai berikut:

1. Pada kondisi *exposed*, pipa akan secara langsung menerima beban hidrodinamis lingkungan sementara tidak ada tahanan tanah yang menyangganya. Dengan berat terendam sebesar 924 N/m (KP 0+273 – KP 1+393) dan 1584 N/m (KP 1+393 – KP 5+725), pipa dinyatakan tidak stabil di dasar laut dengan nilai *safety factor* untuk kondisi operasi adalah 9.151 (horizontal) dan 1.908 (vertikal) serta 12.703 (horizontal) dan 2.253 (vertikal). Sedangkan pada kondisi *trenched*, akan terbentuk gaya tahanan tanah yang mampu mereduksi beban hidrodinamis lingkungan. Sehingga dengan berat terendam seperti yang telah disebutkan, pipa dinyatakan stabil di dasar laut dengan nilai *safety factor* untuk kondisi operasi adalah 0.024 (horizontal) dan 0.0 (vertikal) serta 0.079 (horizontal) dan 0.0 (vertikal).
2. Aktivitas *trenching* yang dilakukan akan mempengaruhi penetrasi pipa yang terjadi dimana peningkatan kedalaman penetrasi akan semakin meningkatkan faktor reduksi beban hidrodinamis. Pada pipa *exposed* beban hidrodinamis yang bekerja saat kondisi operasi adalah 731 N/m (horizontal) dan 963 N/m (vertikal) (KP 0+273 – KP 1+393) serta 3312 N/m (horizontal) dan 3568 N/m (vertikal) (KP 1+393 – KP 5+725). Sedangkan apabila pipa di-*trench*, besar beban hidrodinamis yang bekerja akan tereduksi menjadi 50 N/m (KP 0+273 – KP 1+393) dan 360 N/m (KP 1+393 – 5+725) untuk arah horizontal sementara pada arah vertikal beban hidrodinamis tereduksi hingga 0 N/m.
3. Kenaikan besar *imperfection height* yang terjadi berbanding lurus terhadap gaya tahanan tanah yang dibutuhkan untuk mencegah terjadinya *upheaval buckling*. *Safety factor* terkecil ditemukan pada

KP 2+160 dengan nilai 2.29 untuk pipa dengan ketebalan lapisan beton pemberat sebesar 60 mm dan pada KP 1+170 dengan nilai 2.17 untuk pipa dengan lapisan beton pemberat sebesar 40 mm. Sesuai batas keamanan terhadap *upheaval buckling* yaitu minimal 1.2, maka pada penelitian ini dapat disimpulkan bahwa tidak terjadi *upheaval buckling* di sepanjang jalur pipa.

5.2. Saran

Dari penelitian yang telah dilakukan didapatkan kesimpulan sebagai berikut:

1. Dapat dilakukan pemodelan menggunakan *software* yang lebih kompleks agar didapatkan hasil yang representative.
2. Dapat dilakukan analisis perlindungan katodik untuk mendapatkan spesifikasi anoda yang sesuai sehingga berat terendam pipa dapat mendekati kondisi nyata di lapangan.
3. Dapat melakukan analisa mitigasi apabila terjadi *upheaval buckling.*

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LAMPIRAN I

PERHITUNGAN *ON-BOTTOM STABILITY*

PADA *EXPOSED PIPELINES* (KONDISI INSTALASI)

ON-BOTTOM STABILITY CALCULATION

Project : On-Bottom Stability Analysis on Piggyback Pipeline

Calculated by : ASM

Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline : 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline

Section : KP 0+273 - KP 1+393 (Minimum Water Depth)

Condition : Installation (Exposed to Seabed)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position $Pos := \text{"Seabed"}$

Trenching Depth to Top of Steel (if applicable) $H_{trench} := 0m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) $h := 0.1m$ $h = 0.328 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) $ca\% := 0\%$

Location Class (1 or 2) $LC := 1$
Section 2 C300 DNV OS F101Table 2-2, page 28)

Note:
Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\,kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\,kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 40mm$
Concrete Coating Density	$\rho_{cc} := 3040\,kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\,kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\,kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 0\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 0\,kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 0\,kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.31m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 0.1m$

Peak Wave Period $T_p := 7.72s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness

Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline $gap := 80mm$

Trenching Slope $\theta_t := 45deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 9.5 \times 10^{-3}$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.149\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\ 2} - D_{i.6}^{\ 2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 364.85\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\ 2} - D_{o.6}^{\ 2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\ 2} - D_{o.6}^{\ 2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\ 2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 0\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 382.259\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\ 2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 139.655\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 139.655 \cdot N \cdot m^{-}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 0.013\,m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.381\,m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\,m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.493\,m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.493\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{\;2} - D_{i.16}^{\;2}\right) \cdot \rho_s \cdot g \qquad W_{st.16} = 1.209 \times 10^{3} \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 1.643 \times 10^{3} \cdot N \cdot m^{-}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 14.083 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 0 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{\;2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 0 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 2.908 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}^{2} \cdot \rho_w \cdot g$ $B_{16} = 1.922 \times 10^{3} \cdot N \cdot m^{-}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 985.83 \cdot N \cdot m^{-1}$$

Total Submerged Weight $W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 1.125 \times 10^{3} \cdot N \cdot m$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight (based on condition) $w_s := W_{sub.pig}$ $w_s = 1.125 \times 10^{3} \cdot N \cdot m^{-}$

Buoyancy of Pipeline $b := B_{16} + B_6$ $b = 2.165 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight (Section 3.2 DNVGL RP F109 2017) $\gamma_w := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNVGL RP F109 2017):

Stability in Water $\gamma_w \cdot \frac{b}{w_s + b} = \frac{\gamma_w}{S_g} \le 1.0$

Check Stability

$$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_w \cdot \frac{b}{w_s + b} \le 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$$w_{sub} = \text{"OK"}$$

$$SF_v := \gamma_w \cdot \frac{b}{w_s + b} \qquad SF_v = 0.724$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.493\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.31\,\frac{m}{s}$

$V(z) = 0.292\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.267\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.267\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $\quad H_{sdim} := \frac{H_s}{m}$ $\quad T_{pdim} := \frac{T_p}{s}$ $\quad D_{dim} := \frac{D_{top}}{m}$ $\quad h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\quad \omega_p = 0.814$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\quad \phi = 24.413$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases}$$

$\gamma = 1$

Spectral Width Parameter (Eq. 3.6):

$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

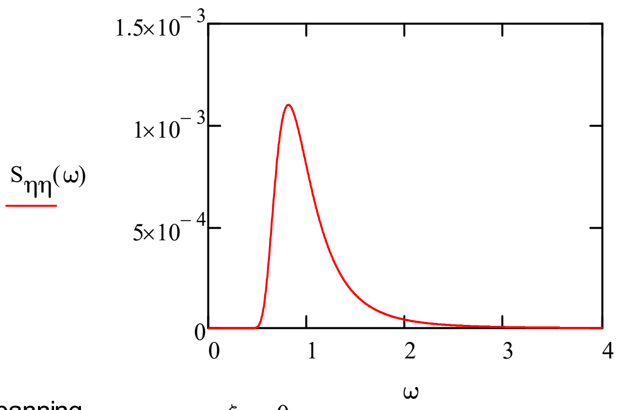
Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}^{2}\cdot\omega_p^{4}}{g_{dim}^{2}}\cdot(1-0.287\ln(\gamma))$$

$\alpha = 1.426\times10^{-5}$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}^{2}\cdot\omega^{-5}\, e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^{2}}}$$



Seabed Gap in Used for Spanning $\zeta := 0$

Guess Values $k := 100$ $a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh\left(k\cdot h_{dim}\right)-\frac{\omega^{2}}{g_{dim}},k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk\left(a_\omega\right)h_{dim}-\text{asinh}(\infty),a_\omega\right)$$

$\omega_{max} = 263.421$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh\left(kk(\omega)\cdot h_{dim}\right)} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^{2}\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11):

$$M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$$

Zeroth Order Spectral Moment $M_n(0) = 0.061$

First Order Spectral Moment $M_n(1) = 0.064$

Second Order Spectral Moment $M_n(2) = 0.078$

Fourth Order Spectral Moment $M_n(4) = 0.284$

Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12):

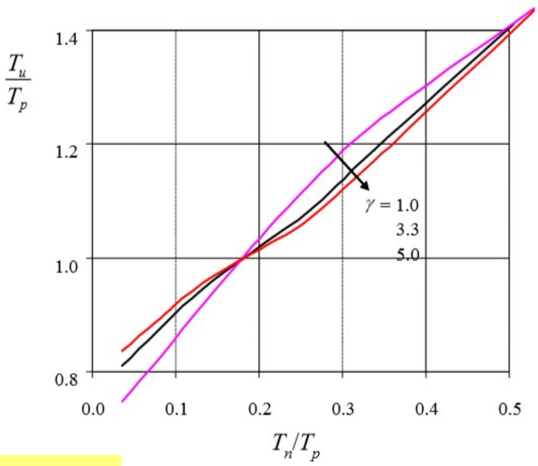
$$U_s := 2\sqrt{M_n(0)}\,\frac{m}{s} \qquad U_s = 0.493\,\frac{m}{s}$$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13):

$$T_u := 2\cdot\pi\sqrt{\frac{M_n(0)}{M_n(2)}}\,s \qquad T_u = 5.55\,s$$

Reference Period (Eq. 3.14):

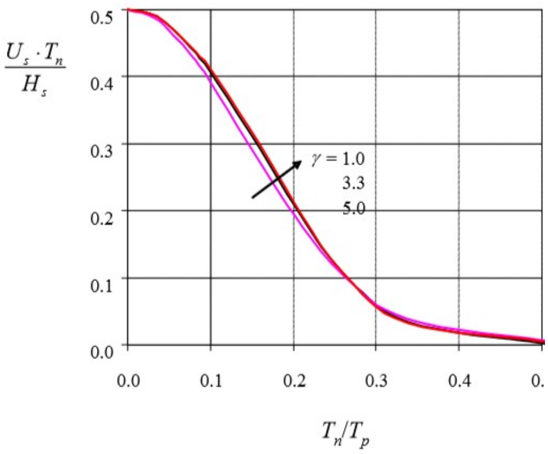
$$T_n := \sqrt{\frac{h}{g}} \qquad T_n = 0.101\,s$$



$$\frac{T_u}{T_p} = 0.719$$

$$\frac{T_n}{T_p} = 0.013$$

$$U_s \cdot \frac{T_n}{H_s} = 0.498$$



Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u}$$ $$\tau = 1.946 \times 10^3$$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right)$$ $$k_U = 2.02$$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s$$ $$U' = 0.996\,\frac{m}{s}$$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \dfrac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases}$$ $$k_t = 1.25$$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

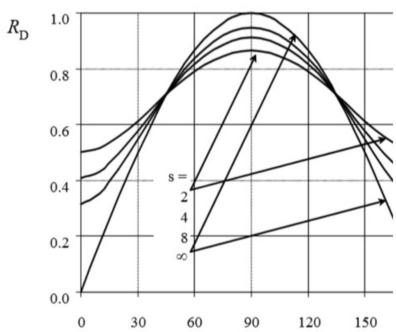
$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\dfrac{T_n}{T_u} & \text{if } \dfrac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \dfrac{T_n}{T_u} > 0.2 \end{cases}$$ $$k_T = 1.227$$

Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u$$ $$T' = 6.812\,s$$

4.3. Wave Directionality and Spreading (DNVGL RP F109 2017)

Spectral Spreading Exponent $s_p := 8$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\dfrac{1}{\pi}\cdot\dfrac{\Gamma\left(1 + \dfrac{s_p}{2}\right)}{\Gamma\left(\dfrac{1}{2} + \dfrac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2} & \text{if } |\theta| < \dfrac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\,d(\theta)}$$ $$R_D = 0.949$$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U_w := R_D \cdot U_s$ $\qquad U_w = 0.468 \frac{m}{s}$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U'_w := R_D \cdot U'$ $\qquad U'_w = 0.945 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio

$M := \frac{V(z)}{U_w}$ $\qquad M = 0.625$

Significant Keulegan-Carpenter Number

$K_s := \frac{U_w \cdot T_u}{D_{top}}$ $\qquad K_s = 5.261$

For Single Oscillation

Steady to Oscillatory Velocity Ratio

$M' := \frac{V'}{U'_w}$ $\qquad M' = 0.282$

Significant Keulegan-Carpenter Number

$K'_s := \frac{U'_w \cdot T'}{D_{top}}$ $\qquad K'_s = 13.043$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.282$ and $K'_s = 13.043$

Horizontal Peak load coefficient $C'_Y = 2.613$

Vertical Peak load coefficient $C'_Z = 3.158$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay) $k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}}$ $k_{ci} = 0.877$

Soil Stiffness Parameter (Clay) $G_{ci} := \frac{S_u}{D_{conc.16} \cdot (\gamma'_{soil})}$ $G_{ci} = 0.223$

Initial Penetration of Pipe (Clay) $z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}}\right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}}\right)^{0.7}\right] D_{conc.16}$

$z_{pi} = 0.026\,m$ $\%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}}$ $\%z_{pi} = 5.219$

Penetration due to Movement
(assumed due to absolute lateral stability) $z_{pm} := 0\% \cdot D_{conc.16}$ $z_{pm} = 0$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration) $z_{pl} := 5\% \cdot D_{conc.16}$ $z_{pl} = 0.025\,m$

Total Penetration of Pipe $z_p := z_{pi} + z_{pm} + z_{pl}$ $z_p = 0.05\,m$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth $z_t := 0m$ $z_t = 0$

Penetration due to Trenching $z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases}$ $z_{pt} = 0\,m$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.05\ \text{m}$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe
and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4 \cdot \left(\dfrac{z_p}{D_{top}}\right) & \text{if } \dfrac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.857$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \dfrac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3 \cdot \left(\dfrac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \dfrac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 0.997$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

$\theta_t :=$

Horizontal Direction (Eq. 3.21):

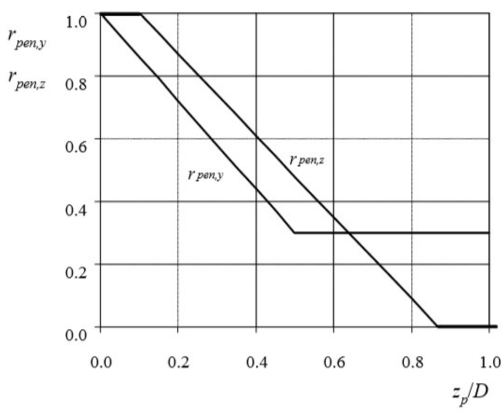
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18 \cdot (\theta_t - 5)^{0.25} \cdot \left(\dfrac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

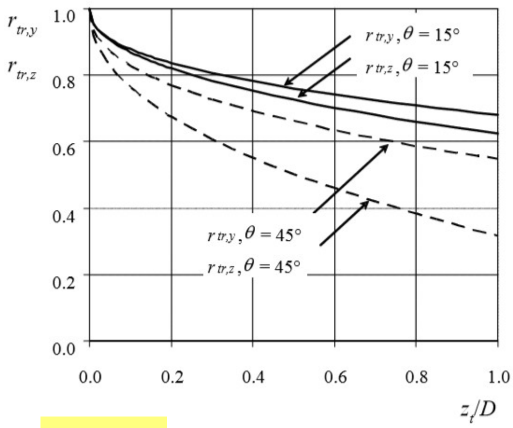
$r_{tr\_y} = 1$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 \text{ if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} < 0 \\ 1 \text{ otherwise} \end{cases}$$

$r_{tr\_z} = 1$





$\dfrac{z_p}{D_{top}} = 0.102$ $\qquad r_{pen\_y} = 0.857$ $\qquad r_{pen\_z} = 0.997$

$\dfrac{z_t}{D_{top}} = 0$ $\qquad r_{tr\_y} = 1$ $\qquad r_{tr\_z} = 1$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} & \text{if Pos} = \text{"Trench"} \\ r_{pen\_y} & \text{if Pos} = \text{"Seabed"} \end{cases}$$

$r_{tot\_y} = 0.857$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} & \text{if Pos} = \text{"Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} & \text{if Pos} = \text{"Seabed"} \end{cases}$$

$r_{tot\_z} = 0.997$

6.7. Hydrodinamic Loads Calculation (DNVGL RP F109 2017)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 830.782\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 1.168\times10^{3}\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNVGL RP F109 2017)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = -42.917 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = -22.993 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.223$$

$$F'_R := F'_C \cdot \begin{cases} \frac{4.1 \cdot \kappa'_c}{G'_c{}^{0.39}} \cdot \left(\frac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 0 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$$\gamma_{SC} := 1$$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 4.729$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 1.038$$

$$Lateral_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC} \cdot \dfrac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC} \cdot \dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$Lateral_{check} = \text{"No"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 40 \cdot mm$
Full outside diameter pipe	$D_{conc.16} = 493.4 \cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 1.125 \times 10^{3} \cdot N \cdot m$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.52$
Current Velocity over Pipe Diameter	$V' = 0.267 \dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 0.468 \dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 0.945 \dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.282$
Significant Keulegan-Carpenter Number	$K'_s = 13.043$
Horizontal Peak load coefficient	$C'_Y = 2.613$
Vertical Peak load coefficient	$C'_Z = 3.158$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.05\,m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.857$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 0.997$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 830.782 \cdot N \cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 1.168 \times 10^{3} \cdot N \cdot m^{-1}$
Passive Soil Resistance	$F'_R = 0 \cdot N \cdot m^{-1}$

ON-BOTTOM STABILITY CALCULATION

Project : On-Bottom Stability Analysis on Piggyback Pipeline

Calculated by : ASM

Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline : 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline

Section : KP 1+393 - KP 5+725 (Minimum Water Depth)

Condition : Installation (Exposed to Seabed)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position — Pos := "Seabed"

Trenching Depth to Top of Steel (if applicable) — $H_{trench} := 0m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) — $h := 1.31m$ $h = 4.298 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) — $ca\% := 0\%$

Location Class (1 or 2) *Section 2 C300 DNV OS F101Table 2-2, page 28)* — $LC := 1$

Note:

Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\,kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\,kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 60mm$
Concrete Coating Density	$\rho_{cc} := 3040\,kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\,kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\,kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 0\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 0\,kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 0\,kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025 kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.31 m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 1.022 m$

Peak Wave Period $T_p := 7.72 s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness

Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090 N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2 kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline gap := 80mm

Trenching Slope $\theta_t := 45 deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\% \cdot CA$ $t_{nom.6} = 9.5 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2 \cdot t_{nom.6}$ $D_{i.6} = 0.149\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2 \cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25 \cdot \pi \cdot \left(D_{o.6}{}^2 - D_{i.6}{}^2\right) \cdot \rho_s \cdot g \qquad W_{st.6} = 364.85 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25 \cdot \pi \cdot \left(D_{acc.6}{}^2 - D_{o.6}{}^2\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.6} = 16.985 \cdot N \cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25 \cdot \pi \cdot \left(D_{acc.6}{}^2 - D_{o.6}{}^2\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.6} = 0.424 \cdot N \cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content

$$W_{cont.6} := 0.25 \cdot \pi \cdot D_{i.6}{}^2 \rho_{cont.6} \cdot g$$

$$W_{cont.6} = 0 \cdot N \cdot m^{-1}$$

Total Weight of 6" Gas Lift Pipeline

$$W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$$

$$W_{tot.6} = 382.259 \cdot N \cdot m^{-1}$$

Buoyancy of 6" Gas Lift Pipeline

$$B_6 := 0.25 \cdot \pi \cdot OD_6{}^2 \cdot \rho_w \cdot g \qquad B_6 = 242.604 \cdot N \cdot m^{-1}$$

Submerged Weight of 6" Gas Lift Pipeline

$$W_{sub.6} := W_{tot.6} - B_6 \qquad W_{sub.6} = 139.655 \cdot N \cdot m^{-1}$$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 139.655 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 0.013\,m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.381\,m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\,m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.533\,m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.533\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{\;2} - D_{i.16}^{\;2}\right) \cdot \rho_s \cdot g \qquad W_{st.16} = 1.209 \times 10^3 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 2.573 \times 10^3 \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 22.056 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 0 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{\;2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 0 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 3.846 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}^{\;2} \cdot \rho_w \cdot g$ $B_{16} = 2.246 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 1.6 \times 10^{3} \cdot N \cdot m^{-1}$$

Total Submerged Weight $W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 1.739 \times 10^{3} \cdot N \cdot m^{-1}$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight
(based on condition) $w_s := W_{sub.pig}$ $w_s = 1.739 \times 10^{3} \cdot N \cdot m^{-1}$

Buoyancy of Pipeline $b := B_{16} + B_6$ $b = 2.489 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight
(Section 3.2 DNV RP F109 2010) $\gamma_w := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNV RP F109 2010):

Stability in Water $\gamma_w \cdot \frac{b}{w_s + b} = \frac{\gamma_w}{S_g} \le 1.0$

Check Stability

$$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_w \cdot \frac{b}{w_s + b} \le 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$$w_{sub} = \text{"OK"}$$

$$SF_v := \gamma_w \cdot \frac{b}{w_s + b} \qquad SF_v = 0.647$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.533\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\left(\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.31\,\frac{m}{s}$

$V(z) = 0.294\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.269\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.269\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $H_{sdim} := \frac{H_s}{m}$ $T_{pdim} := \frac{T_p}{s}$ $D_{dim} := \frac{D_{top}}{m}$ $h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\omega_p = 0.814$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\phi = 7.636$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases}$$

$\gamma = 1$

Spectral Width Parameter (Eq. 3.6):

$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

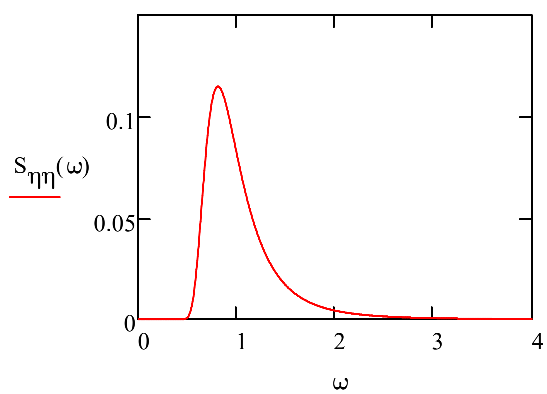
Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}^{2}\cdot\omega_p^{4}}{g_{dim}^{2}}\cdot(1 - 0.287\ln(\gamma))$$

$\alpha = 1.489 \times 10^{-3}$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}^{2}\cdot\omega^{-5}\, e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^{2}}}$$



Seabed Gap in Used for Spanning

$\zeta := 0$

Guess Values

$k := 100 \qquad a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh(k\cdot h_{dim}) - \frac{\omega^2}{g_{dim}}, k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk(a_\omega)\,h_{dim} - \text{asinh}(\infty), a_\omega\right)$$

$\omega_{max} = 72.78$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh(kk(\omega)\cdot h_{dim})} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^2\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11):

$$M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$$

Zeroth Order Spectral Moment $M_n(0) = 0.436$

First Order Spectral Moment $M_n(1) = 0.439$

Second Order Spectral Moment $M_n(2) = 0.491$

Fourth Order Spectral Moment $M_n(4) = 0.938$

Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12):

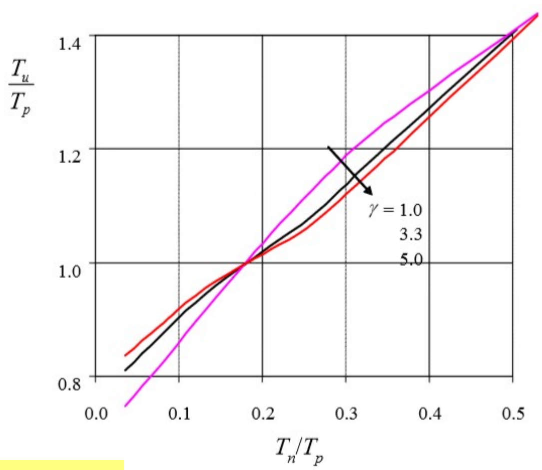
$$U_s := 2\sqrt{M_n(0)}\,\frac{m}{s} \qquad U_s = 1.321\,\frac{m}{s}$$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13):

$$T_u := 2\cdot\pi\sqrt{\frac{M_n(0)}{M_n(2)}}\,s \qquad T_u = 5.923\,s$$

Reference Period (Eq. 3.14):

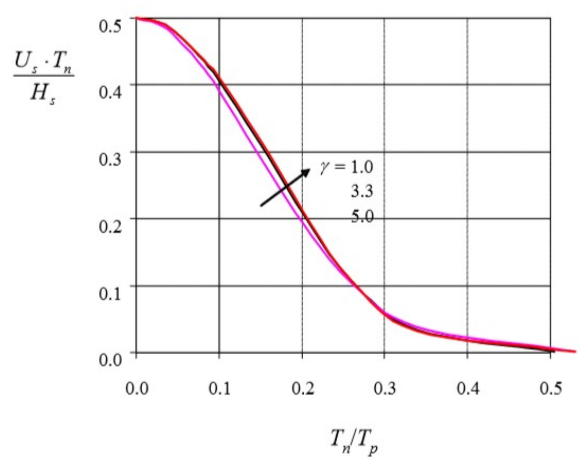
$$T_n := \sqrt{\frac{h}{g}} \qquad T_n = 0.365\,s$$



$$\frac{T_u}{T_p} = 0.767$$

$$\frac{T_n}{T_p} = 0.047$$

$$U_s\cdot\frac{T_n}{H_s} = 0.472$$



Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u}$$

$$\tau = 1.823 \times 10^3$$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right)$$

$$k_U = 2.012$$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s$$

$$U' = 2.658\,\frac{m}{s}$$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \frac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases}$$

$$k_t = 1.25$$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\frac{T_n}{T_u} & \text{if } \frac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \frac{T_n}{T_u} > 0.2 \end{cases}$$

$$k_T = 1.173$$

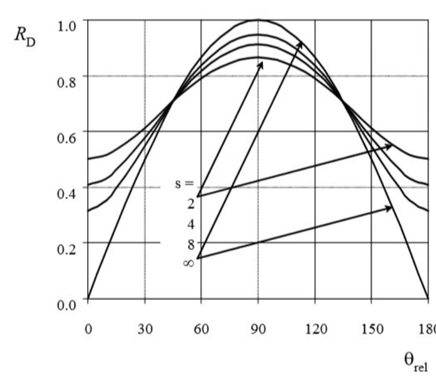
Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u$$

$$T' = 6.947\,s$$

4.3. Wave Directionality and Spreading (DNV RP F109 2010)

Spectral Spreading Exponent $s_p := 8$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\frac{1}{\pi}}\cdot\frac{\Gamma\left(1 + \frac{s_p}{2}\right)}{\Gamma\left(\frac{1}{2} + \frac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2 & \text{if } |\theta| < \frac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\, d(\theta)}$$

$$R_D = 0.949$$

Velocity Normal to the Pipe Including the Effect of Wave Spreading - Spectrum $U_w := R_D \cdot U_s$ $U_w = 1.253 \frac{m}{s}$

Velocity Normal to the Pipe Including the Effect of Wave Spreading - Spectrum $U'_w := R_D \cdot U'$ $U'_w = 2.521 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio $M := \frac{V(z)}{U_w}$ $M = 0.235$

Significant Keulegan-Carpenter Number $K_s := \frac{U_w \cdot T_u}{D_{top}}$ $K_s = 13.916$

For Single Oscillation

Steady to Oscillatory Velocity Ratio $M' := \frac{V'}{U'_w}$ $M' = 0.107$

Significant Keulegan-Carpenter Number $K'_s := \frac{U'_w \cdot T'}{D_{top}}$ $K'_s = 32.84$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.107$ and $K'_s = 32.84$

Horizontal Peak load coefficient $C'_Y = 2.092$

Vertical Peak load coefficient $C'_Z = 2.023$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay) $k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}}$ $k_{ci} = 0.613$

Soil Stiffness Parameter (Clay) $G_{ci} := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})}$ $G_{ci} = 0.207$

Initial Penetration of Pipe (Clay)

$$z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}}\right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}}\right)^{0.7}\right] D_{top}$$

$z_{pi} = 0.037\,m$ $\%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}}$ $\%z_{pi} = 7.016$

Penetration due to Movement
(assumed due to absolute lateral stability) $z_{pm} := 0\% \cdot D_{conc.16}$ $z_{pm} = 0$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration) $z_{pl} := 5\% \cdot D_{conc.16}$ $z_{pl} = 0.027\,m$

Total Penetration of Pipe $z_p := z_{pi} + z_{pm} + z_{pl}$ $z_p = 0.064\,m$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth $z_t := H_{trench}$ $z_t = 0$

Penetration due to Trenching

$$z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases}$$

$z_{pt} = 0\,m$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.064\,m$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4 \cdot \left(\frac{z_p}{D_{top}}\right) & \text{if } \frac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.832$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \frac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3 \cdot \left(\frac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \frac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 0.974$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

Horizontal Direction (Eq. 3.21): $\theta_t := 45$

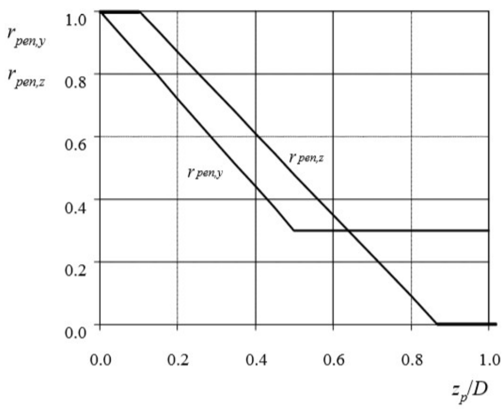
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18 \cdot (\theta_t - 5)^{0.25} \cdot \left(\frac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

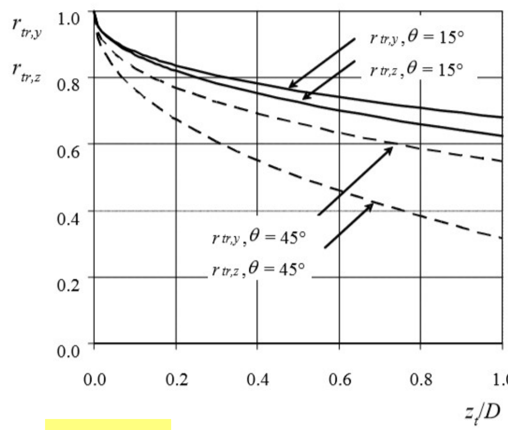
$r_{tr\_y} = 1$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 \text{ if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} < 0 \\ 1 \text{ otherwise} \end{cases}$$

$r_{tr\_z} = 1$





$\dfrac{z_p}{D_{top}} = 0.12$ $\quad r_{pen\_y} = 0.832$ $\quad r_{pen\_z} = 0.974$

$\dfrac{z_t}{D_{top}} = 0$ $\quad r_{tr\_y} = 1$ $\quad r_{tr\_z} = 1$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} & \text{if Pos = "Trench"} \\ r_{pen\_y} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_y} = 0.832$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} & \text{if Pos = "Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_z} = 0.974$

6.7. Hydrodinamic Loads Calculation (DNV RP F109 2010)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 3.704\times 10^3\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 4.191\times 10^3\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNV RP F109 2010)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = -2.452 \times 10^3 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = -0.435 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.207$$

$$F'_R := F'_C \cdot \begin{cases} \frac{4.1 \cdot \kappa'_c}{G'_c{}^{0.39}} \cdot \left(\frac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 0 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$$\gamma_{SC} := 1$$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 13.056$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 2.41$$

$$Lateral_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC} \cdot \dfrac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC} \cdot \dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$Lateral_{check} = \text{"No"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 60 \cdot mm$
Full outside diameter pipe	$D_{conc.16} = 533.4 \cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 1.739 \times 10^3 \cdot N \cdot m^{-1}$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.699$
Current Velocity over Pipe Diameter	$V' = 0.269 \dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 1.253 \dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 2.521 \dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.107$
Significant Keulegan-Carpenter Number	$K'_s = 32.84$
Horizontal Peak load coefficient	$C'_Y = 2.092$
Vertical Peak load coefficient	$C'_Z = 2.023$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.064 m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.832$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 0.974$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 3.704 \times 10^3 \cdot N \cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 4.191 \times 10^3 \cdot N \cdot m^{-1}$
Passive Soil Resistance	$F'_R = 0 \cdot N \cdot m^{-1}$

LAMPIRAN II

PERHITUNGAN *ON-BOTTOM STABILITY*

PADA *EXPOSED PIPELINES* (KONDISI OPERASI)

ON-BOTTOM STABILITY CALCULATION

Project : On-Bottom Stability Analysis on Piggyback Pipeline
Calculated by : ASM
Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline : 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline

Section : KP 0+273 - KP 1+393 (Minimum Water Depth)

Condition : Operation (Exposed to Seabed)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position $Pos := \text{"Seabed"}$

Trenching Depth to Top of Steel (if applicable) $H_{trench} := 0m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) $h := 0.1m$ $h = 0.328 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) $ca\% := 100\%$

Location Class (1 or 2) $LC := 1$
Section 2 C300 DNV OS F101Table 2-2, page 28)

Note:
<u>Location Class Definition :</u>

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\,kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\,kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 40mm$
Concrete Coating Density	$\rho_{cc} := 3040\,kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\,kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\,kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 5\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 109.85\,kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 73.83\,kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025 kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.35 m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 0.1 m$

Peak Wave Period $T_p := 10.13 s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness

Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090 N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2 kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline gap := 80mm

Trenching Slope $\theta_t := 45 deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 6.5 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.155\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\;2} - D_{i.6}^{\;2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 254.35\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\;2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 20.406\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 292.165\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\;2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 49.561\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 49.561 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 9.7 \times 10^{-3}\, m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.387\, m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\, m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.493\, m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.493\, m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{2} - D_{i.16}^{2}\right) \cdot \rho_{s} \cdot g \qquad W_{st.16} = 930.624 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{2} - D_{o.16}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{2} - D_{acc.16}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 1.643 \times 10^{3} \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{2} - D_{o.16}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{2} - D_{acc.16}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 14.083 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 82.144 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 85.166 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 2.796 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}^{2} \cdot \rho_w \cdot g$ $B_{16} = 1.922 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 874.533 \cdot N \cdot m^{-1}$$

Total Submerged Weight

$$W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 924.093 \cdot N \cdot m^{-1}$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight (based on condition) $w_s := W_{sub.pig}$ $w_s = 924.093 \cdot N \cdot m^{-1}$

Buoyancy of Pipeline $b := B_{16} + B_6$ $b = 2.165 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight (Section 3.2 DNV RP F109 2010) $\gamma_w := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNV RP F109 2010):

Stability in Water

$$\gamma_w \cdot \frac{b}{w_s + b} = \frac{\gamma_w}{S_g} \le 1.0$$

Check Stability

$$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_w \cdot \frac{b}{w_s + b} \le 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$$w_{sub} = \text{"OK"}$$

$$SF_v := \gamma_w \cdot \frac{b}{w_s + b} \qquad SF_v = 0.771$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.493\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\left(\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.35\,\frac{m}{s}$

$V(z) = 0.33\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.301\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.301\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $H_{sdim} := \frac{H_s}{m}$ $T_{pdim} := \frac{T_p}{s}$ $D_{dim} := \frac{D_{top}}{m}$ $h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\omega_p = 0.62$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\phi = 32.034$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases}$$

$\gamma = 1$

Spectral Width Parameter (Eq. 3.6):

$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

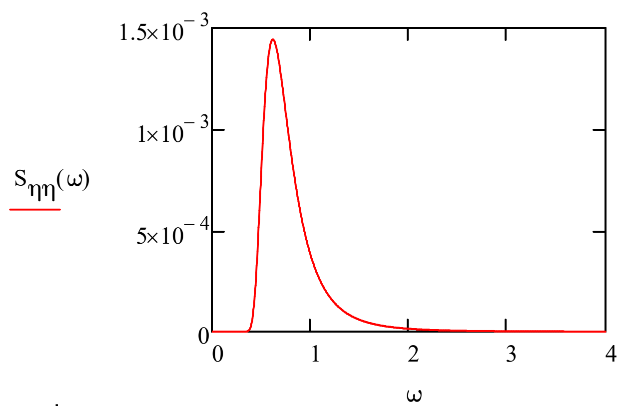
Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}{}^2\cdot\omega_p{}^4}{g_{dim}{}^2}\cdot(1 - 0.287\ln(\gamma))$$

$\alpha = 4.809 \times 10^{-6}$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}{}^2\cdot\omega^{-5}\, e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^2}}$$



Seabed Gap in Used for Spanning $\zeta := 0$

Guess Values $k := 100$ $a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh(k\cdot h_{dim}) - \frac{\omega^2}{g_{dim}}, k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk(a_\omega)\,h_{dim} - \text{asinh}(\infty), a_\omega\right)$$

$\omega_{max} = 263.421$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh(kk(\omega)\cdot h_{dim})} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^2\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11):

$$M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$$

Zeroth Order Spectral Moment $M_n(0) = 0.061$

First Order Spectral Moment $M_n(1) = 0.049$

Second Order Spectral Moment $M_n(2) = 0.046$

Fourth Order Spectral Moment $M_n(4) = 0.108$

Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12):

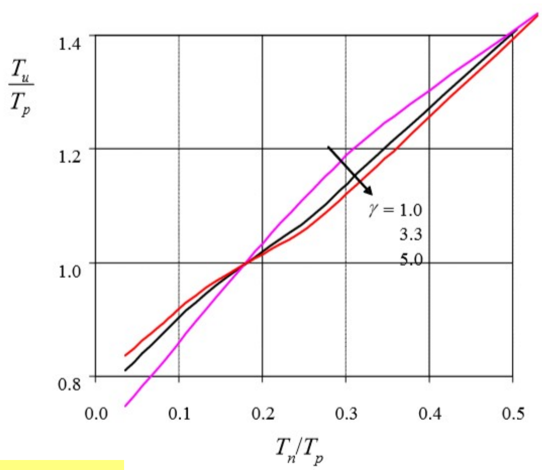
$$U_s := 2\sqrt{M_n(0)}\,\frac{m}{s} \qquad U_s = 0.494\,\frac{m}{s}$$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13):

$$T_u := 2\cdot\pi\sqrt{\frac{M_n(0)}{M_n(2)}}\,s \qquad T_u = 7.253\,s$$

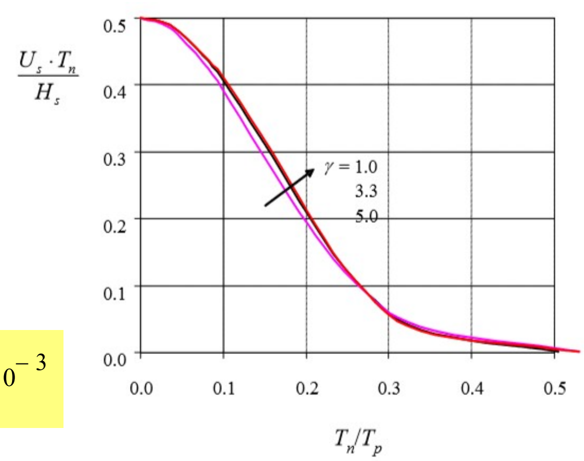
Reference Period (Eq. 3.14):

$$T_n := \sqrt{\frac{h}{g}} \qquad T_n = 0.101\,s$$



$$\frac{T_u}{T_p} = 0.716$$

$$U_s\cdot\frac{T_n}{H_s} = 0.499$$



$$\frac{T_n}{T_p} = 9.969\times 10^{-3}$$

Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u}$$ $\tau = 1.489 \times 10^3$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right)$$ $k_U = 1.987$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s$$ $U' = 0.981\,\frac{m}{s}$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \frac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases}$$ $k_t = 1.25$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

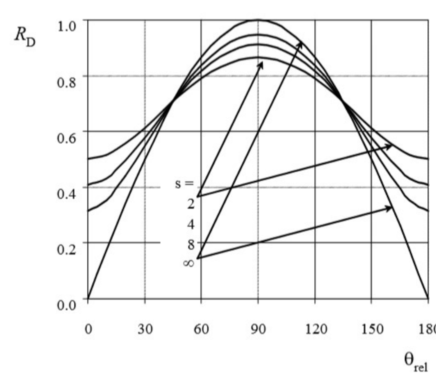
$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\frac{T_n}{T_u} & \text{if } \frac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \frac{T_n}{T_u} > 0.2 \end{cases}$$ $k_T = 1.233$

Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u$$ $T' = 8.94\,s$

4.3. Wave Directionality and Spreading (DNV RP F109 2010)

Spectral Spreading Exponent $s_p := 8$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\frac{1}{\pi}\cdot\frac{\Gamma\left(1 + \frac{s_p}{2}\right)}{\Gamma\left(\frac{1}{2} + \frac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2} & \text{if } |\theta| < \frac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\, d(\theta)}$$ $R_D = 0.949$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U_w := R_D \cdot U_s$

$U_w = 0.469 \frac{m}{s}$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U'_w := R_D \cdot U'$

$U'_w = 0.931 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio

$M := \frac{V(z)}{U_w}$

$M = 0.704$

Significant Keulegan-Carpenter Number

$K_s := \frac{U_w \cdot T_u}{D_{top}}$

$K_s = 6.887$

For Single Oscillation

Steady to Oscillatory Velocity Ratio

$M' := \frac{V'}{U'_w}$

$M' = 0.323$

Significant Keulegan-Carpenter Number

$K'_s := \frac{U'_w \cdot T'}{D_{top}}$

$K'_s = 16.865$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.323$ and $K'_s = 16.865$

Horizontal Peak load coefficient $C'_Y = 2.197$

Vertical Peak load coefficient $C'_Z = 2.511$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay)

$$k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}} \qquad k_{ci} = 1.068$$

Soil Stiffness Parameter (Clay)

$$G_{ci} := \frac{S_u}{D_{conc.16} \cdot (\gamma'_{soil})} \qquad G_{ci} = 0.223$$

Initial Penetration of Pipe (Clay)

$$z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}{}^{0.3}}{k_{ci}}\right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}{}^{0.3}}{k_{ci}}\right)^{0.7}\right] D_{conc.16}$$

$$z_{pi} = 0.022\,m \qquad \%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}} \qquad \%z_{pi} = 4.459$$

Penetration due to Movement
(assumed due to absolute lateral stability)

$$z_{pm} := 0\% \cdot D_{conc.16} \qquad z_{pm} = 0$$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration)

$$z_{pl} := 5\% \cdot D_{conc.16} \qquad z_{pl} = 0.025\,m$$

Total Penetration of Pipe

$$z_p := z_{pi} + z_{pm} + z_{pl} \qquad z_p = 0.047\,m$$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth

$$z_t := 0m \qquad z_t = 0$$

Penetration due to Trenching

$$z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases}$$

$$z_{pt} = 0\,m$$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.047\,m$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4 \cdot \left(\dfrac{z_p}{D_{top}}\right) & \text{if } \dfrac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.868$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \dfrac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3 \cdot \left(\dfrac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \dfrac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 1$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

Horizontal Direction (Eq. 3.21): $\theta_t := 45$

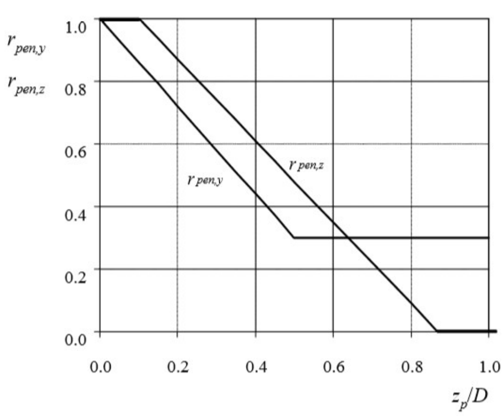
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18 \cdot (\theta_t - 5)^{0.25} \cdot \left(\dfrac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

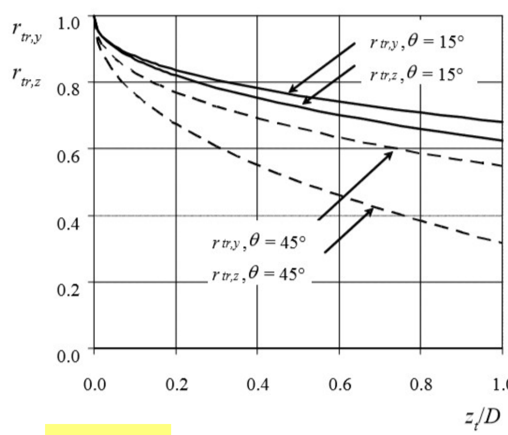
$r_{tr\_y} = 1$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.46} < 0 \\ 1 & \text{otherwise} \end{cases}$$

$r_{tr\_z} = 1$





$\frac{z_p}{D_{top}} = 0.095$ $\quad r_{pen\_y} = 0.868$ $\quad r_{pen\_z} = 1$

$\frac{z_t}{D_{top}} = 0$ $\quad r_{tr\_y} = 1$ $\quad r_{tr\_z} = 1$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} & \text{if Pos = "Trench"} \\ r_{pen\_y} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_y} = 0.868$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} & \text{if Pos = "Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_z} = 1$

6.7. Hydrodinamic Loads Calculation (DNV RP F109 2010)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 731.435\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 963.613\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNV RP F109 2010)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = -39.519 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = -24.97 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.223$$

$$F'_R := F'_C \cdot \begin{cases} \frac{4.1 \cdot \kappa'_c}{G'_c{}^{0.39}} \cdot \left(\frac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 0 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea

	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$$\gamma_{SC} := 1.4$$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean

	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf

	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)

	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 7$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 1.46$$

$$Lateral_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC} \cdot \dfrac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC} \cdot \dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$Lateral_{check} = \text{"No"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 40 \cdot mm$
Full outside diameter pipe	$D_{conc.16} = 493.4 \cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 924.093 \cdot N \cdot m^{-1}$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.427$
Current Velocity over Pipe Diameter	$V' = 0.301 \dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 0.469 \dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 0.931 \dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.323$
Significant Keulegan-Carpenter Number	$K'_s = 16.865$
Horizontal Peak load coefficient	$C'_Y = 2.197$
Vertical Peak load coefficient	$C'_Z = 2.511$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.047 m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.868$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 1$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 731.435 \cdot N \cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 963.613 \cdot N \cdot m^{-1}$
Passive Soil Resistance	$F'_R = 0 \cdot N \cdot m^{-1}$

ON-BOTTOM STABILITY CALCULATION

Project : On-Bottom Stability Analysis on Piggyback Pipeline
Calculated by : ASM
Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline : 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline

Section : KP 1+393 - KP 5+725 (Minimum Water Depth)

Condition : Operation (Exposed to Seabed)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position — Pos := "Seabed"

Trenching Depth to Top of Steel (if applicable) — $H_{trench} := 0m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) — $h := 1.31m$ $h = 4.298 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) — $ca\% := 100\%$

Location Class (1 or 2) *Section 2 C300 DNV OS F101Table 2-2, page 28)* — $LC := 1$

Note:
Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\,kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\,kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 60mm$
Concrete Coating Density	$\rho_{cc} := 3040\,kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\,kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\,kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 5\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 109.85\,kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 73.83\,kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025 kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.35 m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 1.022 m$

Peak Wave Period $T_p := 10.13 s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness

Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090 N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2 kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline $gap := 80 mm$

Trenching Slope $\theta_t := 45 deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 6.5 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.155\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\,2} - D_{i.6}^{\,2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 254.35\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\,2} - D_{o.6}^{\,2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\,2} - D_{o.6}^{\,2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\,2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 20.406\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 292.165\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\,2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 49.561\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 49.561 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 9.7 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.387\,m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\,m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.533\,m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.533\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{\;2} - D_{i.16}^{\;2}\right) \cdot \rho_s \cdot g \qquad W_{st.16} = 930.624 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 2.573 \times 10^{3} \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 22.056 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 128.652 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{\;2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 85.166 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 3.781 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}^{\;2} \cdot \rho_w \cdot g$ $B_{16} = 2.246 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 1.535 \times 10^{3} \cdot N \cdot m^{-1}$$

Total Submerged Weight

$$W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 1.584 \times 10^{3} \cdot N \cdot m^{-1}$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight (based on condition) $w_s := W_{sub.pig}$ $w_s = 1.584 \times 10^{3} \cdot N \cdot m^{-1}$

Buoyancy of Pipeline $b := B_{16} + B_6$ $b = 2.489 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight (Section 3.2 DNV RP F109 2010) $\gamma_w := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNV RP F109 2010):

Stability in Water

$$\gamma_w \cdot \frac{b}{w_s + b} = \frac{\gamma_w}{S_g} \le 1.0$$

Check Stability

$$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_w \cdot \frac{b}{w_s + b} \le 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$$w_{sub} = \text{"OK"}$$

$$SF_v := \gamma_w \cdot \frac{b}{w_s + b} \qquad SF_v = 0.672$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.533\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\left(\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.35\,\frac{m}{s}$

$V(z) = 0.332\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.303\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.303\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $H_{sdim} := \frac{H_s}{m}$ $T_{pdim} := \frac{T_p}{s}$ $D_{dim} := \frac{D_{top}}{m}$ $h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\omega_p = 0.62$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\phi = 10.02$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases}$$

$\gamma = 1$

Spectral Width Parameter (Eq. 3.6):

$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

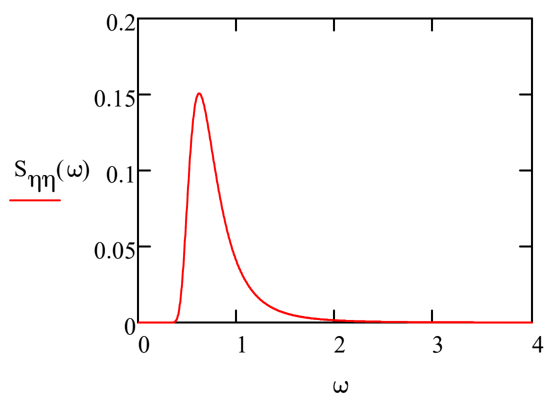
Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}{}^2\cdot\omega_p{}^4}{g_{dim}{}^2}\cdot(1 - 0.287\ln(\gamma))$$

$\alpha = 5.023 \times 10^{-4}$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}{}^2\cdot\omega^{-5}\, e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^2}}$$



Seabed Gap in Used for Spanning

$\zeta := 0$

Guess Values

$k := 100 \qquad a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh\left(k\cdot h_{dim}\right) - \frac{\omega^2}{g_{dim}}, k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk\left(a_\omega\right) h_{dim} - \text{asinh}(\infty), a_\omega\right)$$

$\omega_{max} = 72.78$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh\left(kk(\omega)\cdot h_{dim}\right)} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^2\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11): $M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$

Zeroth Order Spectral Moment $M_n(0) = 0.457$

First Order Spectral Moment $M_n(1) = 0.357$

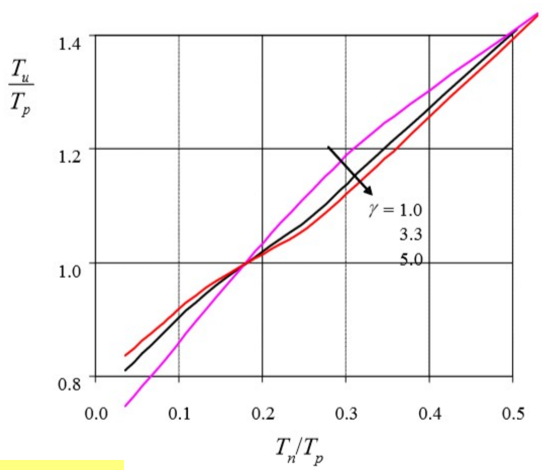
Second Order Spectral Moment $M_n(2) = 0.313$

Fourth Order Spectral Moment $M_n(4) = 0.406$

Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12): $U_s := 2\sqrt{M_n(0)}\,\frac{m}{s}$ $U_s = 1.352\,\frac{m}{s}$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13): $T_u := 2 \cdot \pi \sqrt{\frac{M_n(0)}{M_n(2)}}\, s$ $T_u = 7.592\, s$

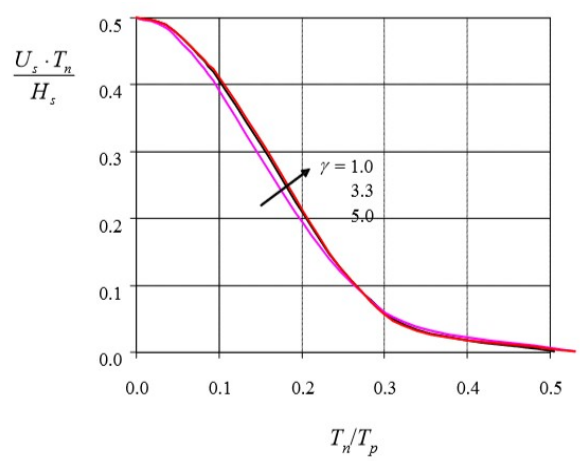
Reference Period (Eq. 3.14): $T_n := \sqrt{\frac{h}{g}}$ $T_n = 0.365\, s$



$U_s \cdot \frac{T_n}{H_s} = 0.484$

$\frac{T_u}{T_p} = 0.749$

$\frac{T_n}{T_p} = 0.036$



Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u}$$ $$\tau = 1.423 \times 10^3$$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right)$$ $$k_U = 1.981$$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s$$ $$U' = 2.679\,\frac{m}{s}$$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \dfrac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases}$$ $$k_t = 1.25$$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

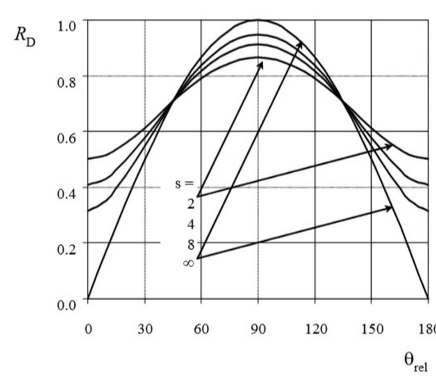
$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\dfrac{T_n}{T_u} & \text{if } \dfrac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \dfrac{T_n}{T_u} > 0.2 \end{cases}$$ $$k_T = 1.19$$

Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u$$ $$T' = 9.033\,s$$

4.3. Wave Directionality and Spreading (DNV RP F109 2010)

Spectral Spreading Exponent $s_p := 8$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\dfrac{1}{\pi}}\cdot\dfrac{\Gamma\left(1 + \dfrac{s_p}{2}\right)}{\Gamma\left(\dfrac{1}{2} + \dfrac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2 & \text{if } |\theta| < \dfrac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\, d(\theta)}$$ $$R_D = 0.949$$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U_w := R_D \cdot U_s$ $\qquad U_w = 1.283 \frac{m}{s}$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U'_w := R_D \cdot U'$ $\qquad U'_w = 2.542 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio

$M := \frac{V(z)}{U_w}$ $\qquad M = 0.259$

Significant Keulegan-Carpenter Number

$K_s := \frac{U_w \cdot T_u}{D_{top}}$ $\qquad K_s = 18.262$

For Single Oscillation

Steady to Oscillatory Velocity Ratio

$M' := \frac{V'}{U'_w}$ $\qquad M' = 0.119$

Significant Keulegan-Carpenter Number

$K'_s := \frac{U'_w \cdot T'}{D_{top}}$ $\qquad K'_s = 43.044$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.119$ and $K'_s = 43.044$

Horizontal Peak load coefficient $C'_Y = 1.782$

Vertical Peak load coefficient $C'_Z = 1.643$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay) $k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}}$ $k_{ci} = 0.673$

Soil Stiffness Parameter (Clay) $G_{ci} := \frac{S_u}{D_{conc.16} \cdot (\gamma'_{soil})}$ $G_{ci} = 0.207$

Initial Penetration of Pipe (Clay)

$$z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}{}^{0.3}}{k_{ci}}\right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}{}^{0.3}}{k_{ci}}\right)^{0.7}\right] D_{conc.16}$$

$z_{pi} = 0.034\,m$ $\%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}}$ $\%z_{pi} = 6.427$

Penetration due to Movement
(assumed due to absolute lateral stability) $z_{pm} := 0\% \cdot D_{conc.16}$ $z_{pm} = 0$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration) $z_{pl} := 5\% \cdot D_{conc.16}$ $z_{pl} = 0.027\,m$

Total Penetration of Pipe $z_p := z_{pi} + z_{pm} + z_{pl}$ $z_p = 0.061\,m$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth $z_t := 0m$ $z_t = 0$

Penetration due to Trenching

$$z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases}$$

$\frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} = 0.267\,m$ $z_{pt} = 0\,m$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.061\,m$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4 \cdot \left(\dfrac{z_p}{D_{top}}\right) & \text{if } \dfrac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.84$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \dfrac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3 \cdot \left(\dfrac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \dfrac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 0.981$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

Horizontal Direction (Eq. 3.21): $\theta_t := 45$

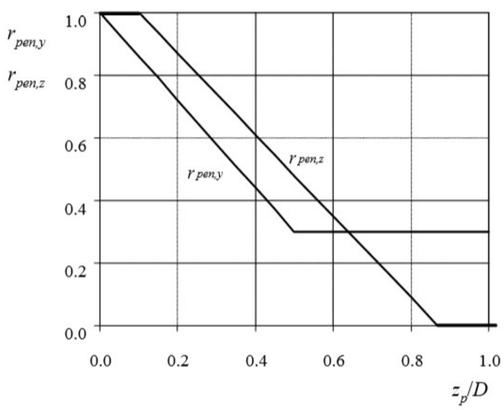
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18 \cdot (\theta_t - 5)^{0.25} \cdot \left(\dfrac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

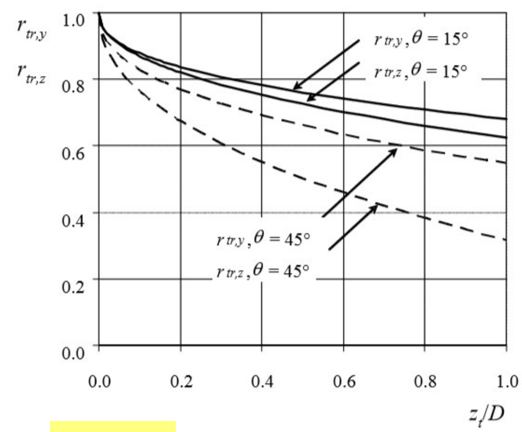
$r_{tr\_y} = 1$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} < 0 \\ 1 & \text{otherwise} \end{cases}$$

$r_{tr\_z} = 1$





$\frac{z_p}{D_{top}} = 0.114$ $\quad r_{pen\_y} = 0.84$ $\quad r_{pen\_z} = 0.981$

$\frac{z_t}{D_{top}} = 0$ $\quad r_{tr\_y} = 1$ $\quad r_{tr\_z} = 1$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} & \text{if Pos = "Trench"} \\ r_{pen\_y} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_y} = 0.84$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} & \text{if Pos = "Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_z} = 0.981$

6.7. Hydrodinamic Loads Calculation (DNV RP F109 2010)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 3.312\times 10^3\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 3.568\times 10^3\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNV RP F109 2010)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = -1.983 \times 10^3 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = -0.538 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.207$$

$$F'_R := \begin{cases} F'_C \cdot \frac{4.1 \cdot \kappa'_c}{G'^{0.39}_c} \cdot \left(\frac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 0 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$$\gamma_{SC} := 1.4$$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 17.784$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 3.152$$

$$\text{Lateral}_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC} \cdot \dfrac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC} \cdot \dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$\text{Lateral}_{check} = \text{"No"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 60 \cdot mm$
Full outside diameter pipe	$D_{conc.16} = 533.4 \cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 1.584 \times 10^3 \cdot N \cdot m^{-1}$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.637$
Current Velocity over Pipe Diameter	$V' = 0.303 \dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 1.283 \dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 2.542 \dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.119$
Significant Keulegan-Carpenter Number	$K'_s = 43.044$
Horizontal Peak load coefficient	$C'_Y = 1.782$
Vertical Peak load coefficient	$C'_Z = 1.643$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.061\, m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.84$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 0.981$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 3.312 \times 10^3 \cdot N \cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 3.568 \times 10^3 \cdot N \cdot m^{-1}$
Passive Soil Resistance	$F'_R = 0 \cdot N \cdot m^{-1}$

LAMPIRAN III

PERHITUNGAN *ON-BOTTOM STABILITY*

PADA *TRENCHED PIPELINES* (KONDISI INSTALASI)

ON-BOTTOM STABILITY CALCULATION

Project	: On-Bottom Stability Analysis on Piggyback Pipeline
Calculated by	: ASM
Checked by	: IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline	: 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline
Section	: KP 0+273 - KP 1+393 (Minimum Water Depth)
Condition	: Installation (Pre-trenched Seabed)
Design Life	: 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position — Pos := "Trench"

Trenching Depth to Top of Steel (if applicable) — $H_{trench} := 2.749m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) — $h := 0.1m$ $h = 0.328 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) — $ca\% := 0\%$

Location Class (1 or 2) *Section 2 C300 DNV OS F101Table 2-2, page 28)* — $LC := 1$

Note:
Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850 kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940 kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 40mm$
Concrete Coating Density	$\rho_{cc} := 3040 kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930 kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025 kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 0\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 0 kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 0 kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025 kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.31 m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 0.1m$

Peak Wave Period $T_p := 7.72s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness

Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090 N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline gap := 80mm

Trenching Slope $\theta_t := 45deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 9.5 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.149\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\,2} - D_{i.6}^{\,2}\right)\cdot\rho_s\cdot g$ $W_{st.6} = 364.85\cdot N\cdot m^{-1}$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\,2} - D_{o.6}^{\,2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right)$$ $W_{acc.6} = 16.985\cdot N\cdot m^{-1}$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\,2} - D_{o.6}^{\,2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right)$$ $W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\,2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 0\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 382.259\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\,2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 139.655\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 139.655 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 0.013\,m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.381\,m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\,m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.493\,m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.493\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{\;2} - D_{i.16}^{\;2}\right) \cdot \rho_s \cdot g \qquad W_{st.16} = 1.209 \times 10^3 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 1.643 \times 10^3 \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\;2} - D_{o.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\;2} - D_{acc.16}^{\;2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 14.083 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 0 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{\;2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 0 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 2.908 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}{}^{2} \cdot \rho_w \cdot g$ $B_{16} = 1.922 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 985.83 \cdot N \cdot m^{-1}$$

Total Submerged Weight

$$W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 1.125 \times 10^{3} \cdot N \cdot m^{-1}$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight
(based on condition) $w_s := W_{sub.pig}$ $w_s = 1.125 \times 10^{3} \cdot N \cdot m^{-1}$

Buoyancy of Pipeline $b := B_{16} + B_6$ $b = 2.165 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight
(Section 3.2 DNV RP F109 2010) $\gamma_w := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNV RP F109 2010):

Stability in Water

$$\gamma_w \cdot \frac{b}{w_s + b} = \frac{\gamma_w}{S_g} \le 1.0$$

Check Stability

$$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_w \cdot \frac{b}{w_s + b} \le 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$$w_{sub} = \text{"OK"}$$

$$SF_v := \gamma_w \cdot \frac{b}{w_s + b} \qquad SF_v = 0.724$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.493\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\left(\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.31\,\frac{m}{s}$

$V(z) = 0.292\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.267\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.267\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $H_{sdim} := \frac{H_s}{m}$ $T_{pdim} := \frac{T_p}{s}$ $D_{dim} := \frac{D_{top}}{m}$ $h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\omega_p = 0.814$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\phi = 24.413$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases} \qquad \gamma = 1$$

Spectral Width Parameter (Eq. 3.6):

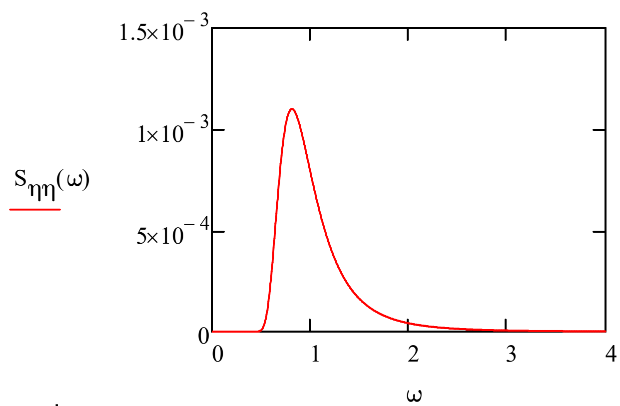
$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}{}^2\cdot\omega_p{}^4}{g_{dim}{}^2}\cdot(1 - 0.287\ln(\gamma)) \qquad \alpha = 1.426\times 10^{-5}$$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}{}^2\cdot\omega^{-5}\,e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^2}}$$



Seabed Gap in Used for Spanning $\quad \zeta := 0$

Guess Values $\quad k := 100 \qquad a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh\left(k\cdot h_{dim}\right) - \frac{\omega^2}{g_{dim}}, k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk\left(a_\omega\right)h_{dim} - \text{asinh}(\infty), a_\omega\right)$$

$$\omega_{max} = 263.421$$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh\left(kk(\omega)\cdot h_{dim}\right)} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^2\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11):

$$M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$$

Zeroth Order Spectral Moment $M_n(0) = 0.061$

First Order Spectral Moment $M_n(1) = 0.064$

Second Order Spectral Moment $M_n(2) = 0.078$

Fourth Order Spectral Moment $M_n(4) = 0.284$

Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12):

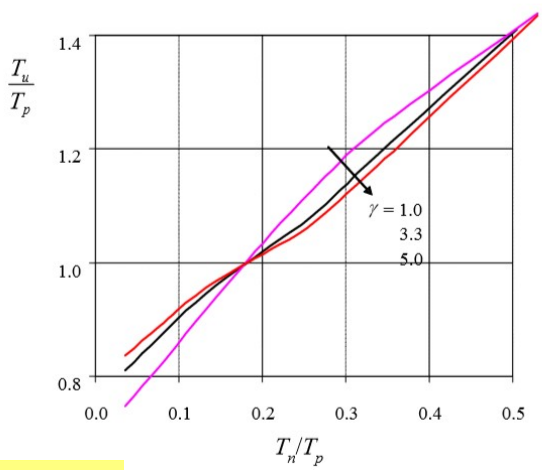
$$U_s := 2\sqrt{M_n(0)}\,\frac{m}{s} \qquad U_s = 0.493\,\frac{m}{s}$$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13):

$$T_u := 2\cdot\pi\sqrt{\frac{M_n(0)}{M_n(2)}}\,s \qquad T_u = 5.55\,s$$

Reference Period (Eq. 3.14):

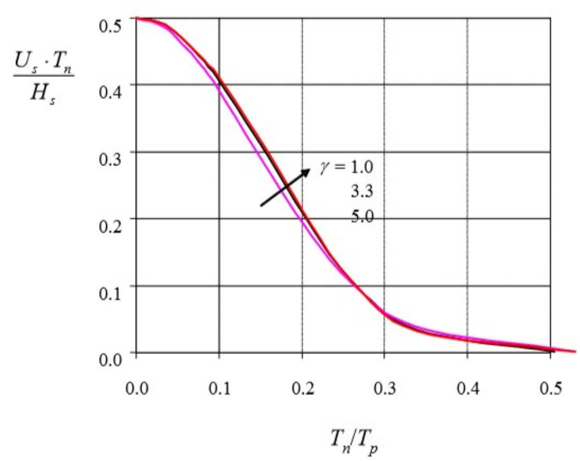
$$T_n := \sqrt{\frac{h}{g}} \qquad T_n = 0.101\,s$$



$$\frac{T_u}{T_p} = 0.719$$

$$\frac{T_n}{T_p} = 0.013$$

$$U_s \cdot \frac{T_n}{H_s} = 0.498$$



Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u}$$ $\tau = 1.946 \times 10^3$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right)$$ $k_U = 2.02$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s$$ $U' = 0.996 \frac{m}{s}$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \dfrac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases}$$ $k_t = 1.25$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

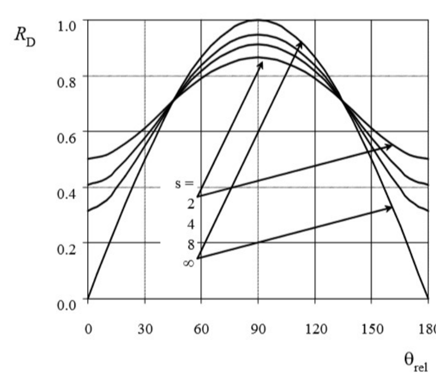
$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\dfrac{T_n}{T_u} & \text{if } \dfrac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \dfrac{T_n}{T_u} > 0.2 \end{cases}$$ $k_T = 1.227$

Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u$$ $T' = 6.812\,s$

4.3. Wave Directionality and Spreading (DNV RP F109 2010)

Spectral Spreading Exponent $s_p := 8$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\dfrac{1}{\pi}\cdot\dfrac{\Gamma\left(1 + \dfrac{s_p}{2}\right)}{\Gamma\left(\dfrac{1}{2} + \dfrac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2} & \text{if } |\theta| < \dfrac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\, d(\theta)}$$ $R_D = 0.949$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U_w := R_D \cdot U_s$ $\quad U_w = 0.468 \frac{m}{s}$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U'_w := R_D \cdot U'$ $\quad U'_w = 0.945 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio

$M := \frac{V(z)}{U_w}$ $\quad M = 0.625$

Significant Keulegan-Carpenter Number

$K_s := \frac{U_w \cdot T_u}{D_{top}}$ $\quad K_s = 5.261$

For Single Oscillation

Steady to Oscillatory Velocity Ratio

$M' := \frac{V'}{U'_w}$ $\quad M' = 0.282$

Significant Keulegan-Carpenter Number

$K'_s := \frac{U'_w \cdot T'}{D_{top}}$ $\quad K'_s = 13.043$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.282$ and $K'_s = 13.043$

Horizontal Peak load coefficient $C'_Y = 2.613$

Vertical Peak load coefficient $C'_Z = 3.158$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay)

$$k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}} \qquad k_{ci} = 0.877$$

Soil Stiffness Parameter (Clay)

$$G_{ci} := \frac{S_u}{D_{conc.16} \cdot (\gamma'_{soil})} \qquad G_{ci} = 0.223$$

Initial Penetration of Pipe (Clay)

$$z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}^{\;0.3}}{k_{ci}}\right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}^{\;0.3}}{k_{ci}}\right)^{0.7}\right] D_{conc.16}$$

$$z_{pi} = 0.026\,\mathrm{m} \qquad \%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}} \qquad \%z_{pi} = 5.219$$

Penetration due to Movement
(assumed due to absolute lateral stability)

$$z_{pm} := 0\% \cdot D_{conc.16} \qquad z_{pm} = 0$$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration)

$$z_{pl} := 5\% \cdot D_{conc.16} \qquad z_{pl} = 0.025\,\mathrm{m}$$

Total Penetration of Pipe

$$z_p := z_{pi} + z_{pm} + z_{pl} \qquad z_p = 0.05\,\mathrm{m}$$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth

$$z_t := H_{trench} \qquad z_t = 2.749\,\mathrm{m}$$

Penetration due to Trenching

$$z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases} \qquad z_{pt} = 0.247\,\mathrm{m}$$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.297\,m$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4\cdot\left(\dfrac{z_p}{D_{top}}\right) & \text{if } \dfrac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.857$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \dfrac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3\cdot\left(\dfrac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \dfrac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 0.997$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

Horizontal Direction (Eq. 3.21): $\theta_t := 45$

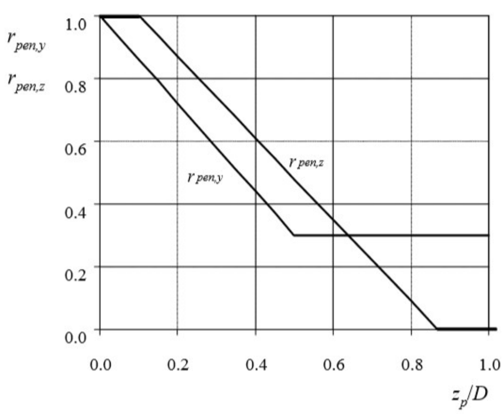
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18\cdot(\theta_t - 5)^{0.25}\cdot\left(\dfrac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

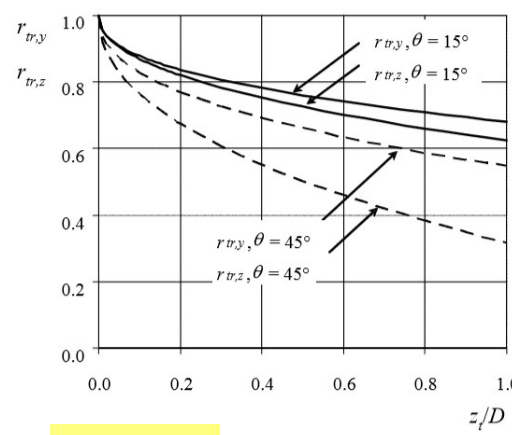
$r_{tr\_y} = 0.069$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 \text{ if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} < 0 \\ 1 \text{ otherwise} \end{cases}$$

$r_{tr\_z} = 0$





$\frac{z_p}{D_{top}} = 0.102$ $r_{pen\_y} = 0.857$ $r_{pen\_z} = 0.997$

$\frac{z_t}{D_{top}} = 5.572$ $r_{tr\_y} = 0.069$ $r_{tr\_z} = 0$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} \text{ if } Pos = \text{"Trench"} \\ r_{pen\_y} \text{ if } Pos = \text{"Seabed"} \end{cases}$$

$r_{tot\_y} = 0.059$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} \text{ if } Pos = \text{"Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} \text{ if } Pos = \text{"Seabed"} \end{cases}$$

$r_{tot\_z} = 0$

6.7. Hydrodinamic Loads Calculation (DNV RP F109 2010)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 57.061\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 0\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNV RP F109 2010)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = 1.125 \times 10^3 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = 0.877 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.223$$

$$F'_R := F'_C \cdot \begin{cases} \dfrac{4.1 \cdot \kappa'_c}{G'^{\,0.39}_c} \cdot \left(\dfrac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 3.735 \times 10^3 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$$\gamma_{SC} := 1$$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 0.014$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 0$$

$$Lateral_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC} \cdot \dfrac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC} \cdot \dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$Lateral_{check} = \text{"Yes"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 40 \cdot mm$
Full outside diameter pipe	$D_{conc.16} = 493.4 \cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 1.125 \times 10^3 \cdot N \cdot m^{-1}$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.52$
Current Velocity over Pipe Diameter	$V' = 0.267 \dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 0.468 \dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 0.945 \dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.282$
Significant Keulegan-Carpenter Number	$K'_s = 13.043$
Horizontal Peak load coefficient	$C'_Y = 2.613$
Vertical Peak load coefficient	$C'_Z = 3.158$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.297 m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.059$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 0$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 57.061 \cdot N \cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 0 \cdot N \cdot m^{-1}$
Passive Soil Resistance	$F'_R = 3.735 \times 10^3 \cdot N \cdot m^{-1}$

ON-BOTTOM STABILITY CALCULATION

Project : On-Bottom Stability Analysis on Piggyback Pipeline
Calculated by : ASM
Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline : 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline

Section : KP 1+393 - KP 5+725 (Minimum Water Depth)

Condition : Installation (Pre-trenched Seabed)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position $Pos := \text{"Trench"}$

Trenching Depth to Top of Steel (if applicable) $H_{trench} := 2.789m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) $h := 1.31m$ $h = 4.298 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) $ca\% := 0\%$

Location Class (1 or 2) $LC := 1$
Section 2 C300 DNV OS F101Table 2-2, page 28)

Note:
Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\,kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\,kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 60mm$
Concrete Coating Density	$\rho_{cc} := 3040\,kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\,kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\,kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 0\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 0\,kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 0\,kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.31m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 1.022m$

Peak Wave Period $T_p := 7.72s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness			
Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline $gap := 80mm$

Trenching Slope $\theta_t := 45deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 9.5 \times 10^{-3}\, m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.149\, m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\, m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\, m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\ 2} - D_{i.6}^{\ 2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 364.85\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\ 2} - D_{o.6}^{\ 2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\ 2} - D_{o.6}^{\ 2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\ 2}\rho_{cont.6}\cdot g$

$W_{cont.6} = 0\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 382.259\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\ 2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 139.655\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 139.655 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 0.013\,m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.381\,m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\,m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.533\,m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.533\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{\ 2} - D_{i.16}^{\ 2}\right) \cdot \rho_s \cdot g \qquad W_{st.16} = 1.209 \times 10^3 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\ 2} - D_{o.16}^{\ 2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\ 2} - D_{acc.16}^{\ 2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 2.573 \times 10^3 \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\ 2} - D_{o.16}^{\ 2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\ 2} - D_{acc.16}^{\ 2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 22.056 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 0 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{\ 2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 0 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 3.846 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}{}^{2} \cdot \rho_{w} \cdot g$ $B_{16} = 2.246 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 1.6 \times 10^{3} \cdot N \cdot m^{-1}$$

Total Submerged Weight

$$W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 1.739 \times 10^{3} \cdot N \cdot m^{-1}$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight (based on condition) $w_{s} := W_{sub.pig}$ $w_{s} = 1.739 \times 10^{3} \cdot N \cdot m^{-1}$

Buoyancy of Pipeline $b := B_{16} + B_{6}$ $b = 2.489 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight (Section 3.2 DNV RP F109 2010) $\gamma_{w} := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNV RP F109 2010):

Stability in Water $\gamma_{w} \cdot \frac{b}{w_{s} + b} = \frac{\gamma_{w}}{S_{g}} \leq 1.0$

Check Stability

$$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_{w} \cdot \frac{b}{w_{s} + b} \leq 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$$w_{sub} = \text{"OK"}$$

$$SF_{v} := \gamma_{w} \cdot \frac{b}{w_{s} + b} \qquad SF_{v} = 0.647$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.533\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\left(\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.31\,\frac{m}{s}$

$V(z) = 0.294\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.269\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.269\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $H_{sdim} := \frac{H_s}{m}$ $T_{pdim} := \frac{T_p}{s}$ $D_{dim} := \frac{D_{top}}{m}$ $h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\omega_p = 0.814$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\phi = 7.636$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases}$$

$\gamma = 1$

Spectral Width Parameter (Eq. 3.6):

$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

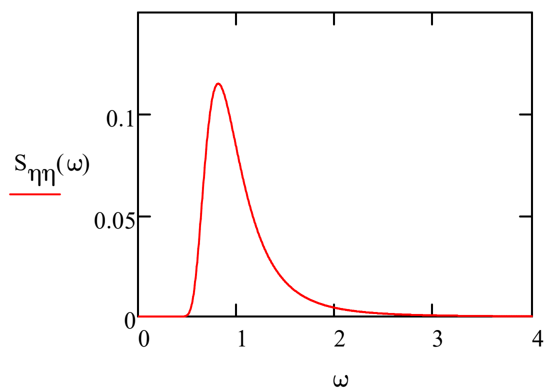
Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}{}^{2}\cdot\omega_p{}^{4}}{g_{dim}{}^{2}}\cdot(1 - 0.287\ln(\gamma))$$

$\alpha = 1.489 \times 10^{-3}$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}{}^{2}\cdot\omega^{-5}\, e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^{2}}}$$



Seabed Gap in Used for Spanning $\zeta := 0$

Guess Values $k := 100$ $a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh\left(k\cdot h_{dim}\right) - \frac{\omega^2}{g_{dim}}, k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk\left(a_\omega\right)h_{dim} - \text{asinh}(\infty), a_\omega\right)$$

$$\omega_{max} = 72.78$$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh\left(kk(\omega)\cdot h_{dim}\right)} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^2\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11):

$$M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$$

Zeroth Order Spectral Moment $M_n(0) = 0.436$

First Order Spectral Moment $M_n(1) = 0.439$

Second Order Spectral Moment $M_n(2) = 0.491$

Fourth Order Spectral Moment $M_n(4) = 0.938$

Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12):

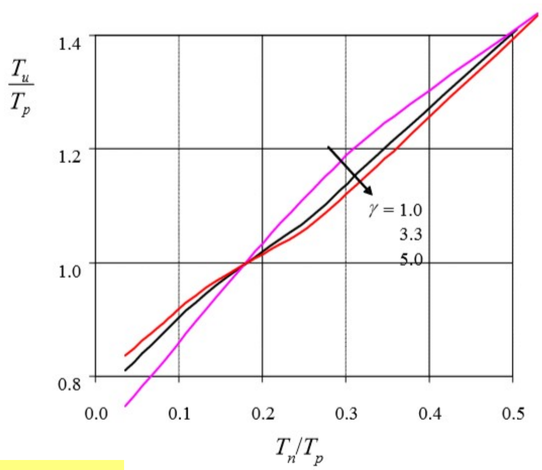
$$U_s := 2\sqrt{M_n(0)}\,\frac{m}{s} \qquad U_s = 1.321\,\frac{m}{s}$$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13):

$$T_u := 2\cdot\pi\sqrt{\frac{M_n(0)}{M_n(2)}}\,s \qquad T_u = 5.923\,s$$

Reference Period (Eq. 3.14):

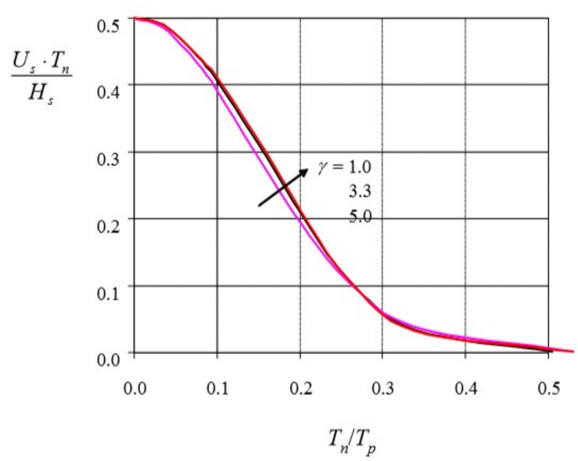
$$T_n := \sqrt{\frac{h}{g}} \qquad T_n = 0.365\,s$$



$$\frac{T_u}{T_p} = 0.767$$

$$\frac{T_n}{T_p} = 0.047$$

$$U_s\cdot\frac{T_n}{H_s} = 0.472$$



Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u} \qquad \tau = 1.823 \times 10^3$$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right) \qquad k_U = 2.012$$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s \qquad U' = 2.658\,\frac{m}{s}$$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \dfrac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases} \qquad k_t = 1.25$$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\dfrac{T_n}{T_u} & \text{if } \dfrac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \dfrac{T_n}{T_u} > 0.2 \end{cases} \qquad k_T = 1.173$$

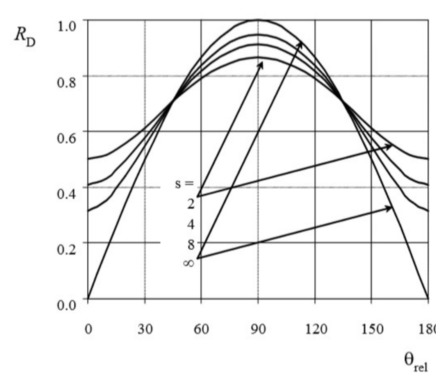
Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u \qquad T' = 6.947\,s$$

4.3. Wave Directionality and Spreading (DNV RP F109 2010)

Spectral Spreading Exponent

$$s_p := 8$$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\dfrac{1}{\pi}\cdot\dfrac{\Gamma\left(1 + \dfrac{s_p}{2}\right)}{\Gamma\left(\dfrac{1}{2} + \dfrac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2} & \text{if } |\theta| < \dfrac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\, d(\theta)} \qquad R_D = 0.949$$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U_w := R_D \cdot U_s$ $\quad U_w = 1.253 \frac{m}{s}$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U'_w := R_D \cdot U'$ $\quad U'_w = 2.521 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio

$M := \frac{V(z)}{U_w}$ $\quad M = 0.235$

Significant Keulegan-Carpenter Number

$K_s := \frac{U_w \cdot T_u}{D_{top}}$ $\quad K_s = 13.916$

For Single Oscillation

Steady to Oscillatory Velocity Ratio

$M' := \frac{V'}{U'_w}$ $\quad M' = 0.107$

Significant Keulegan-Carpenter Number

$K'_s := \frac{U'_w \cdot T'}{D_{top}}$ $\quad K'_s = 32.84$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.107$ and $K'_s = 32.84$

Horizontal Peak load coefficient $C'_Y = 2.092$

Vertical Peak load coefficient $C'_Z = 2.023$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay) $k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}}$ $k_{ci} = 0.613$

Soil Stiffness Parameter (Clay) $G_{ci} := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})}$ $G_{ci} = 0.207$

Initial Penetration of Pipe (Clay)

$$z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}}\right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}}\right)^{0.7}\right] D_{top}$$

$z_{pi} = 0.037\,\text{m}$ $\%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}}$ $\%z_{pi} = 7.016$

Penetration due to Movement
(assumed due to absolute lateral stability) $z_{pm} := 0\% \cdot D_{conc.16}$ $z_{pm} = 0$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration) $z_{pl} := 5\% \cdot D_{conc.16}$ $z_{pl} = 0.027\,\text{m}$

Total Penetration of Pipe $z_p := z_{pi} + z_{pm} + z_{pl}$ $z_p = 0.064\,\text{m}$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth $z_t := H_{trench}$ $z_t = 2.789\,\text{m}$

Penetration due to Trenching

$$z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases}$$

$z_{pt} = 0.267\,\text{m}$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.331\,m$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4 \cdot \left(\frac{z_p}{D_{top}}\right) & \text{if } \frac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.832$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \frac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3 \cdot \left(\frac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \frac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 0.974$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

Horizontal Direction (Eq. 3.21): $\theta_t := 45$

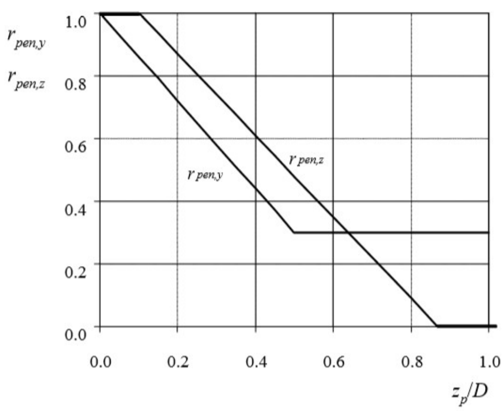
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18 \cdot (\theta_t - 5)^{0.25} \cdot \left(\frac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

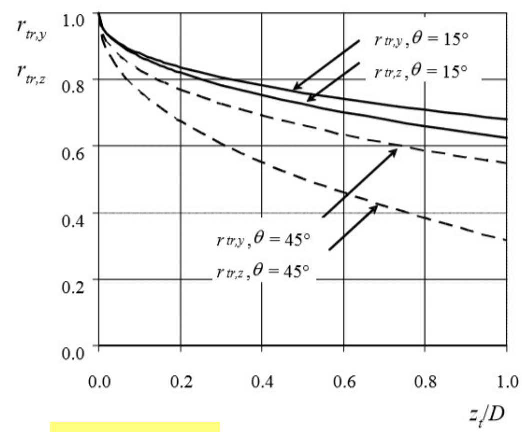
$r_{tr\_y} = 0.093$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 \text{ if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} < 0 \\ 1 \text{ otherwise} \end{cases}$$

$r_{tr\_z} = 0$





$\frac{z_p}{D_{top}} = 0.12$ $r_{pen\_y} = 0.832$

$r_{pen\_z} = 0.974$

$\frac{z_t}{D_{top}} = 5.229$ $r_{tr\_y} = 0.093$

$r_{tr\_z} = 0$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} & \text{if Pos = "Trench"} \\ r_{pen\_y} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_y} = 0.078$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} & \text{if Pos = "Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_z} = 0$

6.7. Hydrodinamic Loads Calculation (DNV RP F109 2010)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 345.153\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 0\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNV RP F109 2010)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = 1.739 \times 10^3 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = 0.613 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.207$$

$$F'_R := F'_C \cdot \begin{cases} \frac{4.1 \cdot \kappa'_c}{G'_c{}^{0.39}} \cdot \left(\frac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 4.326 \times 10^3 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$\gamma_{SC} := 1$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 0.074$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 0$$

$$Lateral_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC} \cdot \dfrac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC} \cdot \dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$Lateral_{check} = \text{"Yes"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 60 \cdot mm$
Full outside diameter pipe	$D_{conc.16} = 533.4 \cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 1.739 \times 10^3 \cdot N \cdot m^{-1}$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.699$
Current Velocity over Pipe Diameter	$V' = 0.269 \dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 1.253 \dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 2.521 \dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.107$
Significant Keulegan-Carpenter Number	$K'_s = 32.84$
Horizontal Peak load coefficient	$C'_Y = 2.092$
Vertical Peak load coefficient	$C'_Z = 2.023$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.331\,m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.078$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 0$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 345.153 \cdot N \cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 0 \cdot N \cdot m^{-1}$
Passive Soil Resistance	$F'_R = 4.326 \times 10^3 \cdot N \cdot m^{-1}$

LAMPIRAN IV

PERHITUNGAN *ON-BOTTOM STABILITY*

PADA *TRENCHED PIPELINES* (KONDISI OPERASI)

ON-BOTTOM STABILITY CALCULATION

Project : On-Bottom Stability Analysis on Piggyback Pipeline
Calculated by : ASM
Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline : 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline

Section : KP 0+273 - KP 1+393 (Minimum Water Depth)

Condition : Operation (Burried 2 m TOP)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position $Pos := \text{"Trench"}$

Trenching Depth to Top of Steel (if applicable) $H_{trench} := 2.749m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) $h := 0.1m$ $h = 0.328 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) $ca\% := 100\%$

Location Class (1 or 2) *Section 2 C300 DNV OS F101Table 2-2, page 28)* $LC := 1$

Note:
Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\,kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\,kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 40mm$
Concrete Coating Density	$\rho_{cc} := 3040\,kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\,kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\,kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 5\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 109.85\,kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 73.83\,kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.35m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 0.1m$

Peak Wave Period $T_p := 10.13s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness

Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline gap := 80mm

Trenching Slope $\theta_t := 45deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 6.5\times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.155\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\;2} - D_{i.6}^{\;2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 254.35\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\;2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 20.406\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 292.165\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\;2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 49.561\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 49.561 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 9.7 \times 10^{-3}\, m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.387\, m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\, m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.493\, m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.493\, m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{\ 2} - D_{i.16}^{\ 2} \right) \cdot \rho_s \cdot g \qquad W_{st.16} = 930.624 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\ 2} - D_{o.16}^{\ 2} \right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g \right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\ 2} - D_{acc.16}^{\ 2} \right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g \right) \qquad W_{conc.16} = 1.643 \times 10^{3} \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{\ 2} - D_{o.16}^{\ 2} \right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g \right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{\ 2} - D_{acc.16}^{\ 2} \right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g \right) \qquad W_{im.16} = 14.083 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 82.144 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{\ 2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 85.166 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 2.796 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}{}^{2} \cdot \rho_{w} \cdot g$ $B_{16} = 1.922 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 874.533 \cdot N \cdot m^{-1}$$

Total Submerged Weight

$$W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 924.093 \cdot N \cdot m^{-1}$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight (based on condition) $w_{s} := W_{sub.pig}$ $w_{s} = 924.093 \cdot N \cdot m^{-1}$

Buoyancy of Pipeline $b := B_{16} + B_{6}$ $b = 2.165 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight (Section 3.2 DNV RP F109 2010) $\gamma_{w} := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNV RP F109 2010):

Stability in Water $$\gamma_{w} \cdot \frac{b}{w_{s} + b} = \frac{\gamma_{w}}{S_{g}} \le 1.0$$

Check Stability $$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_{w} \cdot \dfrac{b}{w_{s} + b} \le 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$w_{sub} = $ "OK"

$$SF_{v} := \gamma_{w} \cdot \frac{b}{w_{s} + b} \qquad SF_{v} = 0.771$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.493\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\left(\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.35\,\frac{m}{s}$

$V(z) = 0.33\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.301\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.301\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $\quad H_{sdim} := \frac{H_s}{m}$ $\quad T_{pdim} := \frac{T_p}{s}$ $\quad D_{dim} := \frac{D_{top}}{m}$ $\quad h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\quad \omega_p = 0.62$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\quad \phi = 32.034$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases}$$

$\gamma = 1$

Spectral Width Parameter (Eq. 3.6):

$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

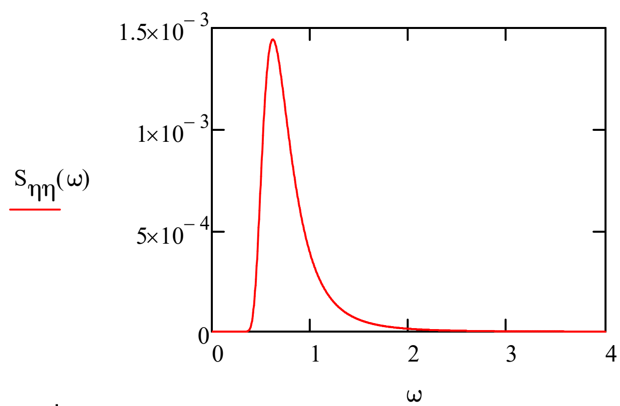
Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}^{\,2}\cdot\omega_p^{\,4}}{g_{dim}^{\,2}}\cdot(1 - 0.287\ln(\gamma))$$

$\alpha = 4.809 \times 10^{-6}$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}^{\,2}\cdot\omega^{-5}\,e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^2}}$$



Seabed Gap in Used for Spanning $\quad \zeta := 0$

Guess Values $\quad k := 100 \qquad a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh\left(k\cdot h_{dim}\right) - \frac{\omega^2}{g_{dim}}, k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk\left(a_\omega\right)h_{dim} - \text{asinh}(\infty), a_\omega\right)$$

$$\omega_{max} = 263.421$$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh\left(kk(\omega)\cdot h_{dim}\right)} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^2\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11): $M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$

Zeroth Order Spectral Moment $M_n(0) = 0.061$

First Order Spectral Moment $M_n(1) = 0.049$

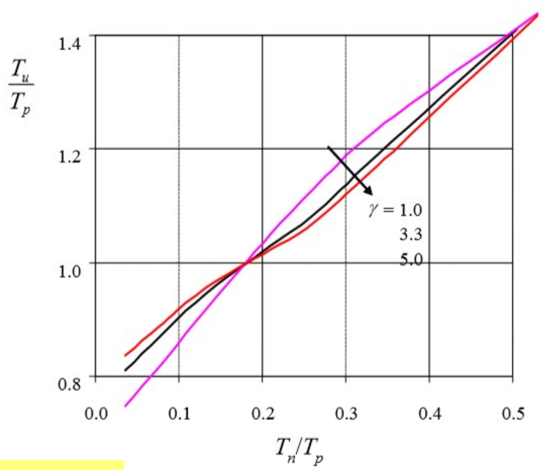
Second Order Spectral Moment $M_n(2) = 0.046$

Fourth Order Spectral Moment $M_n(4) = 0.108$

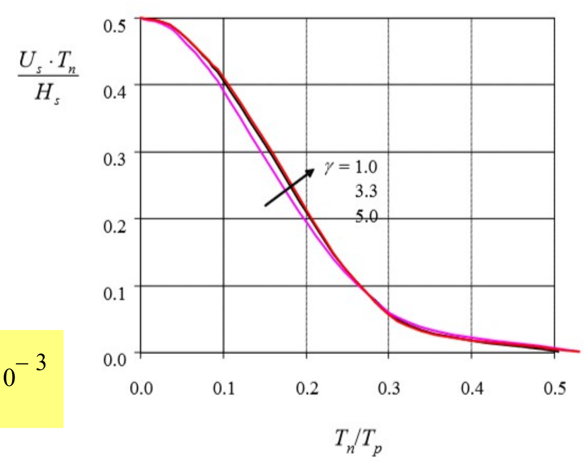
Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12): $U_s := 2\sqrt{M_n(0)}\,\frac{m}{s}$ $U_s = 0.494\,\frac{m}{s}$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13): $T_u := 2\cdot\pi\sqrt{\frac{M_n(0)}{M_n(2)}}\,s$ $T_u = 7.253\,s$

Reference Period (Eq. 3.14): $T_n := \sqrt{\frac{h}{g}}$ $T_n = 0.101\,s$



$U_s\cdot\frac{T_n}{H_s} = 0.499$



$\frac{T_u}{T_p} = 0.716$

$\frac{T_n}{T_p} = 9.969\times 10^{-3}$

Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u}$$ $$\tau = 1.489 \times 10^3$$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right)$$ $$k_U = 1.987$$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s$$ $$U' = 0.981\,\frac{m}{s}$$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \dfrac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases}$$ $$k_t = 1.25$$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

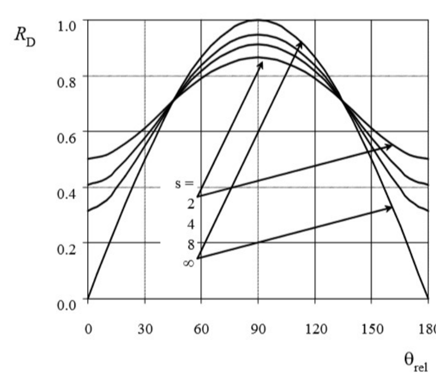
$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\dfrac{T_n}{T_u} & \text{if } \dfrac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \dfrac{T_n}{T_u} > 0.2 \end{cases}$$ $$k_T = 1.233$$

Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u$$ $$T' = 8.94\,s$$

4.3. Wave Directionality and Spreading (DNV RP F109 2010)

Spectral Spreading Exponent $s_p := 8$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\dfrac{1}{\pi}\cdot\dfrac{\Gamma\left(1+\dfrac{s_p}{2}\right)}{\Gamma\left(\dfrac{1}{2}+\dfrac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2} & \text{if } |\theta| < \dfrac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\, d(\theta)}$$ $$R_D = 0.949$$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U_w := R_D \cdot U_s$ $\quad U_w = 0.469 \frac{m}{s}$

Velocity Normal to the Pipe Including
the Effect of Wave Spreading - Spectrum

$U'_w := R_D \cdot U'$ $\quad U'_w = 0.931 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio $\quad M := \frac{V(z)}{U_w}$ $\quad M = 0.704$

Significant Keulegan-Carpenter Number $\quad K_s := \frac{U_w \cdot T_u}{D_{top}}$ $\quad K_s = 6.887$

For Single Oscillation

Steady to Oscillatory Velocity Ratio $\quad M' := \frac{V'}{U'_w}$ $\quad M' = 0.323$

Significant Keulegan-Carpenter Number $\quad K'_s := \frac{U'_w \cdot T'}{D_{top}}$ $\quad K'_s = 16.865$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.323$ and $K'_s = 16.865$

Horizontal Peak load coefficient $C'_Y = 2.197$

Vertical Peak load coefficient $C'_Z = 2.511$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay) $k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}}$ $k_{ci} = 1.068$

Soil Stiffness Parameter (Clay) $G_{ci} := \frac{S_u}{D_{conc.16} \cdot (\gamma'_{soil})}$ $G_{ci} = 0.223$

Initial Penetration of Pipe (Clay)

$$z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}} \right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}^{0.3}}{k_{ci}} \right)^{0.7} \right] D_{conc.16}$$

$z_{pi} = 0.022\,m$ $\%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}}$ $\%z_{pi} = 4.459$

Penetration due to Movement
(assumed due to absolute lateral stability) $z_{pm} := 0\% \cdot D_{conc.16}$ $z_{pm} = 0$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration) $z_{pl} := 5\% \cdot D_{conc.16}$ $z_{pl} = 0.025\,m$

Total Penetration of Pipe $z_p := z_{pi} + z_{pm} + z_{pl}$ $z_p = 0.047\,m$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth $z_t := H_{trench}$ $z_t = 2.749\,m$

Penetration due to Trenching

$$z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases}$$

$z_{pt} = 0.247\,m$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.293\,m$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4 \cdot \left(\frac{z_p}{D_{top}}\right) & \text{if } \frac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.868$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \frac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3 \cdot \left(\frac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \frac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 1$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

Horizontal Direction (Eq. 3.21): $\theta_t := 45$

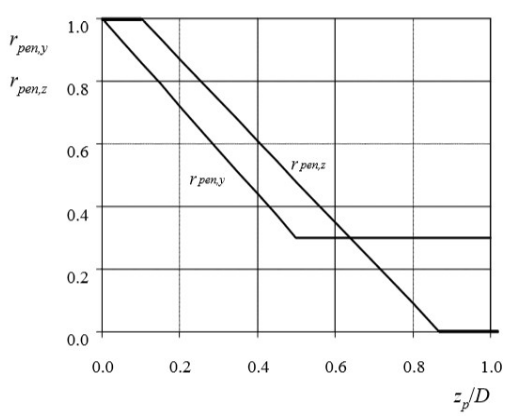
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18 \cdot (\theta_t - 5)^{0.25} \cdot \left(\frac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

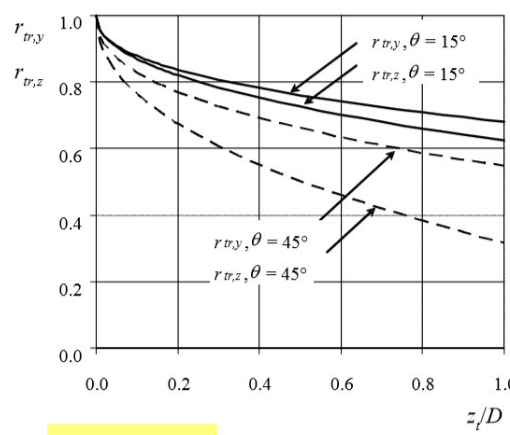
$r_{tr\_y} = 0.069$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 \text{ if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} < 0 & \\ 1 \text{ otherwise} & \end{cases}$$

$r_{tr\_z} = 0$





$\frac{z_p}{D_{top}} = 0.095$ $r_{pen\_y} = 0.868$

$r_{pen\_z} = 1$

$\frac{z_t}{D_{top}} = 5.572$ $r_{tr\_y} = 0.069$

$r_{tr\_z} = 0$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} & \text{if Pos = "Trench"} \\ r_{pen\_y} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_y} = 0.06$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} & \text{if Pos = "Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_z} = 0$

6.7. Hydrodinamic Loads Calculation (DNV RP F109 2010)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 50.238\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 0\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNV RP F109 2010)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = 924.093 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = 1.068 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.223$$

$$F'_R := F'_C \cdot \begin{cases} \dfrac{4.1 \cdot \kappa'_c}{{G'_c}^{0.39}} \cdot \left(\dfrac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 3.673 \times 10^3 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$$\gamma_{SC} := 1.4$$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 0.018$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 0$$

$$Lateral_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC}\cdot\dfrac{F'_Y + \mu\cdot F'_Z}{\mu\cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC}\cdot\dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$Lateral_{check} = \text{"Yes"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 40\cdot mm$
Full outside diameter pipe	$D_{conc.16} = 493.4\cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 924.093\cdot N\cdot m^{-1}$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.427$
Current Velocity over Pipe Diameter	$V' = 0.301\,\dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 0.469\,\dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 0.931\,\dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.323$
Significant Keulegan-Carpenter Number	$K'_s = 16.865$
Horizontal Peak load coefficient	$C'_Y = 2.197$
Vertical Peak load coefficient	$C'_Z = 2.511$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.293\,m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.06$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 0$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 50.238\cdot N\cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 0\cdot N\cdot m^{-1}$
Passive Soil Resistance	$F'_R = 3.673\times 10^{3}\cdot N\cdot m^{-1}$

ON-BOTTOM STABILITY CALCULATION

Project : On-Bottom Stability Analysis on Piggyback Pipeline
Calculated by : ASM
Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required thickness of concrete weight coating of piggyback pipeline to meet absolute stability criteria in accordance with DNVGL RP F109 req.

Pipeline : 16" Production Pipeline Piggybacked with 6" Gas Lift Pipeline

Section : KP 1+393 - KP 5+725 (Minimum Water Depth)

Condition : Operation (Burried 2 m TOP)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F109, On-Bottom Stability Design of Submarine Pipelines, 2017

[2]. DNVGL-RP-F114, Pipe Soil Interaction for Submarine Pipelines, 2017

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position — Pos := "Trench"

Trenching Depth to Top of Steel (if applicable) — $H_{trench} := 2.789m$

Water depth (Worst case at KP 0.0, KB Platform, Shallowest Location) — $h := 1.31m$ $h = 4.298 \cdot ft$

Percentage of corrosion allowance in operation (In this Case, Pipeline is Corroded) — $ca\% := 100\%$

Location Class (1 or 2) *Section 2 C300 DNV OS F101Table 2-2, page 28)* — $LC := 1$

Note:
<u>Location Class Definition :</u>

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\,kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\,kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 60mm$
Concrete Coating Density	$\rho_{cc} := 3040\,kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\,kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\,kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 5\%$
Minimum Density of 6" Gas Lift Pipeline Content	$\rho_{cont.6} := 109.85\,kg \cdot m^{-3}$
Minimum Density of 16" Production Pipeline Content	$\rho_{cont.16} := 73.83\,kg \cdot m^{-3}$

1.2. Environmental Parameters: Hydrodinamic

Density of Seawater $\rho_w := 1025 kg \cdot m^{-3}$

Current Velocity 1 m above the Sea Bed $v(z_r) := 0.35 m \cdot s^{-1}$

Significant Wave Height during Sea State $H_s := 1.022 m$

Peak Wave Period $T_p := 10.13 s$

Angle between Current Velocity and Pipeline Axis $\theta_c := 90°$

Angle between Current Velocity and Pipeline Axis $\theta_w := 90°$

1.3. Environmental Parameters: Soil

Table 3-1 Seabed roughness			
Type	Seabed	Grain size d50 [mm]	Roughness z0 [m]
1	Silt and Clay	0.0625	5.E-06
2	Fine sand	0.25	1.E-05
3	Medium sand	0.5	4.E-05
4	Coarse sand	1	1.E-04
5	Gravel	4	3.E-04
6	Pebble	25	2.E-03
7	Cobble	125	1.E-02
8	Boulder	500	4.E-02

Soil Type Soil := "Clay"

Sea Bed Roughness $z_0 := 5 \cdot 10^{-6} m$

Submerged Unit Soil Weight for Clay $\gamma'_c := 8090 N \cdot m^{-3}$

Submerged Weight of Soil $\frac{\gamma'_c}{g} = 824.95 \frac{kg}{m^3}$

Spesific Weight of Soil (including water) $\gamma'_{soil} := \gamma'_c + \rho_w \cdot g$

Undrained Clay Shear Strength $S_u := 2 kPa$

Soil Friction Factor $\mu := 0.2$

Gap between pipeline $gap := 80 mm$

Trenching Slope $\theta_t := 45 deg$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 6.5 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.155\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\;2} - D_{i.6}^{\;2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 254.35\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\;2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 20.406\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 292.165\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\;2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 49.561\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 49.561 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 9.7 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.387\,m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\,m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.533\,m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.533\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}{}^{2} - D_{i.16}{}^{2}\right) \cdot \rho_s \cdot g \qquad W_{st.16} = 930.624 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}{}^{2} - D_{o.16}{}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}{}^{2} - D_{acc.16}{}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 2.573 \times 10^{3} \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}{}^{2} - D_{o.16}{}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}{}^{2} - D_{acc.16}{}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 22.056 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 128.652 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}{}^{2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 85.166 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 3.781 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}^{2} \cdot \rho_{w} \cdot g$ $B_{16} = 2.246 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 1.535 \times 10^{3} \cdot N \cdot m^{-}$$

Total Submerged Weight $W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 1.584 \times 10^{3} \cdot N \cdot m^{-1}$$

3. DESIGN METHOD: VERTICAL STABILITY IN WATER

Total Pipeline Submerged Weight
(based on condition) $w_s := W_{sub.pig}$ $w_s = 1.584 \times 10^{3} \cdot N \cdot m^{-1}$

Buoyancy of Pipeline $b := B_{16} + B_{6}$ $b = 2.489 \times 10^{3} \cdot N \cdot m^{-1}$

Safety Factor for Weight
(Section 3.2 DNV RP F109 2010) $\gamma_w := 1.1$

In order to avoid floatation in water, the submerged weight of the pipeline shall meet the following criterion (Eq 3.1 DNV RP F109 2010):

Stability in Water $$\gamma_w \cdot \frac{b}{w_s + b} = \frac{\gamma_w}{S_g} \le 1.0$$

Check Stability $$w_{sub} := \begin{cases} \text{"OK"} & \text{if } \gamma_w \cdot \frac{b}{w_s + b} \le 1.0 \\ \text{"Not OK, Increase Concrete Thickness"} & \text{otherwise} \end{cases}$$

$$w_{sub} = \text{"OK"}$$

$$SF_v := \gamma_w \cdot \frac{b}{w_s + b} \qquad SF_v = 0.672$$

4. DESIGN METHOD: ABSOLUTE LATERAL STATIC STABILITY

4.1. Current Conditions: Current Velocity Calculation (DNVGL RP F109 2017)

Elevation above Sea Bed $z := D_{top} = 0.533\,m$

Reference Measurement Height over Sea Bed $z_r := 1m$

Current velocity by taken into effect of boundary layer and directionality (Eq. 3.2):

$$V(z) := v(z_r)\cdot\frac{\left(\ln\left(\frac{z}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)\right)}{\ln\left(\frac{z_r}{m}+\frac{z_0}{m}\right)-\ln\left(\frac{z_0}{m}\right)}\cdot\sin(\theta_c)$$

$v(z_r) = 0.35\,\frac{m}{s}$

$V(z) = 0.332\,\frac{m}{s}$

Mean perpendicular current velocity over the pipe diameter (Eq. 3.3):

$$V_c := V(z)\cdot\frac{\left(1+\frac{\frac{z_0}{m}}{\frac{D_{top}}{m}}\right)\cdot\ln\left(\frac{\frac{D_{top}}{m}}{\frac{z_0}{m}}+1\right)-1}{\ln\left(\frac{\frac{z}{m}}{\frac{z_0}{m}}+1\right)}$$

$V_c = 0.303\,\frac{m}{s}$

Steady current velocity associated with single design oscillation at pipe level $V' := V_c = 0.303\,\frac{m}{s}$

4.2. Short Term Wave: Wave Induced Parameter Calculation (DNVGL RP F109 2017)

Irregular sea states may be described by a wave spectrum Sηη(ω) i.e. the power spectral density function of the sea surface elevation. The parameters calculated down below:

$g_{dim} := \frac{g}{\frac{m}{sec^2}}$ $H_{sdim} := \frac{H_s}{m}$ $T_{pdim} := \frac{T_p}{s}$ $D_{dim} := \frac{D_{top}}{m}$ $h_{dim} := \frac{h}{m}$

Peak Wave Frequency $\omega_p := 2\frac{\pi}{T_{pdim}}$ $\omega_p = 0.62$

Peak Enchancement Parameter $\phi := \frac{T_{pdim}}{\sqrt{H_{sdim}}}$ $\phi = 10.02$

Peak Enhancement Factor (Eq. 3.7):

$$\gamma := \begin{cases} 5 & \text{if } \phi \le 3.6 \\ e^{5.75-1.15\cdot\phi} & \text{if } 3.6 < \phi < 5 \\ 1 & \text{otherwise} \end{cases}$$

$\gamma = 1$

Spectral Width Parameter (Eq. 3.6):

$$\sigma(\omega) := \begin{cases} 0.07 & \text{if } \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

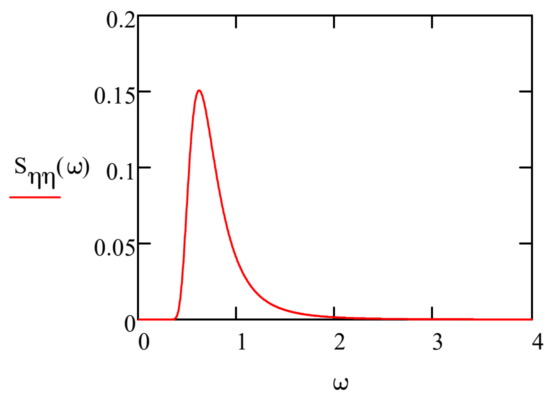
Generalised Philips' Constant (Eq. 3.5):

$$\alpha := \frac{5}{16}\cdot\frac{H_{sdim}^{\,2}\cdot\omega_p^{\,4}}{g_{dim}^{\,2}}\cdot(1 - 0.287\ln(\gamma))$$

$\alpha = 5.023 \times 10^{-4}$

JONSWAP Spectral Density Function (Eq. 3.4):

$$S_{\eta\eta}(\omega) := \alpha\cdot g_{dim}^{\,2}\cdot\omega^{-5}\, e^{\frac{-5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}}\cdot\gamma^{e^{-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma(\omega)\cdot\omega_p}\right)^2}}$$



Seabed Gap in Used for Spanning

$\zeta := 0$

Guess Values

$k := 100 \qquad a_\omega := 2$

Determine Wave Number (with Guess Value)

$$kk(\omega) := \text{root}\left(k\cdot\tanh\left(k\cdot h_{dim}\right) - \frac{\omega^2}{g_{dim}}, k\right)$$

Determine Omega Max (with Guess Value) to Avoid Non Convergence

$$\omega_{max} := \text{root}\left(kk\left(a_\omega\right) h_{dim} - \text{asinh}(\infty), a_\omega\right)$$

$\omega_{max} = 72.78$

Transfer Function to Seabed (Eq. 3.9):

$$G(\omega) := \begin{cases} \dfrac{\omega}{\sinh\left(kk(\omega)\cdot h_{dim}\right)} & \text{if } \omega < \omega_{max} \\ 0 & \text{otherwise} \end{cases}$$

Wave Induced Velocity Spectrum at the Seabed (E.q. 3.8):

$$S_{UU}(\omega) := G(\omega)^2\cdot S_{\eta\eta}(\omega)$$

Spectral Moments of Order-n (Eq. 3.11):

$$M_n(n) := \int_0^{(\omega_{max})} \omega^n \cdot S_{UU}(\omega)\, d\omega$$

Zeroth Order Spectral Moment $M_n(0) = 0.457$

First Order Spectral Moment $M_n(1) = 0.357$

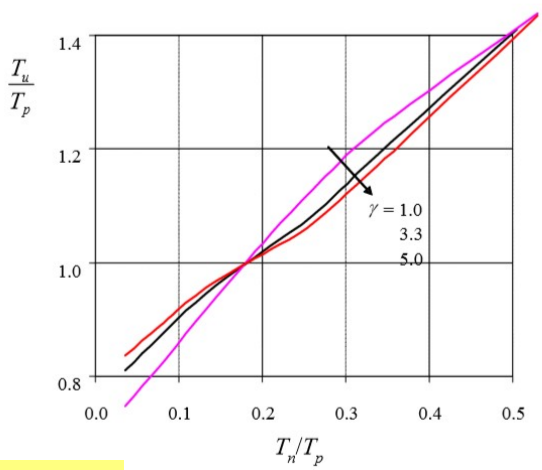
Second Order Spectral Moment $M_n(2) = 0.313$

Fourth Order Spectral Moment $M_n(4) = 0.406$

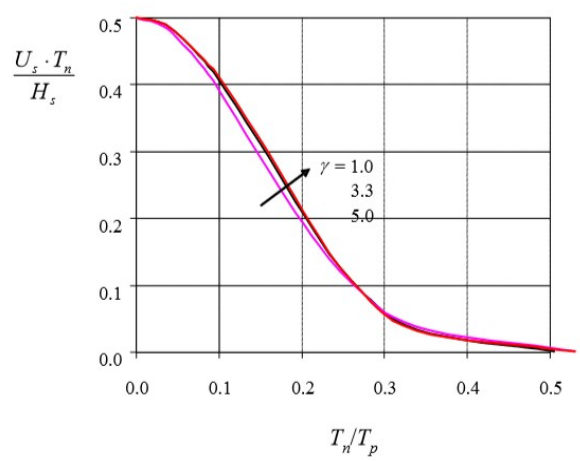
Significant Flow Velocity Amplitude for Design Spectrum, Perpendicular to Pipeline (Eq. 3.12): $U_s := 2\sqrt{M_n(0)}\,\frac{m}{s}$ $U_s = 1.352\,\frac{m}{s}$

Mean Zero Up-Crossing Period of Oscillating Flow at Pipe Level (Eq. 3.13): $T_u := 2\cdot\pi\sqrt{\frac{M_n(0)}{M_n(2)}}\,s$ $T_u = 7.592\,s$

Reference Period (Eq. 3.14): $T_n := \sqrt{\frac{h}{g}}$ $T_n = 0.365\,s$



$U_s \cdot \frac{T_n}{H_s} = 0.484$



$\frac{T_u}{T_p} = 0.749$

$\frac{T_n}{T_p} = 0.036$

Number of Oscillations in the Design Bottom Velocity Spectrum

$$\tau := \frac{3hr}{T_u}$$ $\tau = 1.423 \times 10^3$

Ratio between Oscillatory Velocity Amplitude of Single Design Oscillation and with Design Spectrum (Eq. 3.15):

$$k_U := \frac{1}{2}\left(\sqrt{2\ln(\tau)} + \frac{0.5772}{\sqrt{2\ln(\tau)}}\right)$$ $k_U = 1.981$

Oscillatory Velocity Amplitude for Single Design Oscillation, Perpendicular to Pipeline

$$U' := k_U \cdot U_s$$ $U' = 2.679\,\frac{m}{s}$

Parameter of Wave Period

$$k_t := \begin{cases} 1.25 & \text{if } \gamma = 1 \\ 1.17 & \text{if } \gamma = 5 \\ 1.17 + \frac{(1.25 - 1.17)\cdot(\gamma - 1)}{4} & \text{otherwise} \end{cases}$$ $k_t = 1.25$

Ratio between Period of Single Design Oscillation and with Design Spectrum (Eq. 3.16):

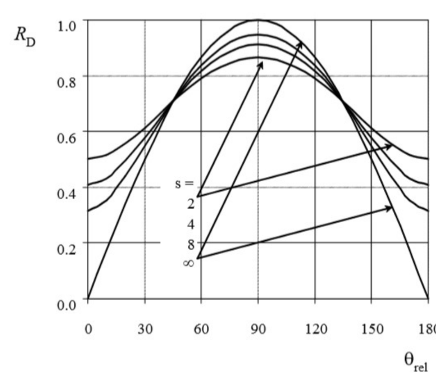
$$k_T := \begin{cases} k_t - 5\cdot(k_t - 1)\cdot\frac{T_n}{T_u} & \text{if } \frac{T_n}{T_u} \le 0.2 \\ 1 & \text{if } \frac{T_n}{T_u} > 0.2 \end{cases}$$ $k_T = 1.19$

Period Associated with Single Design Oscillation

$$T' := k_T \cdot T_u$$ $T' = 9.033\,s$

4.3. Wave Directionality and Spreading (DNV RP F109 2010)

Spectral Spreading Exponent $s_p := 8$



Wave Energy Spreading Directional Function

$$D_w(\theta) := \begin{cases} \sqrt{\frac{1}{\pi}\cdot\frac{\Gamma\left(1 + \frac{s_p}{2}\right)}{\Gamma\left(\frac{1}{2} + \frac{s_p}{2}\right)}\cdot\cos(\theta)^{s_p}\cdot\sin(\theta_w - \theta)^2} & \text{if } |\theta| < \frac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$$

Reduction Factor

$$R_D := \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D_w(\theta)\, d(\theta)}$$ $R_D = 0.949$

Velocity Normal to the Pipe Including the Effect of Wave Spreading - Spectrum $U_w := R_D \cdot U_s$ $U_w = 1.283 \frac{m}{s}$

Velocity Normal to the Pipe Including the Effect of Wave Spreading - Spectrum $U'_w := R_D \cdot U'$ $U'_w = 2.542 \frac{m}{s}$

6.4. Hydrodinamic Coefficient (DNV RP F109 2010)

For Design Spectrum

Steady to Oscillatory Velocity Ratio $M := \frac{V(z)}{U_w}$ $M = 0.259$

Significant Keulegan-Carpenter Number $K_s := \frac{U_w \cdot T_u}{D_{top}}$ $K_s = 18.262$

For Single Oscillation

Steady to Oscillatory Velocity Ratio $M' := \frac{V'}{U'_w}$ $M' = 0.119$

Significant Keulegan-Carpenter Number $K'_s := \frac{U'_w \cdot T'}{D_{top}}$ $K'_s = 43.044$

Table 3-9 Peak horizontal load coefficients

C_Y		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	13.00	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.70	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.05
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.00
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00

Table 3-10 Peak vertical load coefficients

C_Z		K										
		2.5	5	10	20	30	40	50	60	70	100	140
M	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90

Peak load coefficients C_Y and C_Z are taken from Tables 3-9 and 3-10 page 18 DNV F109 2010

With value of : $M' = 0.119$ and $K'_s = 43.044$

Horizontal Peak load coefficient $C'_Y = 1.782$

Vertical Peak load coefficient $C'_Z = 1.643$

6.5. Penetration Depth Calculation (DNV RP F109 2010)

to calculate initial penetration, maximum pipe weight and zero lift force can be assumed in calculation below:

Passive Resistance Factor (Clay)

$$k_{ci} := \frac{S_u \cdot D_{conc.16}}{W_{sub.pig}} \qquad k_{ci} = 0.673$$

Soil Stiffness Parameter (Clay)

$$G_{ci} := \frac{S_u}{D_{conc.16} \cdot (\gamma'_{soil})} \qquad G_{ci} = 0.207$$

Initial Penetration of Pipe (Clay)

$$z_{pi} := \left[0.0071 \cdot \left(\frac{G_{ci}^{\ 0.3}}{k_{ci}}\right)^{3.2} + 0.062 \cdot \left(\frac{G_{ci}^{\ 0.3}}{k_{ci}}\right)^{0.7}\right] D_{conc.16}$$

$$z_{pi} = 0.034\,m \qquad \%z_{pi} := \frac{z_{pi} \cdot 100}{D_{conc.16}} \qquad \%z_{pi} = 6.427$$

Penetration due to Movement
(assumed due to absolute lateral stability)

$$z_{pm} := 0\% \cdot D_{conc.16} \qquad z_{pm} = 0$$

Penetration due to Dynamic Laying
(assumed as a reasonable consideration)

$$z_{pl} := 5\% \cdot D_{conc.16} \qquad z_{pl} = 0.027\,m$$

Total Penetration of Pipe

$$z_p := z_{pi} + z_{pm} + z_{pl} \qquad z_p = 0.061\,m$$

If pipeline is being trenched, these equations should be considered in calculation:

Trench Depth

$$z_t := H_{trench} \qquad z_t = 2.789\,m$$

Penetration due to Trenching

$$z_{pt} := \begin{cases} \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} & \text{if } \frac{1}{2} \cdot \tan(\theta_t) \cdot D_{conc.16} \le \frac{z_t}{2} \\ \frac{z_t}{2} & \text{otherwise} \end{cases}$$

$$z_{pt} = 0.267\,m$$

Total Penetration Including Trenching Penetration

$$z_{tp} := \begin{cases} (z_p + z_{pt}) & \text{if } Pos = \text{"Trench"} \\ z_p & \text{if } Pos = \text{"Seabed"} \end{cases}$$

$z_{tp} = 0.328\,m$

6.6. Load Reduction Calculation (DNV RP F109 2010)

Load Reduction due to Permeable Seabed

A permeable seabed will allow flow in the seabed underneath the pipe and thus reduce the vertical load (Eq 3.18):

$$r_{perm\_z} := \begin{cases} 0.7 & \text{if } Soil = \text{"Sand"} \\ 1 & \text{if } Soil = \text{"Clay"} \end{cases}$$

$r_{perm\_z} = 1$

Load Reduction due to Penetration

Horizontal Direction (Eq. 3.19):

$$r_{pen\_y} := \begin{cases} 1.0 - 1.4 \cdot \left(\frac{z_p}{D_{top}}\right) & \text{if } \frac{z_p}{D_{top}} \le 0.5 \\ 0.3 & \text{otherwise} \end{cases}$$

$r_{pen\_y} = 0.84$

Vertical Direction (Eq. 3.20):

$$r_{pen\_z} := \begin{cases} 1 & \text{if } \frac{z_p}{D_{top}} \le 0.1 \\ 1.0 - 1.3 \cdot \left(\frac{z_p}{D_{top}} - 0.1\right) & \text{if } 0.1 \le \frac{z_p}{D_{top}} \le 0.8667 \\ 0 & \text{otherwise} \end{cases}$$

$r_{pen\_z} = 0.981$

Load Reduction due to Trenching

The trench depth is to be taken relative to the seabed level at a width not greater than 3.D away from the pipe

Horizontal Direction (Eq. 3.21): $\theta_t := 45$

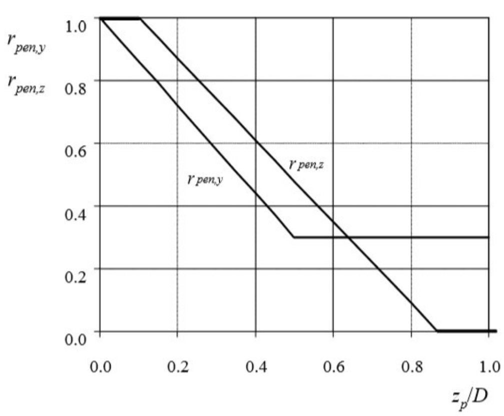
$$r_{tr\_y} := \begin{cases} 1.0 - 0.18 \cdot (\theta_t - 5)^{0.25} \cdot \left(\frac{z_t}{D_{top}}\right)^{0.42} & \text{if } 5 \le \theta_t \le 45 \\ 1 & \text{otherwise} \end{cases}$$

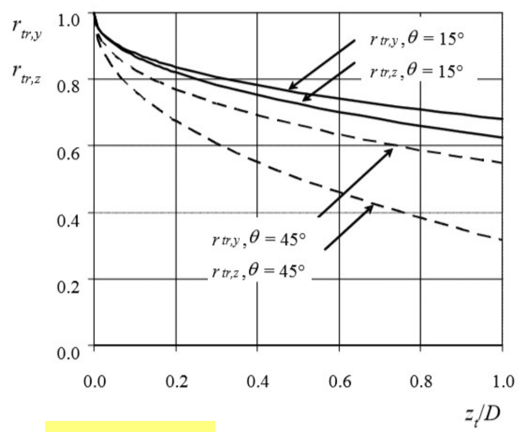
$r_{tr\_y} = 0.093$

Vertical Direction (Eq. 3.20)

$$r_{tr\_z} := \begin{cases} 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} > 0 \\ 0 & \text{if } 1.0 - 0.14\cdot(\theta_t - 5)^{0.43}\cdot\left(\frac{z_t}{D_{top}}\right)^{0.46} < 0 \\ 1 & \text{otherwise} \end{cases}$$

$r_{tr\_z} = 0$





$\frac{z_p}{D_{top}} = 0.114$ $r_{pen\_y} = 0.84$

$r_{pen\_z} = 0.981$

$\frac{z_t}{D_{top}} = 5.229$ $r_{tr\_y} = 0.093$

$r_{tr\_z} = 0$

Total Reduction Factor (Eq. 3.17)

Total Reduction Factor for Horizontal Load

$$r_{tot\_y} := \begin{cases} r_{pen\_y}\cdot r_{tr\_y} & \text{if Pos = "Trench"} \\ r_{pen\_y} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_y} = 0.078$

Total Reduction Factor for Vertical Load

$$r_{tot\_z} := \begin{cases} r_{perm\_z}\cdot r_{pen\_z}\cdot r_{tr\_z} & \text{if Pos = "Trench"} \\ r_{perm\_z}\cdot r_{pen\_z} & \text{if Pos = "Seabed"} \end{cases}$$

$r_{tot\_z} = 0$

6.7. Hydrodinamic Loads Calculation (DNV RP F109 2010)

Horizontal Peak Loads (Drag and Inertia)

$$F'_Y := r_{tot\_y}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Y\cdot(U'_w + V')^2$$

$F'_Y = 308.669\cdot N\cdot m^{-1}$

Vertical Peak Loads (Lift)

$$F'_Z := r_{tot\_z}\cdot\frac{1}{2}\cdot\rho_w\cdot D_{top}\cdot C'_Z\cdot(U'_w + V')^2$$

$F'_Z = 0\cdot N\cdot m^{-1}$

6.8. Passive Soil Resistance Calculation (DNV RP F109 2010)

Vertical Contact Force between Pipe and Soil

$$F'_C := W_{sub.pig} - F'_Z \qquad F'_C = 1.584 \times 10^3 \cdot N \cdot m^{-1}$$

Passive Soil Resistance

$$\kappa'_c := S_u \cdot \frac{D_{top}}{F'_C} = 0.673 \qquad G'_c := \frac{S_u}{D_{top} \cdot (\gamma'_{soil})} = 0.207$$

$$F'_R := F'_C \cdot \begin{cases} \dfrac{4.1 \cdot \kappa'_c}{G'^{0.39}_c} \cdot \left(\dfrac{z_{tp}}{D_{top}}\right)^{1.31} & \text{if } F'_C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad F'_R = 4.272 \times 10^3 \cdot N \cdot m^{-1}$$

6.9. Lateral Stability Check (DNVGL RP F109 2017)

Table 3-5 Safety factors, winter storm in North Sea			
	Low	*Normal*	*High*
Sand and rock	0.98	1.32	1.67
Clay	1.00	1.40	1.83

$$\gamma_{SC} := 1.4$$

Table 3-6 Safety factors, winter storm in GoM and Southern Ocean			
	Low	*Normal*	*High*
Sand and rock	0.95	1.41	1.99
Clay	0.97	1.50	2.16

Table 3-7 Safety factors, cyclonic conditions in North West Shelf			
	Low	*Normal*	*High*
Sand and rock	0.95	1.50	2.16
Clay	0.95	1.56	2.31

Table 3-8 Safety factors, cyclonic conditions Gulf of Mexico (GoM)			
	Low	*Normal*	*High*
Sand and rock	0.95	1.64	2.46
Clay	0.93	1.64	2.54

Requirements 1

$$SF_{L1} := \gamma_{SC} \cdot \frac{F'_Y + \mu \cdot F'_Z}{\mu \cdot W_{sub.pig} + F'_R} \qquad SF_{L1} = 0.094$$

Requirements 2

$$SF_{L2} := \gamma_{SC} \cdot \frac{F'_Z}{W_{sub.pig}} \qquad SF_{L2} = 0$$

$$Lateral_{check} := \begin{cases} \text{"Yes"} & \text{if } \gamma_{SC}\cdot\dfrac{F'_Y + \mu\cdot F'_Z}{\mu\cdot W_{sub.pig} + F'_R} \le 1.0 \wedge \gamma_{SC}\cdot\dfrac{F'_Z}{W_{sub.pig}} \le 1.0 \\ \text{"No"} & \text{otherwise} \end{cases}$$

$Lateral_{check} = \text{"Yes"}$

7. OUTPUT SUMMARY:

Used concrete thickness	$t_{cc.16} = 60\cdot mm$
Full outside diameter pipe	$D_{conc.16} = 533.4\cdot mm$
Submerged weight of empty or product filled pipe	$W_{sub.pig} = 1.584\times 10^{3}\cdot N\cdot m^{-1}$
Specific Gravity of the pipe	$\dfrac{W_{sub.pig} + b}{b} = 1.637$
Current Velocity over Pipe Diameter	$V' = 0.303\,\dfrac{m}{s}$
Design Velocity Induced by Waves - Spectrum	$U_w = 1.283\,\dfrac{m}{s}$
Design Velocity Induced by Waves - Single Oscillation	$U'_w = 2.542\,\dfrac{m}{s}$
Steady to Oscillatory Velocity Ratio	$M' = 0.119$
Significant Keulegan-Carpenter Number	$K'_s = 43.044$
Horizontal Peak load coefficient	$C'_Y = 1.782$
Vertical Peak load coefficient	$C'_Z = 1.643$
Total Penetration Including Trenching Penetration	$z_{tp} = 0.328\,m$
Total Reduction Factor for Horizontal Load	$r_{tot\_y} = 0.078$
Total Reduction Factor for Vertical Load	$r_{tot\_z} = 0$
Horizontal Peak Loads (Drag and Inertia)	$F'_Y = 308.669\cdot N\cdot m^{-1}$
Vertical Peak Loads (Lift)	$F'_Z = 0\cdot N\cdot m^{-1}$
Passive Soil Resistance	$F'_R = 4.272\times 10^{3}\cdot N\cdot m^{-1}$

LAMPIRAN V

PERHITUNGAN *UPHEAVAL BUCKLING*

PADA PIPA (*CORRODED CASE*)

PIPELINE UPHEAVAL BUCKLING CALCULATION

Project : Upheaval Buckling Analysis of 16" Production Pipeline
Calculated by : ASM
Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required downward force on the pipeline to prevent upheaval buckling as a result of axial compression. The required downward force is calculated using an equation developed by Palmer in OTC 6335

Pipeline : 16" Production Pipeline

Section : KP 0+273 - KP 1+393

Condition : Operation (Corroded Case)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F110, Global Buckling of Submarine Pipelines, 2007

[2]. OTC 6335 - Design of Submarine Pipelines against Upheaval Buckling, A.C Palmer et.al, 1990

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position — Pos := "Trench"

Trenching Depth to Top of Steel (if applicable) — $H_{trench} := 2.749m$

Water depth — $h := 0.1m$ $h = 0.328 \cdot ft$

Percentage of corrosion allowance in operation
(In this Case, Pipeline is Corroded) — $ca\% := 100\%$

Location Class (1 or 2)
Section 2 C300 DNV OS F101Table 2-2, page 28) — $LC := 1$

Note:
Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850 kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940 kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 40mm$
Concrete Coating Density	$\rho_{cc} := 3040 kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930 kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025 kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 5\%$

1.3. Design and Operating Parameters

Installation Pressure $P_{ins.16} := 0MPa$

Installation Temperature $T_{ins.16} := 25\,°C$

Maximum Operating Pressure of 16" Production Pipeline $P_{opr.16} := 1.92MPa$

Maximum Operating Temperature of 16" Production Pipeline $T_{opr.16} := 69.34\,°C$

Maximum Operating Pressure of 6" Gas Lift Pipeline $P_{opr.6} := 9.51MPa$

Maximum Operating Temperature of 6" Gas Lift Pipeline $T_{opr.6} := 35\,°C$

Minimum Density of 16" Production Pipeline Content $\rho_{cont.16} := 73.83\,kg \cdot m^{-3}$

Minimum Density of 6" Gas Lift Pipeline Content $\rho_{cont.6} := 109.85\,kg \cdot m^{-3}$

Density of Seawater $\rho_w := 1025kg \cdot m^{-3}$

Uplift Coefficient $U_c := 0.5$

Residual Lay Tension $T_{lay} := 0kN$

1.4. Soil and Environmental Parameters

Imperfection Height

$h_1 := 0.6m$ $h_2 := 1.2m$ $h_3 := 1.9m$ $h_4 := 2.6m$ $h_5 := 3.4m$ $h_6 := 4m$

Soil Type type := "clay"

Soil Classification soil := "cohessive"

Soil Friction Coefficient $\mu_c := 0.31$

Density of Soil $\rho_{soil} := 1540kg \cdot m^{-3}$

Undrained Shear Strength $S_u := 2kPa$

Pipe Condition pipe := "burried"

Minimum Burial Depth $h_{burried} := 2m$

Submerged Unit Weight $\gamma_s := 5.29\,kN \cdot m^{-3}$

Passive Earth Pressure Coefficient $K_o := 0.8$

Impact Force $F_i := 5.1kN$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 6.5 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.155\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\,2} - D_{i.6}^{\,2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 254.35\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\,2} - D_{o.6}^{\,2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\,2} - D_{o.6}^{\,2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\,2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 20.406\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 292.165\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\,2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 49.561\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 49.561 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 9.7 \times 10^{-3}\ m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.387\ m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\ m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.493\ m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.493\ m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{2} - D_{i.16}^{2}\right) \cdot \rho_s \cdot g \qquad W_{st.16} = 930.624 \cdot N \cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{2} - D_{o.16}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right) \qquad W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{2} - D_{acc.16}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right) \qquad W_{conc.16} = 1.643 \times 10^{3} \cdot N \cdot m^{-1}$$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{2} - D_{o.16}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right) \qquad W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{2} - D_{acc.16}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right) \qquad W_{im.16} = 14.083 \cdot N \cdot m^{-1}$$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 82.144 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{2} \rho_{cont.16} \cdot g \qquad W_{cont.16} = 85.166 \cdot N \cdot m^{-1}$$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 2.796 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $\quad B_{16} := 0.25 \cdot \pi \cdot OD_{16}^{2} \cdot \rho_{w} \cdot g \quad B_{16} = 1.922 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 874.533 \cdot N \cdot m^{-1}$$

Total Submerged Weight

$$W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 924.093 \cdot N \cdot m^{-1}$$

3. PIPELINE STRESS CALCULATION

3.1. Hoop Stress (ASME B31.4, 2002)

$$S_{H.16} := P_{opr.16} \cdot \frac{D_{o.16}}{2 \cdot t_{nom.16}} \qquad S_{H.6} := P_{opr.6} \cdot \frac{D_{o.6}}{2 \cdot t_{nom.6}}$$

$$S_{H.16} = 4.022 \times 10^{7}\ Pa \qquad S_{H.6} = 1.231 \times 10^{8}\ Pa$$

ALLOWABLE STRESS

$$S_{Hmax} := 0.72 \cdot SMYS$$

$$S_{Hmax} = 3.24 \times 10^{8}\ Pa$$

$$S_{Hcheck.16} := \begin{cases} \text{"OK"} & \text{if } S_{H.16} < S_{Hmax} \\ \text{"Overstress"} & \text{if } S_{H.16} > S_{Hmax} \end{cases} \qquad S_{Hcheck.6} := \begin{cases} \text{"OK"} & \text{if } S_{H.6} < S_{Hmax} \\ \text{"Overstress"} & \text{if } S_{H.6} > S_{Hmax} \end{cases}$$

$$S_{Hcheck.16} = \text{"OK"} \qquad S_{Hcheck.6} = \text{"OK"}$$

3.2. Longitudinal Stress (ASME B31.4, 2002)

Longitudinal Stress due to Thermal Expansion

$S_{T.16} := E_s \cdot \alpha_{th} \cdot \left(T_{ins.16} - T_{opr.16}\right)$ $S_{T.16} = -1.074 \times 10^{8}\ Pa$

Longitudinal Stress due to Pressure Expansion Stress (Poisson's Effect)

$S_{P.16} := \upsilon \cdot S_{H.16}$ $S_{P.16} = 1.207 \times 10^{7}\ Pa$

Total Longitudinal Stress

$S_{L.16} := S_{T.16} - S_{P.16}$ $S_{L.16} = -1.195 \times 10^{8}\ Pa$

ALLOWABLE STRESS

$S_{Lmax} := 0.8 \cdot SMYS$

$S_{Lmax} = 3.6 \times 10^{8}\ Pa$

$$S_{Lcheck.16} := \begin{cases} \text{"OK"} & \text{if } S_{L.16} < S_{Lmax} \\ \text{"Overstress"} & \text{if } S_{L.16} > S_{Lmax} \end{cases}$$

$S_{Lcheck.16} = \text{"OK"}$

Longitudinal Stress due to Thermal Expansion

$S_{T.6} := E_s \cdot \alpha_{th} \cdot \left(T_{ins.16} - T_{opr.6}\right)$ $S_{T.6} = -2.422 \times 10^{7}\ Pa$

Longitudinal Stress due to Pressure Expansion Stress (Poisson's Effect)

$S_{P.6} := \upsilon \cdot S_{H.6}$ $S_{P.6} = 3.694 \times 10^{7}\ Pa$

Total Longitudinal Stress

$S_{L.6} := S_{T.6} - S_{P.6}$ $S_{L.6} = -6.115 \times 10^{7}\ Pa$

ALLOWABLE STRESS

$S_{L.max} := 0.8 \cdot SMYS$

$S_{Lmax} = 3.6 \times 10^{8}\ Pa$

$$S_{Lcheck.6} := \begin{cases} \text{"OK"} & \text{if } S_{L.16} < S_{Lmax} \\ \text{"Overstress"} & \text{if } S_{L.16} > S_{Lmax} \end{cases}$$

$S_{Lcheck.6} = \text{"OK"}$

3.3. Combined Stress (ASME B31.4, 2002)

Combined Stress (Equivalent Von Mises Stress)

$$S_{E.16} := \left[\left(S_{H.16}^{2} + S_{L.16}^{2}\right) - \left(S_{H.16} \cdot S_{L.16}\right)\right]^{0.5} \qquad S_{E.16} = 1.438 \times 10^{8}\,Pa$$

ALLOWABLE STRESS

$$S_{Emax} := 0.9 \cdot SMYS$$

$$S_{Emax} = 4.05 \times 10^{8}\,Pa$$

$$S_{Echeck.16} := \begin{cases} \text{"OK"} & \text{if } S_{E.16} < S_{Emax} \\ \text{"Overstress"} & \text{if } S_{E.16} > S_{Emax} \end{cases}$$

$$S_{Echeck.16} = \text{"OK"}$$

Combined Stress (Equivalent Von Mises Stress)

$$S_{E.6} := \left[\left(S_{H.6}^{2} + S_{L.6}^{2}\right) - \left(S_{H.6} \cdot S_{L.6}\right)\right]^{0.5} \qquad S_{E.6} = 1.626 \times 10^{8}\,Pa$$

ALLOWABLE STRESS

$$S_{E.max} := 0.9 \cdot SMYS$$

$$S_{Emax} = 4.05 \times 10^{8}\,Pa$$

$$S_{Echeck.6} := \begin{cases} \text{"OK"} & \text{if } S_{E.6} < S_{Emax} \\ \text{"Overstress"} & \text{if } S_{E.6} > S_{Emax} \end{cases}$$

$$S_{Echeck.16} = \text{"OK"}$$

4. PIPELINE AXIAL FORCE CALCULATION

Internal Area of Steel Pipe

$$A_{int.16} := 0.25 \cdot \pi \cdot \left(D_{o.16} - 2 \cdot t_{nom.16}\right)^{2} \qquad A_{int.16} = 0.118\,m^{2}$$

Sectional Area of Steel Pipe

$$A_{sect.16} := \pi \cdot \left(D_{o.16} - t_{nom.16}\right) \cdot t_{nom.16} \qquad A_{sect.16} = 0.012\,m^{2}$$

Effective Axial Force Acting on Pipeline

$$F_{ax.} := \left[\left(P_{ins.16} - P_{opr.16}\right) \cdot (1 - 2\upsilon)\right] \cdot A_{int.16} + \left[E_{s} \cdot \alpha_{th} \cdot \left(T_{ins.16} - T_{opr.16}\right)\right] \cdot A_{sect.16} + T_{lay}$$

$$F_{ax.} = -1.389 \times 10^{6}\,N$$

5. AVAILABLE DOWNWARD FORCE CALCULATION

Soil Uplift Resistance per Unit Length
(OTTC 6335, 1990)

$$q := S_{u} \cdot OD_{16} \cdot \min\left(3, \frac{h}{OD_{16}}\right) \qquad q := 2960\,\frac{N}{m}$$

Available Downward Force

$$W_{down.} := W_{sub.pig} + q \qquad W_{down} := 3834.93\,\frac{N}{m}$$

6. REQUIRED DOWNWARD FORCE CALCULATION

Moment of Inertia $I_{16} := \frac{\pi}{64}\cdot\left(OD_{16}{}^4 - D_{i.16}{}^4\right)$ $I_{16} = 1.808\times 10^{-3}\,m^4$

Natural Half Wave Length

Natural Half Wave Length for Imperfection Height 1 $L_1 := \left(\frac{72\cdot E_s\cdot I_{16}\cdot h_1}{W_{sub.pig}}\right)^{0.25}$ $L_1 = 64.675\,m$

Natural Half Wave Length for Imperfection Height 2 $L_2 := \left(\frac{72\cdot E_s\cdot I_{16}\cdot h_2}{W_{sub.pig}}\right)^{0.25}$ $L_2 = 76.912\,m$

Natural Half Wave Length for Imperfection Height 3 $L_3 := \left(\frac{72\cdot E_s\cdot I_{16}\cdot h_3}{W_{sub.pig}}\right)^{0.25}$ $L_3 = 86.276\,m$

Natural Half Wave Length for Imperfection Height 4 $L_4 := \left(\frac{72\cdot E_s\cdot I_{16}\cdot h_4}{W_{sub.pig}}\right)^{0.25}$ $L_4 = 93.314\,m$

Natural Half Wave Length for Imperfection Height 5 $L_5 := \left(\frac{72\cdot E_s\cdot I_{16}\cdot h_5}{W_{sub.pig}}\right)^{0.25}$ $L_5 = 99.786\,m$

Natural Half Wave Length for Imperfection Height 6 $L_6 := \left(\frac{72\cdot E_s\cdot I_{16}\cdot h_6}{W_{sub.pig}}\right)^{0.25}$ $L_6 = 103.924\,m$

Dimensionless Imperfection Length

Dimensionless Imperfection Length for Imperfection Height 1 $\phi_{L.1.} := L_1\cdot\left(\frac{F_{ax.}}{E_s\cdot I_{16}}\right)^{0.5}$ $\phi_{L.1} := 3.94$

Dimensionless Imperfection Length for Imperfection Height 2 $\phi_{L.2.} := L_2\cdot\left(\frac{F_{ax.}}{E_s\cdot I_{16}}\right)^{0.5}$ $\phi_{L.2} := 4.68$

Dimensionless Imperfection Length for Imperfection Height 3 $\phi_{L.3.} := L_3\cdot\left(\frac{F_{ax.}}{E_s\cdot I_{16}}\right)^{0.5}$ $\phi_{L.3} := 5.25$

Dimensionless Imperfection Length
for Imperfection Height 4

$$\phi_{L.4.} := L_4 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$$

$\phi_{L.4} := 5.68$

Dimensionless Imperfection Length
for Imperfection Height 5

$$\phi_{L.5.} := L_5 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$$

$\phi_{L.5} := 6.08$

Dimensionless Imperfection Length
for Imperfection Height 6

$$\phi_{L.6.} := L_6 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$$

$\phi_{L.6} := 6.33$

Dimensionless Maximum Downward Force Parameter (OTTC, 1990)

For Imperfection Height 1

$\phi_{w.1} := 0.0646$

For Imperfection Height 2

$$\phi_{w.2} := \frac{5.68}{\phi_{L.2}^{\,2}} - \frac{88.35}{\phi_{L.2}^{\,4}}$$

$\phi_{w.2} = 0.075$

For Imperfection Height 3

$$\phi_{w.3} := \frac{5.68}{(\phi_{L.3})^2} - \frac{88.35}{(\phi_{L.3})^4}$$

$\phi_{w.3} = 0.09$

For Imperfection Height 4

$$\phi_{w.4} := \frac{5.68}{(\phi_{L.4})^2} - \frac{88.35}{(\phi_{L.4})^4}$$

$\phi_{w.4} = 0.091$

For Imperfection Height 5

$$\phi_{w.5} := \frac{5.68}{(\phi_{L.5})^2} - \frac{88.35}{(\phi_{L.5})^4}$$

$\phi_{w.5} = 0.089$

For Imperfection Height 6

$$\phi_{w.6} := \frac{5.68}{(\phi_{L.6})^2} - \frac{88.35}{(\phi_{L.6})^4}$$

$\phi_{w.6} = 0.087$

Required Downward Force

Required Downward Force
for Imperfection Height 1

$$w_{req.1.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}^{\;2}\right)}{W_{down} E_s \cdot I_{16}}$$

$w_{req.1} := 199.56 \frac{N}{m}$

Required Downward Force
for Imperfection Height 2

$$w_{req.2.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}^{\;2}\right)}{W_{down} E_s \cdot I_{16}}$$

$w_{req.2} := 482.87 \frac{N}{m}$

Required Downward Force for Imperfection Height 3	$w_{req.3.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}^{2}\right)}{W_{down} E_s \cdot I_{16}}$	$w_{req.3} := 884.79 \frac{N}{m}$
Required Downward Force for Imperfection Height 4	$w_{req.4.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}^{2}\right)}{W_{down} E_s \cdot I_{16}}$	$w_{req.4} := 1217.24 \frac{N}{m}$
Required Downward Force for Imperfection Height 5	$w_{req.5.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}^{2}\right)}{W_{down} E_s \cdot I_{16}}$	$w_{req.5} := 1546.01 \frac{N}{m}$
Required Downward Force for Imperfection Height 6	$w_{req.6.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}^{2}\right)}{W_{down} E_s \cdot I_{16}}$	$w_{req.6} := 1767.72 \frac{N}{m}$

7. UPHEAVAL BUCKLING ANALSYSIS

For Imperfection 1	$SF_1 := \frac{W_{down}}{w_{req.1}}$	$SF_1 = 19.217$	Not Occurred
For Imperfection 2	$SF_2 := \frac{W_{down}}{w_{req.2}}$	$SF_2 = 7.942$	Not Occurred
For Imperfection 3	$SF_3 := \frac{W_{down}}{w_{req.3}}$	$SF_3 = 4.334$	Not Occurred
For Imperfection 4	$SF_4 := \frac{W_{down}}{w_{req.4}}$	$SF_4 = 3.151$	Not Occurred
For Imperfection 5	$SF_5 := \frac{W_{down}}{w_{req.5}}$	$SF_5 = 2.481$	Not Occurred
For Imperfection 6	$SF_6 := \frac{W_{down}}{w_{req.6}}$	$SF_6 = 2.169$	Not Occurred

PIPELINE UPHEAVAL BUCKLING CALCULATION

Project : Upheaval Buckling Analysis of 16" Production Pipeline
Calculated by : ASM
Checked by : IMR/HDY

A. INTRODUCTION

The objective of this spreadsheet is to determine the required downward force on the pipeline to prevent upheaval buckling as a result of axial compression. The required downward force is calculated using an equation developed by Palmer in OTC 6335

Pipeline : 16" Production Pipeline

Section : KP 1+393 - KP 5+725

Condition : Operation (Corroded Case)

Design Life : 15 Years

B. REFERENCES

The following references are used in this spreadsheet:

[1]. DNVGL-RP-F110, Global Buckling of Submarine Pipelines, 2007

[2]. OTC 6335 - Design of Submarine Pipelines against Upheaval Buckling, A.C Palmer et.al, 1990

1. INPUT DATA

1.1 General

"Trench" of "Seabed" position $Pos := \text{"Trench"}$

Trenching Depth to Top of Steel (if applicable) $H_{trench} := 2.789m$

Water depth $h := 1.31m$ $h = 4.298 \cdot ft$

Percentage of corrosion allowance in operation
(In this Case, Pipeline is Corroded) $ca\% := 100\%$

Location Class (1 or 2) $LC := 1$
Section 2 C300 DNV OS F101Table 2-2, page 28)

Note:
Location Class Definition :

1. The area where no frequent human activity is anticipated along the pipeline route
2. The part of the pipeline/riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed a minimum distance of 500 m shall be adopted.

1.2. Pipeline Properties

Material Grade of Pipeline	API 5L X65
Specified Minimum Yield Strength	$SMYS := 450MPa$
Coefficient of Thermal Expansion	$\alpha_{th} := 1.17 \times 10^{-5} \Delta°C^{-1}$
Young's Modulus of Steel	$E_s := 207000MPa$
Poisson's Ratio of Steel	$\upsilon := 0.3$
Density of Steel	$\rho_s := 7850\, kg \cdot m^{-3}$
Pipeline Length	$L_{pl} := 4332m$
Pipe Joint Length	$L_{pj} := 12.2m$
Nominal Outside Diameter of 6" Gas Lift Pipeline	$D_{o.6} := 168.3mm$
Selected Wall Thickness of 6" Gas Lift Pipeline	$t_{s.6} := 9.5mm$
Nominal Outside Diameter of 16" Production Pipeline	$D_{o.16} := 406.4mm$
Selected Wall Thickness of 16" Production Pipeline	$t_{s.16} := 12.7mm$
Corrosion Allowance of Pipeline	$CA := 3mm$
Anti Corrosion Coating Thickness	$t_{acc} := 3.5mm$
Anti Corrosion Coating Density	$\rho_{acc} := 940\, kg \cdot m^{-3}$
Anti Corrosion Coating Cutback Length	$l_{cbc} := 150mm$
Concrete Coating Thickness of 6" Gas Lift Pipeline	$t_{cc.6} := 0mm$
Concrete Coating Thickness of 16" Production	$t_{cc.16} := 60mm$
Concrete Coating Density	$\rho_{cc} := 3040\, kg \cdot m^{-3}$
Concrete Coating Cutback Length	$l_{cb} := 200mm$
Field Joint Coating Density	$\rho_{fjc} := 930\, kg \cdot m^{-3}$
Infill Material Density	$\rho_{im} := 1025\, kg \cdot m^{-3}$
Max. Concrete Coating Water Absorption	$w_{abs} := 5\%$

1.3. Design and Operating Parameters

Installation Pressure $P_{ins.16} := 0MPa$

Installation Temperature $T_{ins.16} := 25\,°C$

Maximum Operating Pressure of 16" Production Pipeline $P_{opr.16} := 1.92MPa$

Maximum Operating Temperature of 16" Production Pipeline $T_{opr.16} := 69.34\,°C$

Maximum Operating Pressure of 6" Gas Lift Pipeline $P_{opr.6} := 9.51MPa$

Maximum Operating Temperature of 6" Gas Lift Pipeline $T_{opr.6} := 35\,°C$

Minimum Density of 16" Production Pipeline Content $\rho_{cont.16} := 73.83\,kg \cdot m^{-3}$

Minimum Density of 6" Gas Lift Pipeline Content $\rho_{cont.6} := 109.85\,kg \cdot m^{-3}$

Density of Seawater $\rho_w := 1025kg \cdot m^{-3}$

Uplift Coefficient $U_c := 0.5$

Residual Lay Tension $T_{lay} := 0kN$

1.4. Soil and Environmental Parameters

Imperfection Height

$h_1 := 1.1m$ $h_2 := 2.2m$ $h_3 := 3.4m$ $h_4 := 4.6m$ $h_5 := 5.8m$ $h_6 := 7m$

Soil Type $type := "clay"$

Soil Classification $soil := "cohessive"$

Soil Friction Coefficient $\mu_c := 0.31$

Density of Soil $\rho_{soil} := 1540kg \cdot m^{-3}$

Undrained Shear Strength $S_u := 2kPa$

Pipe Condition $pipe := "burried"$

Minimum Burial Depth $h_{burried} := 2m$

Submerged Unit Weight $\gamma_s := 5.29\,kN \cdot m^{-3}$

Passive Earth Pressure Coefficient $K_o := 0.8$

Impact Force $F_i := 5.1kN$

2. PIPELINE SUBMERGED WEIGHT CALCULATION

2.1 6" Gas Lift Pipeline

Actual Wall Thickness for Operating Condition $t_{nom.6} := t_{s.6} - ca\%\cdot CA$ $t_{nom.6} = 6.5 \times 10^{-3}\,m$

Internal Diameter of Pipeline $D_{i.6} := D_{o.6} - 2\cdot t_{nom.6}$ $D_{i.6} = 0.155\,m$

Diameter of Anti-Corrosion Coating $D_{acc.6} := D_{o.6} + 2\cdot t_{acc}$ $D_{acc.6} = 0.175\,m$

Diameter of Concrete Weight Coating *(6" Gas Lift Pipeline has no concrete coating)*

Total Outside Diameter of Pipeline $OD_6 := D_{acc.6}$ $OD_6 = 0.175\,m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.6} := 0.25\cdot\pi\cdot\left(D_{o.6}^{\;2} - D_{i.6}^{\;2}\right)\cdot\rho_s\cdot g \qquad W_{st.6} = 254.35\cdot N\cdot m^{-1}$$

Weight of Anti-Corrosion Coating

$$W_{acc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{L_{pj} - 2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{acc}\cdot g\right) \qquad W_{acc.6} = 16.985\cdot N\cdot m^{-1}$$

(no concrete weight coating needed so there's no infill material nor water absorption by cocncrete weight coating)

Weight of Field Joint Coating

$$W_{fjc.6} := 0.25\cdot\pi\cdot\left(D_{acc.6}^{\;2} - D_{o.6}^{\;2}\right)\cdot\frac{2\cdot l_{cbc}}{L_{pj}}\cdot\left(\rho_{fjc}\cdot g\right) \qquad W_{fjc.6} = 0.424\cdot N\cdot m^{-1}$$

Weight of 6" Gas Lift Pipe Content $W_{cont.6} := 0.25\cdot\pi\cdot D_{i.6}^{\;2}\,\rho_{cont.6}\cdot g$

$W_{cont.6} = 20.406\cdot N\cdot m^{-1}$

Total Weight of 6" Gas Lift Pipeline $W_{tot.6} := W_{st.6} + W_{acc.6} + W_{fjc.6} + W_{cont.6}$

$W_{tot.6} = 292.165\cdot N\cdot m^{-1}$

Buoyancy of 6" Gas Lift Pipeline $B_6 := 0.25\cdot\pi\cdot OD_6^{\;2}\cdot\rho_w\cdot g$ $B_6 = 242.604\cdot N\cdot m^{-1}$

Submerged Weight of 6" Gas Lift Pipeline $W_{sub.6} := W_{tot.6} - B_6$ $W_{sub.6} = 49.561\cdot N\cdot m^{-1}$

Total Submerged Weight $W_{sub.tot.6} := W_{sub.6}$ $W_{sub.tot.6} = 49.561 \cdot N \cdot m^{-1}$

2.2 16" Production Pipeline

Actual Wall Thickness for Operating Cond. $t_{nom.16} := t_{s.16} - ca\% \cdot CA$ $t_{nom.16} = 9.7 \times 10^{-3}\ m$

Internal Diameter of Pipeline $D_{i.16} := D_{o.16} - 2 \cdot t_{nom.16}$ $D_{i.16} = 0.387\ m$

Diameter of Anti-Corrosion Coating $D_{acc.16} := D_{o.16} + 2 \cdot t_{acc}$ $D_{acc.16} = 0.413\ m$

Diameter of Concrete Weight Coating $D_{conc.16} := D_{acc.16} + 2 \cdot t_{cc.16}$ $D_{conc.16} = 0.533\ m$

Total Outside Diameter of Pipeline $OD_{16} := D_{conc.16}$ $OD_{16} = 0.533\ m$

Weight of Steel Pipe (Uncorroded)

$$W_{st.16} := 0.25 \cdot \pi \cdot \left(D_{o.16}^{2} - D_{i.16}^{2}\right) \cdot \rho_s \cdot g$$ $W_{st.16} = 930.624 \cdot N \cdot m^{-1}$

Weight of Anti-Corrosion Coating

$$W_{acc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{2} - D_{o.16}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{acc} \cdot g\right)$$ $W_{acc.16} = 40.526 \cdot N \cdot m^{-1}$

Weight of Concrete Weight Coating

$$W_{conc.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{2} - D_{acc.16}^{2}\right) \cdot \frac{L_{pj} - 2 \cdot l_{cb}}{L_{pj}} \cdot \left(\rho_{cc} \cdot g\right)$$ $W_{conc.16} = 2.573 \times 10^{3} \cdot N \cdot m^{-1}$

Weight of Field Joint Coating

$$W_{fjc.16} := 0.25 \cdot \pi \cdot \left(D_{acc.16}^{2} - D_{o.16}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{fjc} \cdot g\right)$$ $W_{fjc.16} = 1.011 \cdot N \cdot m^{-1}$

Weight of Infill Material

$$W_{im.16} := 0.25 \cdot \pi \cdot \left(D_{conc.16}^{2} - D_{acc.16}^{2}\right) \cdot \frac{2 \cdot l_{cbc}}{L_{pj}} \cdot \left(\rho_{im} \cdot g\right)$$ $W_{im.16} = 22.056 \cdot N \cdot m^{-1}$

Weight of Absorbed Water $W_{abs.16} := w_{abs} \cdot W_{conc.16}$ $W_{abs.16} = 128.652 \cdot N \cdot m^{-1}$

Weight of 16" Production Pipeline Content

$$W_{cont.16} := 0.25 \cdot \pi \cdot D_{i.16}^{2} \rho_{cont.16} \cdot g$$ $W_{cont.16} = 85.166 \cdot N \cdot m^{-1}$

Total Weight of 16" Production Pipeline

$$W_{tot.16} := W_{st.16} + W_{acc.16} + W_{conc.16} + W_{fjc.16} + W_{im.16} + W_{cont.16} + W_{abs.16}$$

$$W_{tot.16} = 3.781 \times 10^{3} \cdot N \cdot m^{-1}$$

Buoyancy of 16" Production Pipeline $B_{16} := 0.25 \cdot \pi \cdot OD_{16}^{2} \cdot \rho_{w} \cdot g$ $B_{16} = 2.246 \times 10^{3} \cdot N \cdot m^{-1}$

Submerged Weight of 16" Production Pipeline

$$W_{sub.16} := W_{tot.16} - B_{16} \qquad W_{sub.16} = 1.535 \times 10^{3} \cdot N \cdot m^{-1}$$

Total Submerged Weight

$$W_{sub.tot.16} := W_{sub.6} + W_{sub.16}$$

$$W_{sub.pig} := W_{sub.tot.16} \qquad W_{sub.pig} = 1.584 \times 10^{3} \cdot N \cdot m^{-1}$$

3. PIPELINE STRESS CALCULATION

3.1. Hoop Stress (ASME B31.4, 2002)

$$S_{H.16} := P_{opr.16} \cdot \frac{D_{o.16}}{2 \cdot t_{nom.16}} \qquad S_{H.6} := P_{opr.6} \cdot \frac{D_{o.6}}{2 \cdot t_{nom.6}}$$

$$S_{H.16} = 4.022 \times 10^{7}\ Pa \qquad S_{H.6} = 1.231 \times 10^{8}\ Pa$$

ALLOWABLE STRESS

$$S_{Hmax} := 0.72 \cdot SMYS$$

$$S_{Hmax} = 3.24 \times 10^{8}\ Pa$$

$$S_{Hcheck.16} := \begin{cases} \text{"OK"} & \text{if } S_{H.16} < S_{Hmax} \\ \text{"Overstress"} & \text{if } S_{H.16} > S_{Hmax} \end{cases} \qquad S_{Hcheck.6} := \begin{cases} \text{"OK"} & \text{if } S_{H.6} < S_{Hmax} \\ \text{"Overstress"} & \text{if } S_{H.6} > S_{Hmax} \end{cases}$$

$$S_{Hcheck.16} = \text{"OK"} \qquad S_{Hcheck.6} = \text{"OK"}$$

3.2. Longitudinal Stress (ASME B31.4, 2002)

Longitudinal Stress due to Thermal Expansion

$S_{T.16} := E_s \cdot \alpha_{th} \cdot (T_{ins.16} - T_{opr.16})$ $S_{T.16} = -1.074 \times 10^8 \, Pa$

Longitudinal Stress due to Pressure Expansion Stress (Poisson's Effect)

$S_{P.16} := \upsilon \cdot S_{H.16}$ $S_{P.16} = 1.207 \times 10^7 \, Pa$

Total Longitudinal Stress

$S_{L.16} := S_{T.16} - S_{P.16}$ $S_{L.16} = -1.195 \times 10^8 \, Pa$

ALLOWABLE STRESS

$S_{Lmax} := 0.8 \cdot SMYS$

$S_{Lmax} = 3.6 \times 10^8 \, Pa$

$$S_{Lcheck.16} := \begin{cases} \text{"OK"} & \text{if } S_{L.16} < S_{Lmax} \\ \text{"Overstress"} & \text{if } S_{L.16} > S_{Lmax} \end{cases}$$

$S_{Lcheck.16} = \text{"OK"}$

Longitudinal Stress due to Thermal Expansion

$S_{T.6} := E_s \cdot \alpha_{th} \cdot (T_{ins.16} - T_{opr.6})$ $S_{T.6} = -2.422 \times 10^7 \, Pa$

Longitudinal Stress due to Pressure Expansion Stress (Poisson's Effect)

$S_{P.6} := \upsilon \cdot S_{H.6}$ $S_{P.6} = 3.694 \times 10^7 \, Pa$

Total Longitudinal Stress

$S_{L.6} := S_{T.6} - S_{P.6}$ $S_{L.6} = -6.115 \times 10^7 \, Pa$

ALLOWABLE STRESS

$S_{L.max} := 0.8 \cdot SMYS$

$S_{Lmax} = 3.6 \times 10^8 \, Pa$

$$S_{Lcheck.6} := \begin{cases} \text{"OK"} & \text{if } S_{L.16} < S_{Lmax} \\ \text{"Overstress"} & \text{if } S_{L.16} > S_{Lmax} \end{cases}$$

$S_{Lcheck.6} = \text{"OK"}$

3.3. Combined Stress (ASME B31.4, 2002)

Combined Stress (Equivalent Von Mises Stress)

$$S_{E.16} := \left[\left(S_{H.16}{}^{2} + S_{L.16}{}^{2}\right) - \left(S_{H.16} \cdot S_{L.16}\right)\right]^{0.5}$$

$$S_{E.16} = 1.438 \times 10^{8}\,\text{Pa}$$

ALLOWABLE STRESS

$$S_{Emax} := 0.9 \cdot SMYS$$

$$S_{Emax} = 4.05 \times 10^{8}\,\text{Pa}$$

$$S_{Echeck.16} := \begin{cases} \text{"OK"} & \text{if } S_{E.16} < S_{Emax} \\ \text{"Overstress"} & \text{if } S_{E.16} > S_{Emax} \end{cases}$$

$$S_{Echeck.16} = \text{"OK"}$$

Combined Stress (Equivalent Von Mises Stress)

$$S_{E.6} := \left[\left(S_{H.6}{}^{2} + S_{L.6}{}^{2}\right) - \left(S_{H.6} \cdot S_{L.6}\right)\right]^{0.5}$$

$$S_{E.6} = 1.626 \times 10^{8}\,\text{Pa}$$

ALLOWABLE STRESS

$$S_{E.max} := 0.9 \cdot SMYS$$

$$S_{Emax} = 4.05 \times 10^{8}\,\text{Pa}$$

$$S_{Echeck.6} := \begin{cases} \text{"OK"} & \text{if } S_{E.6} < S_{Emax} \\ \text{"Overstress"} & \text{if } S_{E.6} > S_{Emax} \end{cases}$$

$$S_{Echeck.16} = \text{"OK"}$$

4. PIPELINE AXIAL FORCE CALCULATION

Internal Area of Steel Pipe

$$A_{int.16} := 0.25 \cdot \pi \cdot \left(D_{o.16} - 2 \cdot t_{nom.16}\right)^{2} \qquad A_{int.16} = 0.118\,\text{m}^{2}$$

Sectional Area of Steel Pipe

$$A_{sect.16} := \pi \cdot \left(D_{o.16} - t_{nom.16}\right) \cdot t_{nom.16} \qquad A_{sect.16} = 0.012\,\text{m}^{2}$$

Effective Axial Force Acting on Pipeline

$$F_{ax.} := \left[\left(P_{ins.16} - P_{opr.16}\right) \cdot (1 - 2\upsilon)\right] \cdot A_{int.16} + \left[E_{s} \cdot \alpha_{th} \cdot \left(T_{ins.16} - T_{opr.16}\right)\right] \cdot A_{sect.16} + T_{lay}$$

$$F_{ax.} = -1.389 \times 10^{6}\,\text{N}$$

5. AVAILABLE DOWNWARD FORCE CALCULATION

Soil Uplift Resistance per Unit Length
(OTTC 6335, 1990)

$$q := S_{u} \cdot OD_{16} \cdot \min\left(3, \frac{h}{OD_{16}}\right) \qquad q := 3200.4\,\frac{\text{N}}{\text{m}}$$

Available Downward Force

$$W_{down.} := W_{sub.pig} + q \qquad W_{down} := 4785.31\,\frac{\text{N}}{\text{m}}$$

6. REQUIRED DOWNWARD FORCE CALCULATION

Moment of Inertia $I_{16} := \frac{\pi}{64} \cdot \left(OD_{16}{}^{4} - D_{i.16}{}^{4}\right)$ $I_{16} = 2.873 \times 10^{-3}\,m^{4}$

Natural Half Wave Length

Natural Half Wave Length for Imperfection Height 1 $L_1 := \left(\frac{72 \cdot E_s \cdot I_{16} \cdot h_1}{W_{sub.pig}}\right)^{0.25}$ $L_1 = 73.836\,m$

Natural Half Wave Length for Imperfection Height 2 $L_2 := \left(\frac{72 \cdot E_s \cdot I_{16} \cdot h_2}{W_{sub.pig}}\right)^{0.25}$ $L_2 = 87.806\,m$

Natural Half Wave Length for Imperfection Height 3 $L_3 := \left(\frac{72 \cdot E_s \cdot I_{16} \cdot h_3}{W_{sub.pig}}\right)^{0.25}$ $L_3 = 97.902\,m$

Natural Half Wave Length for Imperfection Height 4 $L_4 := \left(\frac{72 \cdot E_s \cdot I_{16} \cdot h_4}{W_{sub.pig}}\right)^{0.25}$ $L_4 = 105.587\,m$

Natural Half Wave Length for Imperfection Height 5 $L_5 := \left(\frac{72 \cdot E_s \cdot I_{16} \cdot h_5}{W_{sub.pig}}\right)^{0.25}$ $L_5 = 111.886\,m$

Natural Half Wave Length for Imperfection Height 6 $L_6 := \left(\frac{72 \cdot E_s \cdot I_{16} \cdot h_6}{W_{sub.pig}}\right)^{0.25}$ $L_6 = 117.272\,m$

Dimensionless Imperfection Length

Dimensionless Imperfection Length for Imperfection Height 1 $\phi_{L.1.} := L_1 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$ $\phi_{L.1} := 3.57$

Dimensionless Imperfection Length for Imperfection Height 2 $\phi_{L.2.} := L_2 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$ $\phi_{L.2} := 4.24$

Dimensionless Imperfection Length for Imperfection Height 3 $\phi_{L.3.} := L_3 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$ $\phi_{L.3} := 4.73$

Dimensionless Imperfection Length for Imperfection Height 4

$$\phi_{L.4.} := L_4 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$$

$$\phi_{L.4} := 5.10$$

Dimensionless Imperfection Length for Imperfection Height 5

$$\phi_{L.5.} := L_5 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$$

$$\phi_{L.5} := 5.41$$

Dimensionless Imperfection Length for Imperfection Height 6

$$\phi_{L.6.} := L_6 \cdot \left(\frac{F_{ax.}}{E_s \cdot I_{16}}\right)^{0.5}$$

$$\phi_{L.6} := 5.67$$

Dimensionless Maximum Downward Force Parameter (OTTC, 1990)

For Imperfection Height 1

$$\phi_{w.1} := 0.0646$$

For Imperfection Height 2

$$\phi_{w.2} := 0.0646$$

For Imperfection Height 3

$$\phi_{w.3} := \frac{5.68}{(\phi_{L.3})^2} - \frac{88.35}{(\phi_{L.3})^4}$$

$$\phi_{w.3} = 0.077$$

For Imperfection Height 4

$$\phi_{w.4} := \frac{5.68}{(\phi_{L.4})^2} - \frac{88.35}{(\phi_{L.4})^4}$$

$$\phi_{w.4} = 0.088$$

For Imperfection Height 5

$$\phi_{w.5} := \frac{5.68}{(\phi_{L.5})^2} - \frac{88.35}{(\phi_{L.5})^4}$$

$$\phi_{w.5} = 0.091$$

For Imperfection Height 6

$$\phi_{w.6} := \frac{5.68}{(\phi_{L.6})^2} - \frac{88.35}{(\phi_{L.6})^4}$$

$$\phi_{w.6} = 0.091$$

Required Downward Force

Required Downward Force for Imperfection Height 1

$$w_{req.1.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}{}^2\right)}{W_{down} E_s \cdot I_{16}}$$

$$w_{req.1} := 230.29 \frac{N}{m}$$

Required Downward Force for Imperfection Height 2

$$w_{req.2.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}{}^2\right)}{W_{down} E_s \cdot I_{16}}$$

$$w_{req.2} := 460.58 \frac{N}{m}$$

Required Downward Force for Imperfection Height 3 $w_{req.3.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}{}^2\right)}{W_{down} E_s \cdot I_{16}}$ $w_{req.3} := 852.71 \frac{N}{m}$

Required Downward Force for Imperfection Height 4 $w_{req.4.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}{}^2\right)}{W_{down} E_s \cdot I_{16}}$ $w_{req.4} := 1309.06 \frac{N}{m}$

Required Downward Force for Imperfection Height 5 $w_{req.5.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}{}^2\right)}{W_{down} E_s \cdot I_{16}}$ $w_{req.5} := 1708.85 \frac{N}{m}$

Required Downward Force for Imperfection Height 6 $w_{req.6.} := \frac{\left(\phi_{w.1} \cdot h_1 \cdot F_{ax.}{}^2\right)}{W_{down} E_s \cdot I_{16}}$ $w_{req.6} := 2069.00 \frac{N}{m}$

7. UPHEAVAL BUCKLING ANALSYSIS

For Imperfection 1 $SF_1 := \frac{W_{down}}{w_{req.1}}$ $SF_1 = 20.779$ Not Occurred

For Imperfection 2 $SF_2 := \frac{W_{down}}{w_{req.2}}$ $SF_2 = 10.39$ Not Occurred

For Imperfection 3 $SF_3 := \frac{W_{down}}{w_{req.3}}$ $SF_3 = 5.612$ Not Occurred

For Imperfection 4 $SF_4 := \frac{W_{down}}{w_{req.4}}$ $SF_4 = 3.656$ Not Occurred

For Imperfection 5 $SF_5 := \frac{W_{down}}{w_{req.5}}$ $SF_5 = 2.8$ Not Occurred

For Imperfection 6 $SF_6 := \frac{W_{down}}{w_{req.6}}$ $SF_6 = 2.313$ Not Occurred

LAMPIRAN VI

AUTOPIPE *MODELLING REPORT*

```
      *                             *******   **  *******   *******
     ***               **           **   **   **  **    **  **
    ** **            ******         **   **   **  **    **  **
   **   **    **   **  **   *****   *******   **  *******   *****
  *********   **   **  **  **   **  **        **  **        **
 **       **  **   **  **  **   **  **        **  **        **
**         **  *****   **   *****   **        **  **        *******
```

Pipe Stress Analysis and Design Program

Version: 11.01.00.17

Edition: Advanced

Developed and Maintained by

BENTLEY SYSTEMS, INCORPORATED
1600 Riviera Ave., Suite 300
Walnut Creek, CA 94596

```
************************************************************
**                                                        **
**               AUTOPIPE SYSTEM INFORMATION              **
**                                                        **
************************************************************
```

SYSTEM NAME : MODELIN PIPA 2 KM WITH AUTOPIPE CORRODED

PROJECT ID :

PREPARED BY : ______________________________
ANIT SISKA MELINDA

CHECKED BY : ______________________________
IR. IMAM ROCHANI, M.SC

1ST APPROVER : ______________________________
IR. IMAM ROCHANI, M.SC

2ND APPROVER : ______________________________
IR. HANDAYANU, M.SC,PH.D

PIPING CODE : B31.4 Offshore

YEAR : 2006

VERTICAL AXIS : Y

AMBIENT TEMPERATURE : 25.0 deg C

COMPONENT LIBRARY : AUTOPIPE

MATERIAL LIBRARY : B314-06

MODEL REVISION NUMBER : 43

C O M P O N E N T   D A T A   L I S T I N G

```
 ------------------------------------------------------------------------------
 *** SEGMENT A

 ------------------------------------------------------------------------------
 From A00 to A01, DX= 39130.00 mm                                      Run

 PIPE DATA:
   Pipe Id= 16", Material= 5LX-X65, Poisson= 0.300, Nom Size= 400 mm, OD= 406.40 mm, Sch= NS,
   Wall Thk= 9.700 mm, Mill= 1.212 mm, Cor= 0 mm, Pipe Density= 7833.03 kg/m3, Pipe Unit Wgt= 928.61 N/m,
   Content Sp Gr= 0.074, Content Unit Wgt= 85.32 N/m, Insul Thk= 40.000 mm, Insul Material= OTHER,
   Insul Density= 3040.00 kg/m3, Insul Unit Wgt= 1672.35 N/m, Cladding Thickness = 0 mm, Lining Thk= 0 mm,
   Long Weld factor= 1.00, Circ Weld factor= 1.00, Long Modulus= 0.20314 E6 N/mm2,
   Hoop Modulus= 0.20314 E6 N/mm2, Shear Modulus= 0.07813 E6 N/mm2, Syc= 450.0 N/mm2

 OPERATING DATA:
   P1= 1.9200 N/mm2, P2= 1.9200 N/mm2, T1= 25.00 deg C, T2= 69.34 deg C, Exp1= 0 mm/m, Exp2= 0.50675 mm/m,
   E1= 0.20314 E6 N/mm2, E2= 0.20017 E6 N/mm2, Sy1= 450.00 N/mm2, Sy2= 450.00 N/mm2

 POINT DATA:
   A00, Coordinates, X= 99999.99 mm, Y= -7000.00 mm, Z= 0.00 mm
   A00, Hydrodynamic, Cm= Auto, Cd= Auto, Cl= 0.000

 SUPPORT DATA:
   A00, Anchor, KTX= Rigid, KTY= Rigid, KTZ= Rigid, KRX= Rigid, KRY= Rigid, KRZ= Rigid

 SOIL DATA:
   Soil Id= CLAY, 1 point(s) at 100005.00 mm
   Horz K1= 1.070 N/mm/mm, Horz P1= 3673.000 N/m, Horz K2= 0.000 N/mm/mm, Long K1= 0.310 N/mm/mm,
   Long P1= 1770000.0 N/m, Long k2= 0.000 N/mm/mm, Vert Up K1= 0.500 N/mm/mm, Vert Up P1= 2960.000 N/m,
   Vert Up K2= 0.000 N/mm/mm, Vert Dn K1= 0.500 N/mm/mm, Vert Dn P1= 924.093 N/m, Vert Dn K2= 0.000 N/mm/mm

 ------------------------------------------------------------------------------
 From A01 to B01, DX= 30871.00 mm, DY= 600.00 mm, L= 30876.83 mm           Run

 POINT DATA:
   A01, Coordinates, X= 139129.98 mm, Y= -7000.00 mm, Z= 0.00 mm

 SOIL DATA:
   Soil Id= CLAY, 1 point(s) at 100005.00 mm

 ------------------------------------------------------------------------------
 From B01 to A02, DX= 30870.02 mm, DY= -600.00 mm, L= 30875.85 mm          Bend

 COMPONENT DATA (Bend, TIP= B01, Near= B01N, Mid= A03 M, Far= B01F):
   Long Elbow, Radius= 609.60 mm, Bend angle= 2.23 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
   SIFI= 3.18, SIFO= 2.65

 POINT DATA:
   B01, Coordinates, X= 170000.98 mm, Y= -6400.00 mm, Z= 0.00 mm
   B01N, Coordinates, X= 169989.14 mm, Y= -6400.23 mm, Z= 0.00 mm
   A03 M, Coordinates, X= 170000.98 mm, Y= -6400.11 mm, Z= 0.00 mm
   B01F, Coordinates, X= 170012.83 mm, Y= -6400.23 mm, Z= 0.00 mm

 SOIL DATA (B01N to A03 M):
   Soil Id= CLAY, 1 point(s) at 51612.80 mm
```


C O M P O N E N T   D A T A   L I S T I N G

```
 SOIL DATA (A03 M to B01F):
   Soil Id= CLAY, 1 point(s) at 51612.80 mm

 SOIL DATA (B01F to A02):
   Soil Id= CLAY, 1 point(s) at 51612.80 mm

 ------------------------------------------------------------------------------
 From A02 to A03, DX= 112419.99 mm                                     Run

 POINT DATA:
   A02, Coordinates, X= 200871.00 mm, Y= -7000.00 mm, Z= 0.00 mm

 SOIL DATA:
```

Soil Id= CLAY, 1 point(s) at 100005.00 mm

From A03 to B02, DX= 36712.00 mm, DY= 1200.00 mm, L= 36731.61 mm Run

POINT DATA:
A03, Coordinates, X= 313291.00 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
Soil Id= CLAY, 1 point(s) at 100005.00 mm

From B02 to A04, DX= 36710.99 mm, DY= -1200.00 mm, L= 36730.59 mm Bend

COMPONENT DATA (Bend, TIP= B02, Near= B02N, Mid= A06 M, Far= B02F):
Long Elbow, Radius= 609.60 mm, Bend angle= 3.74 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
SIFI= 3.18, SIFO= 2.65

POINT DATA:
B02, Coordinates, X= 350003.00 mm, Y= -5800.00 mm, Z= 0.00 mm
B02N, Coordinates, X= 349983.06 mm, Y= -5800.65 mm, Z= 0.00 mm
A06 M, Coordinates, X= 350003.00 mm, Y= -5800.32 mm, Z= 0.00 mm
B02F, Coordinates, X= 350022.91 mm, Y= -5800.65 mm, Z= 0.00 mm

SOIL DATA (B02N to A06 M):
Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (A06 M to B02F):
Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (B02F to A04):
Soil Id= CLAY, 1 point(s) at 51612.80 mm

From A04 to A05, DX= 82109.99 mm Run

POINT DATA:
A04, Coordinates, X= 386713.97 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
Soil Id= CLAY, 1 point(s) at 100005.00 mm

C O M P O N E N T   D A T A   L I S T I N G

From A05 to B03, DX= 41180.94 mm, DY= 1900.00 mm, L= 41224.75 mm Run

POINT DATA:
A05, Coordinates, X= 468823.97 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
Soil Id= CLAY, 1 point(s) at 51612.80 mm

From B03 to A06, DX= 41180.99 mm, DY= -1900.00 mm, L= 41224.80 mm Bend

COMPONENT DATA (Bend, TIP= B03, Near= B03N, Mid= A09 M, Far= B03F):
Long Elbow, Radius= 609.60 mm, Bend angle= 5.28 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
SIFI= 3.18, SIFO= 2.65

POINT DATA:
B03, Coordinates, X= 510004.91 mm, Y= -5100.00 mm, Z= 0.00 mm
B03N, Coordinates, X= 509976.81 mm, Y= -5101.29 mm, Z= 0.00 mm
A09 M, Coordinates, X= 510004.91 mm, Y= -5100.65 mm, Z= 0.00 mm
B03F, Coordinates, X= 510033.00 mm, Y= -5101.29 mm, Z= 0.00 mm

SOIL DATA (B03N to A09 M):
Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (A09 M to B03F):
Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (B03F to A06):
Soil Id= CLAY, 1 point(s) at 51612.80 mm

```
-------------------------------------------------------------------------------
From A06 to A07, DX= 84280.02 mm                                           Run

POINT DATA:
  A06, Coordinates, X= 551185.88 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 100005.00 mm

-------------------------------------------------------------------------------
From A07 to B04, DX= 44539.99 mm, DY= 2600.00 mm, L= 44615.82 mm           Run

POINT DATA:
  A07, Coordinates, X= 635465.94 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 100005.00 mm

-------------------------------------------------------------------------------
From B04 to A08, DX= 44550.01 mm, DY= -2600.00 mm, L= 44625.82 mm          Bend

COMPONENT DATA (Bend, TIP= B04, Near= B04N, Mid= A12 M, Far= B04F):
  Long Elbow, Radius= 609.60 mm, Bend angle= 6.68 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
  SIFI= 3.18, SIFO= 2.65
```


C O M P O N E N T   D A T A   L I S T I N G

```
POINT DATA:
  B04, Coordinates, X= 680005.94 mm, Y= -4400.00 mm, Z= 0.00 mm
  B04N, Coordinates, X= 679970.38 mm, Y= -4402.07 mm, Z= 0.00 mm
  A12 M, Coordinates, X= 680005.94 mm, Y= -4401.04 mm, Z= 0.00 mm
  B04F, Coordinates, X= 680041.44 mm, Y= -4402.07 mm, Z= 0.00 mm

SOIL DATA (B04N to A12 M):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (A12 M to B04F):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (B04F to A08):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

-------------------------------------------------------------------------------
From A08 to A09, DX= 77830.02 mm                                           Run

POINT DATA:
  A08, Coordinates, X= 724555.94 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 100005.00 mm

-------------------------------------------------------------------------------
From A09 to B05, DX= 47630.01 mm, DY= 3400.00 mm, L= 47751.21 mm           Run

POINT DATA:
  A09, Coordinates, X= 802385.94 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 100005.00 mm

-------------------------------------------------------------------------------
From B05 to A10, DX= 47629.96 mm, DY= -3400.00 mm, L= 47751.16 mm          Bend

COMPONENT DATA (Bend, TIP= B05, Near= B05N, Mid= A15 M, Far= B05F):
  Long Elbow, Radius= 609.60 mm, Bend angle= 8.17 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
  SIFI= 3.18, SIFO= 2.65

POINT DATA:
  B05, Coordinates, X= 850015.94 mm, Y= -3600.00 mm, Z= 0.00 mm
  B05N, Coordinates, X= 849972.56 mm, Y= -3603.10 mm, Z= 0.00 mm
  A15 M, Coordinates, X= 850015.94 mm, Y= -3601.55 mm, Z= 0.00 mm
  B05F, Coordinates, X= 850059.31 mm, Y= -3603.10 mm, Z= 0.00 mm

SOIL DATA (B05N to A15 M):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (A15 M to B05F):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm
```

SOIL DATA (B05F to A10):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

C O M P O N E N T   D A T A   L I S T I N G

From A10 to A11, DX= 52765.03 mm Run

POINT DATA:
  A10, Coordinates, X= 897645.94 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 100005.00 mm

From A11 to B06, DX= 49605.01 mm, DY= 4000.00 mm, L= 49766.02 mm Run

POINT DATA:
  A11, Coordinates, X= 950410.94 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 100005.00 mm

From B06 to A012, DX= 49605.01 mm, DY= -4000.00 mm, L= 49766.02 mm Bend

COMPONENT DATA (Bend, TIP= B06, Near= B06N, Mid= A18 M, Far= B06F):
  Long Elbow, Radius= 609.60 mm, Bend angle= 9.22 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
  SIFI= 3.18, SIFO= 2.65

POINT DATA:
  B06, Coordinates, X= 1000016 mm, Y= -3000.00 mm, Z= 0.00 mm
  B06N, Coordinates, X= 999966.94 mm, Y= -3003.95 mm, Z= 0.00 mm
  A18 M, Coordinates, X= 1000016 mm, Y= -3001.98 mm, Z= 0.00 mm
  B06F, Coordinates, X= 1000065 mm, Y= -3003.95 mm, Z= 0.00 mm

SOIL DATA (B06N to A18 M):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (A18 M to B06F):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

SOIL DATA (B06F to A012):
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

From A012 to A13, DX= 50394.99 mm Run

POINT DATA:
  A012, Coordinates, X= 1049621 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 51612.80 mm

From A13 to A14, DX= 100000.00 mm Run

PIPE DATA:
  Pipe Id= 16" 60, Mill= 1.212 mm, Pipe Density= 7833.03 kg/m3, Pipe Unit Wgt= 928.61 N/m,
  Content Sp Gr= 0.074, Content Unit Wgt= 85.32 N/m, Insul Thk= 60.000 mm, Insul Density= 3040.00 kg/m3,

C O M P O N E N T   D A T A   L I S T I N G

  Insul Unit Wgt= 2620.92 N/m, Syc= 448.2 N/mm2

OPERATING DATA:
  Sy1= 448.16 N/mm2, Sy2= 448.16 N/mm2

POINT DATA:
  A13, Coordinates, X= 1100016 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 100005.00 mm

```
 -----------------------------------------------------------------------------
 From A14 to B07, DX= 35894.96 mm, DY= 1100.00 mm, L= 35911.81 mm           Run

 POINT DATA:
   A14, Coordinates, X= 1200016 mm, Y= -7000.00 mm, Z= 0.00 mm

 SOIL DATA:
   Soil Id= CLAY, 1 point(s) at 35893.15 mm

 -----------------------------------------------------------------------------
 From B07 to A15, DX= 35895.06 mm, DY= -1100.00 mm, L= 35911.91 mm          Bend

 COMPONENT DATA (Bend, TIP= B07, Near= B07N, Mid= B07 M, Far= B07F):
   Long Elbow, Radius= 609.60 mm, Bend angle= 3.51 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
   SIFI= 3.18, SIFO= 2.65

 POINT DATA:
   B07, Coordinates, X= 1235911 mm, Y= -5900.00 mm, Z= 0.00 mm
   B07N, Coordinates, X= 1235892 mm, Y= -5900.57 mm, Z= 0.00 mm
   B07 M, Coordinates, X= 1235911 mm, Y= -5900.29 mm, Z= 0.00 mm
   B07F, Coordinates, X= 1235930 mm, Y= -5900.57 mm, Z= 0.00 mm

 SOIL DATA (B07N to B07 M):
   Soil Id= CLAY, 1 point(s) at 37.35 mm

 SOIL DATA (B07 M to B07F):
   Soil Id= CLAY, 1 point(s) at 37.35 mm

 SOIL DATA (B07F to A15):
   Soil Id= CLAY, 1 point(s) at 35893.25 mm

 -----------------------------------------------------------------------------
 From A15 to A16, DX= 100000.00 mm                                          Run

 POINT DATA:
   A15, Coordinates, X= 1271806 mm, Y= -7000.00 mm, Z= 0.00 mm

 SOIL DATA:
   Soil Id= CLAY, 1 point(s) at 100000.00 mm

 -----------------------------------------------------------------------------
 From A16 to B08, DX= 42685.00 mm, DY= 2200.00 mm, L= 42741.65 mm           Run

 POINT DATA:
```



```
                  C O M P O N E N T   D A T A   L I S T I N G

   A16, Coordinates, X= 1371806 mm, Y= -7000.00 mm, Z= 0.00 mm

 SOIL DATA:
   Soil Id= CLAY, 1 point(s) at 42710.26 mm

 -----------------------------------------------------------------------------
 From B08 to A17, DX= 42685.00 mm, DY= -2200.00 mm, L= 42741.65 mm          Bend

 COMPONENT DATA (Bend, TIP= B08, Near= B08N, Mid= B08 M, Far= B08F):
   Long Elbow, Radius= 609.60 mm, Bend angle= 5.90 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
   SIFI= 3.18, SIFO= 2.65

 POINT DATA:
   B08, Coordinates, X= 1414491 mm, Y= -4800.00 mm, Z= 0.00 mm
   B08N, Coordinates, X= 1414460 mm, Y= -4801.62 mm, Z= 0.00 mm
   B08 M, Coordinates, X= 1414491 mm, Y= -4800.81 mm, Z= 0.00 mm
   B08F, Coordinates, X= 1414522 mm, Y= -4801.62 mm, Z= 0.00 mm

 SOIL DATA (B08N to B08 M):
   Soil Id= CLAY, 1 point(s) at 62.78 mm

 SOIL DATA (B08 M to B08F):
   Soil Id= CLAY, 1 point(s) at 62.78 mm

 SOIL DATA (B08F to A17):
   Soil Id= CLAY, 1 point(s) at 42710.26 mm

 -----------------------------------------------------------------------------
 From A17 to A18, DX= 100000.00 mm                                          Run

 POINT DATA:
   A17, Coordinates, X= 1457176 mm, Y= -7000.00 mm, Z= 0.00 mm
```

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 200000.00 mm

From A18 to B09, DX= 47589.88 mm, DY= 3400.00 mm, L= 47711.17 mm Run

POINT DATA:
  A18, Coordinates, X= 1557176 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 47667.61 mm

From B09 to A19, DX= 47590.07 mm, DY= -3400.00 mm, L= 47711.37 mm Bend

COMPONENT DATA (Bend, TIP= B09, Near= B09N, Mid= B09 M, Far= B09F):
  Long Elbow, Radius= 609.60 mm, Bend angle= 8.17 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
  SIFI= 3.18, SIFO= 2.65

POINT DATA:
  B09, Coordinates, X= 1604766 mm, Y= -3600.00 mm, Z= 0.00 mm
  B09N, Coordinates, X= 1604722 mm, Y= -3603.10 mm, Z= 0.00 mm

C O M P O N E N T   D A T A   L I S T I N G

  B09 M, Coordinates, X= 1604766 mm, Y= -3601.55 mm, Z= 0.00 mm
  B09F, Coordinates, X= 1604809 mm, Y= -3603.10 mm, Z= 0.00 mm

SOIL DATA (B09N to B09 M):
  Soil Id= CLAY, 1 point(s) at 86.96 mm

SOIL DATA (B09 M to B09F):
  Soil Id= CLAY, 1 point(s) at 86.96 mm

SOIL DATA (B09F to A19):
  Soil Id= CLAY, 1 point(s) at 47667.80 mm

From A19 to A20, DX= 100000.00 mm Run

POINT DATA:
  A19, Coordinates, X= 1652356 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 500000.00 mm

From A20 to B10, DX= 51330.03 mm, DY= 4600.00 mm, L= 51535.73 mm Run

POINT DATA:
  A20, Coordinates, X= 1752356 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 51481.14 mm

From B10 to A21, DX= 51330.03 mm, DY= -4600.00 mm, L= 51535.73 mm Bend

COMPONENT DATA (Bend, TIP= B10, Near= B10N, Mid= B10 M, Far= B10F):
  Long Elbow, Radius= 609.60 mm, Bend angle= 10.24 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
  SIFI= 3.18, SIFO= 2.65

POINT DATA:
  B10, Coordinates, X= 1803686 mm, Y= -2400.00 mm, Z= 0.00 mm
  B10N, Coordinates, X= 1803632 mm, Y= -2404.88 mm, Z= 0.00 mm
  B10 M, Coordinates, X= 1803686 mm, Y= -2402.44 mm, Z= 0.00 mm
  B10F, Coordinates, X= 1803740 mm, Y= -2404.88 mm, Z= 0.00 mm

SOIL DATA (B10N to B10 M):
  Soil Id= CLAY, 1 point(s) at 108.97 mm

SOIL DATA (B10 M to B10F):
  Soil Id= CLAY, 1 point(s) at 108.97 mm

SOIL DATA (B10F to A21):
  Soil Id= CLAY, 1 point(s) at 51481.14 mm

From A21 to A32, DX= 100000.00 mm   Run

C O M P O N E N T   D A T A   L I S T I N G

POINT DATA:
  A21, Coordinates, X= 1855016 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 500000.00 mm

From A32 to A22, DX= 54389.93 mm, DY= 5800.00 mm, L= 54698.31 mm   Run

POINT DATA:
  A32, Coordinates, X= 1955016 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 54633.25 mm

From A22 to A23, DX= 54390.13 mm, DY= -5800.00 mm, L= 54698.50 mm   Bend

COMPONENT DATA (Bend, TIP= A22, Near= A22N, Mid= A22 M, Far= A22F):
  Long Elbow, Radius= 609.60 mm, Bend angle= 12.17 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
  SIFI= 3.18, SIFO= 2.65

POINT DATA:
  A22, Coordinates, X= 2009406 mm, Y= -1200.00 mm, Z= 0.00 mm
  A22N, Coordinates, X= 2009341 mm, Y= -1206.89 mm, Z= 0.00 mm
  A22 M, Coordinates, X= 2009406 mm, Y= -1203.45 mm, Z= 0.00 mm
  A22F, Coordinates, X= 2009471 mm, Y= -1206.89 mm, Z= 0.00 mm

SOIL DATA (A22N to A22 M):
  Soil Id= CLAY, 1 point(s) at 129.52 mm

SOIL DATA (A22 M to A22F):
  Soil Id= CLAY, 1 point(s) at 129.52 mm

SOIL DATA (A22F to A23):
  Soil Id= CLAY, 1 point(s) at 54633.45 mm

From A23 to A24, DX= 100000.00 mm   Run

POINT DATA:
  A23, Coordinates, X= 2063796 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 500000.00 mm

From A24 to B12, DX= 57009.90 mm, DY= 7000.00 mm, L= 57438.04 mm   Run

POINT DATA:
  A24, Coordinates, X= 2163796 mm, Y= -7000.00 mm, Z= 0.00 mm

SOIL DATA:
  Soil Id= CLAY, 1 point(s) at 57363.27 mm

C O M P O N E N T   D A T A   L I S T I N G

From B12 to A25, DX= 57009.90 mm, DY= -7000.00 mm, L= 57438.04 mm   Bend

COMPONENT DATA (Bend, TIP= B12, Near= B12N, Mid= B12 M, Far= B12F):
  Long Elbow, Radius= 609.60 mm, Bend angle= 14.00 deg, Mid point at 50.00 percent, End flanges= 0, Flex= Auto,
  SIFI= 3.18, SIFO= 2.65

POINT DATA:
  B12, Coordinates, X= 2220806 mm, Y= 0.00 mm, Z= 0.00 mm
  B12N, Coordinates, X= 2220732 mm, Y= -9.12 mm, Z= 0.00 mm
  B12 M, Coordinates, X= 2220806 mm, Y= -4.58 mm, Z= 0.00 mm

B12F, Coordinates, X= 2220880 mm, Y= -9.12 mm, Z= 0.00 mm

SOIL DATA (B12N to B12 M):
Soil Id= CLAY, 1 point(s) at 148.95 mm

SOIL DATA (B12 M to B12F):
Soil Id= CLAY, 1 point(s) at 148.95 mm

SOIL DATA (B12F to A25):
Soil Id= CLAY, 1 point(s) at 57363.27 mm

From A25 to A26, DX= 32744.17 mm Run

POINT DATA:
A25, Coordinates, X= 2277816 mm, Y= -7000.00 mm, Z= 0.00 mm
A26, Coordinates, X= 2310560 mm, Y= -7000.00 mm, Z= 0.00 mm

SUPPORT DATA:
A26, Anchor, KTX= Rigid, KTY= Rigid, KTZ= Rigid, KRX= Rigid, KRY= Rigid, KRZ= Rigid

SOIL DATA:
Soil Id= CLAY, 1 point(s) at 32744.17 mm
Soil Id= CLAY, End at A26

Number of points in the system (Pipe + Frame + Soil): 87 + 0 + 62 = 149

Weight of Empty Pipes + Weight of Contents = Total Weight of System
704448.3 kg + 19260.7 kg = 723709.0 kg

C O O R D I N A T E S   D A T A   L I S T I N G

POINT NAME	X (mm)	Y (mm)	Z (mm)
*** SEGMENT A			
A00	99999.99	-7000.00	0.00
A01	139129.98	-7000.00	0.00
B01N	169989.14	-6400.23	0.00
B01	170000.98	-6400.00	0.00
A03 M	170000.98	-6400.11	0.00
B01F	170012.83	-6400.23	0.00
A02	200871.00	-7000.00	0.00
A03	313291.00	-7000.00	0.00
B02N	349983.06	-5800.65	0.00
B02	350003.00	-5800.00	0.00
A06 M	350003.00	-5800.32	0.00
B02F	350022.91	-5800.65	0.00
A04	386713.97	-7000.00	0.00
A05	468823.97	-7000.00	0.00
B03N	509976.81	-5101.29	0.00
B03	510004.91	-5100.00	0.00
A09 M	510004.91	-5100.65	0.00
B03F	510033.00	-5101.29	0.00
A06	551185.88	-7000.00	0.00
A07	635465.94	-7000.00	0.00
B04N	679970.38	-4402.07	0.00
B04	680005.94	-4400.00	0.00
A12 M	680005.94	-4401.04	0.00
B04F	680041.44	-4402.07	0.00
A08	724555.94	-7000.00	0.00
A09	802385.94	-7000.00	0.00
B05N	849972.56	-3603.10	0.00
B05	850015.94	-3600.00	0.00
A15 M	850015.94	-3601.55	0.00
B05F	850059.31	-3603.10	0.00
A10	897645.94	-7000.00	0.00
A11	950410.94	-7000.00	0.00
B06N	999966.94	-3003.95	0.00
B06	1000015.94	-3000.00	0.00
A18 M	1000015.94	-3001.98	0.00
B06F	1000064.94	-3003.95	0.00
A012	1049621.00	-7000.00	0.00
A13	1100016.00	-7000.00	0.00
A14	1200015.88	-7000.00	0.00

B07N	1235892.25	-5900.57	0.00
B07	1235910.88	-5900.00	0.00
B07 M	1235910.88	-5900.29	0.00
B07F	1235929.50	-5900.57	0.00
A15	1271806.00	-7000.00	0.00
A16	1371806.00	-7000.00	0.00
B08N	1414459.62	-4801.62	0.00
B08	1414491.00	-4800.00	0.00
B08 M	1414491.00	-4800.81	0.00
B08F	1414522.25	-4801.62	0.00
A17	1457176.00	-7000.00	0.00
A18	1557176.00	-7000.00	0.00

C O O R D I N A T E S   D A T A   L I S T I N G

POINT NAME	X	Y	Z
	--------COORDINATE (mm	)---------	
B09N	1604722.38	-3603.10	0.00
B09	1604765.88	-3600.00	0.00
B09 M	1604765.88	-3601.55	0.00
B09F	1604809.25	-3603.10	0.00
A19	1652355.88	-7000.00	0.00
A20	1752355.88	-7000.00	0.00
B10N	1803631.50	-2404.88	0.00
B10	1803685.88	-2400.00	0.00
B10 M	1803685.88	-2402.44	0.00
B10F	1803740.25	-2404.88	0.00
A21	1855016.00	-7000.00	0.00
A32	1955016.00	-7000.00	0.00
A22N	2009341.12	-1206.89	0.00
A22	2009405.88	-1200.00	0.00
A22 M	2009405.88	-1203.45	0.00
A22F	2009470.62	-1206.89	0.00
A23	2063796.00	-7000.00	0.00
A24	2163796.00	-7000.00	0.00
B12N	2220731.75	-9.12	0.00
B12	2220806.00	0.00	0.00
B12 M	2220806.00	-4.58	0.00
B12F	2220880.00	-9.12	0.00
A25	2277815.75	-7000.00	0.00
A26	2310560.00	-7000.00	0.00

S E G M E N T   D A T A   L I S T I N G

Segment Name	First Node	Last Node	Line Number	Apply Wind	Apply Bowing	Apply Buoyancy
A	A00	A26		No	No	No

P I P E   D A T A   L I S T I N G

```
Pipe ID/     Nom/ O.D.  -----Thickness(mm  )----- Spec  InsuDen/   Weight(N/m   )    ZL/ Composition/
Material     Sch  mm    W.Th. Corr Mill Insu Ling Grav/ LingDen/  Pipe/ Ling/ Total  ZC
CladMaterial            Clad                      InsMt CladDen   Cont  Insu/
---Line Class---                                        kg/m3           Clad
------------ ---- ----- ----- ---- ---- ---- ---- ----- --------  ----- ----- ----- ---- --------------------

Tag No. : <None>
16"          400 406.40 9.700    0 1.21   40    0  0.07 3040.000    929     0  2686 1.00
5LX-X65      NS                                   Other    0.000  85.32  1672       1.00
                           0                               0.000            0


Tag No. : <None>
16" 60       400 406.40 9.700    0 1.21   60    0  0.07 3040.000    929     0  3635 1.00
5LX-X65      NS                                   Other    0.000  85.32  2621       1.00
                           0                               0.000            0
```

M A T E R I A L   D A T A   L I S T I N G

Material Name	Pipe ID	Density kg/m3	Pois. Ratio	Temper. deg C	Modulus E6 N/mm2 Axial	Hoop	Shear	Expans. mm/m	Composition
5LX-X65	16"	7833.0	0.30	25.0	0.20314	0.20314	0.07813		
				69.3	0.20017			0.5068	
5LX-X65	16" 60	7833.0	0.30	25.0	0.20314	0.20314	0.07813		
				69.3	0.20017			0.5068	

M A T E R I A L   A L L O W A B L E   D A T A   L I S T I N G

Material Name	Pipe ID	Temper. deg C	Yield N/mm2
5LX-X65	16"	25.0	450.00
5LX-X65	16" 60	25.0	448.16

OPERATING TEMPERATURE AND PRESSURE DATA
STRESSES IN N/mm2

POINT NAME	CASE	PRESS. N/mm2	TEMPER deg C	EXPAN. mm/m	MODULUS E6 N/mm	YIELD STRESS
*** SEGMENT A						
A00	T1	1.9200	25.00	0.000	0.20314	450.00
	T2	1.9200	69.34	0.507	0.20017	450.00
A13	T1	1.9200	25.00	0.000	0.20314	448.16
	T2	1.9200	69.34	0.507	0.20017	448.16
A26	Same as previous point.					

u User-defined value
* Non-code material for allowable stress;
Non-standard material for expansion and modulus

SOIL DATA LISTING

SOIL STIFFNESS PROPERTIES (CLAY)

Dirn	Auto	Initial K (N/mm/mm)	Auto	Yield P (N/m)	Final K (N/mm/mm)	Yield disp (mm)
Low Stiffness						
Horiz.	Y	1.070	Y	3673.000	0.000	3.4327
Long.	Y	0.310	Y	1770000.0	0.000	5709.6479
Vert. Up	Y	0.500	Y	2960.000	0.000	5.9200
Vert. Dn	Y	0.500	Y	924.093	0.000	1.8482
High Stiffness						
Horiz.	Y	0.575	Y	14593.899	0.000	25.4000
Long.	Y	0.575	Y	14593.899	0.000	25.4000
Vert. Up	Y	0.575	Y	14593.899	0.000	25.4000
Vert. Dn	Y	0.575	Y	14593.899	0.000	25.4000

Average Stiffness						
Horiz.	Y	0.575	Y	14593.899	0.000	25.4000
Long.	Y	0.575	Y	14593.899	0.000	25.4000
Vert. Up	Y	0.575	Y	14593.899	0.000	25.4000
Vert. Dn	Y	0.575	Y	14593.899	0.000	25.4000

SOIL PARAMETERS (CLAY)

Calculation Method : American Lifeline Alliance (ASCE 2001)
Soil Type : Stiff Clay
Pipe Direction : Horizontal

Parameters	Low	High	Average
Outside Diameter, D [mm]	406.40		
Depth to Centerline, H [mm]	2203.00		
Effective Unit Wt. above pipe [kg/m3]	1601.85	5290.00	3445.93
Total Unit Wt. below pipe [kg/m3]	1601.85	5290.00	3445.93
Dry Unit Wt. above pipe [kg/m3]	1601.85	1601.85	1601.85
Soil Cohesion, c [N/m2]	47880.00	47880.00	47880.00
Friction Angle, phi [deg]	0.00	0.00	0.00
Horizontal Yield Displacement, dp [mm]	40.64	40.64	40.64
Longitudinal Yield Displacement, dt [mm]	7.62	7.62	7.62
Vertical Up Yield Displacement, dqu [mm]	81.28	81.28	81.28
Vertical Dn Yield Displacement, dqd [mm]	81.28	81.28	81.28

Computed soil parameters (ASCE Method):

		Low	High	Average
Longitudinal	Adhesion alpha	0.00	0.00	0.00
	Pipe/Soil delta=f*phi [deg]	0.00	0.00	0.00
Horizontal	Nch	0.00	0.00	0.00
	Nqh	0.00	0.00	0.00
Vertical Up	Ncv	0.00	0.00	0.00
	Nqv	0.00	0.00	0.00
	Soil Weight on top Ws [N/m]	0.00	0.00	0.00
Vertical Down	Nc	0.00	0.00	0.00
	Nq	0.00	0.00	0.00
	Ngamma	0.00	0.00	0.00

L O A D S S U M M A R Y D A T A L I S T I N G

WAVE LOAD : WAVE 1

Wave Type : Stokes Load case : User 1

Water - Elevation : 0.00 mm
Depth : 4500.00 mm
Density : 1025.00 kg/m3

Wave - Height : 1022.00 mm
Period : 10.13 sec
Phase : 0.00 deg

Drag coefficient : 1.00
Inertia coefficient : 2.00

Direction - X= 1.000 Y= 0.000 Z= 0.000

Water Depth (mm)	Current Velocity (mm/s)	Marine Growth (mm)
0.00	440.00	0.00
2250.00	390.00	0.00
4500.00	310.00	0.00

L O A D S S U M M A R Y D A T A L I S T I N G

WAVE LOAD : WAVE 2

Wave Type : Stokes Load case : User 2

Water - Elevation : 0.00 mm
Depth : 4500.00 mm
Density : 1025.00 kg/m3

Wave - Height : 1022.00 mm
Period : 10.13 sec
Phase : 0.00 deg

Drag coefficient : 1.00
Inertia coefficient : 2.00

Direction - X= 0.000 Y= 1.000 Z= 0.000

Water Depth (mm)	Current Velocity (mm/s)	Marine Growth (mm)
0.00	440.00	0.00
2250.00	390.00	0.00
4500.00	310.00	0.00

S U P P O R T D A T A L I S T I N G

Point Name	Support Type	Support ID	Conn.to /Dir	Comp.Wt (kg)	Stiff.	Gap 1 (mm)	Gap 2 (mm)	Fric. Fact.	GapSet /#hgr	Preload (N)	Ld.Var	Size	Figure

Spring Manufacturer: Anvil/Grinnell
NOTE 1: Soil supports are present but not listed.
Gap 1 : V-stop,Guide-V=down, Linestop,Incline,Tie/link=backward, Guide-H=Left
Gap 2 : V-stop,Guide-V=Up , Linestop,Incline,Tie/link=forward , Guide-H=Right
Stiffness units for rotation support: N.m/deg , all others: N/mm

B E N D D A T A L I S T I N G

Point Name	Bend Type	Radius (mm)	Angle (deg)	OD (mm)	tnom (mm)	Material	Flan^ /Cuts	SIF in	SIF out	Analysis Set	Flexibility (K)	Pressure Case
B01	*Elbow	610L	2.2	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B02	*Elbow	610L	3.7	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B03	*Elbow	610L	5.3	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B04	*Elbow	610L	6.7	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B05	*Elbow	610L	8.2	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B06	*Elbow	610L	9.2	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B07	*Elbow	610L	3.5	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B08	*Elbow	610L	5.9	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B09	*Elbow	610L	8.2	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B10	*Elbow	610L	10.2	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
A22	*Elbow	610L	12.2	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None
B12	*Elbow	610L	14.0	406.4	9.7	5LX-X65	0/0	3.18	2.65	1	10.98	None

^ = Number of bend ends where either a flange or valve is within distance
(L/D) x Nominal diameter, where L/D is defined under Tools > Model options > Edit
* = Mid-point present
L = Long radius

C E N T E R O F G R A V I T Y R E P O R T

Description		Weight (kg)	X CoG (mm)	Y CoG (mm)	Z CoG (mm)
Valve	:	0.00	0.00	0.00	0.00
Support	:	0.00	0.00	0.00	0.00
Flange	:	0.00	0.00	0.00	0.00
Flexible Joint	:	0.00	0.00	0.00	0.00
Additional Weight	:	0.00	0.00	0.00	0.00
Pipes (Run, Bend, Tee, Reducer)	:	209622.14	1205909.6	-6155.03	0.00
PipeTot (Valve+Support+Flange+Flex. Jt.+Add. Wt.+Pipes)	:	209622.14	1205909.6	-6155.03	0.00
Insulation	:	494826.16	1324419.5	-6110.60	0.00
Cladding	:	0.00	0.00	0.00	0.00
Lining	:	0.00	0.00	0.00	0.00
Contents	:	19260.71	1205909.9	-6155.04	0.00
Beam	:	0.00	0.00	0.00	0.00
PipeTot + Ins.	:	704448.31	1289154.4	-6123.82	0.00
PipeTot + Ins. + Clad.	:	704448.31	1289154.4	-6123.82	0.00
PipeTot + Ins. + Clad. + Lin.	:	704448.31	1289154.4	-6123.82	0.00
PipeTot + Ins. + Clad. + Lin. + Cont.	:	723709.06	1286938.8	-6124.65	0.00
PipeTot + Beam	:	209622.14	1205909.6	-6155.03	0.00
PipeTot + Ins. + Beam	:	704448.31	1289154.4	-6123.82	0.00
PipeTot + Ins. + Clad. + Beam	:	704448.31	1289154.4	-6123.82	0.00
PipeTot + Ins. + Clad. + Lin. + Beam	:	704448.31	1289154.4	-6123.82	0.00
PipeTot + Ins. + Clad. + Lin. + Cont. + Beam	:	723709.06	1286938.8	-6124.65	0.00

NOTE: COG report only includes the currently visible beams and segments.
All pipe segments are included.
No beams present in the model.

A N A L Y S I S S U M M A R Y

Current model revision number : 43

Constant values used
- Acceleration due to gravity............... 9814.55985 mm/s2
- Density of water for specific gravity Cal.. 999.552 kg/m3
- Density of sea water...................... 999.552 kg/m3
- Density of ground water 999.552 kg/m3

Static - Analysis set number 1
- Date and Time of analysis .... Jan 25, 2020 3:53 PM
- Model Revision Number 43
- Number of load cases 5
- Load cases analyzed .... GR T1 T2 P1 P2
- Description .... Analysis Set No.1
- Gaps/Friction/Soil considered .... No
- Hanger design run .... No
- Cut short included .... No
- Thermal bowing included .... No
- Include Bourdon rotational effect ..... No
- Pipe radius for Bourdon calculation ... Mean
- Weight of contents included .... Yes
- Fluid density factor for contents 1.00
- Pressure stiffening case .... None
- Hot modulus case .... None
- Pressure Extension.................... Yes
- Soil Stiffness .... Low
- Water elevation for buoyancy loads .... Not considered
- Use corroded thickness in analysis .... No
- Rigid stiffness factor 1000.0
- Support rigid stiffness (translation) . 0.175100E+10 N/mm
- Support rigid stiffness (rotation) .... 0.135582E+11 N.m/deg
- Anchor rigid stiffness (translation) .. 0.175100E+10 N/mm
- Anchor rigid stiffness (rotation) ..... 0.135582E+11 N.m/deg
- Remove Lift-Off Supports .... No

D I S P L A C E M E N T S

Point name	Load combination	TRANSLATIONS (mm) X	Y	Z	ROTATIONS (deg) X	Y	Z
*** Segment A begin ***							
A00	Gravity{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Pressure 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.00	0.00	0.00	0.00	0.00	0.00
	GRTP1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	GRTP2{1}	0.00	0.00	0.00	0.00	0.00	0.00
+1	Gravity{1}	0.00	-6.71	0.00	0.00	0.00	-0.01
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.07	0.98	0.00	0.00	0.00	-0.01
	Pressure 1{1}	0.01	0.07	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.01	0.07	0.00	0.00	0.00	0.00
	GRTP1{1}	0.00	-6.64	0.00	0.00	0.00	-0.01
	GRTP2{1}	0.08	-5.66	0.00	0.00	0.00	-0.02
A01	Gravity{1}	0.00	-5.05	0.00	0.00	0.00	0.01
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.15	-4.13	0.00	0.00	0.00	-0.01
	Pressure 1{1}	0.01	-0.30	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.01	-0.30	0.00	0.00	0.00	0.00
	GRTP1{1}	0.01	-5.35	0.00	0.00	0.00	0.00
	GRTP2{1}	0.16	-9.48	0.00	0.00	0.00	-0.01
+1	Gravity{1}	0.00	-5.42	0.00	0.00	0.00	0.00
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.16	-1.17	0.00	0.00	0.00	0.04
	Pressure 1{1}	0.01	-0.09	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.01	-0.09	0.00	0.00	0.00	0.00
	GRTP1{1}	0.01	-5.51	0.00	0.00	0.00	0.00
	GRTP2{1}	0.17	-6.68	0.00	0.00	0.00	0.04
B01N	Gravity{1}	0.00	-5.37	0.00	0.00	0.00	0.00
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.02	9.63	0.00	0.00	0.00	0.00
	Pressure 1{1}	0.00	0.70	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.00	0.70	0.00	0.00	0.00	0.00
	GRTP1{1}	0.00	-4.68	0.00	0.00	0.00	0.00
	GRTP2{1}	0.02	4.96	0.00	0.00	0.00	0.00
+1	Gravity{1}	0.00	-5.37	0.00	0.00	0.00	0.00
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.02	9.63	0.00	0.00	0.00	0.00
	Pressure 1{1}	0.00	0.70	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.00	0.70	0.00	0.00	0.00	0.00
	GRTP1{1}	0.00	-4.68	0.00	0.00	0.00	0.00
	GRTP2{1}	0.02	4.96	0.00	0.00	0.00	0.00

D I S P L A C E M E N T S

Point name	Load combination	TRANSLATIONS (mm) X	Y	Z	ROTATIONS (deg) X	Y	Z
B12F	Gravity{1}	-0.02	-7.43	0.00	0.00	0.00	0.00
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.63	29.58	0.00	0.00	0.00	0.00
	Pressure 1{1}	0.05	2.15	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.05	2.15	0.00	0.00	0.00	0.00
	GRTP1{1}	0.03	-5.28	0.00	0.00	0.00	0.00
	GRTP2{1}	0.66	24.30	0.00	0.00	0.00	0.00
+1	Gravity{1}	0.04	-7.27	0.00	0.00	0.00	0.00
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	-1.57	-2.77	0.00	0.00	0.00	-0.09
	Pressure 1{1}	-0.11	-0.20	0.00	0.00	0.00	-0.01
	Pressure 2{1}	-0.11	-0.20	0.00	0.00	0.00	-0.01
	GRTP1{1}	-0.08	-7.47	0.00	0.00	0.00	0.00
	GRTP2{1}	-1.64	-10.24	0.00	0.00	0.00	-0.09

A25	Gravity{1}	0.04	-7.09	0.00	0.00	0.00	-0.01
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	-1.74	-17.59	0.00	0.00	0.00	0.06
	Pressure 1{1}	-0.13	-1.28	0.00	0.00	0.00	0.00
	Pressure 2{1}	-0.13	-1.28	0.00	0.00	0.00	0.00
	GRTP1{1}	-0.08	-8.37	0.00	0.00	0.00	-0.01
	GRTP2{1}	-1.82	-25.96	0.00	0.00	0.00	0.05
+1	Gravity{1}	0.02	-8.92	0.00	0.00	0.00	0.02
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	-0.86	3.99	0.00	0.00	0.00	0.03
	Pressure 1{1}	-0.06	0.29	0.00	0.00	0.00	0.00
	Pressure 2{1}	-0.06	0.29	0.00	0.00	0.00	0.00
	GRTP1{1}	-0.04	-8.63	0.00	0.00	0.00	0.02
	GRTP2{1}	-0.90	-4.64	0.00	0.00	0.00	0.05
A26	Gravity{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal 2{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Pressure 1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	Pressure 2{1}	0.00	0.00	0.00	0.00	0.00	0.00
	GRTP1{1}	0.00	0.00	0.00	0.00	0.00	0.00
	GRTP2{1}	0.00	0.00	0.00	0.00	0.00	0.00

*** Segment A end ***

G L O B A L F O R C E S & M O M E N T S

Point name	Load combination	FORCES (N) X	Y	Z	Result	MOMENTS (N.m) X	Y	Z	Result
*** Segment A begin ***									
A00	Gravity{1}	246	354	0	431	0	0	3998	3998
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1235090	-160	0	1235090	0	0	-1288	1288
	Pressure 1{1}	89660	-12	0	89660	0	0	-94	94
	Pressure 2{1}	89660	-12	0	89660	0	0	-94	94
	GRTP1{1}	89906	342	0	89907	0	0	3905	3905
	GRTP2{1}	1324996	182	0	1324996	0	0	2617	2617
+1 -	Gravity{1}	246	354	0	431	0	0	-2925	2925
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1235090	-160	0	1235090	0	0	1838	1838
	Pressure 1{1}	89660	-12	0	89660	0	0	133	133
	Pressure 2{1}	89660	-12	0	89660	0	0	133	133
	GRTP1{1}	89906	342	0	89907	0	0	-2792	2792
	GRTP2{1}	1324996	182	0	1324996	0	0	-954	954
+1 +	Gravity{1}	258	-220	0	339	0	0	-2925	2925
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1234639	168	0	1234639	0	0	1838	1838
	Pressure 1{1}	89628	12	0	89628	0	0	133	133
	Pressure 2{1}	89628	12	0	89628	0	0	133	133
	GRTP1{1}	89885	-208	0	89886	0	0	-2792	2792
	GRTP2{1}	1324525	-39	0	1324525	0	0	-954	954
A01 -	Gravity{1}	258	-220	0	339	0	0	1378	1378
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1234639	168	0	1234639	0	0	-1458	1458
	Pressure 1{1}	89628	12	0	89628	0	0	-106	106
	Pressure 2{1}	89628	12	0	89628	0	0	-106	106
	GRTP1{1}	89885	-208	0	89886	0	0	1273	1273
	GRTP2{1}	1324525	-39	0	1324525	0	0	-185	185
A01 +	Gravity{1}	125	125	0	177	0	0	1378	1378
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1233799	24159	0	1234036	0	0	-1458	1458
	Pressure 1{1}	89567	1754	0	89584	0	0	-106	106
	Pressure 2{1}	89567	1754	0	89584	0	0	-106	106
	GRTP1{1}	89692	1878	0	89711	0	0	1273	1273
	GRTP2{1}	1323491	26038	0	1323747	0	0	-185	185
+1 -	Gravity{1}	125	125	0	177	0	0	-507	507
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1233799	24159	0	1234036	0	0	-4227	4227
	Pressure 1{1}	89567	1754	0	89584	0	0	-307	307
	Pressure 2{1}	89567	1754	0	89584	0	0	-307	307

	GRTP1{1}	89692	1878	0	89711	0	0	-814	814
	GRTP2{1}	1323491	26038	0	1323747	0	0	-5041	5041

G L O B A L F O R C E S & M O M E N T S

Point name	Load combination	FORCES (N) X	Y	Z	Result	MOMENTS (N.m) X	Y	Z	Result
+1 +	Gravity{1}	3280	-760	0	3367	0	0	-5089	5089
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1116076	1103	0	1116077	0	0	10617	10617
	Pressure 1{1}	81021	80	0	81021	0	0	771	771
	Pressure 2{1}	81021	80	0	81021	0	0	771	771
	GRTP1{1}	84301	-680	0	84304	0	0	-4318	4318
	GRTP2{1}	1200377	423	0	1200377	0	0	6298	6298
A26	Gravity{1}	3280	-760	0	3367	0	0	7355	7355
	Thermal 1{1}	0	0	0	0	0	0	0	0
	Thermal 2{1}	1116076	1103	0	1116077	0	0	-7448	7448
	Pressure 1{1}	81021	80	0	81021	0	0	-541	541
	Pressure 2{1}	81021	80	0	81021	0	0	-541	541
	GRTP1{1}	84301	-680	0	84304	0	0	6815	6815
	GRTP2{1}	1200377	423	0	1200377	0	0	-633	633

*** Segment A end ***

G E N E R A L P I P E S T R E S S R E P O R T

(Stress in N/mm2)

Point name	Load combination	Hoop Stress	Longitudinal Max	Longitudinal Min	Shear Stress	Principal Max	Principal Min	Total Stress	Loc
*** Segment A begin ***									
A00	SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	3.39	-3.43	0.00	3.39	-3.43	1.72	180
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	-101.07	-103.27	0.00	0.00	-103.27	51.63	0
	Pressure 1{1}	40.22	11.35	11.19	0.00	40.22	11.19	20.11	180
	Pressure 2{1}	40.22	11.35	11.19	0.00	40.22	11.19	20.11	180
	GRTP1{1}	40.22	14.58	7.91	0.00	40.22	7.91	20.11	0
	GRTP2{1}	40.22	-88.69	-93.16	0.00	40.22	-93.16	66.69	180
+1 -	SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	2.48	-2.52	0.00	2.48	-2.52	1.26	0
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	-100.60	-103.74	0.00	0.00	-103.74	51.87	180
	Pressure 1{1}	40.22	11.38	11.15	0.00	40.22	11.15	20.11	0
	Pressure 2{1}	40.22	11.38	11.15	0.00	40.22	11.15	20.11	0
	GRTP1{1}	40.22	13.63	8.86	0.00	40.22	8.86	20.11	180
	GRTP2{1}	40.22	-90.11	-91.74	0.00	40.22	-91.74	65.98	0
+1 +	SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Pressure 1{1}	40.22	18.68	18.68	0.00	40.22	18.68	20.11	270
	Pressure 2{1}	40.22	18.68	18.68	0.00	40.22	18.68	20.11	270
	GRTP1{1}	40.22	13.63	8.86	0.00	40.22	8.86	20.11	180
	GRTP2{1}	40.22	-90.07	-91.70	0.00	40.22	-91.70	65.96	0
A01	SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	1.16	-1.20	0.00	1.16	-1.20	0.60	180
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	-100.89	-103.38	0.00	0.00	-103.38	51.69	0
	Pressure 1{1}	40.22	11.36	11.18	0.00	40.22	11.18	20.11	180
	Pressure 2{1}	40.22	11.36	11.18	0.00	40.22	11.18	20.11	180
	GRTP1{1}	40.22	12.33	10.16	0.00	40.22	10.16	20.11	0
	GRTP2{1}	40.22	-90.73	-91.04	0.00	40.22	-91.04	65.63	0
+1 -	SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	0.42	-0.44	0.00	0.42	-0.44	0.22	0
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	-98.47	-105.69	0.00	0.00	-105.69	52.85	0

Point name	Load combination	Hoop Stress	Longitudinal Max	Longitudinal Min	Shear Stress	Principal Max	Principal Min	Total Stress	Loc
	Pressure 1{1}	40.22	11.53	11.01	0.00	40.22	11.01	20.11	180
	Pressure 2{1}	40.22	11.53	11.01	0.00	40.22	11.01	20.11	180
	GRTP1{1}	40.22	11.96	10.57	0.00	40.22	10.57	20.11	180
	GRTP2{1}	40.22	-86.51	-95.12	0.00	40.22	-95.12	67.67	0
+1	+ SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270

G E N E R A L P I P E S T R E S S R E P O R T

(Stress in N/mm2)

Point name	Load combination	Hoop Stress	Longitudinal Max	Longitudinal Min	Shear Stress	Principal Max	Principal Min	Total Stress	Loc
	Pressure 1{1}	40.22	12.36	11.88	0.00	40.22	11.88	20.11	180
	Pressure 2{1}	40.22	12.36	11.88	0.00	40.22	11.88	20.11	180
	GRTP1{1}	40.22	13.63	11.14	0.00	40.22	11.14	20.11	180
	GRTP2{1}	40.22	-73.52	-82.63	0.00	40.22	-82.63	61.43	0
+1	+ SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Pressure 1{1}	40.22	18.68	18.68	0.00	40.22	18.68	20.11	270
	Pressure 2{1}	40.22	18.68	18.68	0.00	40.22	18.68	20.11	270
	GRTP1{1}	40.22	12.33	11.55	0.00	40.22	11.55	20.11	180
	GRTP2{1}	40.22	-78.00	-80.86	0.00	40.22	-80.86	60.54	0
A25	SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	1.10	-1.32	0.00	1.10	-1.32	0.66	180
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	-85.02	-97.71	0.00	0.00	-97.71	48.86	0
	Pressure 1{1}	40.22	12.51	11.59	0.00	40.22	11.59	20.11	180
	Pressure 2{1}	40.22	12.51	11.59	0.00	40.22	11.59	20.11	180
	GRTP1{1}	40.22	12.69	11.19	0.00	40.22	11.19	20.11	0
	GRTP2{1}	40.22	-73.84	-85.02	0.00	40.22	-85.02	62.62	0
+1	- SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	4.07	-4.63	0.00	4.07	-4.63	2.31	0
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	-82.90	-101.03	0.00	0.00	-101.03	50.51	180
	Pressure 1{1}	40.22	12.66	11.35	0.00	40.22	11.35	20.11	0
	Pressure 2{1}	40.22	12.66	11.35	0.00	40.22	11.35	20.11	0
	GRTP1{1}	40.22	15.41	8.04	0.00	40.22	8.04	20.11	180
	GRTP2{1}	40.22	-74.86	-85.61	0.00	40.22	-85.61	62.92	180
+1	+ SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Pressure 1{1}	40.22	18.68	18.68	0.00	40.22	18.68	20.11	270
	Pressure 2{1}	40.22	18.68	18.68	0.00	40.22	18.68	20.11	270
	GRTP1{1}	40.22	15.40	8.02	0.00	40.22	8.02	20.11	180
	GRTP2{1}	40.22	-75.24	-85.99	0.00	40.22	-85.99	63.11	180
A26	SIFI= 1.00 SIFO= 1.00								
	Gravity{1}	0.00	6.01	-6.55	0.00	6.01	-6.55	3.28	180
	Thermal 1{1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270
	Thermal 2{1}	0.00	-85.96	-98.68	0.00	0.00	-98.68	49.34	0
	Pressure 1{1}	40.22	12.44	11.52	0.00	40.22	11.52	20.11	180
	Pressure 2{1}	40.22	12.44	11.52	0.00	40.22	11.52	20.11	180
	GRTP1{1}	40.22	17.53	5.89	0.00	40.22	5.89	20.11	0
	GRTP2{1}	40.22	-80.07	-81.16	0.00	40.22	-81.16	60.69	0

*** Segment A end ***

R E S U L T   S U M M A R Y

Maximum displacements (mm)

```
Maximum X :      0.66      Point : A24        Load Comb.: GRTP2{1}
Maximum Y :     24.31      Point : B12 M      Load Comb.: Thermal 2{1}
Max. total:     24.31      Point : B12 M      Load Comb.: Thermal 2{1}
```

Maximum rotations (deg)

```
Maximum Z :     -0.09      Point : B12F       Load Comb.: GRTP2{1}
Max. total:      0.09      Point : B12F       Load Comb.: GRTP2{1}
```

Maximum restraint forces (N)

```
Maximum X :  -1325073      Point : A00        Load Comb.: GRTP2{1}
Maximum Y :    -23007      Point : A26        Load Comb.: GRTP2{1}
Max. total:   1325185      Point : A00        Load Comb.: GRTP2{1}
```

Maximum restraint moments (N.m)

```
Maximum Z :     -7448      Point : A26        Load Comb.: Thermal 2{1}
Max. total:      7448      Point : A26        Load Comb.: Thermal 2{1}
```


R E S U L T   S U M M A R Y

Maximum Hoop stress

```
Point            : A01 M
Stress    N/mm2  : 40.22
Allowable N/mm2  : 270.00
Ratio            : 0.15
Load combination : Max P{1}
```

Maximum Longitudinal stress

```
Point            : A01 M
Stress    N/mm2  : 116.90
Allowable N/mm2  : 360.00
Ratio            : 0.32
Load combination : GRTP2{1}
```

Maximum Combined stress

```
Point            : A01 M
Stress    N/mm2  : 139.18
Allowable N/mm2  : 405.00
Ratio            : 0.34
Load combination : GRTP2{1}
```

BIODATA PENULIS

Anit Siska Melinda, putri kelahiran Mataram, 1 Mei 1998 merupakan anak sulung dari 2 bersaudara yang telah tumbuh atas jasa dan usaha dari, Bapak Endy Pramadi dan Ibu Tina Suheryani. Penulis mengenal pendidikan formal pertamanya dari SDN 13 pada tahun 2004. Pada tahun 2010 penulis melanjutkan pendidikan di SMPN 02 Mataram dan lulus pada tahun 2013 yang kemudian memilih SMAN 01 Mataram sebagai sekolah selanjutnya. Selama bersekolah, penulis aktif mengikuti kegiatan dan ekstrakulikuler seperti Paskibra dan Pecinta Alam Sekolah. Dengan karakteristik penulis yang senang untuk berkumpul dan berdiskusi, saat menjalani masa perkuliahan di Institut Teknologi Sepuluh Nopember (2016) pun penulis tetap aktif untuk mencari sarana pengembangan diri yang sesuai dengan minat & kepribadian. ITS Billiard menjadi organisasi pertama yang diikuti oleh penulis dengan jabatan sebagai sekreratis umum pada periode 2017/2018 dan Ketua Departemen *Public Relation* untuk periode singkat Tahun 2018. Di tahun yang sama pula penulis juga mengikuti organisasi CLICK ITS sebagai staff Departemen Eksebisi periode 2017/2018 dan organisasi Lembaga Minat Bakat sebagai staff Departemen Eksternal sekaligus menjadi ketua pelaksana kegiatan Anjangsana Minat Bakat 2018. Di tahun selanjutnya, penulis memilih HIMATEKLA ITS sebagai tempat persinggahan untuk pengembangan diri. Menjabat sebagai staff kestari dan staff pelatihan untuk BSO OORC, memberikan pengalaman yang bervariasi bagi penulis untuk belajar. Penulis juga pernah mengikuti kepanitiaan GERIGI ITS 2017 sebagai fasilititator (kestari) serta beberapa pengalaman kepanitiaan lainnya yang tidak bisa disebutkan satu persatu. Berkuliah di Teknik Kelautan ITS memberikan kesempatan bagi penulis untuk dapat memiliki pengalaman melaksanakan kerja praktik di PT. Rekayasa Industri pada tahun 2019. PT. Rekayasa Industri merupakan sarana yang tepat bagi penulis untuk mengenal dan menekuni bidang *pipeline* maupun *offshore operation.*

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