TESIS (RC-142501)

PENILAIAN APLIKASI PEMBEBANAN TERHADAP PARAMETER MATERIAL SEDIMEN DI DAERAH HILIR DAN MUARA SUNGAI BENGAWAN SOLO

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PENILAIAN APLIKASI PEMBEBANAN TERHADAP PARAMETER MATERIAL SEDIMEN DI DAERAH HILIR DAN MUARA SUNGAI BENGAWAN SOLO

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ABSTRAK

Sungai Bengawan Solo mengalami permasalahan yang diakibatkan oleh erosi dan deposisi sedimen. Ketidakseimbangan antara erosi dan deposisi menyebabkan sedimen berlebih di atas dasar sungai dan selanjutnya mengakibatkan banjir dan pembentukan *sandbar*. Satu solusi usulan untuk mengatasi permasalah sedimen berlebih di sungai Bengawan Solo adalah pengerukan yang mempunyai dampak negatif bagi lingkungan. Oleh karena itu diperlukan tindakan yang penuh perhatian serta memerlukan pengetahuan tentang parameter sedimen yang terdeposisi. Pengetahuan tentang parameter sedimen yang terdeposisi, seperti parameter fisik dan kuat geser, didapatkan melalui percobaan di laboratorium yang meliputi tes parameter fisik, tes konsolidasi dan test geser langsung. Dari hasil yang diperoleh, material sedimen dikelompokkan menjadi sedimen pasir yang ditemukan di daerah hilir dan sedimen lempung yang ditemukan di daerah muara. Distribusi parameter sedimen berdasarkan kedalaman adalah bervariasi yang disebabkan oleh erosi dan deposisi yang terjadi secara berulang. Sementara itu, distribusi parameter sedimen berdasarkan lokasi adalah sesuai dengan jenis tanah yang disebabkan oleh sifat dan perilaku jenis tanah dari material sedimen itu sendiri. Erosi lebih dominan terjadi di Lokasi 1, 2 dan 4, sementara deposisi lebih dominan di Lokasi 3 dan 5. Kuat geser sedimen mengalami perubahan yang disebabkan oleh perubahan aplikasi pembebanan yang berupa beban sendiri dari lapisan sedimen itu sendiri. Sebagian besar sedimen mempunyai kuat geser yang lebih besar dari batas penggunaan metode pengerukan dengan kapasitas kecil (>20 kPa), sehingga memerlukan metode pengerukan dengan kapasitas besar (*grab dredger*) untuk mengeruk sedimen berlebih. Di masa depan, jika diinginkan untuk menggunakan metode pengerukan dengan kapasitas kecil seperti *ploughing* atau *plain suction dredger*, sedimen harus mempunyai kuat geser kurang dari 20 kN/m^2 dengan berat volume kering berkisar antara 10 kN/m^3 hingga 13 kN/m^3.

Kata kunci: aplikasi pembebanan, kuat geser, pengerukan, sedimen, sungai Bengawan Solo,

ASSESSMENT OF LOADING APPLICATION ON SEDIMENT MATERIAL PROPERTIES OF BENGAWAN SOLO RIVER IN DOWNSTREAM AND ESTUARY

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ABSTRACT

Bengawan Solo River undergoes river stream problems which are inflicted by erosion and deposition of sediment. Unbalance between erosion and deposition leads to excessive sediment on top of river bed and further results in flooding and sandbar formation. One proposed solution to solve excessive sediment problem at Bengawan Solo River is dredging which has negative effect on the environment. Hence, considerate action is necessary which requires knowledge of deposited sediment properties. The knowledge of deposited sediment, such as physical properties and shear strength, was obtained by doing laboratory test including physical properties test, consolidation test and direct shear test. From the results, sediment material is broadly grouped into sand sediment which found at downstream areas and clay sediment which found at estuary area. The distribution of sediment properties based on the depth is varies due to subsequent erosion and deposition over times. Meanwhile, the distribution of sediment properties based on the location of sediment sampling is appropriate with the soil type which caused by the behavior of soil type of sediment material. Erosion is more dominant at Location 1, 2 and 4, while deposition is more dominant at Location 3 and 5. Shear strength of sediment experiences alteration which is caused by the alteration of loading application in the form of self-weight of sediment layer itself. Most of sediment has shear strength greater than the limitation of utilization of small capacity dredging method (> 20 kPa) and thus, requires dredging method with large capacity (grab dredger) to remove the excessive sediment. In the future, if preferable to use dredging method with small capacity such as ploughing or plain suction dredger, the sediment should has shear strength less than 20 kN/m^2 with dry unit weight range from 10 kN/m^3 to 13 kN/m^3.

Keywords: Bengawan Solo River, dredging, loading application, sediment, shear strength

PREFACE

All praises to The Almighty Allah SWT for giving His grace and blessings so that I am able to accomplish the thesis entitled "Assessment of Loading Application on Sediment Material Properties of Bengawan Solo River in Downstream and Estuary", as one requirement to obtain Master's degree.

I would like to express my sincere gratitude and appreciation to my Professors: Dr. Ir. Ria Asih Aryani Soemitro, M.Eng., Dr. Toshifumi Mukunoki and Dr. Dwa Desa Warnana, S.Si. M.Sc. for their endless guidance, support and encouragement. I obtain precious knowledge, experience and advice thanks to them.

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This thesis is still far from perfection. Nevertheless, I hope it may contribute in science, especially Geotechnical Engineering, and provide benefits for the readers.

Surabaya, January 2017

Author,

Fatin Adriati

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  "Assessment to the River Embankment Stability with Respect to Rainfall and Seismic – Induced River Embankment Failures" - 2014

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  "Sediment Transport Evaluation on Bengawan Solo River (downstream and estuary) to Minimize Sedimentation and Flood Combining Effect on Nearby Infrastructure"

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CHAPTER 1
INTRODUCTION

1.1 Research Background

Bengawan Solo River, as one of the most important river stream in Java Island, Indonesia, undergoes river stream problems due to the complication of its river networks. Generally, river stream problems are inflicted by flow discharge, erosion and deposition of sediment. In fact, it is normal for river to experience erosion and deposition of sediment over times. It becomes not normal which indicating the occurrence of river stream problems when there is unbalance between erosion and deposition. Merely river with dynamic equilibrium, which is the general balance between erosion and deposition, could minimize the occurrence of river stream problems (Dolores River Dialogue, 2013).

Deforestation in upstream area is one situation that triggers unbalance between erosion and deposition of sediment. Deforestation causes erosion in the river basin and hence the eroded material is brought by river stream. Restrepo et al (2015) confirmed it and was able to estimate the amount of sediment produced by deforestation in tropical drainage basins. Higher amount of eroded material on river stream and in conjunction with low river stream, which is below critical shear stress, increase the deposition rates especially at downstream and estuary area. Continuous and adequately high deposition rate leads to excessive deposition of sediment material. Further, the filing in of the river bed with sediment material due to excessive deposition leads to excessive sediment. The illustration of excessive sediment on river bed is presented in Figure 1.1.

The outcome of excessive sediment material on river bed in downstream area is different with estuary area. Nevertheless, both bring problems not only for natural environment but also human built environment. The immediate consequence of excessive sediment in downstream area is a decline in river channel capacity. When the river effectively having lost its capacity to evacuate flood water, significant risk of flooding is increase (Zahar, 2008). Meanwhile, excessive sediment in estuary area causes frequent river channel blockage which leads to the displacement of river mouth and river mouth branching (distributary). It results in the forming of delta or sandbar at the river mouth (Sukardi et al, 2013).

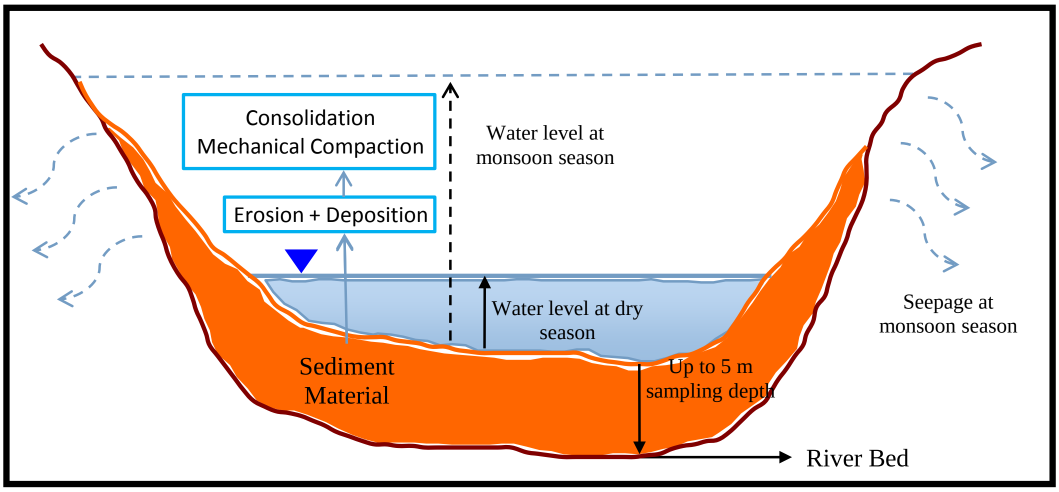


Figure 1.1 Illustration of excessive sediment on river bed

Research on sediment material has been done by some researchers. Harsini et al (2007) described the geotechnical properties of clay sediment. It is said that the geotechnical properties are affected by tidal, river flow current and the condition of sedimentary environment such as the geological features. This study supported the assumption of current research where different area has different geotechnical properties of sediment. However, this study only focused on clay sediment while in reality sediment material can be composed not only from clay but also sand and even composition of clay and sand. Ahiarakwem et al (2014) also described the geotechnical properties of sediment and concluded that sediment of Njaba River is suitable for sub-base and base-coarse in road construction and also suitable to be used in concrete. Although this study cannot be applied generally, at least it gave an idea regarding the utilization of dredged sediment material.

Other researcher, Madhyannapu et al (2008), Ganesalingam et al (2013) and Guo et al (2015) investigated the consolidation process and compressibility of deposited sediment. Madhyannapu et al (2008) found that the compressibility of deposited sediment appears to be dependent on the source material, sedimentation, compaction procedures and stress range. Meanwhile, Ganesalingam et al (2013) more focused on the settling behavior of particles and variation of depth which influenced the consolidation properties of deposited sediment. Guo et al (2015) explained about sediment settlement and consolidation mechanism which affected by initial sediment concentration and initial settlement height. Guo et al (2015) concluded that the settlement and consolidation mechanism divided into three different stages which are initial free settlement, hindered settlement and self-weight consolidation settlement. Guo et al (2015) also found that self-weight load of deposited sediment is linearly distributed in settlement direction. The previous three studies explained the process which experienced by deposited sediment and its affecting factors. Different with current research which discussed the shear strength of sediment material, the previous three studies only focused on the consolidation process. Nevertheless, the previous three studies confirmed that water level of river as one important point in current research is one of the affecting factors of consolidation process.

Besides consolidation process, deposited sediment also experienced mechanical compaction as investigated by Nygard et al (2004) and Brain et al (2011). Nygard et al (2004) investigated how diagenesis affects the hydro-mechanical properties and compaction behavior of argillaeous sediment and found that chemical diagenesis is more influence than mechanical compaction and burial depth. Meanwhile, Brain et al (2011) investigated the compression behavior of minerogenic low energy intertidal sediment and concluded that structural variability decrease with application of higher effective stress. The previous studies indicated alteration on sediment material properties either from consolidation and mechanical compaction process yet did not explain more about the alteration of shear strength of sediment material as the result of consolidation and mechanical compaction process which discussed in current research.

Other than research on sediment, research on Bengawan Solo River also has been done. Soemitro et al (2015) investigated the differences between quantity of sediment at each different point of water depth on dry and monsoon season and concluded that sediment load concentrations around surface level is lower than level below which indicated that sediment load concentration is affected by water depth. Maulana et al (2016) investigated differences between quantity of sediment concentration affected by river water current during dry and monsoon season. Maulana et al (2016) found that sediment concentration and current velocities shows linear correlation. The previous studies focused on suspended sediment of Bengawan Solo River in term of sediment transport of river engineering. Meanwhile, the current research focused on sediment material on top of river bed of Bengawan Solo River in term of geotechnical engineering.

When summarized, the previous studies focused on two conditions. First is the condition when deposited sediment is the part of river environment, experiencing consolidation and mechanical compaction processes. Second is the condition when deposited sediment no longer as part of river environment, the utilization of dredged sediment material. The previous studies did not investigate and explain the middle condition when deposited sediment is removed which associated with the shear strength of deposited sediment. Sediment removal is discussed in current research as it is one proposed solutions to solve the problem of excessive sediment material on river bed at Bengawan Solo River.

Practically, sediment removal by dredging has been done at Bengawan Solo River. Nevertheless, the dredging method which was used is still conventional by doing excavation using human power. It was not an effective method for such a long river with approximately 600 km in length. In-effectiveness of dredging using human power is influenced by the condition of river and the condition of sediment material on top of river bed. When monsoon season the level of river water is relative high. The high water level complicates the dredging application because the worker has to dive to reach the deposited sediment layer and it is very dangerous too. Meanwhile at dry season the level of river water is relative low. The low water level simplifies the worker to reach the deposited sediment layer and to dredge it. However, the low water level leads to denser deposited sediment material on top of river bed which unable to be dredged by human power.

Aside from difficulties of dredging application, dredging has negative effect on the environment at and around the site of operation (Nielsen et al, 2015; Jones et al, 2016). Hence, considerate action is necessary before doing so. The considerate action requires knowledge of deposited sediment material. The knowledge of deposited material refers to the physical properties and shear strength of sediment material. The knowledge of deposited material, especially shear strength of sediment, is an indicator the necessity and the ease of sediment removal.

As implied by previous research (Nygard et al, 2004; Madhyannapu et al, 2008; Brain et al, 2011; Ganesalingam et al, 2013; Guo et al, 2015), physical properties and shear strength of deposited sediment material is determined by consolidation and mechanical compaction process as part of deposition phenomena. Both processes are affected by sediment self-weight, deposition rate, suspended sediment concentration and fall velocity which related to each other. And all of the factors are influenced by the level of river water which depends on the weather condition and is greatly varies due to the great differences of rain fall rate and temperature during dry and monsoon season. By understanding physical properties and shear strength of sediment material, the scenario of sediment removal can be determined effectively. Therefore, the research on assessment of loading application of sediment material properties in downstream and estuary at Bengawan Solo River is conducted.

1.2 Research Objectives

The research aims to assess loading application on sediment material properties in downstream and estuary at Bengawan Solo River. By understanding loading application on sediment material properties in downstream and estuary at Bengawan Solo River, the necessity of sediment removal by dredging and the dredging method is able to be determined. Therefore, in order to achieve the aims the following objectives are conducted as follows:

a. Understand the physical properties of sediment material at Bengawan Solo River and distinguish it based on the area, downstream and estuary area
b. Understand the relation between properties of sediment material at Bengawan Solo River and its sampling location
c. Understand the erosion and deposition phenomena experienced by sediment material at Bengawan Solo River

d. Understand the shear strength of sediment material at Bengawan Solo River

The results of current research are expected to be the basis for estimating the necessity of sediment removal and the determination of dredging method. In the future by using the results, such as consolidation test result, are expected to estimate the sediment removal schedule.

1.3 Scope of Research

The current research focused on deposited sediment material in term of geotechnical engineering. Hence, the sediment transport is not discussed in detail but only critical shear stress of sediment material on top of river bed is discussed. The critical shear stress of sediment material is used to determine whether sediment material is able to be eroded by river stream naturally. In current research, determination of features of river such as river depth, sectional area of river and flow velocity is based on calculation using bathimetry map. In order to understand more regarding the influence of the features of each location toward physical properties and shear strength of sediment material accurately, further investigations in the site is recommended.

CHAPTER 2
LITERATURE STUDY

2.1 Relation between Sampling Location and Properties of Sediment Material

The study location where sediment material was obtained is along Bengawan Solo River, start from Kanor village, Bojonegoro city, East Java Province, until estuary area at Ujung pangkah village, Gresik city, East Java Province, Indonesia. The map of study location is presented in Figure 2.1 with five points were selected as the location of sediment material sampling. Details and cross-section of each sampling locations is presented in Appendix A. The five points are classified into downstream area and estuary area with coordinate of each location as shown in Table 2.1.

Table 2.1 Coordinate of Study Location

Number of Location	Downstream Area			Number of Location	Estuary Area		
	Coordinate of Location		Location Name		Coordinate of Location		Location Name
1	Northing	9216204.94	Kanorejo, Tuban	5	Northing	9236251.17	Pangkah wetan, Ujung pangkah, Gresik
	Easting	612270.29					
2	Northing	9215355.04	Bedahan, Babat, Lamongan				
	Easting	628849.66					
3	Northing	9227448.35	Plangwot, Lamongan		Easting	672875.72	
	Easting	641388.06					
4	Northing	9225818.24	Sugihwaras, Lamongan				
	Easting	657896.22					

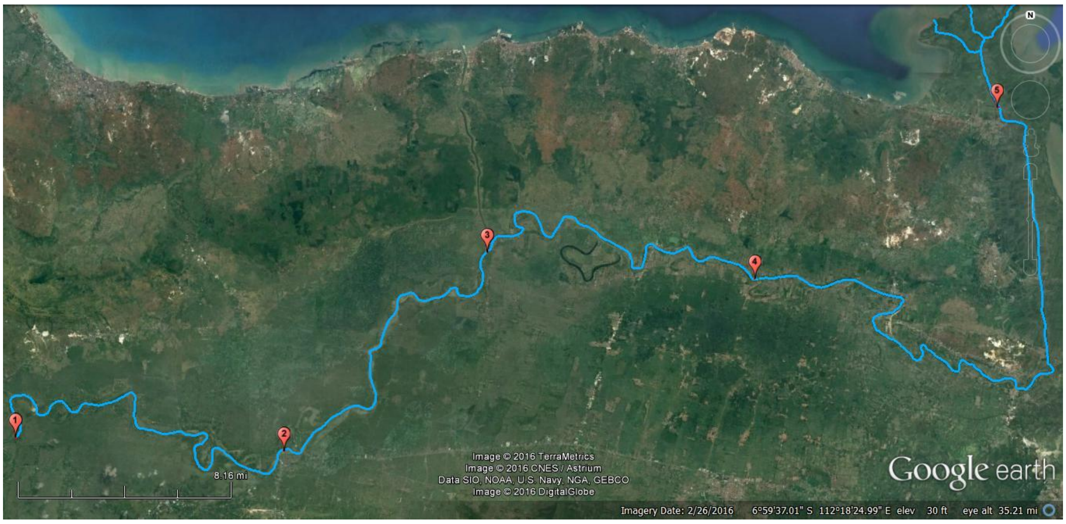
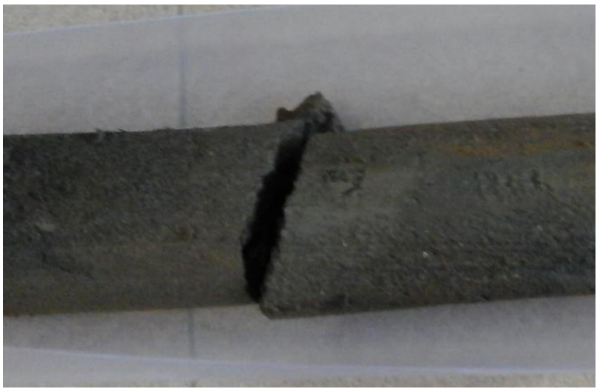
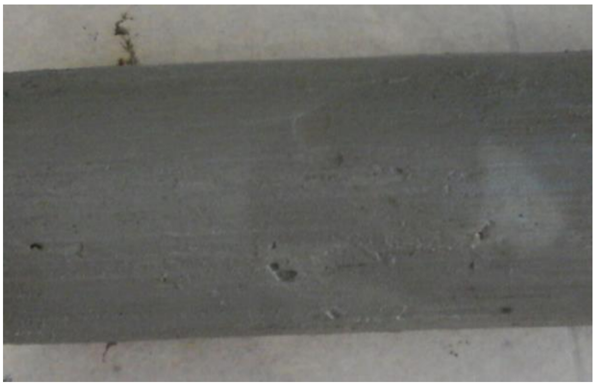


Figure 2.1 Locations of sediment material sampling at Bengawan Solo River (Source: Google Earth)

Sediment material deposited in the study locations is approximately 5 m in thickness which measured from river bed to the surface of sediment material layer. Sediment as material carried by streams and deposited on river bed can be composed of particles range in size either of fine materials, mostly silts or clays, or larger material, such as sand, which vary in specific gravity and vary in mineral composition. It is seen from the grayish color of sediment material which obtained. There is sediment material composed of sand particles and there is sediment material composed of clay particle as presented in Figure 2.2.



(a)



(b)

Figure 2.2 Sediment material (a) sandy sediment (b) clayey sediment

Harsini et al (2007) merely investigated the geotechnical properties of clay sediment, including the shear strength. Meanwhile, in current research there is sand sediment. Therefore, through current research the behavior of sand sediment and clay sediment is obtained and distinguished. Harsini et al (2007) concluded that geotechnical properties of sediment material are influenced by the condition of sedimentary environment. Then, in current research the relation between the condition of sampling location and the geotechnical properties of sediment material is conducted too. In case Harsini et al (2007) described sedimentary environment as geological features such as the mineralogy of sediment material, which determined the formation of sediment. Different with previous study, the sedimentary environment in current research is described as the condition of river, such as the width of river channel, the gradient of base surface and the morphology of river. For example the condition of river which has significant differences is downstream area and estuary area.

2.2 Erosion and Deposition Experienced by Sediment

Erosion and deposition of sediment particles on top of river bed is natural phenomena which determined by various complex natural processes and human activities (Suif et al, 2016). Among erosion and deposition, some researchers (Nygard et al, 2004; Madhyannapu et al, 2008; Brain et al, 2011; Ganesalingam et al, 2013; Guo et al, 2015) more interested to investigate deposition phenomena, especially consolidation process and mechanical compation. Deposition, which is related to sedimentation, defined as the process where particulate matter carried from its point of origin by either natural or human enhanced process is deposited elsewhere on land surfaces or in water bodies. If the stream velocity and turbulence fall below the values needed to keep particles in suspension or moving with the bed load, then the particles will settle (Mitchel and Soga, 2005).

In order to investigate deposited sediment settlement and consolidation mechanism, Guo et al (2015) conducted an experimental using a settlement column. Guo et al (2015) divided deposition of sediment material into three different stages. The three different stages are initial free settlement, hindered settlement and self-weight consolidation stages, where the status of sediment particles changed continuously. During self-weight consolidation settlement stages, the effective stress further develops, intensifying the compression of consolidation process which induced by the self-weight load of sediment material.

The self-weight of sediment material is affected by initial sediment concentration and initial settlement height.

In case Guo et al (2015) focused on the whole process of deposition, Madhyannapu et al (2008) and Ganesalingam et al (2013) preferred to investigate the consolidation stages. Madhyannapu et al (2008) simulated the natural sedimentation and consolidation process. Madhyannapu et al (2013) found that the compressibility of deposited sediment appears to be dependent on the source material, sedimentation, compaction procedures and stress range. Meanwhile, Ganesalingam et al (2013) investigated the self-weight consolidation in reclamation. Ganesalingam et al (2013) focused on the settling behavior of particles and the variation of depth on consolidation properties of sediment. Ganesalingam et al (2013) concluded that the nature of soil structure formed depending on the settlement behavior of particles and further influenced the consolidation properties of deposited sediment and the homogeneity of final sediment.

Another theory said instead of self-weight consolidation settlement stage, the final stage of deposition is autocompaction process. Massey et al (2006) defined autocompaction as process where sediment (such as minerogenic fines and peat) undergo a post-depositional reduction in volume as a result of the weight of overlying sediments, the downward movement being due to the cumulative compression of all the sediment below the level in question. Similarity of both theories is the compression from the weight of overlying sediment which can be regarded as mechanical loading or mechanical compaction. Mechanical compaction changes because effective stress changes due to accumulation of sediment and dissipation of fluid pore pressure. Nygard et al (2004) confirmed that reduction in porosity in the upper 1000 m of sediment or shallow depth is predominantly mechanical due to weight of overlying sediment.

Nygard et al (2004) investigated how diagenesis affects the hydro-mechanical properties and compaction behavior of argillaeous sediment. Nygard et al (2004) focused on the effect of mechanical loading and chemical process on changes in porosity, permeability, compressibility, strength and effective horizontal stress. Nygard et al (2004) then concluded that chemical diagenesis is more influence than mechanical compaction and burial depth on sediment properties and behavior. Meanwhile, Brain et al (2011) investigated the compression behavior of minerogenic low energy intertidal sediment and found that structural variability decrease with application of higher effective stress.

When summarized from previous studies, the mechanism of deposition phenomena especially consolidation and mechanical compaction process is obtained. At first, deposited sediment material generally has high void ratio, high compressibility and high moisture content (Guo et al, 2015) which are the nature of loose and soft sediment material. As time passed, due to consolidation and mechanical compaction process, sediment material properties change. It turns from loose and soft sediment material into dense and stiff sediment material. Consolidation and mechanical compaction process changes particle orientation and pore size distribution with associated decrease in permeability (Nygard et al, 2004). The soil skeleton and the pore fluid are compressible while the solids are incompressible, or in others word both soil frame and water deform while soil particle does not deform (Jeng and Seymour, 1997). Decreasing pore space influences volumetric and elevation of sediment material which further increase the density associated with effective stress (Brain et al, 2011). Smaller void ratio means more compacted material and lead the river bed to be more resistance to erosion. If further deposition occurs in the next time step, a new sediment material layer is formed (Govindaraju, 1999) and it is the beginning of excessive sediment on river bed.

Apart of the mechanism of deposition phenomena, from previous studies the affecting factors of deposition is also summarized. Due to the self-weight of sediment material, consolidation and mechanical compaction begins and sediment material properties start to change. The self-weight of sediment material is strongly affected by:

a. Initial thickness of sediment material layer on top of river bed and configuration overlying and underlying lithologies
b. Initial sediment bulk density
c. Permeability of sediment layer which determined by particles composition and sizes, content of organic material, salinity and water temperature

In addition of self-weight of sediment material on top of river bed, overall deposition process is also influenced by deposition rates, suspended sediment concentration and fall velocity. The three affecting factors are related to each other, for example where more rapid deposition rates from denser suspension creates initially denser structure of sediment material. Rapid deposition rate from denser suspension indicates that deposition rate is affected by initial suspended sediment concentration. Aside from suspended sediment concentration, deposition rate is also affected by initial settlement height simultaneously. For the same initial settlement height, deposition process with a lower initial sediment concentration is faster than that with a higher initial sediment concentration. Meanwhile, for the same initial sediment concentration, consolidation ratio decrease and deposition process slows with the increase of the initial settlement height (Guo et al, 2015).

Same as deposition rates, fall velocity is affected by initial suspended sediment concentration. Fall velocity of a single particle is modified by the presence of other particles. Experiments with uniform suspensions of sediment and fluid have shown that the fall velocity is strongly reduced with respect to that of single particles, when the sediment concentration is large. This effect is known as hindered settling. Other than that, also in term of fall velocity, sand particles with higher sediment rates are concentrated at the bottom part while clay particles are in the upper part.

Sediment concentration as quantity of sediment transported by a stream is a function of stream discharge, soil and land-cover features, land-use activities, weather condition and many other factors. Staub (2000) said that during dry season, the amount of suspended transported decrease while during wet season or monsoon season, the amount of suspended sediment transported increase. Staub (2000) also said that during wet season, the sediment material are coarser grained than during dry season. When sediment concentration is a function of weather condition, so is initial settlement height. Initial settlement height strongly relates to water level of river which varies due to weather condition. During wet season, water level of river increase and has higher initial settlement height while during dry season water level of river decrease and has lower initial settlement height.

Nygard et al (2004) stated that deposition process especially mechanical compaction vary with time due to series of burial and erosion sequences. Burial and erosion sequences itself are depend on river stream which also a function of weather condition.

Along with deposition rates and fall velocity, the settlement pattern of soil particles in the soil-water mixture also influence the end conditions of sediment material layer on top of river bed which formed in terms of its homogeinity, compressibility and consolidation properties over the depth of the fill. Ganesalingam (2013) said that settlement pattern mainly influence the association between particles and aggregates, as group of particles, in the final sediment. The settlement pattern itself is determined by type of clay minerals present in the sediment, water content of the mixture, salt concentration and type of dissolved electrolytes.

The previous studies indicated alteration on sediment material properties either from consolidation and mechanical compaction yet did not explain more about the alteration of shear strength of sediment material as the result of consolidation and mechanical compaction process. Therefore, in current research the shear strength of sediment material is discussed further. Not only that, the shear strength of sediment material then associated with sediment removal such as dredging as one proposed solution to solve the problem of excessive sediment material on river bed at Bengawan Solo River. Further explanation regarding dredging is discussed in the next section.

In case previous studies merely focused on deposition, then in current research erosion is explained. Erosion is as important as deposition because both processes happen subsequently over times. Erosion phenomena could be defined as detachment and movement of soil particles from soil surface by natural forces, primarily by water and wind. Erosion includes all processes of denudation that involves the wearing away of the land surface by mechanical action. The transporting agents are by themselves capable only of limited wearing action on rocks, but the process is reinforced when these agents contain particles of the transported material. Greater average flow velocities in the transporting medium may be required to erode than to transport particles. Particles are eroded when the drag and lift of the fluid exceed the gravitational, cohesive, and frictional forces acting to hold them in place (Mitchell and Soga, 2005). If deposition only, it is difficult to explain the condition of sediment material in current research. The illustration of erosion and deposition phenomena is presented in Figure 2.3.

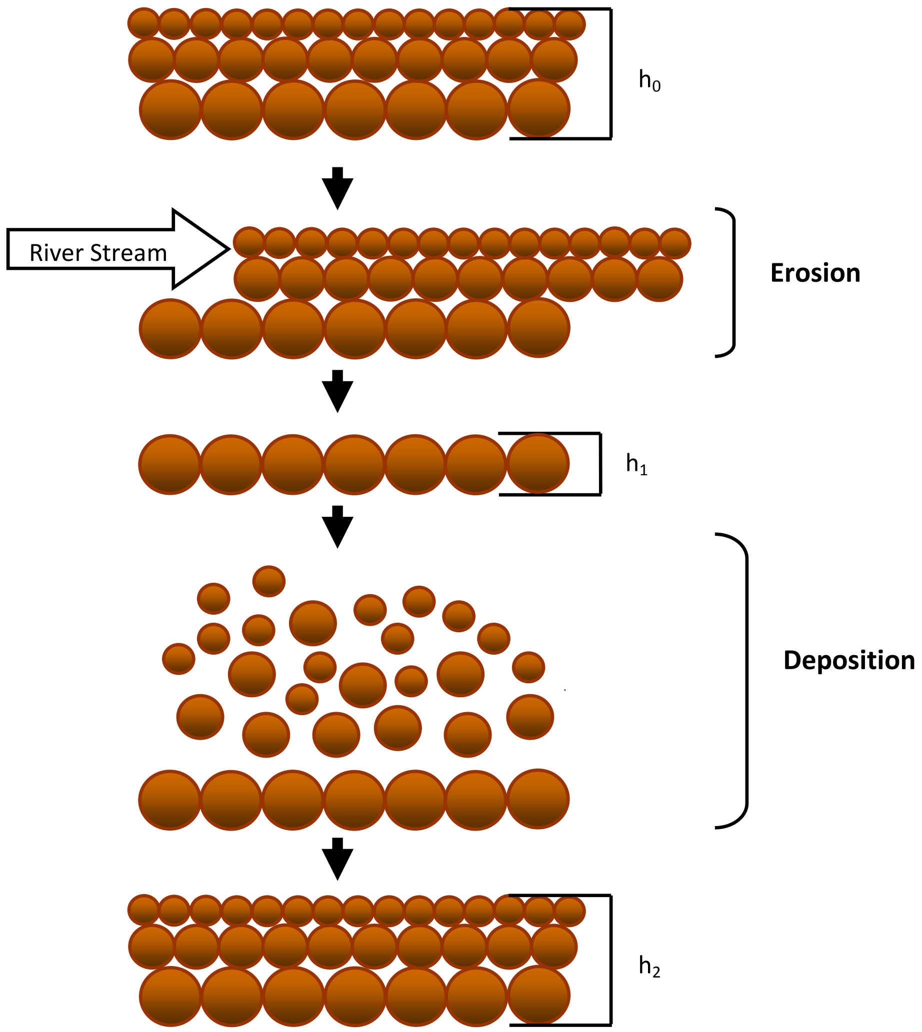


Figure 2.3 The illustration of erosion and deposition

2.3 Shear Strength of Sediment as Indicator of Dredging Method in Bengawan Solo River

2.3.1 Excessive Sediment Suffered by Bengawan Solo River

Natural and human-induced causes such as deforestation in upstream area causes soil erosion in the river basin and increase the sediment material brought by river stream. Higher amount of sediment material on river stream increases deposition in downstream and estuary area. The filling in of river bed with sediment material due to deposition leads to excessive sediment.

Excessive amounts of sediment can result problems not only for natural environment but also human build environment. It results in the destruction of aquatic habitat and reduction in the diversity and abundance of aquatic life. Moreover, the immediate consequence of excessive sediment is a decline in river channel capacity. When river effectively having lost its capacity to evacuate flood's water, downstream flooding increase significantly (Zahar, 2008). The outcome of excessive sediment in downstream area is different with estuary area. In estuary area, excessive sediment causes frequent river channel blockage which leads to the displacement of river mouth and river mouth branching (distributary). Further, it results in the forming of delta or sandbar at the river mouth (Sukardi et al, 2013).

Reducing excessive sediment material in streams could be done by doing several preventive measures include:

a. Do proper repair and maintenance of drainage ditches and levees
b. Minimize disturbance of the stream banks
c. Avoid structural disturbance of the river
d. Reduce sediment excesses arising from construction activities
e. Apply artificial and natural means for preventing erosion
f. Use proper land and water management practices on the water-shed.

Although preventive measures are preferred over remedial measures, remedial measures remain to be done to resolve excessive sediment that has been formed. The examples of remedial measures are including:

a. Construction of detention reservoirs, sedimentation ponds or settling basins
b. Development of side-channel flood-retention basins
c. Removal of deposited sediment by dredging

2.3.2 Dredging as Proposed Solution for Bengawan Solo River

Dredging is the process of removing material from the bed or the banks of a waterway (underwater excavation of soils and rocks) for the purpose of deepening or widening navigation channels or to obtain fill material for land development such as land reclamation (Johnson, 2003). It is very costly operation which requires heavy equipment and long pipelines. Based on its equipment, dredging can be classified into mechanical dredge and hydraulic dredge. Mechanical dredges remove sediment material and lift it by a diggers or buckets, and the excavated material is dumped into disposal barges for unloading at the disposal site. Mechanical dredges have considerable digging power to excavate hard compacted material and blasted-rock fragments. Meanwhile, hydraulic dredges pick up the dredged material by means of suction pipes and pumps, which suitable for slurry material.

Dredging production and costs vary widely by material type to be dredged. The dredging of hard material can be an order of magnitude more expensive than soft soil dredging. Therefore, the classification and physical properties of the materials to be dredged are primary factors in choosing the type and class of dredging equipment required which determine dredging cost. According to Johnson (2003), geotechnical information which determines dredging equipment type and class include:

a. The depth
b. The layer thickness
c. The hard or unsuitable material surface
d. Material profiles (soil layers of varying types)
e. Soil classification (soil types and soil density)
f. Soil physical properties (grain size distribution, density or unit weight, moisture content, liquid limits, plasticity, soil strength)

Information, which is presented in Table 2.2 and Figure 2.4, shows how shear strength parameter can be employed for the selection of determination of dredging methodology.

Table 2.2 Excavation Guidance on Application of Shear Strength Classification

Excavation Method	Strength (Mpa) - UCS and Cu	
	General Practice	Less Frequently Used
Traiilling Suction Hopper Dredger	0 to 5 UCS	0 to 30 UCS
Cutler Suction Dredger	0 to 50 UCS	0 to 150 UCS
Backhoe Dredger	0 to 10 UCS	0 to 30 UCS
Grab Dredger	0 to 0.3 C_u & 0 to 1 UCS	
Water Injection Dredger	0 to 0.005 C_u	0.005 to 0.015 C_u
Ploughing	0 to 0.02 C_u	
Plain Suction Dredger	0 to 0.02 C_u	
Bucket Ladder Dredger	0 to 10 UCS	
Drilling and Blasting	> 50 UCS	

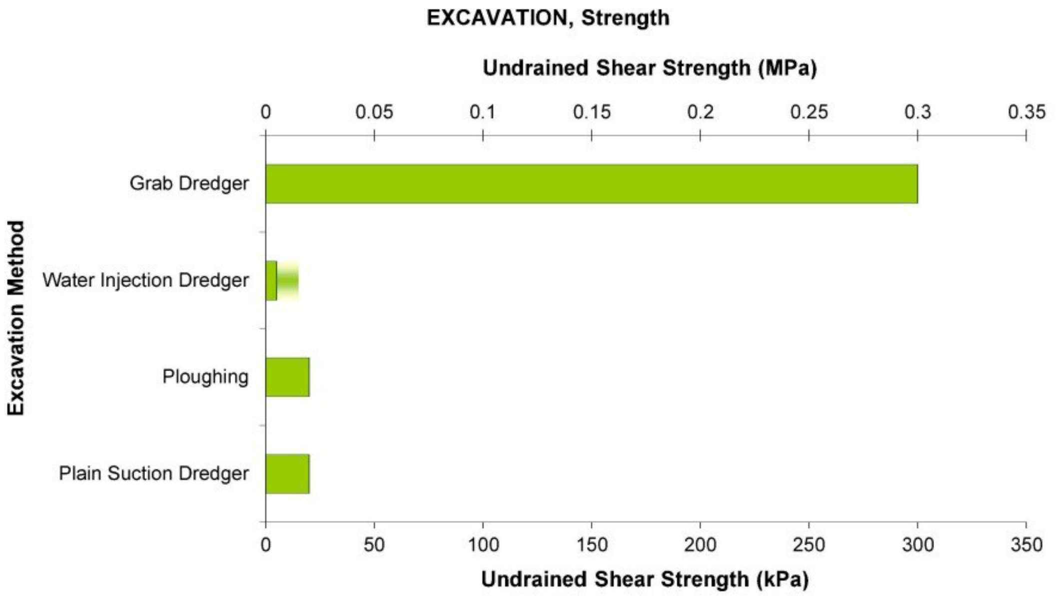


Figure 2.4 Strength versus excavation method graph

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CHAPTER 3
METHODOLOGY

3.1 Investigation of Sediment Properties

Investigation of sediment properties result in the soil type of sediment material which classified by Unified Soil Classification System (U.S.C.S). By understanding the soil type of sediment material, the behavior of sediment material is obtained. Moreover, investigation of sediment properties also result in the distribution of sediment properties based on the location and the depth, and the relation among properties. From the behavior of sediment material which resulted, later it is correlated with the condition of each location to determine the effect of each location to the properties of sediment material. Investigation of sediment properties includes sampling of sediment material and laboratory test.

3.1.1 Sampling of Sediment Material

Material used for current research was sediment material on river bed of Bengawan Solo River. The sediment material was obtained by boring into sediment layer. Within the process of sediment sampling, the first thing to do was constructed the barge. The barge was used as support or footing to put the boring instruments because the sampling location was on the river. After the barge was prepared, the arrangement and installation of boring instruments was done. The next step was boring to obtain the sample of sediment material. The process of sediment sampling is presented in Figure 3.1.

The sampling of sediment material was done slightly at the edge of the river by using thin-walled tube which appropriate with the procedure of sediment sampling based on ASTM D1587. The boring was done merely up to 5 m depth, because apart from the thickness of sediment layer which estimated to be 5 m, also because the limitations in cost and boring instruments.

The sampling of sediment material was done at dry season started from June 15th to June 21st, 2015, at five different locations which classified into downstream and estuary area. The sample of sediment material merely obtained from three different depths which were 1 m, 3 m and 5 m, measured from the surface of sediment layer to river bed. The three different depths was chosen because apart from the limitations in cost, also because the assumption that the results of sediment properties in those three different depths is significantly different.

During dry season, starts from May to October, the level of river water of Bengawan Solo River is relatively low in the range from 3 m to 4 m compared with monsoon season, starts from November to April where the level of river water reach 10 m to 12.5 m. The level of water level was measured from the surface of river water to the surface of sediment layer on top of river bed. The measurement of level of river water was done by using water level sensor. The device of water level sensor is presented in Figure 3.2.

(a)

(b)

3.3.

(c)

Figure 3.1 Process of sediment sampling (a) the barge
(b) sediment sampling at Location 1 (c) sediment sampling at Location 5

Figure 3.2 The device of water level sensor

The condition of sediment material is constantly submerged in the water with the lowest level of river water ranges from 3 m to 4 m. In order to explain more regarding the condition of sampling location including the level of river water and the thickness of sediment layer, an illustration is presented in Figure 3.3.

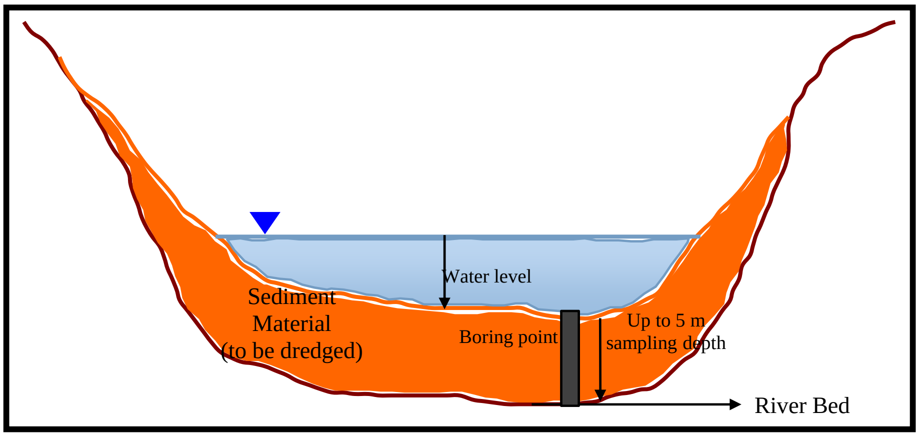


Figure 3.3 The illustration of sampling condition

3.1.2 Laboratory Test for Investigation of Sediment Properties

The properties of sediment which are discussed in current research are listed in Appendix B. Meanwhile, the laboratory test for investigating the properties of sediment material was comprised of physical properties test, consolidation test and direct shear test.

1) Physical properties test

Physical properties test was done to determine the physical properties of sediment material on river bed. The test consisted of several tests including volumetric-gravimetric test, Atterberg limit test, sieve and hydrometer test.

a) Volumetric-gravimetric test

Volumetric-gravimetric test obtained several parameters of physical properties including unit weight (γ_t) based on ASTM D2937-71, water content (w_c) based on ASTM D2216-71, specific gravity (G_s) based on ASTM D854-58, degree of saturation (S_r), porosity (n) and void ratio (e).

b) Atterberg limit test

Atterberg limit obtained liquid limit (LL) based on ASTM D423-66, plastic limit (PL) based on ASTM D424-59 and plasticity index (PI).

c) Sieve and hydrometer test

Sieve test based on ASTM D6913-04 obtained grain size and grain distribution for sediment material with particles size greater than 0.075 mm, while hydrometer test based on ASTM D1140-00 obtained grain size and grain distribution for sediment material with particles size smaller than 0.075 mm.

2) Consolidation test

Consolidation test based on ASTM D2435-04 was done using incremental loading. The incremental loading were 9,8 kN/m^2, 19,6 kN/m^2, 39,2 kN/m^2, 78,5 kN/m^2, 157 kN/m^2, 314 kN/m^2, 628 kN/m^2 and 1256 kN/m^2. It was applied on saturated sample with 2 cm in height and 6 cm in diameter. The test determined one-dimensional consolidation properties of sediment material including preconsolidation stress (p_c'), overconsolidation ratio (OCR), coefficient of compressibility (m_v), compression index (C_c), coefficient of consolidation (C_v) and hydraulic conductivity (k).

3) Direct shear test

Direct shear test based on ASTM D3080-04 was done in consolidated drained (CD) condition. It is done on saturated sample with 2 cm in height and 6 cm in diameter. The used confining pressure determined to be equal with overburden pressure experienced by sediment material on river bed. Following triaxial confining pressure standard, the confining pressure was $0.5\sigma_v$, σ_v and $2\sigma_v$ for each sample with σ_v as overburden pressure. The used loading speed in direct shear test was expected to be able to result complete drainage condition on sediment sample in order to meet the criteria of consolidated drained condition. Because in current research there were two types of sediment material, hence two different loading speeds were used to adjust with the behavior of each sediment material. The used loading speeds were:

- 0.2 mm/minute for sandy sediment
- 0.06 mm/minute for clay sediment

Direct shear test determined the shear strength parameters which were internal friction angle (ϕ) and cohesion (c) of sediment material.

3.2 Analysis of Erosion and Deposition Experienced by Sediment Material

Through analysis of erosion and deposition experienced by sediment material in current research, it is discovered that sediment material not only experiences deposition phenomena as studied by previous research (Nygard et al, 2004; Madhyannapu et al, 2008; Brain et al, 2011; Ganesalingam et al, 2013; Guo et al, 2015). Sediment material also experiences erosion phenomena. Both phenomena happened subsequently over times so that the properties of sediment material constantly changing. Nevertheless, the behavior of sediment material can be learned. The analysis of erosion and deposition was done by using the result of consolidation test and particle size distribution and hence, the evidence of sediment material on top of river bed experienced erosion and deposition phenomena is obtained. The illustration of erosion and deposition phenomena is presented in Figure 2.3 of Chapter 2.

3.3 Analysis of Shear Strength and Critical Shear Stress of Sediment Material

As explained above, sediment material experiences erosion and deposition phenomena. Sediment material experiences erosion when the shear stress caused by water flow or river stream exceeds the resisting forces of sediment on top of river bed and also the self-weight of particles (Bianco, 2014). The resisting force of sediment material on top of river bed is influenced by particle diameter. The resisting force is a limit value which determined whether the sediment is able to be moved by river stream or not. The resisting force is also known as critical shear stress. The approximate values of critical shear stress for non-cohesive particles can be obtained from the extended Shields diagram. The values from Julien (2002), as approximate reference values and also the grade scale commonly used in sedimentation, which was used in current research is presented in Table 1 of Appendix B. To get crude approximations, a shear stress value of $\tau = 0.1$ Pa is sufficient to move silts but not sands, and $\tau_c = 1$ Pa is sufficient to move sands but not gravels.

Shear strength of sediment material obtained from laboratory test was compared with critical shear stress of sediment particles from Julien (2002), to determine whether sediment material is able to be moved by river stream. And if it is able to be moved by river stream which mean critical shear stress is greater than shear strength, the natural erosion is happened and hence, sediment removal is not necessary. However, if shear strength is greater than critical shear stress, it indicates that sediment material cannot be eroded naturally and hence, sediment removal is necessary.

After compared with critical shear stress, the analysis of shear strength was used to determine the ease of sediment to be removed. Shear strength refers to the density of sediment, starts from soft or loose sediment to stiff or hard sediment. The criteria of sediment density based on shear strength are presented in Table 3.1.

Table 3.1 Criteria of Sediment based on Shear Strength

Sand and Gravel	**q_u Mpa**	**Silt and Clay**	**c_u kPa**
Very Loose	0 - 2.5	Extremely Soft	< 10
Loose	2.5 - 5	Very Soft	10 - 20
Medium Dense	5 - 10	Soft	20 - 40
Dense	10 - 20	Medium	40 - 75
Very Dense	> 20	Stiff	75 - 150
		Very Stiff	150 - 300
		Extremely Stiff	> 300

Simply, the soft or loose sediment material is easy to be removed by using dredging equipment with small capacity such as dredging by suction or even by using human power. Otherwise, stiff or hard sediment material needs dredging equipment with large capacity. The method of dredging equipment, based on the shear strength of sediment is presented in Table 2.3 and Figure 2.4 of Chapter 2. The methodology of current research is summarized in a flowchart as presented in Figure 3.4.

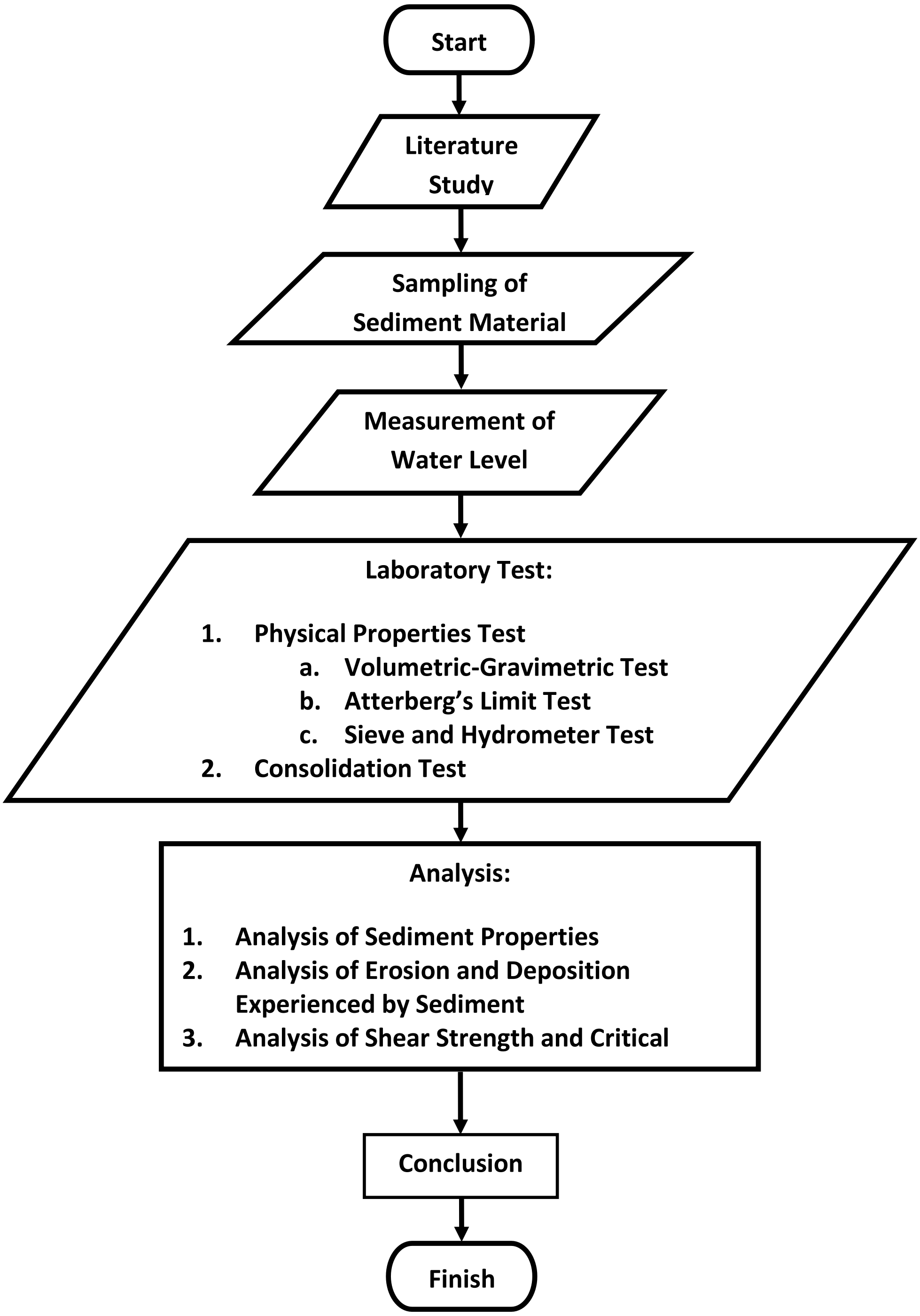


Figure 3.4 Flowchart of research methodology

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Physical Properties of Sediment Material at Five Different Locations

Sediment material at five different locations (see Figure 4.1 and Appendix A) was classified based on its soil type. By understanding the soil type of sediment material, the description regarding behavior of sediment material was obtained. The classification of the soil type of sediment material was done based on Unified Soil Classification System (U.S.C.S) by using the result of sieve and hydrometer test, and also the result of Atterberg's limit test which summarized in Table 4.1. Meanwhile, the whole result of physical properties test is presented in Appendix C.

Table 4.1 Grain Percentage and Atterberg's Limit of Sediment Material

Location Code	Depth (m)	Grain Percentage (%)				Atterberg's limit			Soil Type (USCS)	
		Gravel	Sand	Silt	Clay	LL	PL	IP		
1	1	0.01	99.33	0.66		-			SP	Clear Sand
	3	0.37	60.27	22.61	16.75	27.11	16.07	11.04	SC	Clayey Sand
	5	4.30	76.95	18.75		-			SM	Silty Sand
2	1	0.05	68.92	31.03		-			SM	Silty Sand
	3	0.14	75.19	24.67		-			SM	Silty Sand
	5	0.21	79.12	20.67		-			SM	Silty Sand
3	1	0.34	10.43	60.11	29.12	40.56	27.19	13.37	ML	Silt
	3	0.39	4.14	59.89	35.58	45.95	22.46	23.50	CL	Lean Clay
	5	1.64	6.17	59.84	32.34	45.24	23.34	21.90	CL	Lean Clay
4	1	6.71	73.56	19.74		-			SM	Silty Sand
	3	0.61	96.43	2.96		-			SP	Clear Sand
	5	10.17	73.60	16.24		-			SM	Silty Sand
5	1	0.14	43.23	27.88	28.75	14.01	8.26	5.75	ML	Silt
	3	0.10	0.39	39.35	60.16	67.52	28.78	38.74	CH	Fat Clay
	5	0.00	0.08	36.27	63.65	70.92	29.42	41.50	CH	Fat Clay

As mentioned in Chapter 3, sediment material was obtained from three different depths which were 1 m, 3 m and 5 m, measured from the surface of sediment layer. According to the results which presented in Table 1, the soil type of sediment material based on the depth is relatively similar. Meanwhile based on the location of sediment sampling, sediment material is broadly grouped into sand sediment and clay sediment. Sand sediment was found at downstream areas which were Location 1, Location 2 and Location 4, while clay sediment was found at estuary area which was Location 5. Location 3 was an exception because even though classified into downstream area, it has clay sediment. Further explanation is discussed later in the next section.

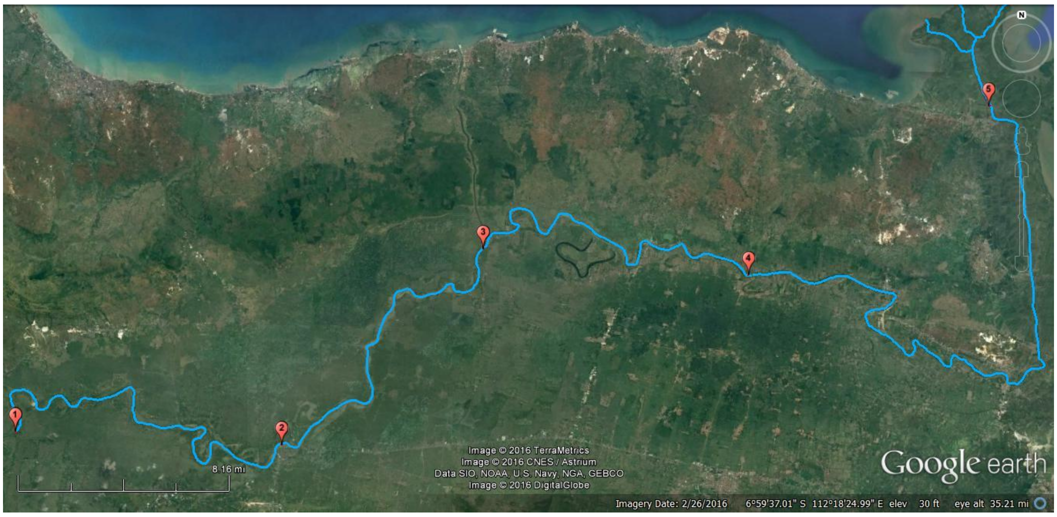


Figure 4.1 Locations of sediment material sampling at Bengawan Solo River (Source: Google Earth)

Although based on the depth the soil type of sediment material is relatively similar, the distribution of sediment properties is varies. The distribution of sediment properties is presented in Figure 4.2 to Figure 4.5.

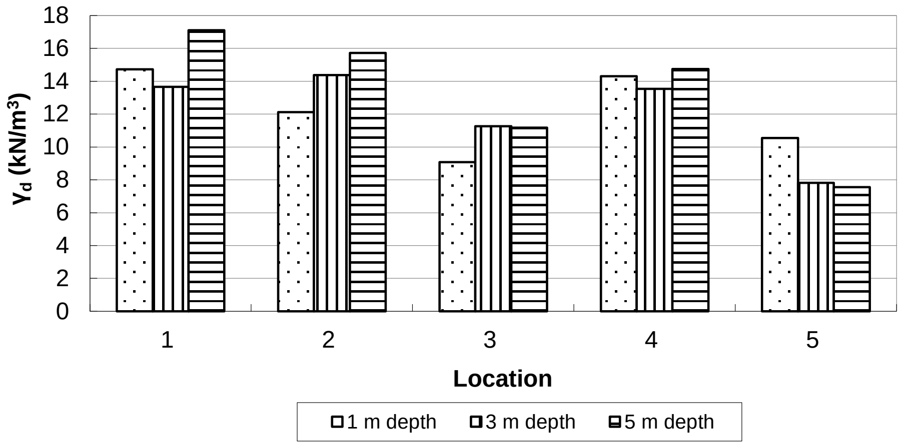


Figure 4.2 Distribution of dry unit weight

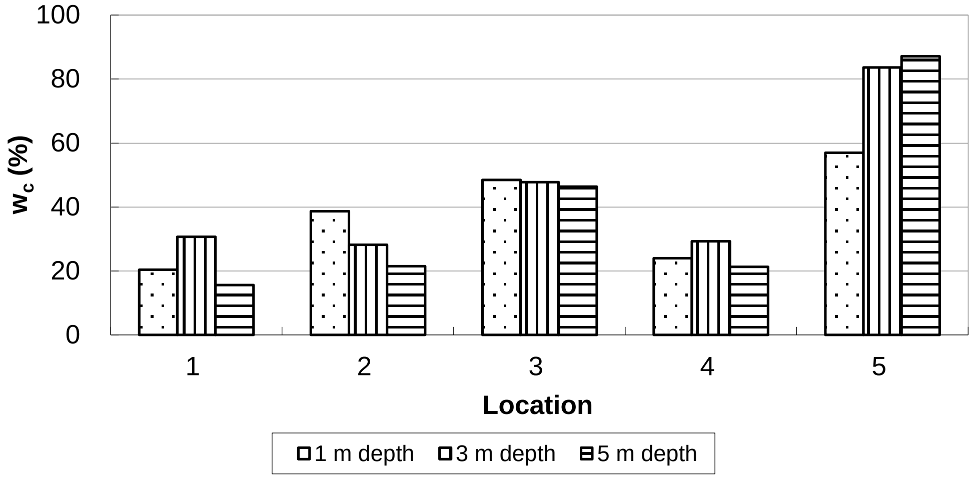


Figure 4.3 Distribution of water content

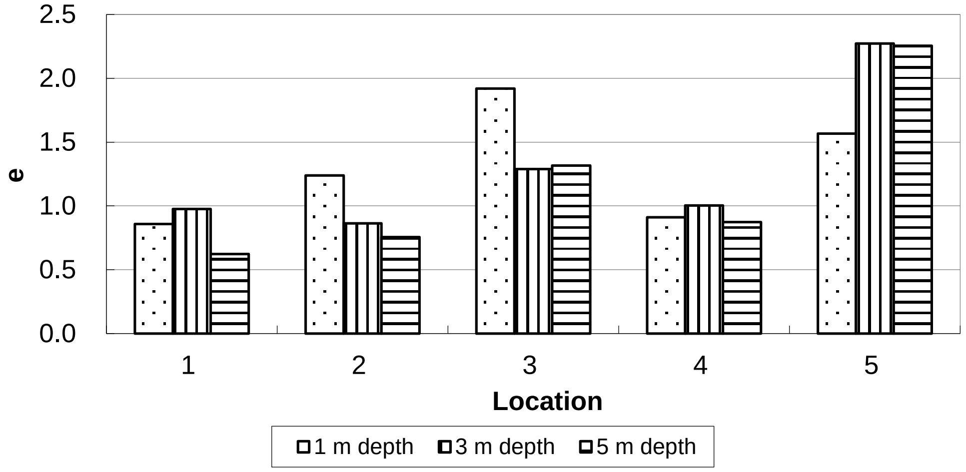


Figure 4.4 Distribution of void ratio

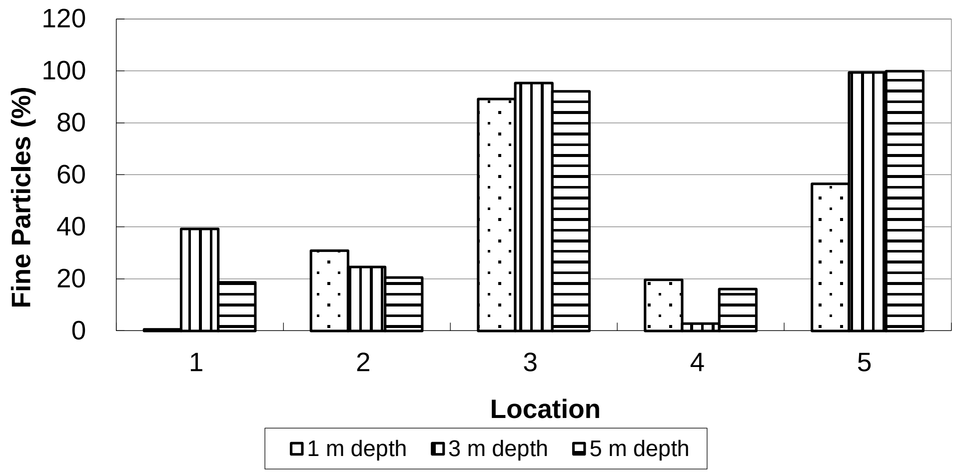


Figure 4.5 Distribution of fine particles

The variation on distribution of sediment properties based on the depth is caused by the subsequent erosion and deposition over times. Meanwhile based on the location of sediment sampling, the distribution of sediment properties is appropriate with the soil type. It can be seen from the Figure 4.2 to Figure 4.5 that downstream area with sand soil has higher dry unit weight, range from 7.71 kN/m^3 to 11.04 kN/m^3, than estuary area with clay soil, range from 4.55 kN/m^3 to 6.98 kN/m^3. The downstream area also has lower water content range from 15.61% to 38.64%, lower void ratio range from 0.62 to 1.24, and lower percentage of fine particle range from 0.66% to 39.366%. The results are caused by the behavior of soil type of sediment material, where sand soil is heavier than clay soil in the same volume. Furthermore, sand soil experiences immediate settlement so that it becomes denser in short time and results in smaller void ratio compared with clay soil. With smaller void ratio, the water fills in the void is lesser and results in lower water content for sand soil, aside from the behavior of sand soil which does not bind water.

The variation on distribution of sediment material based on the location is appropriate with the soil type for some parameters, such as dry unit weight, water content, void ratio and percentage of fine particles. The distribution of D_{50} of sediment material (see Figure 4.6) based on the location tends to change longitudinally corresponding to river flow from downstream to estuary which is known as downstream fining where sand-mud (silt and clay) transition happened.

According to Luo et al (2012), downstream fining happened due to the influence of tributaries which also owned by Bengawan Solo River. Downstream fining generates smaller size for particles that have been transported farther from their source location. It means sediment grain size gets smaller from downstream area (Location 1, 2 and 4) to estuary area (Location 5). At estuary area, clay sediment is probably related to the sudden deposition of suspended fine particles under the effect of tides and as the consequences of freshwater and seawater mixing. Under the influence of strong tides, current in the channel of the estuary oscillate, producing two periods of slack water with very low flow velocity (< 0.1 m/s) which favorable for the deposition of suspended sediment. It is fit with

Julien (2002) where fine grains usually were dominant in low energy condition. From hydraulic perspective, it can be predicted that the coarser fraction of the suspended sediment is deposited first along downstream area (Location 1, 2 and 4), leaving the finer particle in suspension to deposit at estuary (Location 5) which enhanced by flocculation. Meanwhile, according to Menting et al (2015) downstream fining was influenced by the lithology of sediment particle and transport capacity/stream power.

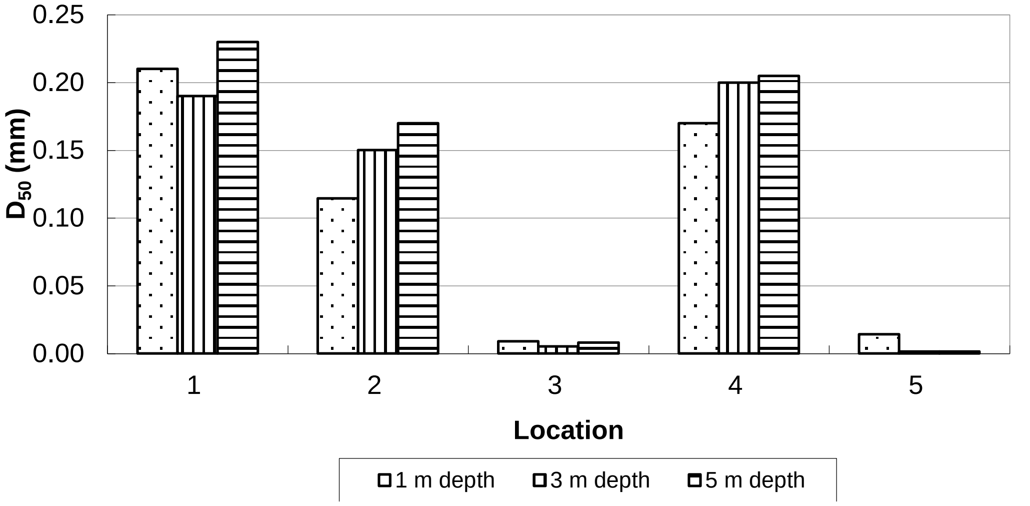


Figure 4.6 Distribution of D_{50}

Figure 4.7 The picture of Babat Barrage

As mentioned above, Location 3 was an exception because even though classified into downstream area, it has clay sediment. It is possibly because there is a dam which known as Babat Barrage (7^{o} 2’ 29.9” S, 112^{o} 13’ 5.88” E) before the third sampling location. The picture of Babat Barrage is presented in Figure 4.7. The coarse particles which literally move alongside the river bed is deposited in the dam area while the fine particles move past the dam area along with river stream. Further the fine particles deposited in river bed for example at Location 3, or carried by river stream to farther location.

4.2 Relation between Properties of Sediment Material and Its Sampling Location

The behavior of sediment material could be decided by its properties which are related to one another, for example dry unit weight with void ratio. The relation between dry unit weight with other properties of sediment material such as water content, void ratio and percentage of fine particles, are presented in Figure 4.8 to Figure 4.10.

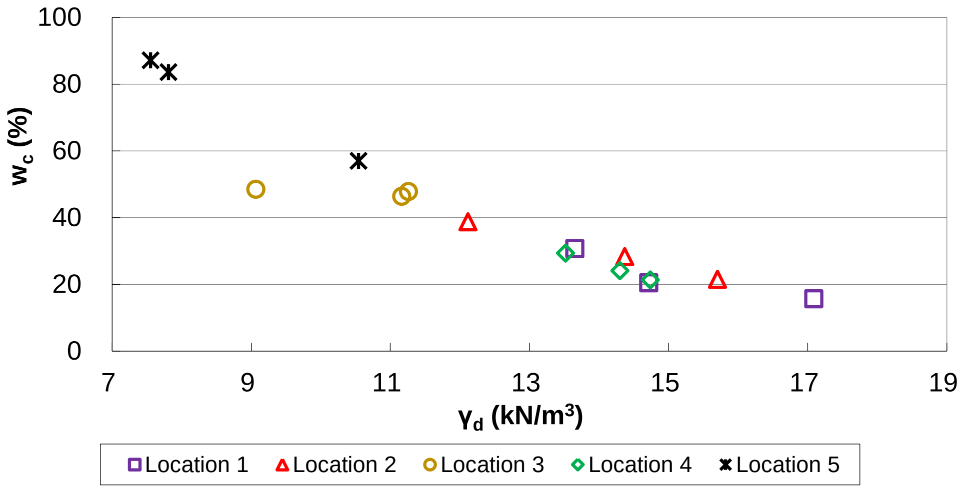


Figure 4.8 Relation between dry unit weight versus water content

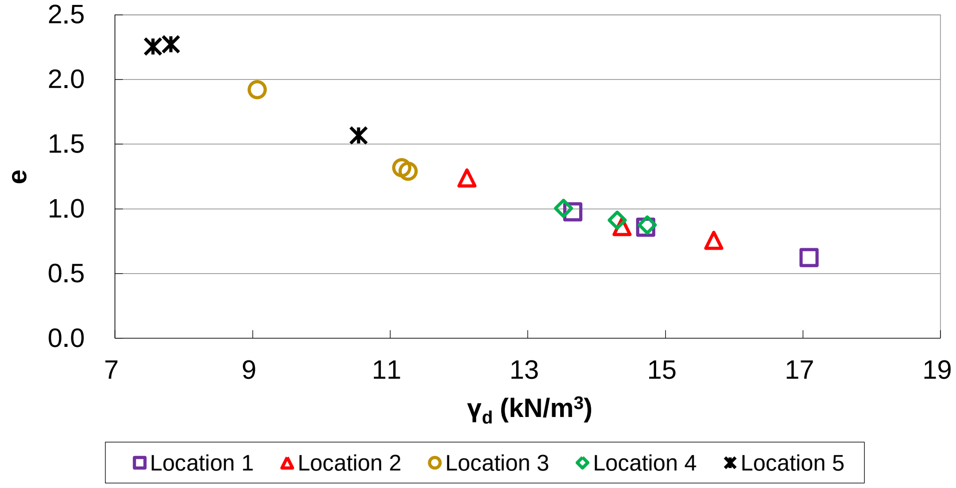


Figure 4.9 Relation between dry unit weight versus void ratio

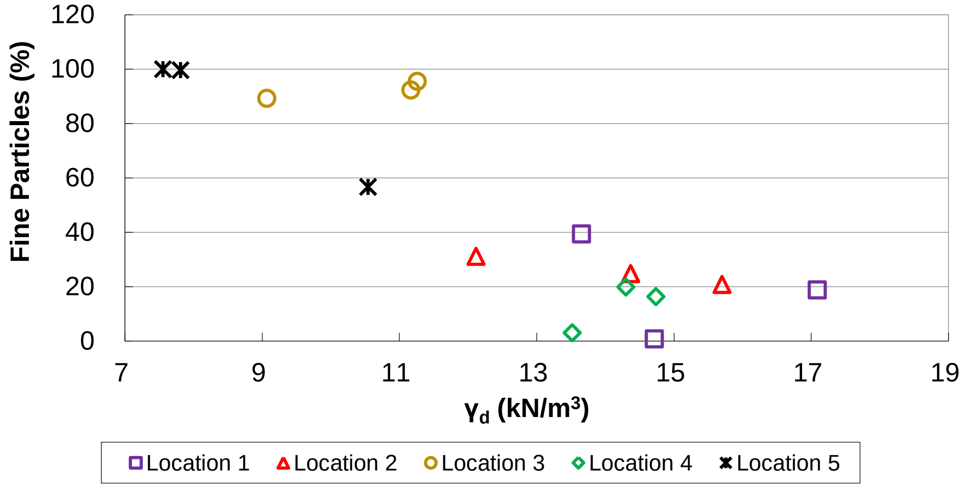
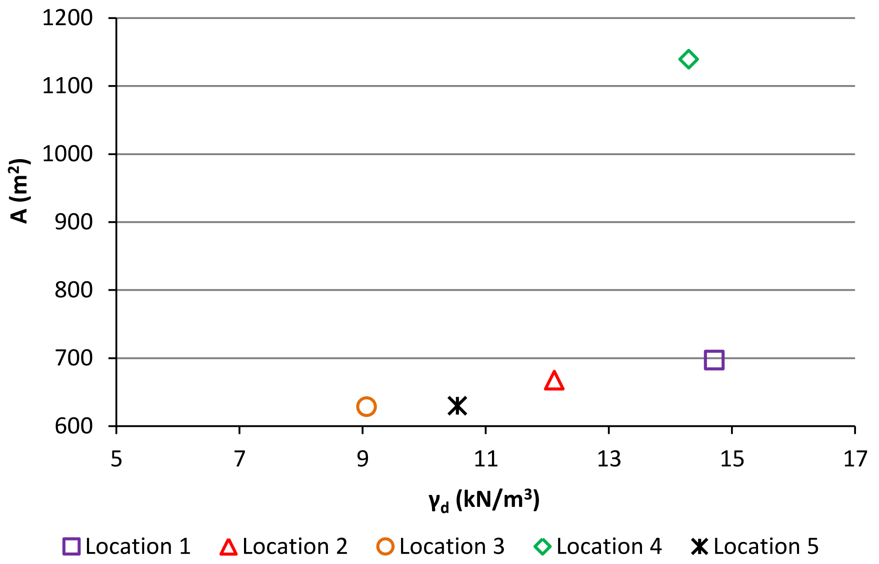


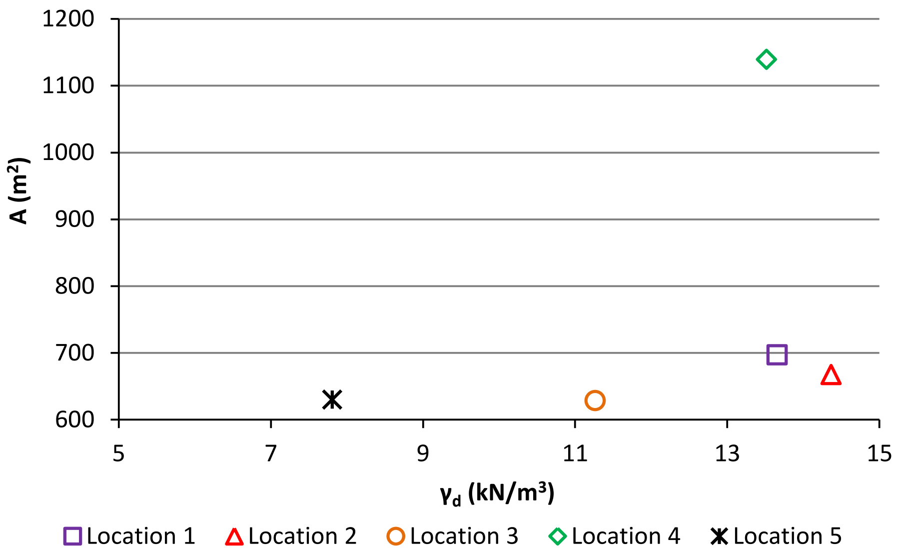
Figure 4.10 Relation between dry unit weight versus percentage of fine particles

From Figure 4.8 to Figure 4.10, it is found that when dry unit weight increases then water content, void ratio and percentage of fine particle of sediment material decreases. Unit weight is defined as the ratio of total weight to total volume. Higher unit weight implies heavier of total weight in current volume which indicates more soil particles with dense arrangement. More soil particles with dense arrangement results in low void to fills in with water and hence, the water content is low.

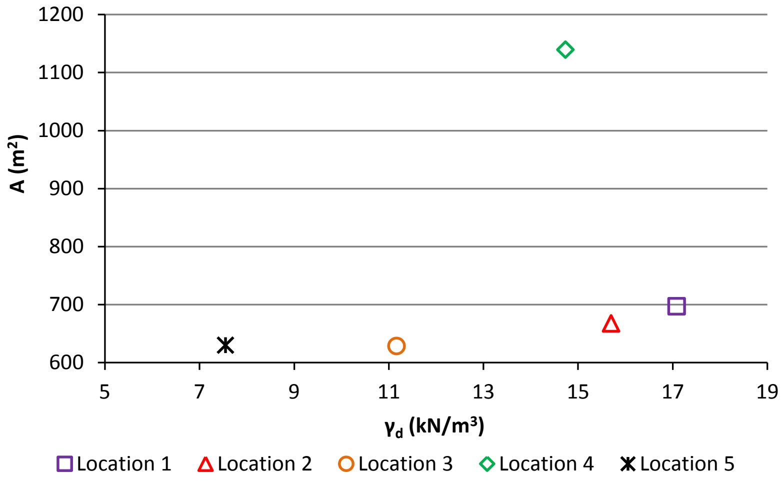
Since the properties of sediment material in each location have relation among them, where one property is influenced by other property, then the properties of sediment material was related to the sampling location as well. It was done apart of to distinguish properties of sediment material based on each location, also to confirm the assumption where properties of sediment material are influenced by sedimentary environment. In current study, sedimentary environment is defined as the condition of sampling location. Parameters used as representation of the condition of sampling location are sampling depth, sectional area of river and flow velocity. The relation between dry unit weight with sampling depth and sectional area of river is presented in Figure 4.11 to Figure 4.12.



(a)

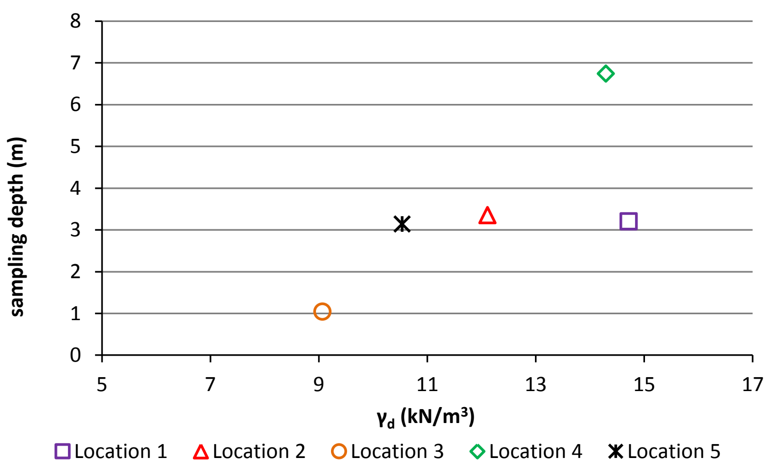


(b)

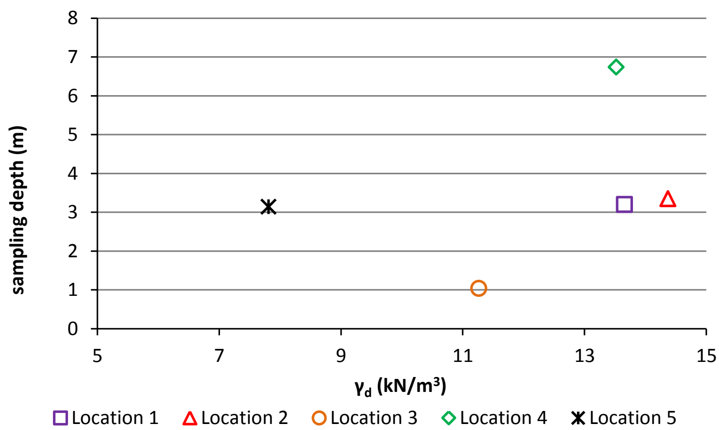


(c)

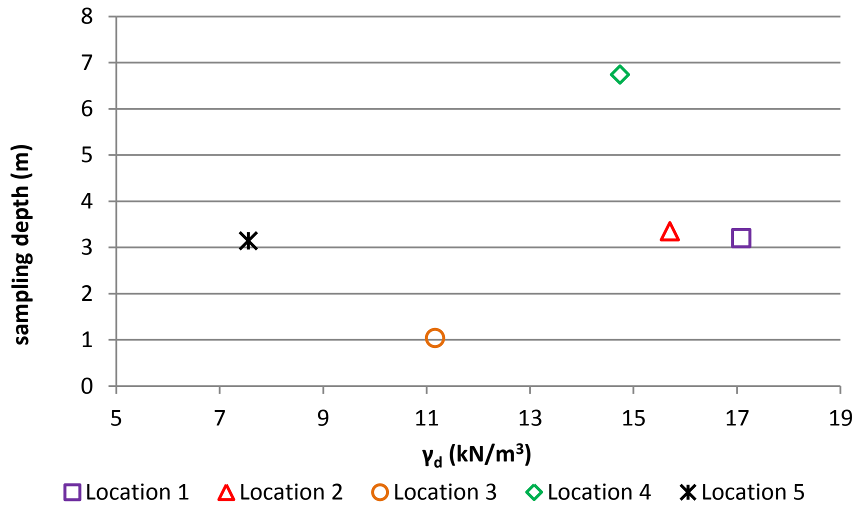
Figure 4.11 Relation between dry unit weight versus sectional area of river (a) 1 m depth (b) 3 m depth (c) 5 m depth



(a)



(b)



(c)

Figure 4.12 Relation between dry unit weight versus sampling depth (a) 1 m depth (b) 3 m depth (c) 5 m depth

Besides related with sampling depth and sectional area of river, dry unit weight of sediment material also related to flow velocity. Because measurement of flow velocity was not done in the site, the value of flow velocity is determined with calculation by using empirical approach. Empirical approach for calculating average flow velocity in current research used Manning equation as presented below:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

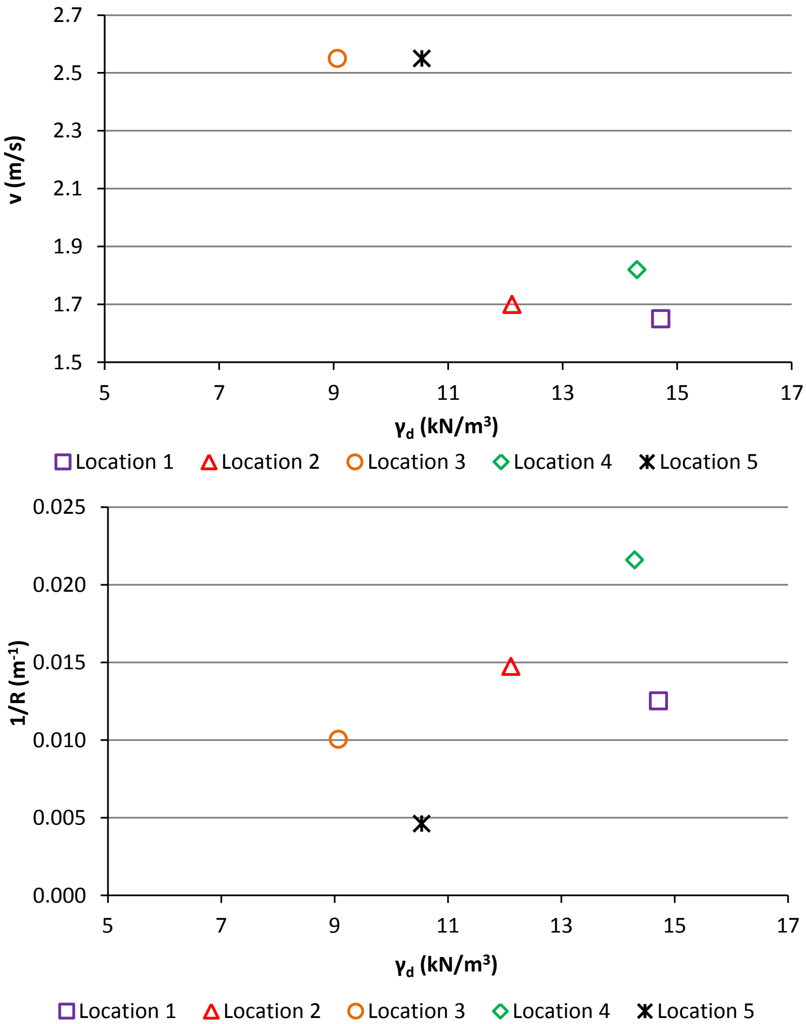
where *n* is Manning coefficient (in current research n = 0.03 for clean and straight natural channel), *R* is hydraulic perimeter and *S* is the gradient of river bed. The relation between dry unit weight of sediment material with average flow velocity is presented in Figure 4.13.

From Figure 4.11 to Figure 4.13, it is found the tendency that dry unit weight of sediment material increases when the sampling depth is deeper, wider sectional area of river, and lower flow velocity. Wider sectional area and deeper depth denote the condition where sediment concentration is high (Soemitro et al, 2015; Maulana et al, 2016). The condition where sediment concentration is high along with low flow velocity enables deposition phenomena to happen. When deposition of sediment is high, then the deposited sediment on top of river bed is getting thicker. Thicker deposited sediment layer accelerates consolidation and mechanical compaction process and further dense sediment with high unit weight is produced. Since unit weight has relation with other properties, then it can be said that deeper sampling depth, wider sectional area of river, and low flow velocity has tendency that water content, void ratio and percentage of fine particles decreases.

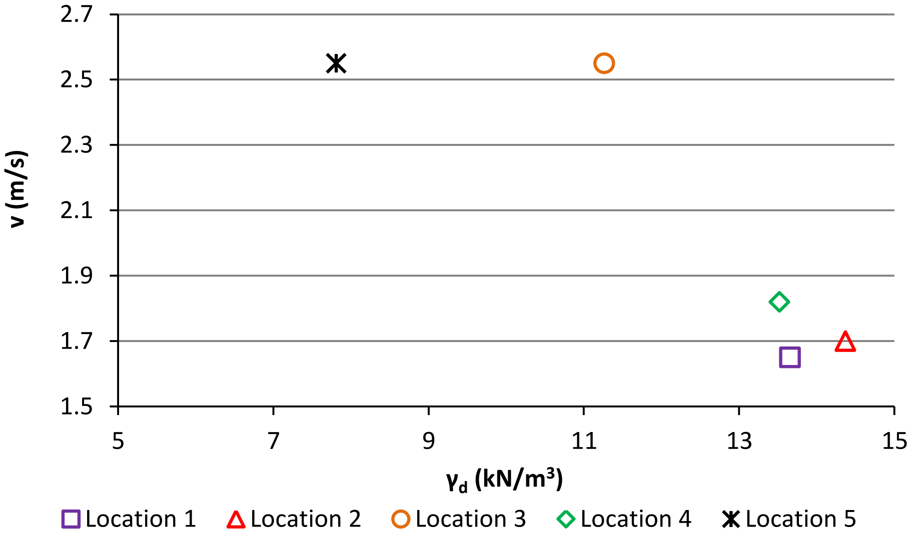
Basically, the estimation in deciding more dominant phenomena between erosion and deposition in each location could be seen through the relation between dry unit weight of sediment material and flow velocity (see Figure 4.13). From the graph in Figure 4.13, it was obtained that Location 3 and 5 experienced more erosion with high flow velocity while Location 1, 2 and 4 experienced more deposition with low velocity. However, when seen from the soil type of sediment material in each location, the results seems not appropriate. It is because Location 1, 2 and 4 with sand sediment assumed to experience more erosion, while Location 3 and 5 with clay sediment assumed to experience more deposition. It is possibly because obtained flow velocity is the calculation result using Manning equation which known as average flow velocity. Average flow velocity takes place di in the middle of sectional area of the river and in 0.4 height of water level (0.4h) measured from the surface of river water. The application of average flow velocity neglects the influence of bed friction due to wide sectional area and thus, flow velocity is directly proportional with hydraulic perimeter (R).

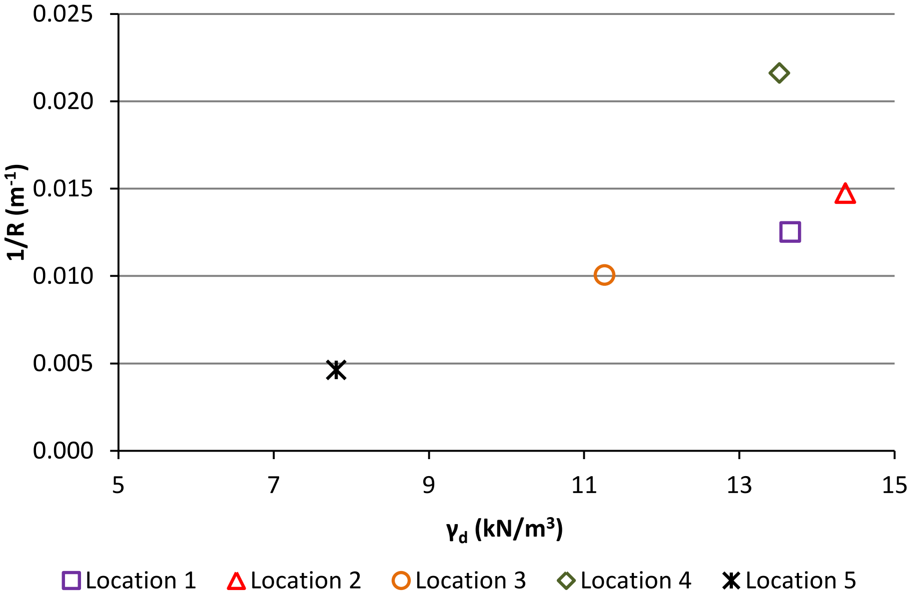
The point where average flow velocity works is different with the sampling point. The samples were obtained at slightly at the edge of the river. And because the current research discussed about the sediment material on top of river bed, the flow velocity should be influenced by bed friction and thus, the flow velocity is inversely with hydraulic perimeter (R). Since the measurement of flow velocity in respective point was not done, instead of flow velocity, the comparison with dry unit weight is done by using hydraulic perimeter for estimating more dominant phenomena between erosion and deposition in each location. In order to simplify the comparison of influence between directly proportional and inversely proportional of hydraulic perimeter toward flow velocity, the graph of relation between dry unit weight and average flow velocity was compared with the graph of relation between dry unit weight and 1/R (see Figure 4.13).

From Figure 4.13, it is found that higher hydraulic perimeter (small 1/R) indicates lower flow velocity result in more deposition is experienced by Location 3 and 5. Meanwhile, lower hydraulic perimeter (high 1/R) indicates higher flow velocity result in more erosion is experienced by Location 1, 2 and 4. This result is appropriate with the soil type of sediment material which is Location 3 and 5 with clay sediment happens in the location with more dominant deposition phenomena while Location 1, 2 and 4 with sand sediment happens in the location with more dominant erosion phenomena.



(a)


2.7
2.5
2.3
2.1
1.9
1.7
1.5
v (m/s)
5
7
9
11
13
15
γd (kN/m3)
Location 1
Location 2
Location 3
Location 4
Location 5


0.025
0.020
0.015
0.010
0.005
0.000
1/R (m-1)
5
7
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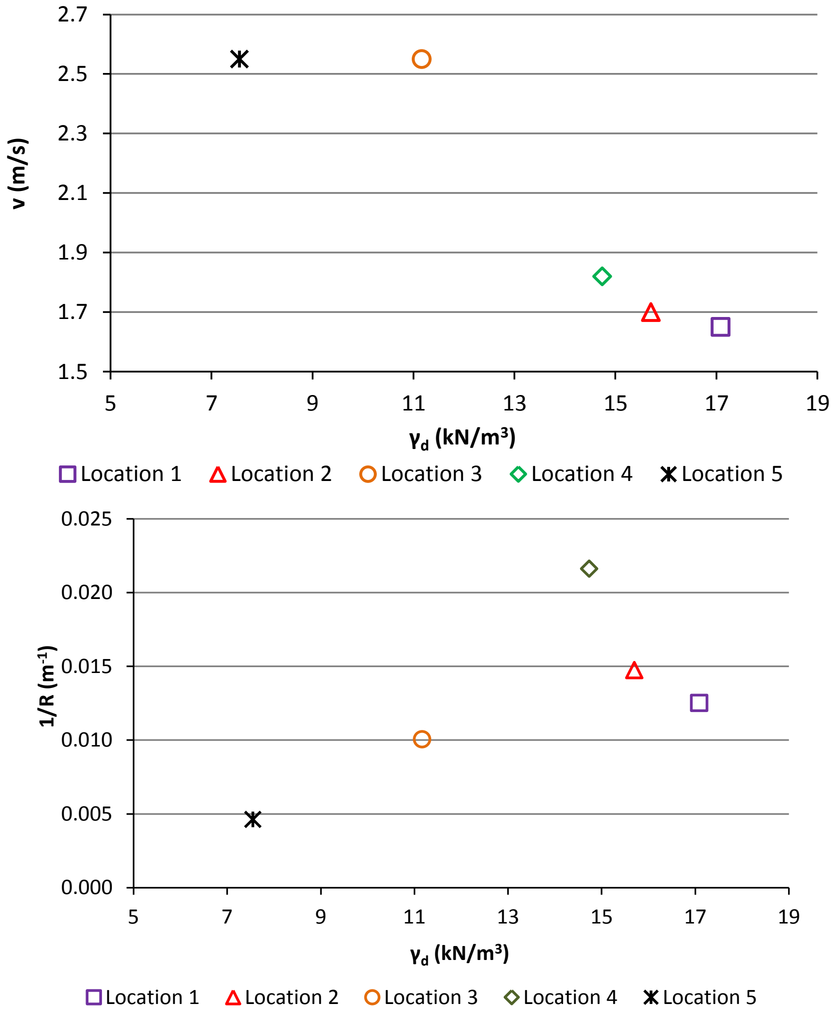
15
γd (kN/m3)
Location 1
Location 2
Location 3
Location 4
Location 5

(b)



(c)

Figure 4.13 Relation between dry unit weight versus flow velocity and hydraulic perimeter (a) 1 m depth (b) 3 m depth (c) 5 m depth

4.3 Erosion and Deposition Experienced by Sediment Material

According to Guo et al (2015), when deposition process happened, sand particle, which is bigger and heavier, was concentrated at the bottom layer with higher deposition rate and fall velocity. Meanwhile clay particle, which is smaller and lighter, was deposited in the upper layer due to lower deposition rate and fall velocity. This explanation gave a description that deeper sediment layer has bigger particle size and the distribution of particle size is getting smaller along approaching the surface of sediment layer. However as there is subsequent erosion and deposition phenomena, the description does not occur at sediment material in current research. Besides due to subsequent erosion and deposition, Guo et al statement is not applicable for sediment material in current research because Stokes law, the terminal velocity of a sphere sinking through a fluid (smaller particles settle more slowly than larger ones) is not applicable. Inapplicability of Stokes law is possibly due to the existence of turbulence in river stream.

The existence of erosion and deposition phenomena can be seen from consolidation properties of sediment material. Sediment material in each location is classified into overconsolidated soil with overconsolidation ratio value greater than 1 (OCR > 1), range from 1.2 to 34.4. OCR > 1 indicated that preconsolidation pressure (p_c') is greater than current pressure. In sediment case of current research, it means that previous sediment layer is thicker than current sediment layer and thus, the reduction in thickness can be the evidence of erosion phenomena. Furthermore, other consolidation properties as result of consolidation test are presented in Appendix D.

Erosion and deposition experienced by sediment material is different in each location. It can be seen from e versus log p curve which presented in Figure 4.14 to Figure 4.18.

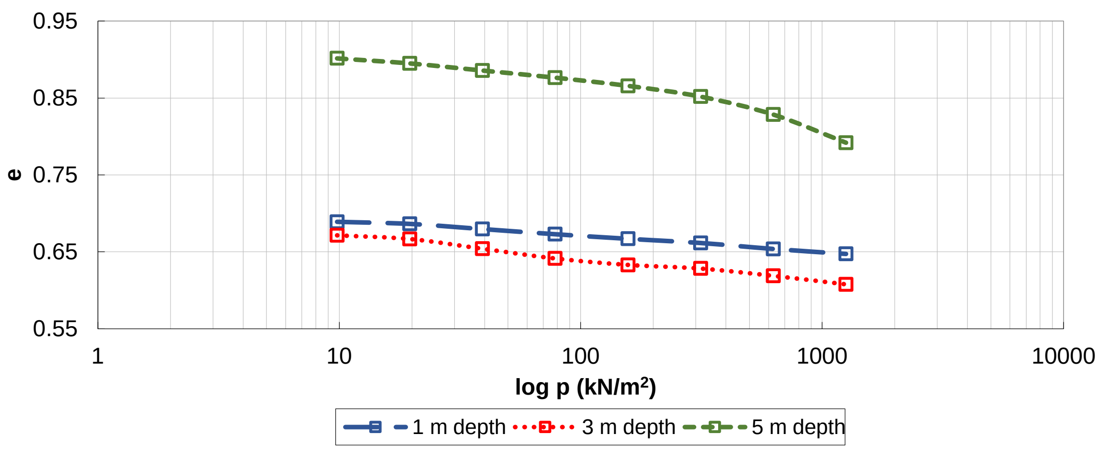


Figure 4.14 e versus log p curve at Location 1

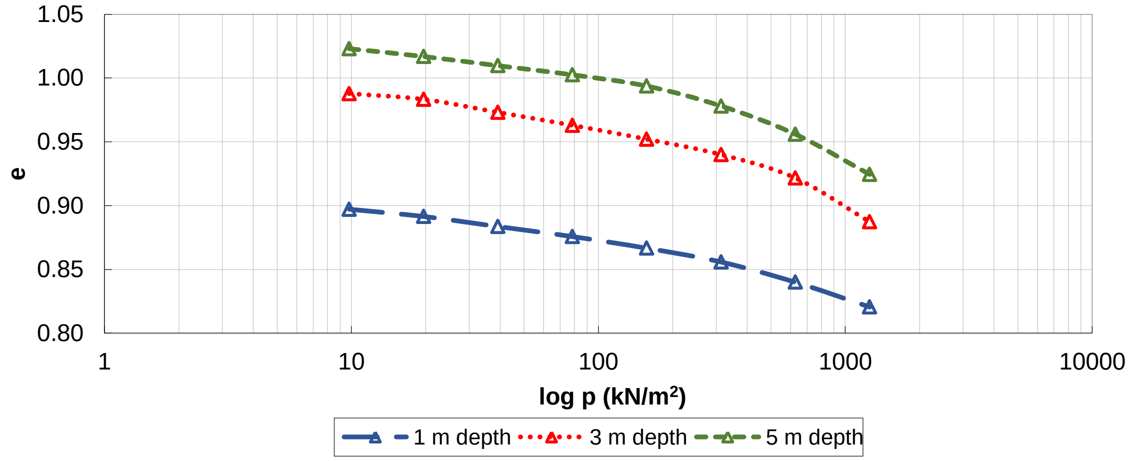


Figure 4.15 e versus log p curve at Location 2

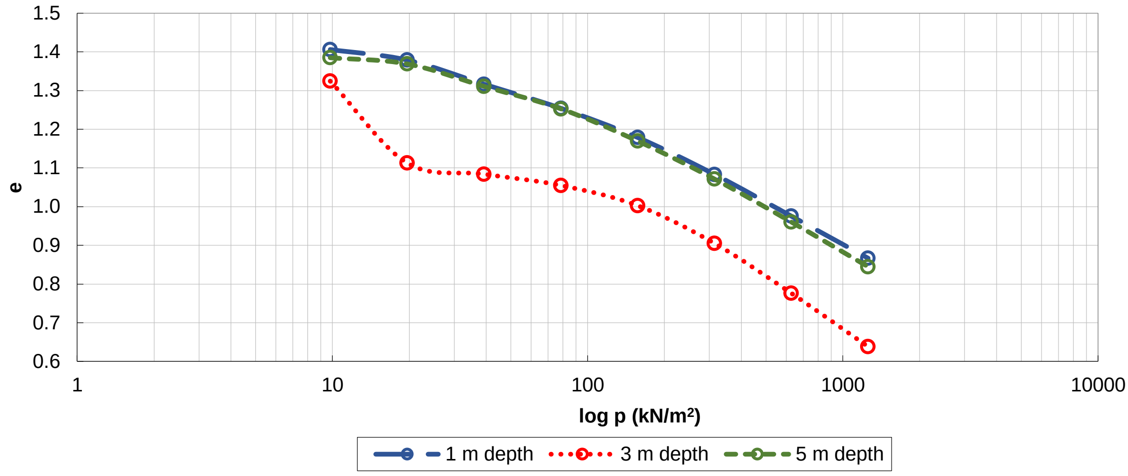


Figure 4.16 e versus log p curve at Location 3

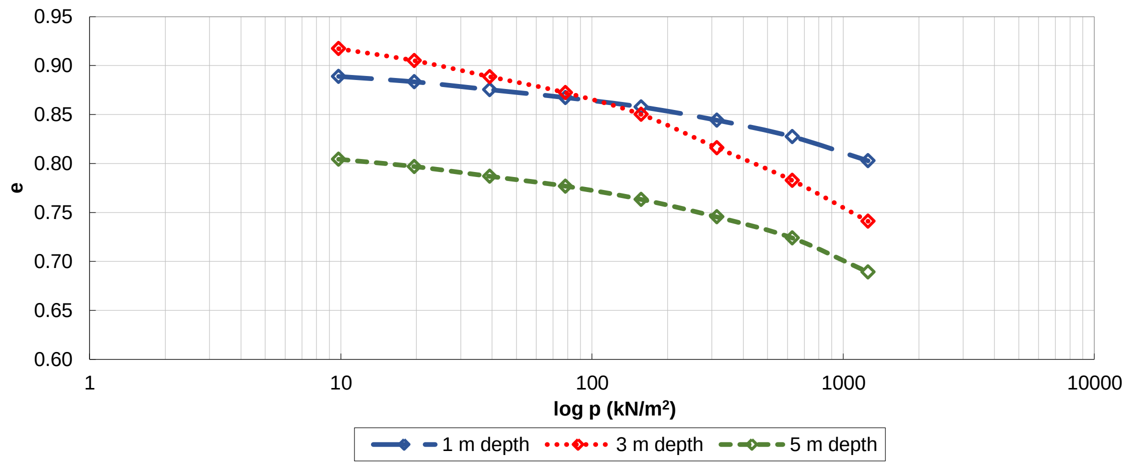


Figure 4.17 e versus log p curve at Location 4

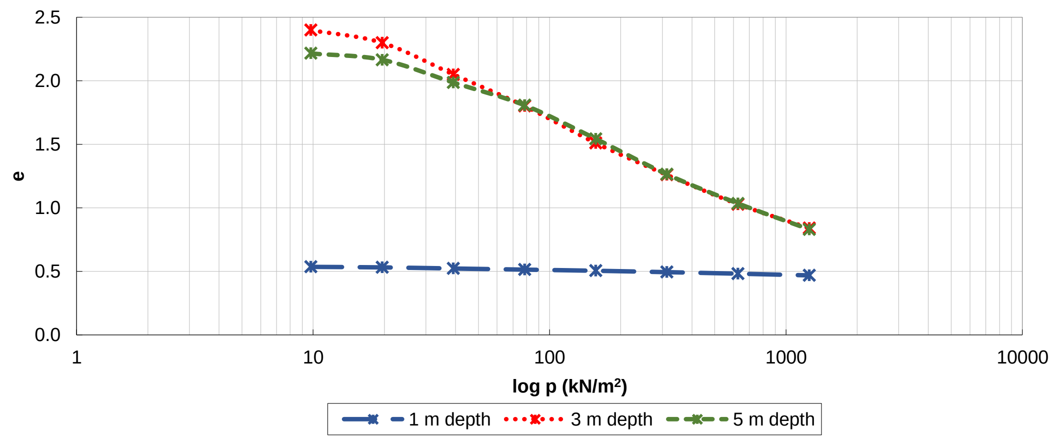


Figure 4.18 e versus log p curve at Location 5

In order to represent the sediment layer in each location, the graph of D_{50} of sediment was made and presented in Figure 4.19 to Figure 4.20. D_{50} is defined as value of particle diameter at 50% in the cumulative distribution, where 50% of the grain size is coarser and 50% of the grain size is fines. D_{50} is also known as the average particle size (Viswanadhan) or the mean grain size of the soil (Hakam, 2016).

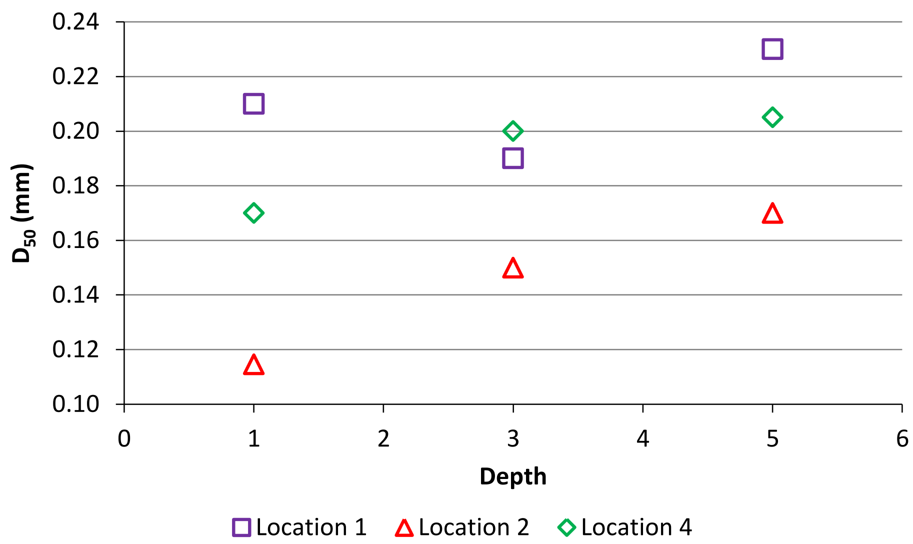


Figure 4.19 D_{50} graph for Location 1, Location 2 and Location 4

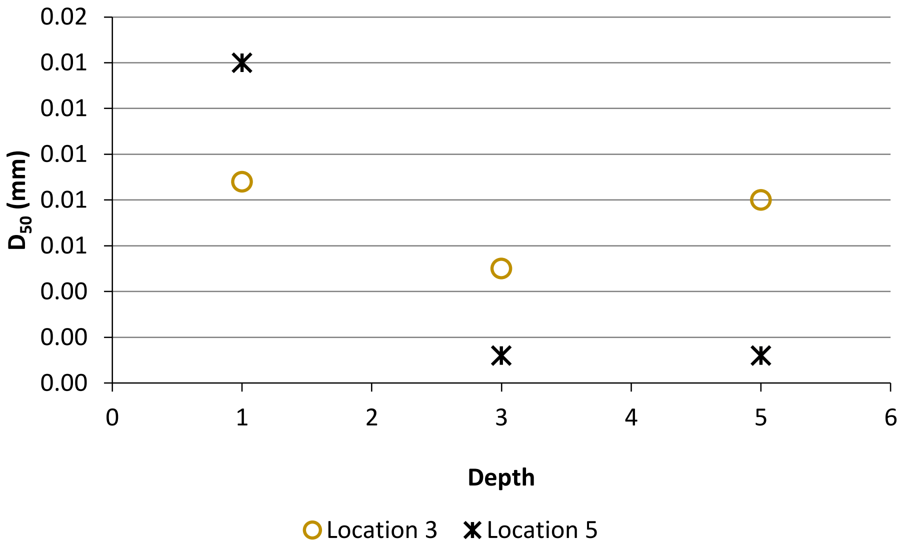


Figure 4.20 D_{50} graph for Location 3 and Location 5

By using sediment material soil type and D_{50} value, the condition of sediment material is illustrated as presented in Figure 4.21

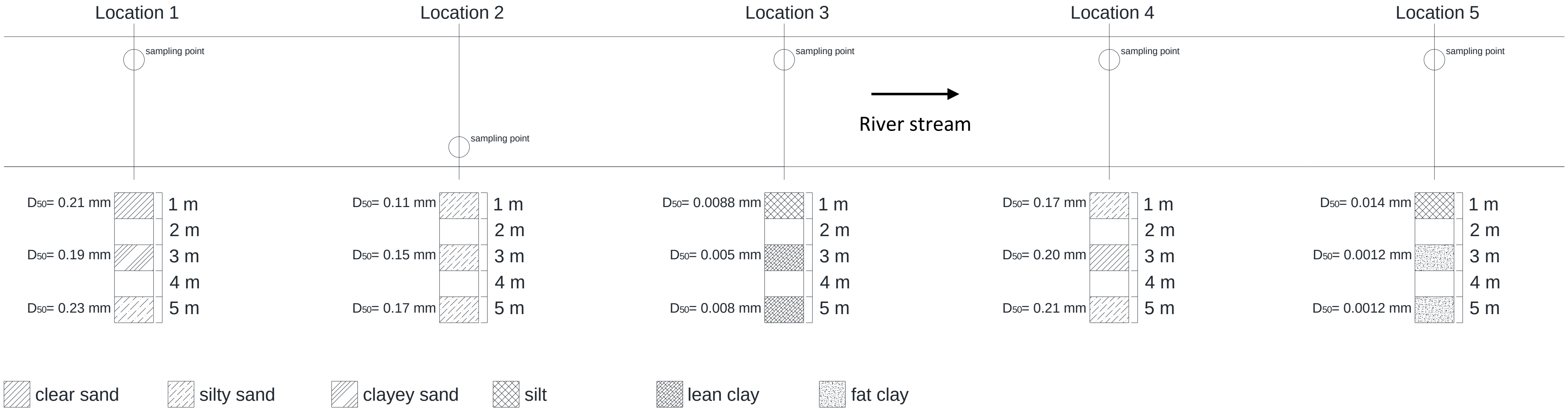


Figure 4.21 Illustration of sediment layer in each location

4.4 Shear Strength of Sediment as Indicator of Dredging Method in Bengawan Solo River

As explained before, properties of sediment undergo alteration as the result of consolidation and mechanical compaction process. One alteration on properties of sediment is the alteration of shear strength of sediment. Consolidation and mechanical compaction process begins and the shear strength of sediment starts to change when there is loading application on the sediment. Loading application happens on the sediment due to the self-weight of sediment layer. Therefore, it can be said that the alteration of shear strength of sediment is caused by the alteration of loading application in the form of self-weight of sediment layer.

The result of direct shear test in order to obtain shear strength of sediment is presented in Appendix E. Meanwhile, the distribution of shear strength of sediment material is presented in Figure 4.22. It can be seen from Figure 4.22 that downstream area with sand soil has higher shear strength, range from 21.90 kPa to 45.91 kPa, than estuary area with clay soil, range from 4.93 kPa to 18.04 kPa. The distribution of shear strength of sediment material based on the depth exhibits that shear strength increase as the depth increases. The result is caused by overburden pressure as shear strength depends on unit weight and depth (thickness). Meanwhile based on the location of sediment sampling, the distribution of shear strength of sediment material is appropriate with the soil type.

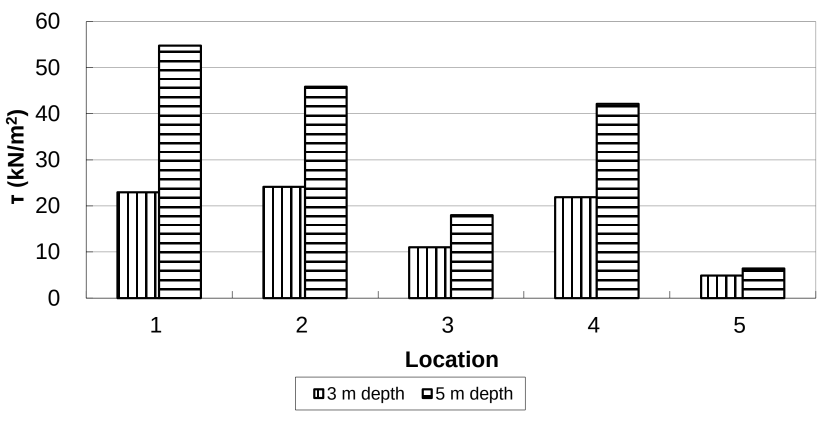


Figure 4.22 Distribution of shear strength

In addition affected by overburden pressure (from dry unit weight and depth/thickness), shear strength is affected by cohesion and internal friction angle as well. The relation between shear strength with overburden pressure and dry unit weight, as the factor to determine overburden pressure is presented in Figure 4.23 and Figure 4.24. From Figure 4.23 and Figure 4.24, it if found out and clearly seen that shear strength increases as overburden pressure and dry unit weight increases. Meanwhile, the relation between shear strength and internal friction angle is represented by the factor which influence internal friction angle such as D_{50}, coefficient of uniformity, percentage of sand and presented in Figure 4.25 to Figure 4.27.

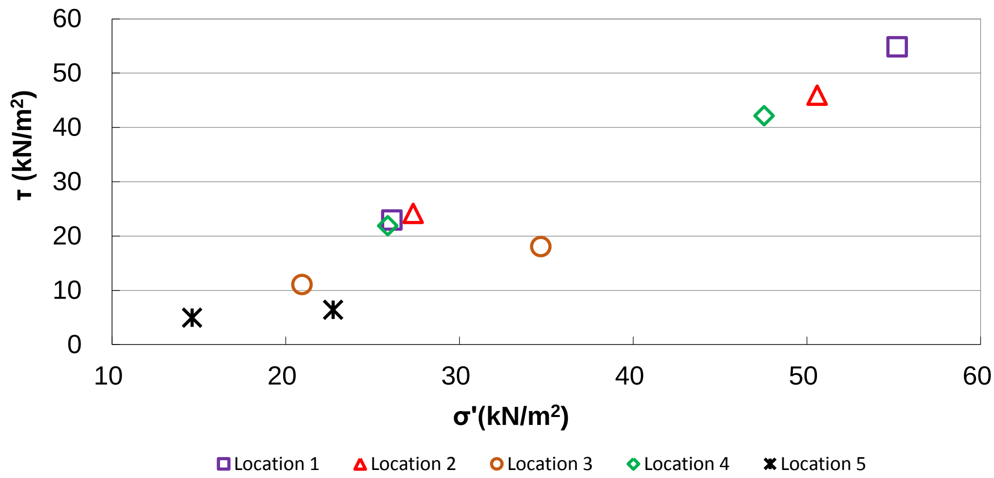


Figure 4.23 Relation between overburden pressure versus shear strength

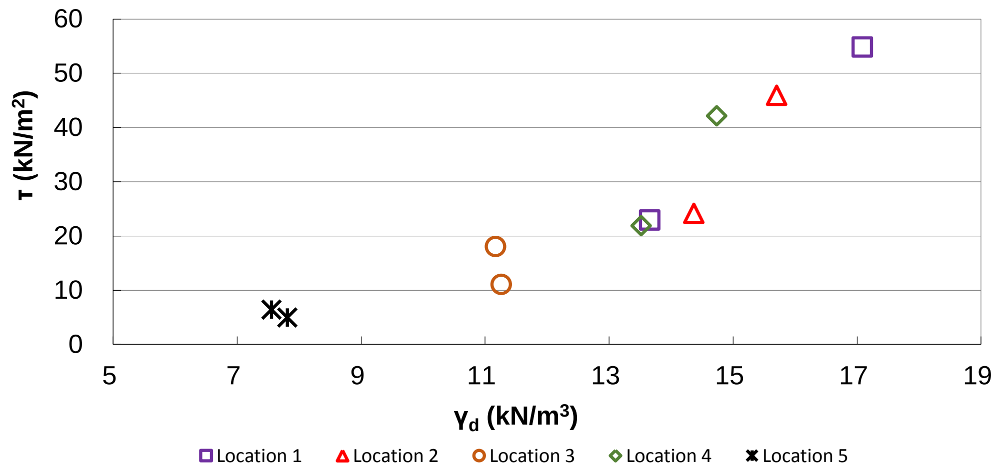


Figure 4.24 Relation between dry unit weight versus shear strength

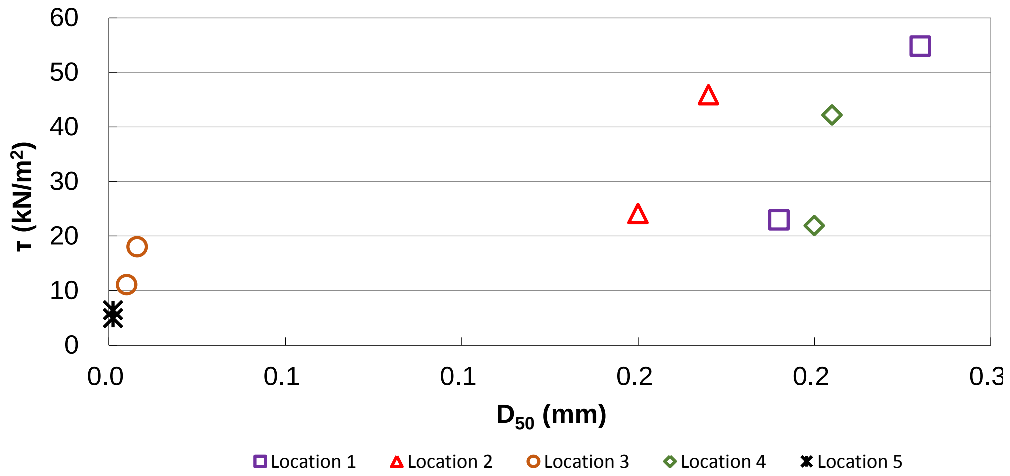


Figure 4.25 Relation between D_{50} versus shear strength

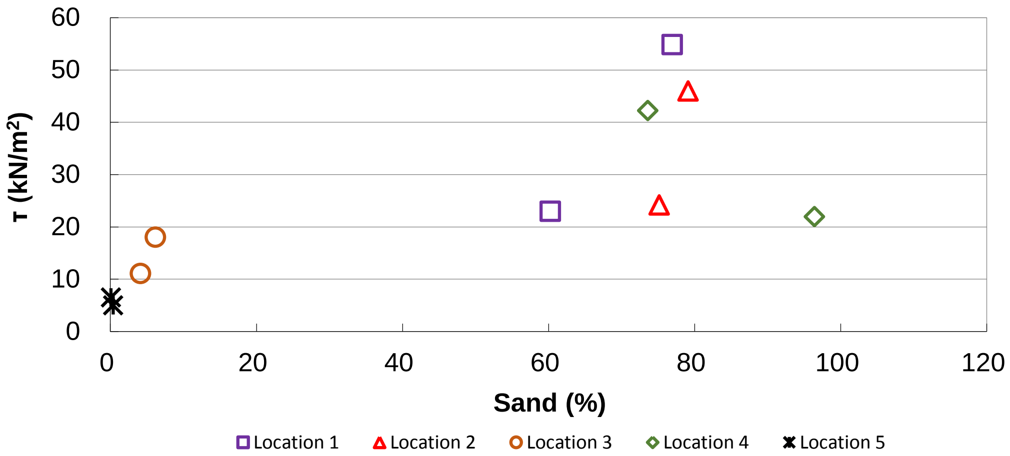


Figure 4.26 Relation between percentage of sand versus shear strength

Despite shear strength is determined by internal friction angle as well, yet the greater influence in determination of shear strength of sediment material is overburden pressure. From Figure 4.25 to Figure 4.27, it could be seen the tendency that shear strength increases when D_{50}, percentage of sand and coefficient of uniformity increases even though the trend is irregular. According to Kara et al (2013) and Vangla and Gali (2016), with the same void ratio, the size of particle does not seem to have significant influence on internal friction angle. It means the size of particle also does not seem to have significant influence on shear strength. Rather than particle size parameters, internal friction angle and shear strength are more affected by the density of sediment and connection among particles.

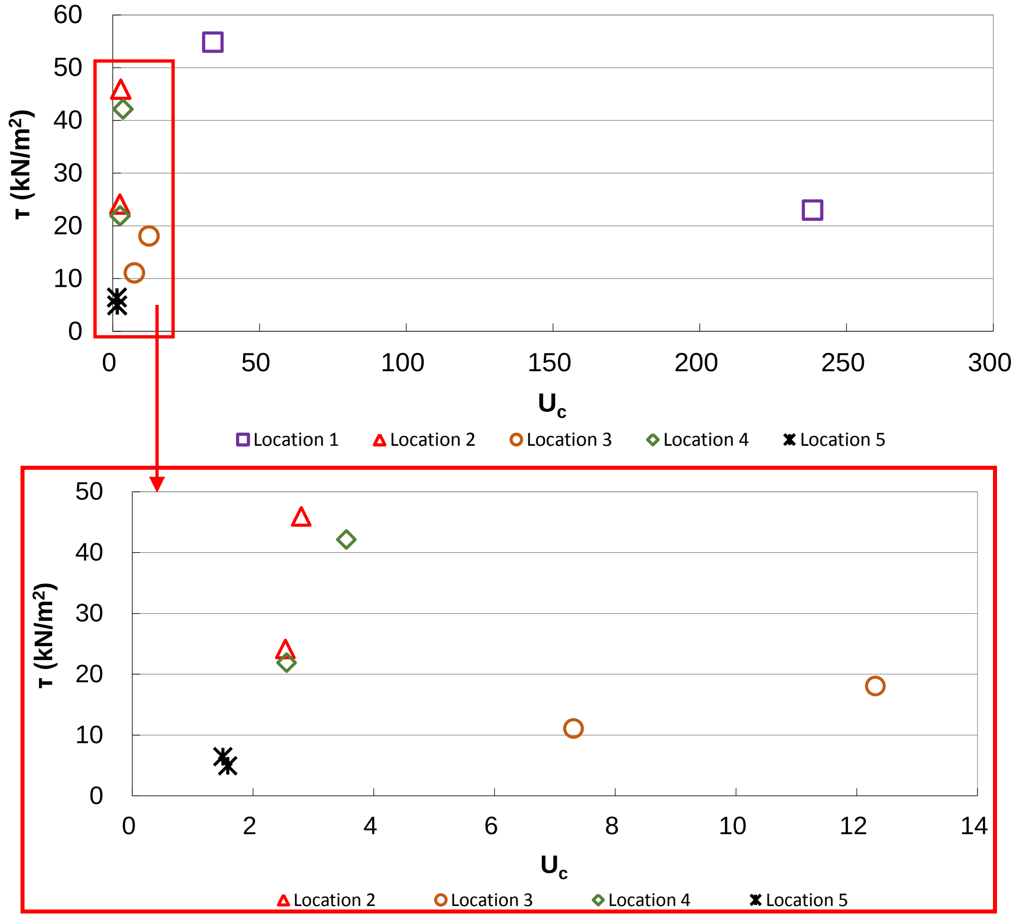
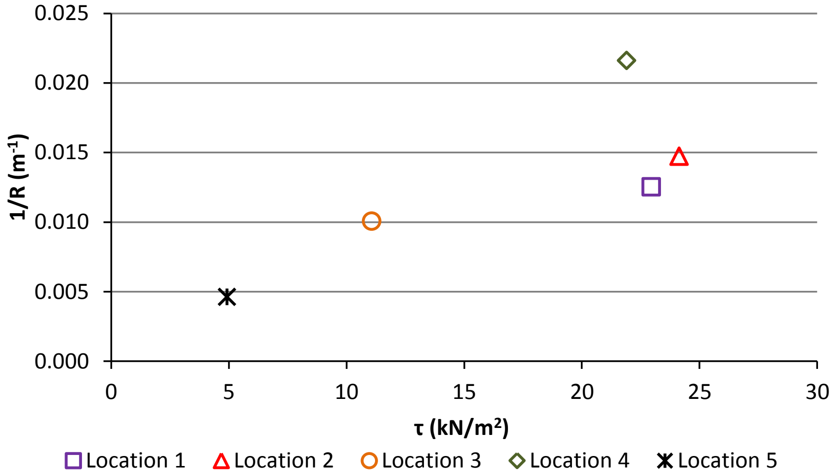


Figure 4.27 Relation between coefficient of uniformity versus shear strength

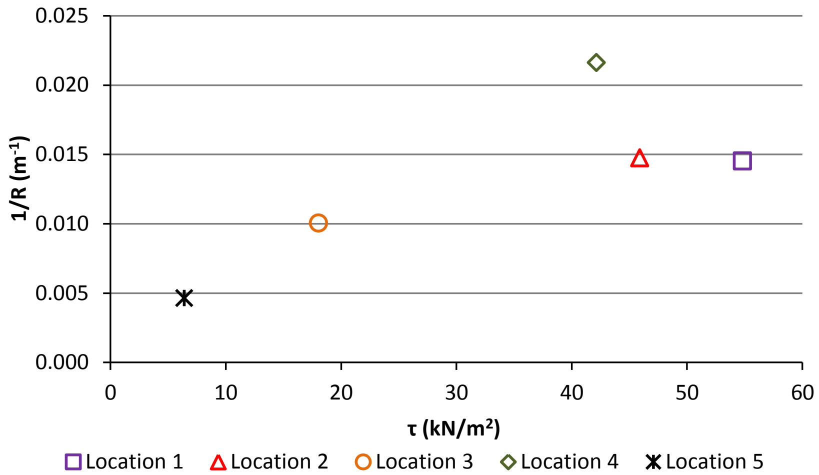
However, different statement was issued by Ahsan et al (2014). Ahsan et al (2014) said that there is linear increasing trend in the internal friction angle value with higher uniformity coefficient. At a certain relative density, angle of internal friction tends to increase with increasing value of uniformity coefficient. Dewangan et al (2015) confirmed the assumption by saying that higher of coefficient of uniformity which in better interlocking and packing among the rock fragment leads to higher shear strength. Particle size affects the shearing strength by influencing the amount of shearing displacement required to overcome interlocking and to bring the grains to a free sliding position.

In Figure 4.27, the irregularity of the trend is possibly caused by the presence of higher fines content which results in reduction of friction angle and thus, reduction of shear strength (see the result of Location 3 and 5). Meanwhile for other results, the irregularity is possibly caused by the application of direct shear test which has some disadvantages. The disadvantages of direct shear test which might be related are (1) failure plane is forced to occur at joint in box, and (2) principal shear stress could not be determined appropriately.

Since sedimentary environment has influence in the properties of sediment material as well as in the shear strength of sediment, the relation between shear strength and hydraulic perimeter is presented in Figure 4.28. From Figure 4.28, it is found the tendency that shear strength of sediment material increases when the river has low hydraulic perimeter (high 1/R) which indicates high flow velocity.



(a)



(b)

Figure 4.28 Relation between shear strength versus hydraulic perimeter (a) 3 m depth (b) 5 m depth

a. Comparison of Shear Strength and Critical Shear Stress of Sediment Material

Sediment material experiences erosion when the shear stress caused by water flow or river stream exceeds the resisting forces of sediment on top of river bed and also the self-weight of particles (Bianco, 2014). The resisting force of sediment material on top of river bed is influenced by particle diameter. The resisting force is a limit value which determined whether the sediment is able to be moved by river stream or not. The resisting force is also known as critical shear stress. The approximate values of critical shear stress are presented in Figure 4.29 based on Table 1 of Appendix B.

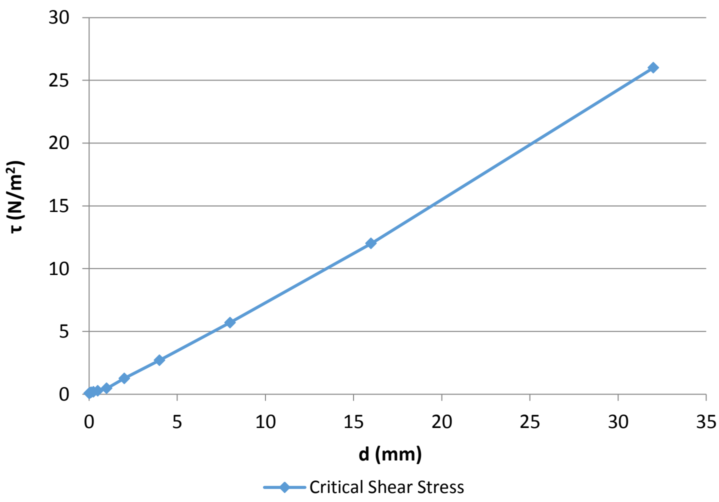


Figure 4.29 Critical shear stress of sediment influenced by particle diameter

Shear strength of sediment material obtained from laboratory test then compared with critical shear stress of sediment particles (see Figure 4.29) in order to determine whether sediment material is able to be moved by river stream. And if it is able to be moved by river stream which mean critical shear stress is greater than shear strength, the natural erosion is happened and hence, sediment removal is not necessary. However, if shear strength is greater than critical shear stress, it indicates that sediment material cannot be eroded naturally and hence, sediment removal is necessary. The comparison between lowest shear strength of sediment (at Location 5) and critical shear stress of sediment which influenced by particles diameter is presented in Figure 4.30.

From Figure 4.30, it can be seen that lowest shear strength of sediment material is much greater than critical shear stress of sediment influenced by particle diameter. It indicates that sediment material cannot be eroded by river stream naturally. Therefore, dredging is necessary to remove excessive sediment material deposited on top of river bed.

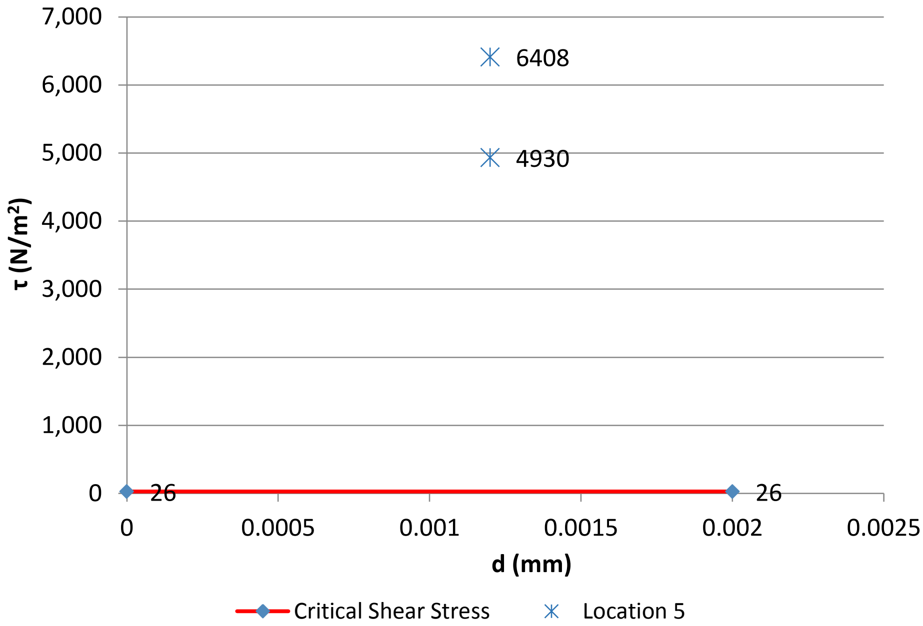


Figure 4.30 Comparison of lowest shear strength and critical shear stress

b. Dredging Method in Bengawan Solo River

Having known that dredging is necessary to remove excessive sediment material on top of river bed by comparing the shear strength of sediment with critical shear stress influenced by particle diameter, then the next step is determine the dredging method. In current research, there are four references of dredging methods which are water injection dredger, ploughing, plain suction dredger and grab dredger. Each dredging method has limitation to dredge the sediment. Water injection dredger has the lowest limitation (< 5 kN/m^2) while grab dredger has the highest limitation (< 300 kN/m^2). Appropriate dredging method determined by comparing the shear strength of sediment material with the limitation of each dredging method which presented in Figure 4.31.

From Figure 4.31, it could be seen that dredging by water injection dredger is appropriate for 3 m depth sample at Location 5 because the limitation for water injection dredger is $\tau < 5$ kPa. Ploughing and plain suction dredger is appropriate for 5 m depth sample at Location 5, 3 m depth sample and 5 m depth sample at Location 3, because the limitation for ploughing and plain suction dredger is $\tau < 20$ kPa. Meanwhile for other samples which $\tau > 20$ kPa, it is appropriate to use grab dredger which has limitation $\tau < 300$ kPa.

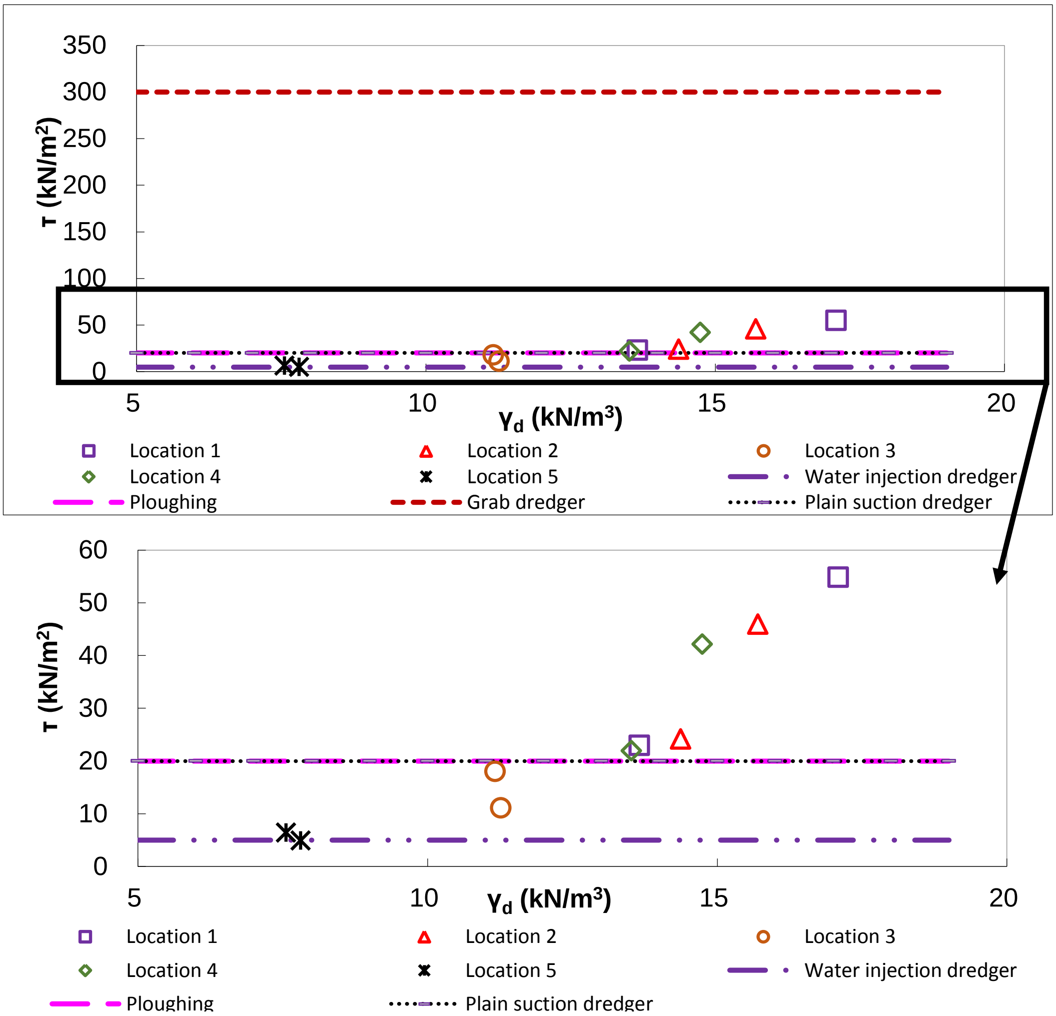


Figure 4.31 Limitation of dredging method

Other than that, from Figure 4.31 also could be known that application of dredging method with small capacity cannot be used anymore because the limitation for small capacity dredging method is 20 kPa while most of sediment have shear strength greater than 20 kPa and thus, requires dredging method with large capacity to remove the excessive sediment. In the future, if preferable to use dredging method with small capacity such as ploughing or plain suction dredger, the sediment should has shear strength less than 20 kN/m^2 with dry unit weight range from 10 kN/m^3 to 13 kN/m^3. Monitoring of condition of sediment material can be focused on the location with low hydraulic perimeter where erosion is more dominant and has high shear strength.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In current research, sediment material on top of river bed of Bengawan Solo River was investigated. The conclusions are as follows:

1. The soil type of sediment material based on the depth is relatively similar with varies properties distribution due to subsequent erosion and deposition over times. Meanwhile based on the location of sediment sampling, sediment material is broadly grouped into sand sediment which found at downstream area and clay sediment which found at estuary area, also with varies properties distribution which appropriate with the soil type due to the behavior of soil itself.
2. Properties of sediment material have relation among them, where one property is influenced by other property. For example, increase in dry unit weight results in decrease of water content, void ratio and percentage of fine particles. Besides that, properties of sediment material were related to sedimentary environment. Dry unit weight of sediment increases as deeper sampling depth, wider sectional area of river and lower flow velocity.
3. Sediment material at Bengawan Solo River experienced erosion and deposition over times. Erosion is more dominant at Location 1, 2 and 4, while deposition is more dominant at Location 3 and 5.
4. Shear strength of sediment material at Bengawan Solo River experiences alteration. The alteration of shear strength of sediment is caused by the alteration of loading application in the form of self-weight of sediment layer. Sediment material at Bengawan Solo River cannot be eroded by river stream naturally and thus, dredging is necessary to remove the excessive sediment. Dredging method with large capacity is required because the sediment has shear strength greater than the limitation of small capacity dredging method (> 20 kN/m^2). In the future, if preferable to use dredging method with small capacity, the sediment should has shear

strength less than 20 kN/m^2 with dry unit weight range from 10 kN/m^3 to 13 kN/m^3. Monitoring of condition of sediment material can be focused on the location with low hydraulic perimeter where erosion is more dominant and has high shear strength.

5.2 Recommendations for Future Research

Based on current research, the following additional studies and measurements are recommended:

1. Sampling of sediment material should be done periodically following the weather condition (dry season and monsoon season cycle), including measurement of thickness of sediment layer.
2. Measurement of other influencing parameters at sampling locations, such as flow velocity for different level of water depth, in order to understand more regarding the relation between properties of sediment material and its sampling location.
3. Additional laboratory tests such as scanning electron microscope (SEM) and x-ray diffraction (XRD) in order to understand the mineral composition of sediment and also triaxial test in order to obtain more accurate value of shear strength of sediment material.

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APPENDIX A

LOCATIONS OF SEDIMENT MATERIAL SAMPLING

Location 1

Location 2

Location 3

Location 4

Location 5

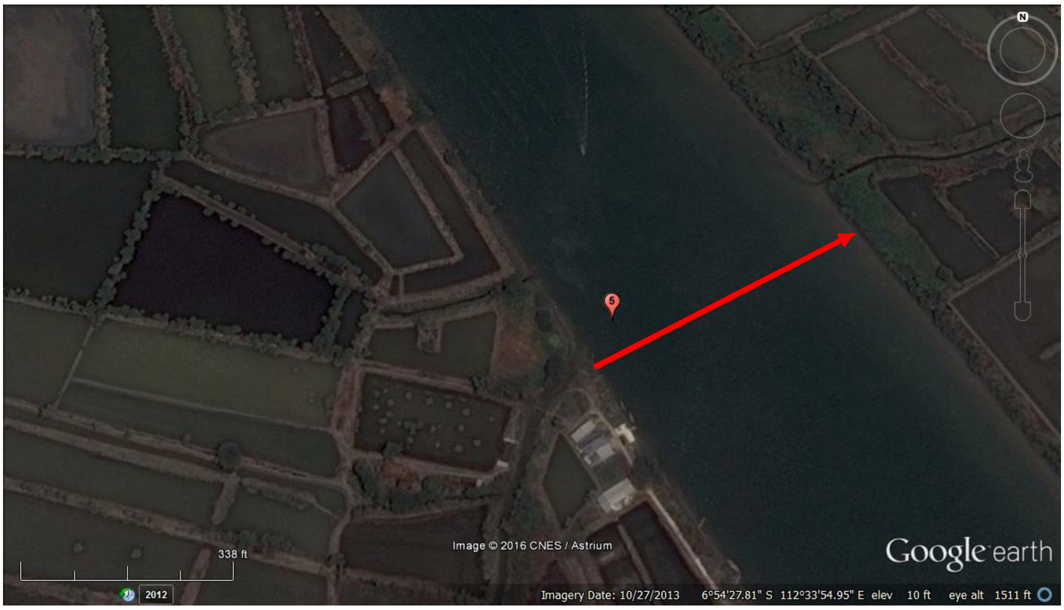
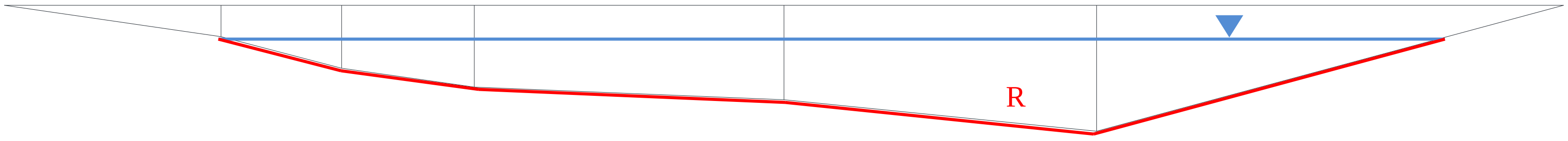
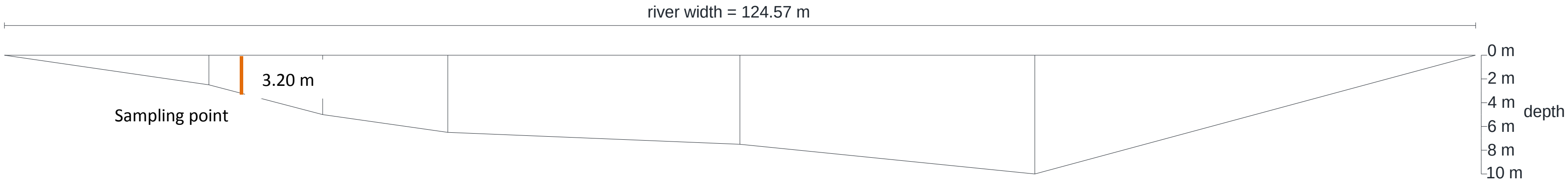


Image © 2016 CNES / Astrium
338 ft
2012
Imagery Date: 10/27/2013
6°54'27.81" S 112°33'54.95" E elev 10 ft eye alt 1511 ft
Google earth



Cross-Section 1



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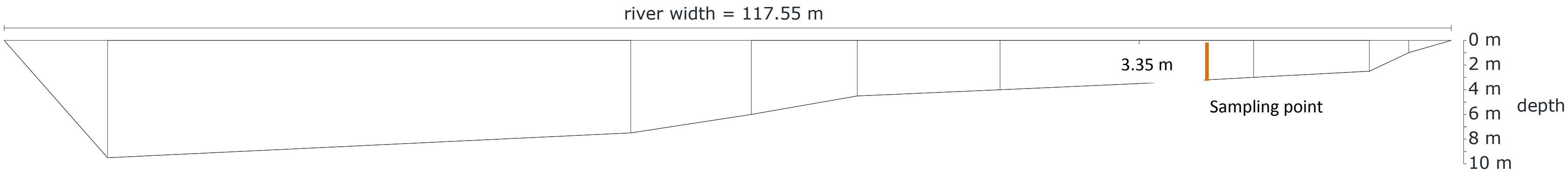

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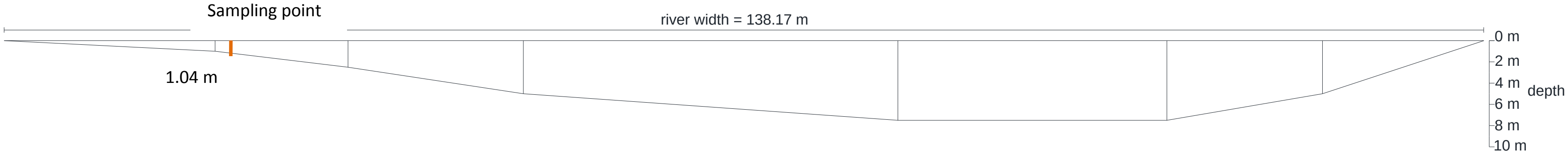

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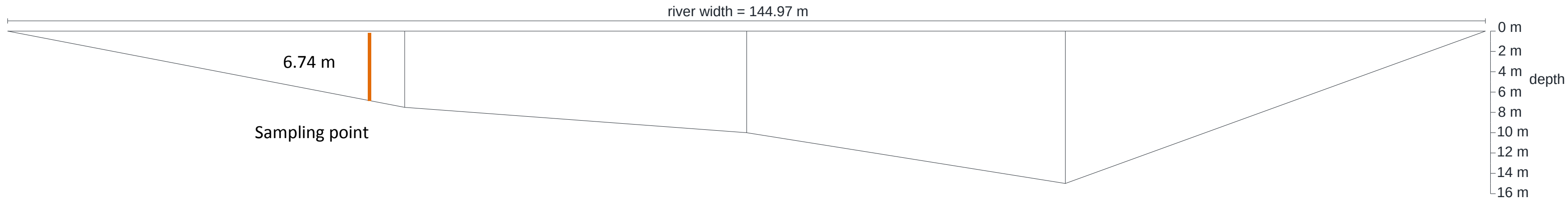
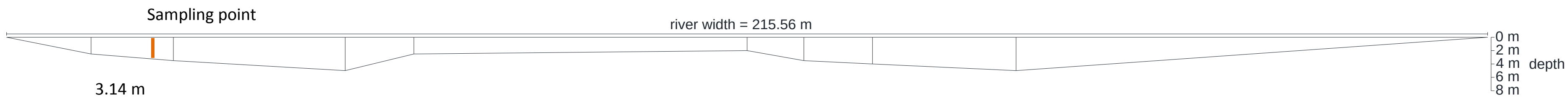


Cross-Section 5



APPENDIX B
PROPERTIES OF SEDIMENT MATERIAL

1. Physical Properties of Sediment

a) Mass density (ρ) and Unit weight (γ)

The mass density of solid particles (ρ_s) describes the solid mass per unit volume. Unit weight (γ) is the ratio of the total weight to the total volume of the soil aggregates which also equals to the product of the mass density of a solid particle times the gravitational acceleration (g). This is sometimes referred to as moist unit weight since it includes the weight of water and the soil solids. If the entire void space is filled with water, it is a saturated soil with submerged unit weight (γ_{sat}) where the unit weight of solid particle, submerged in a fluid of unit weight equals the difference between the two unit weights. If no water in void space, it is a dry soil with dry unit weight (γ_{dry}) as the ratio of the weight of soil solids to the total volume.

b) Water content (w_c)

Water content or moisture content (w_c) defines as the ratio of the weight of water to the weight of soil solids in terms of its dry weight. It generally expressed as a percentage or on a volume basis as the ratio of volume of water present in the soil mass to volume of soil solids and volume of soil voids.

c) Specific gravity (G_s)

Specific gravity (G_s) defines as the ratio of the unit weight of a given material to the unit weight of water, with most of soil fall within a range of 2.6 to 2.9. Julien (2002) defines specific gravity as the ratio of the specific weight of a solid particle to the specific weight of fluid at a standard reference temperature (to distilled or pure water at 4^oC). Specific gravity is a dimensionless ratio of specific weight and its value remains independent of the system of units.

d) Void ratio (e)

Void ratio (e) defines as the ratio of the volume of voids to the volume of solids.

e) Porosity (n)

Porosity (n) is defined as the ratio of the volume of voids to the total volume. Julien (2002) defines porosity as a measure of the volume of void per total volume. The porosity of sediment material is often related to the deposition history of the sediment bed. Loose packing occurs when sediments settle from suspension in still water. Natural sediment with particles of various sizes has relatively small porosity values because the smaller particles can occupy the large void spaces.

f) Degree of saturation (S_r)

Degree of saturation (S_r) is the ratio of the volume of water to the volume of voids and is generally expressed as a percentage.

g) Grain size and grain distribution

Sediment material grain size can be used as an indicator of energy conditions. Fine grains usually are dominant in low-energy condition near river banks, on tidal flats, in protected or sheltered basins. Meanwhile coarse grains are found in high energy conditions near breaker bars along the coast and in the deeper channels of rivers and estuaries, where finer grains cannot easily survive due to strong streams. Besides specified by energy conditions, grain size is also specified by erosion and deposition process. Grain size decreases with distance from the source due to abrasion effect or erosion and deposition of fines in quiescent or idle conditions. Near the source, the size range usually is relatively wide (well-sorted), while a narrow size range (poorly-sorted) is found far away from the source (Julien, 2002).

Grain size distribution, as percentage by weight of material, is an attempt to determine the relative proportions of the different size which make up a given soil mass. Information obtained from grain size distribution leads to soil type through soil classification system such Unified Soil Classification System (U.S.C.S) or American Association of State Highway and Transportation Officials (ASSHTO). Grain size distribution procedure consists by two methods, which are mechanical method by using sieve analysis and hydrometer method. Sieve analysis is used to divide the particulate material into size fractions and then to determine the weight of these fractions. The distribution of particle sizes larger than 75 μm is determined by sieve analysis. Hydrometer analysis is used to obtain the percent clay (an estimation of the distribution of soil particle sizes from 0,075 mm to around 0,001 mm).

h) Liquid limit, plastic limit and plasticity index

Liquid limit is defined as the moisture content, in percent, at which the soil changes from a liquid state to plastic states. It also defined as water content below which the soil behaves as a plastic material, at this water content, the soil is on the verge of becoming a viscous fluid. Meanwhile, plastic limit is defined as the moisture content, in percent, at which the soil changes from a plastic to a semisolid state. It also defined as water content below which the soil is non-plastic. Plasticity index is defined as the difference between the liquid limit and the plastic limit of a soil. Skempton (1953) observed that the plasticity index of a soil linearly increases with the percent of clay-size fraction present in it.

2. Consolidation Properties of Sediment

a) Overconsolidation ratio (OCR)

A soil in the field at some depth has been subjected to a certain maximum effective past pressure in its geologic history, so has sediment material on river bed. This maximum effective past pressure may be equal to, greater than or less than the existing effective overburden pressure at present time. The ratio between maximum past effective overburden pressure (preconsolidation pressure) to present effective overburden pressure is called overconsolidation ratio. Overconsolidation ratio (OCR) leads to two basis definitions of soil based on stress history, which are normally consolidated soil with OCR $\leq$ 1 and overconsolidated soil with OCR > 1.

Sultan et al (2000) stated that overconsolidated is a characteristic of upper layer of sediments especially from 0 to 1 m depth. Sediment is consequently in a state of pre-stress and an additional mechanical loading produces an overconsolidated behavior. Overconsolidation effect is caused by mechanical loading due to erosion, uplift or overpressuring (Nygard et al, 2004). Mechanical or physicochemical plastic strains induce hardening of material which increases preconsolidation pressure.

b) Preconsolidation pressure (p'_c)

Preconsolidation pressure is the maximum effective past pressure. Variability in preconsolidation pressure acts at the depositional surface with overconsolidation due to deposition and erosion. By knowing preconsolidation pressure and overconsolidation, it is possible to calculate the thickness of eroded sediment (Brain et al, 2011).

c) Coefficient of consolidation (C_v)

Coefficient of consolidation (C_v) is defined as coefficient which governing the rate of consolidation process proceeds. Most settlement predictions are done using average values for coefficient of consolidation (Mitchel and Soga, 2005). Coefficient of consolidation generally decreases as the liquid limit of soil increase.

d) Coefficient of compressibility (m_v)

Coefficient of compressibility (m_v) is defined as coefficient which governing the relative volume change of soil as a response to a pressure change. The change in void ratio is often written in terms of compression index or coefficient of compressibility.

e) Hydraulic conductivity (k)

Hydraulic conductivity (k) is soil property which determined the ability of fluid through pore spaces or fractures of soil matrix system under a specific hydraulic gradient. The ratio of velocity to hydraulic gradient indicates permeability of porous media. The dimension of hydraulic conductivity is length per unit of time.

Hydraulic conductivity can be a function of void ratio or effective stress. It also depends on the soil grain size, the structure of soil matrix or intrinsic permeability of soil, the type (density and viscosity) of soil fluid and the relative amount of soil fluid (degree of saturation) present in the soil matrix. Lower hydraulic conductivity of soil, longer time required for pore pressure to dissipate (Mitchel and Soga, 2005).

3. Shear Strength Properties of Sediment

a) Internal angle friction (ϕ)

The angle of (natural) repose (ϕ) is a behavioral property of sand particles which measure the ability of a unit of rock or soil to withstand a shear stress. Grains piled up on each other have an equilibrium slope which is called the angle of natural repose. This parameter appears to be a function of size, shape and porosity. The angle of repose, also referred to as the angle of internal friction, is a characteristic angle related to the particle stability on a horizontal or sloping bed (Rijn, 1993).

Friction angle is defined as the angle between the line through particle center and the point of contact with the line through the particle center normal to the bed surface. It is also defined as the angle which measured between normal force and resultant force that is attained when failure just occurs in response to a shearing stress. Friction angle is determined experimentally. It increases with increase in particle angularity, possibly as a result of an increase in coordination number. Friction angle contains resistance contribution from several sources, including sliding of grains in contact, resistance to volume change (dilatancy), grain rearrangement and grain crushing.

b) Cohesion (c)

Cohesion (c) is shear strength in excess of that generated by frictional resistance to sliding between particles, the rearrangement of particles and particle crushing. It also defined as cohesive force that takes place between adjacent particles. Cohesion resulted from adherence between particles in the absence of any externally applied or self-weight forces or refers to soil shear strength when the compressive stresses are equal to zero. Cohesion is possibly caused by cementation, electrostatic and electromagnetic attractions, and primary valence bonding and adhesion. Other than that, it is also caused by capillary stress and results as apparent cohesion (Mitchel and Soga, 2005).

c) Critical shear stress (τ_c)

Fluid forcing acting on a sediment particle resting on a horizontal bed consists of skin friction forces and pressure forces. The skin friction force acts on the surface of particles by viscous shear. The pressure force consisting of a drag and a lift force is generated by pressure differences along the surface of the particle. Particle movement will occur when the moments of the instantaneous fluid forces with respect to the point of contact are just larger than the stabilizing moment of the submerged particle weight. The previous explanation stated by Rijn (1993) which define critical shear stress. Meanwhile, Dingman (2009) simply defines critical shear stress to indicate the conditions under which entrainment will occur.

According to Shields, critical shear stress is a function of particle diameter at temperature of 10^{o}C, 20^{o}C and 30^{o}C. The approximate values of critical shear stress for non-cohesive particles can be obtained from the extended Shields diagram. The values from Julien (2002) for different particle size, as approximate reference values and also the grade scale commonly used in sedimentation, is presented in Table 1. To get crude approximations, a shear stress value of $\tau = 0.1$ Pa is sufficient to move silts but not sands and $\tau_c = 1$ Pa is sufficient to move sands but not gravels.

Table 1. Sediment Grade Scale and Approximate Properties by Julien (2002)

Class Name		Particle Diameter (d)	Angle of Repose (ϕ)	Critical Shear Stress (τ_c)
		mm	deg	N/m^2
Gravel				
	Very Coarse	>32	40	26
	Coarse	>16	38	12
	Medium	>8	36	5.7
	Fine	>4	35	2.71
	Very Fine	>2	33	1.26
Sand				
	Very Coarse	>1.000	32	0.47
	Coarse	>0.500	31	0.27
	Medium	>0.250	30	0.194
	Fine	>0.125	30	0.145
	Very Fine	>0.062	30	0.11
Silt				
	Coarse	>0.031	30	0.083
	Medium	>0.016	30	0.065
	Fine	>0.008		
	Very Fine	>0.004		
Clay				
	Coarse	>0.0020		
	Medium	>0.0010		
	Fine	>0.0005		
	Very Fine	>0.00024		

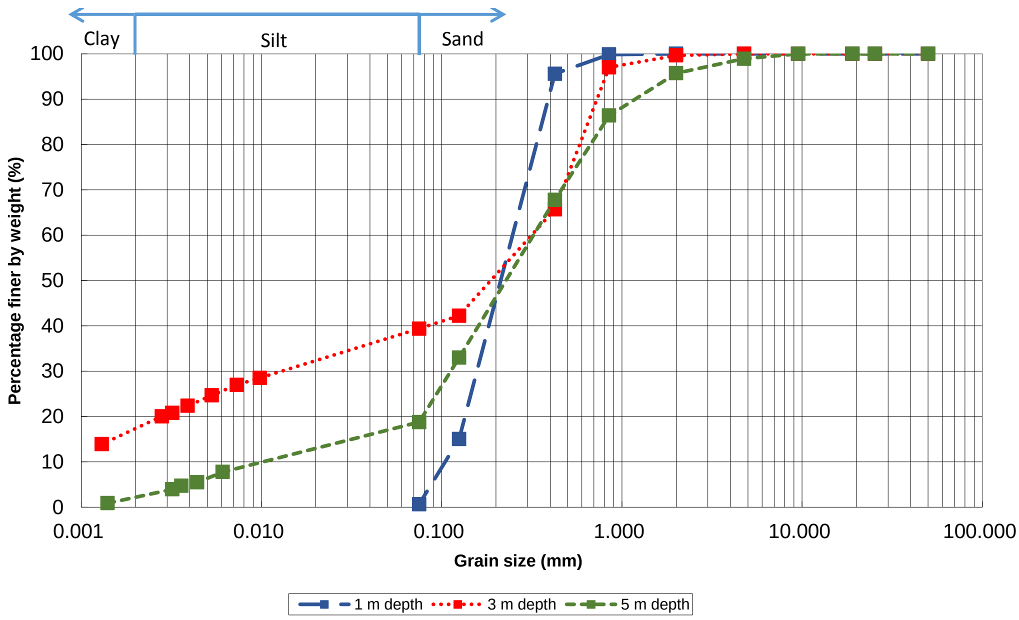
APPENDIX C

PHYSICAL PROPERTIES TEST RESULTS

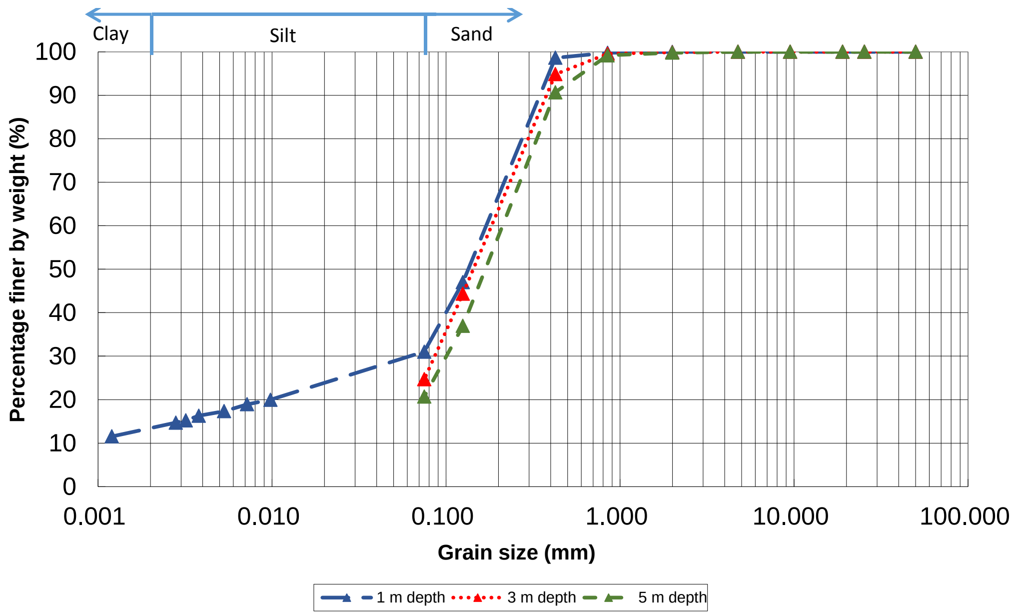
Physical Properties of Sediment Material

Depth	Location									
	1		2		3		4		5	
1	Clear Sand		Silty Sand		Silt		Silty Sand		Silt	
	w_c (%)	20.39	w_c (%)	38.64	w_c (%)	48.43	w_c (%)	24.02	w_c (%)	56.94
	γ_t (kN/m^3)	17.72	γ_t (kN/m^3)	16.80	γ_t (kN/m^3)	13.46	γ_t (kN/m^3)	17.74	γ_t (kN/m^3)	16.55
	γ_{sat} (kN/m^3)	19.54	γ_{sat} (kN/m^3)	17.51	γ_{sat} (kN/m^3)	15.52	γ_{sat} (kN/m^3)	18.94	γ_{sat} (kN/m^3)	16.60
	S_r (%)	59.63	S_r (%)	84.18	S_r (%)	68.17	S_r (%)	73.85	S_r (%)	90.95
	e	0.86	e	1.24	e	1.92	e	0.91	e	1.57
	n	46.17	n	54.75	n	65.72	n	47.56	n	58.69
	G_s	2.85	G_s	2.76	G_s	2.70	G_s	2.78	G_s	2.78
3	Clayey Sand		Silty Sand		Lean Clay		Clear Sand		Fat Clay	
	w_c (%)	30.67	w_c (%)	28.19	w_c (%)	47.76	w_c (%)	29.26	w_c (%)	83.60
	γ_t (kN/m^3)	17.84	γ_t (kN/m^3)	18.42	γ_t (kN/m^3)	16.64	γ_t (kN/m^3)	17.48	γ_t (kN/m^3)	14.34
	γ_{sat} (kN/m^3)	18.51	γ_{sat} (kN/m^3)	18.91	γ_{sat} (kN/m^3)	16.79	γ_{sat} (kN/m^3)	18.43	γ_{sat} (kN/m^3)	14.68
	S_r (%)	86.55	S_r (%)	88.92	S_r (%)	97.07	S_r (%)	80.26	S_r (%)	95.04
	e	0.98	e	0.86	e	1.29	e	1.00	e	2.27
	n	49.33	n	46.29	n	56.25	n	50.04	n	69.41
	G_s	2.75	G_s	2.73	G_s	2.63	G_s	2.76	G_s	2.63
5	Silty Sand		Silty Sand		Lean Clay		Silty Sand		Fat Clay	
	w_c (%)	15.61	w_c (%)	21.49	w_c (%)	46.34	w_c (%)	21.26	w_c (%)	87.12
	γ_t (kN/m^3)	19.75	γ_t (kN/m^3)	19.08	γ_t (kN/m^3)	16.34	γ_t (kN/m^3)	17.87	γ_t (kN/m^3)	14.14
	γ_{sat} (kN/m^3)	20.84	γ_{sat} (kN/m^3)	19.92	γ_{sat} (kN/m^3)	16.74	γ_{sat} (kN/m^3)	19.31	γ_{sat} (kN/m^3)	14.35
	S_r (%)	71.19	S_r (%)	79.94	S_r (%)	92.93	S_r (%)	67.89	S_r (%)	96.95
	e	0.62	e	0.76	e	1.32	e	0.87	e	2.25
	n	38.30	n	43.04	n	56.82	n	46.51	n	69.21
	G_s	2.83	G_s	2.81	G_s	2.64	G_s	2.82	G_s	2.51

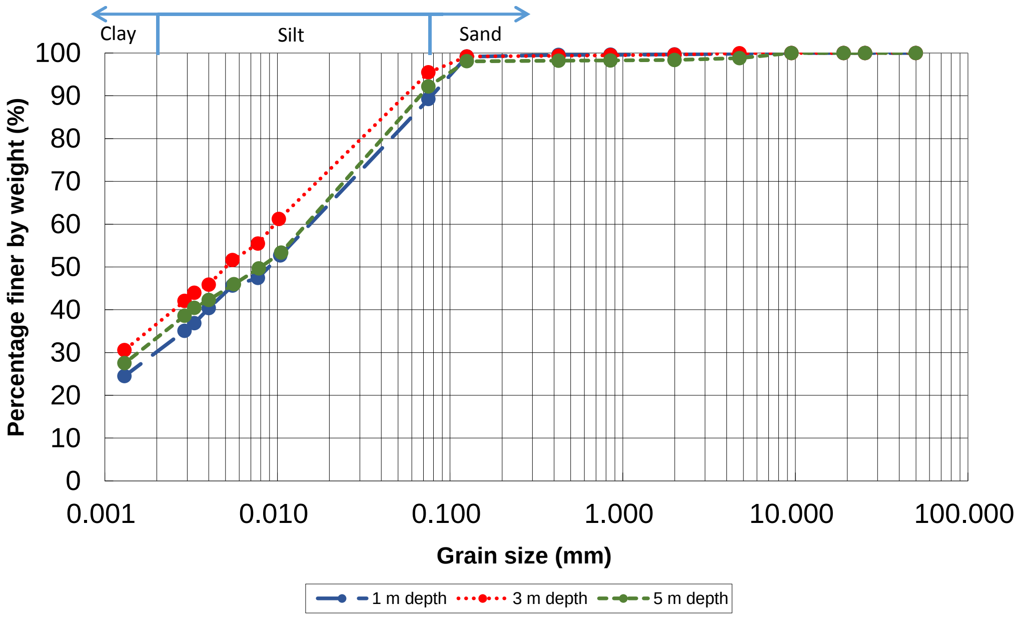
Grain Distribution Curve of Location 1



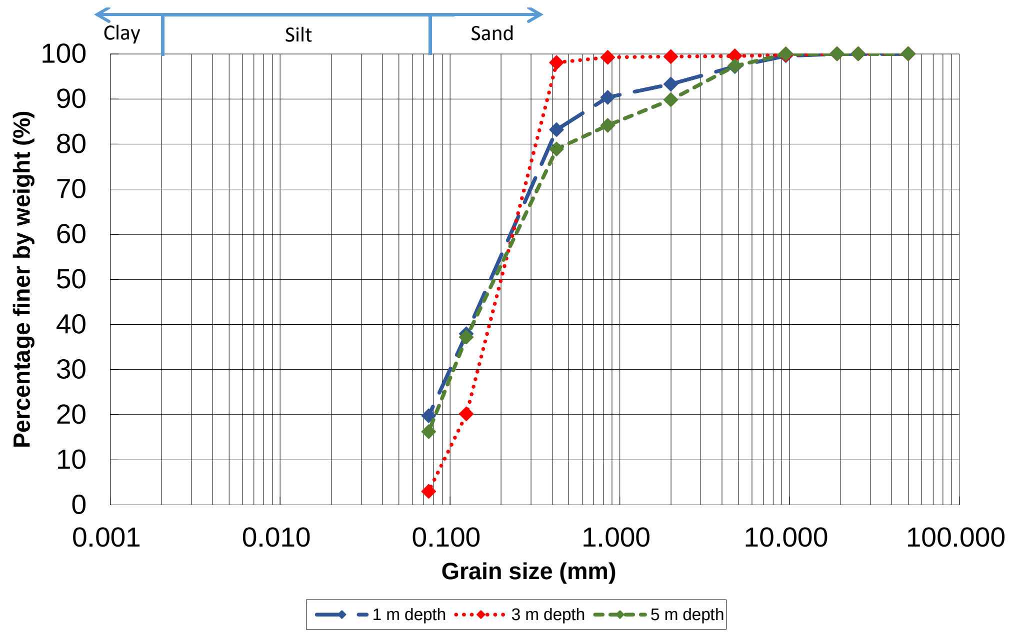
Grain Distribution Curve of Location 2



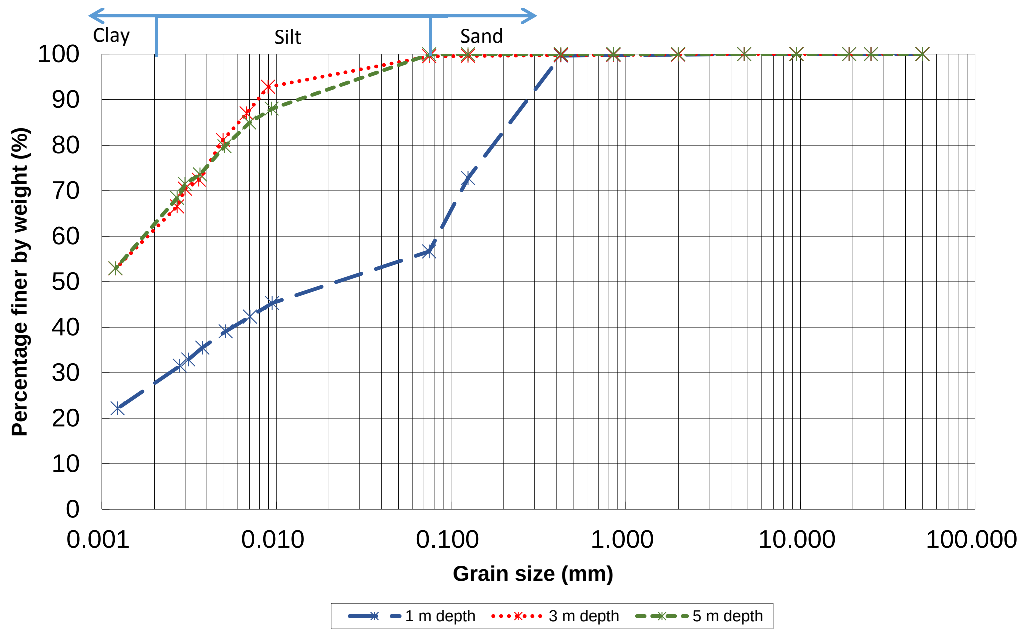
Grain Distribution Curve of Location 3



Grain Distribution Curve of Location 4



Grain Distribution Curve of Location 5



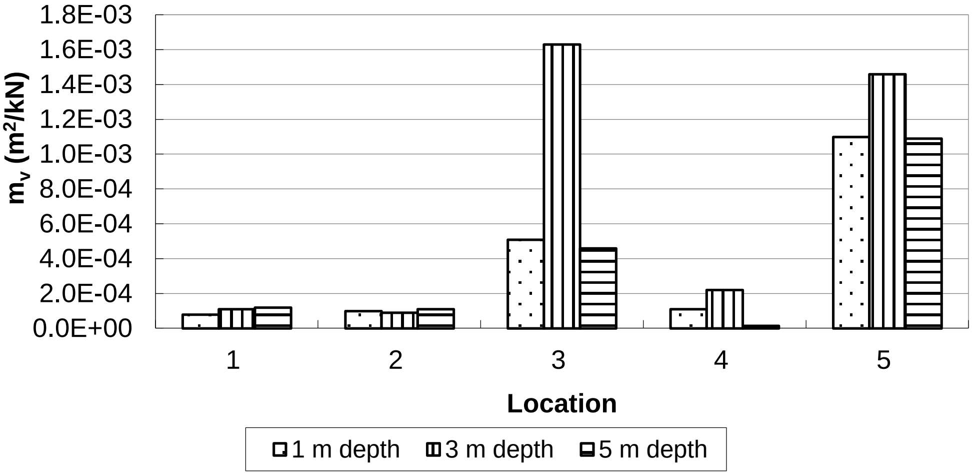
APPENDIX D

CONSOLIDATION TEST RESULTS

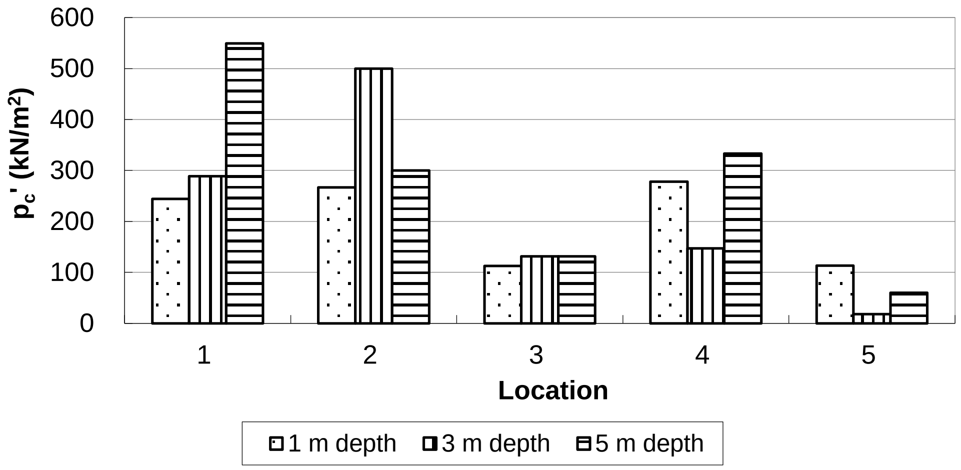
Consolidation Properties of Sediment Material

Variable	Unit	Depth (m)	Location 1	Location 2	Location 3	Location 4	Location 5
p'_c	kN/m^2	1	244.4	267	112.5	278	113.3
		3	288.9	500	131.25	147	18
		5	550	300	131.25	333.33	60
OCR		1	25.1	34.4	19.7	30.4	15.7
		3	11.1	18.3	6.3	5.7	1.2
		5	10	5.9	3.8	7	2.6
m_v	m^2/kN	1	0.00008	0.00010	0.00051	0.00011	0.00110
		3	0.00011	0.00009	0.00163	0.00022	0.00146
		5	0.00012	0.00011	0.00046	0.00002	0.00109
C_v	cm^2/d	1	235.35	141.19	24.85	140.93	31.07
		3	228.13	147.48	13.27	175.80	8.36
		5	459.6	99.96	17.96	116.02	10.04
k	cm/s	1	2.06E-08	1.56E-08	1.43E-08	1.70E-08	3.86E-09
		3	2.97E-08	1.57E-08	2.46E-08	4.44E-08	1.39E-08
		5	6.06E-08	1.29E-08	1.49E-09	2.00E-08	1.25E-08

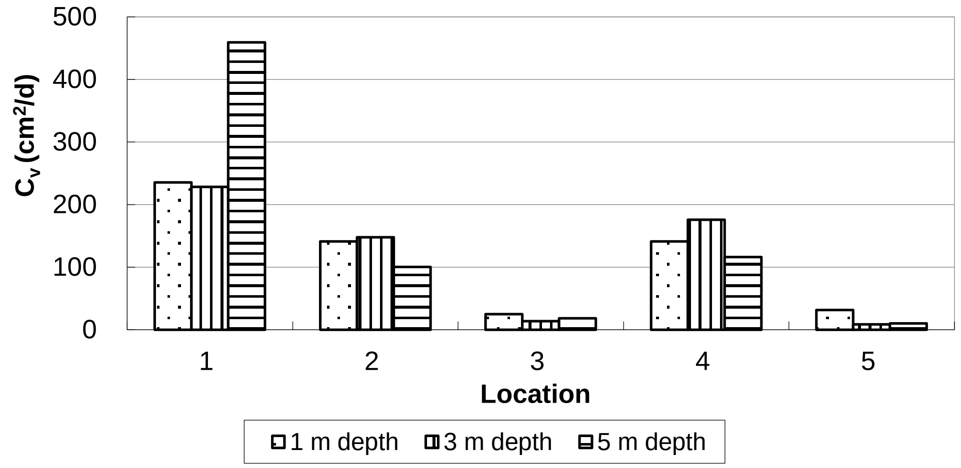
Distribution of Coefficient of Compressibility



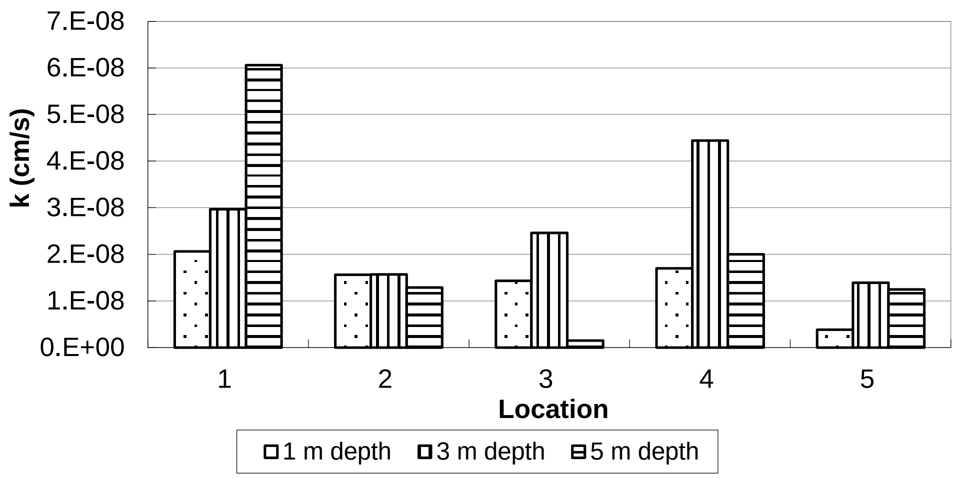
Distribution of Preconsolidation Pressure



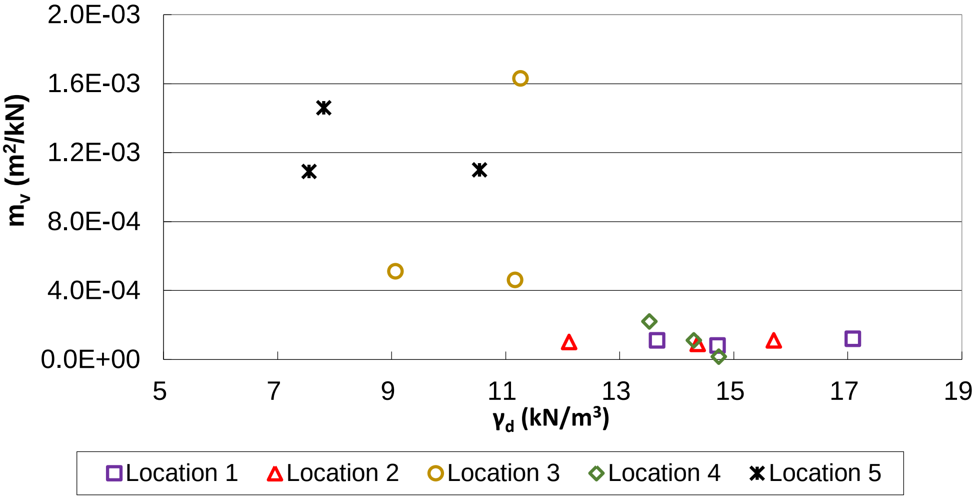
Distribution of Coefficient of Consolidation



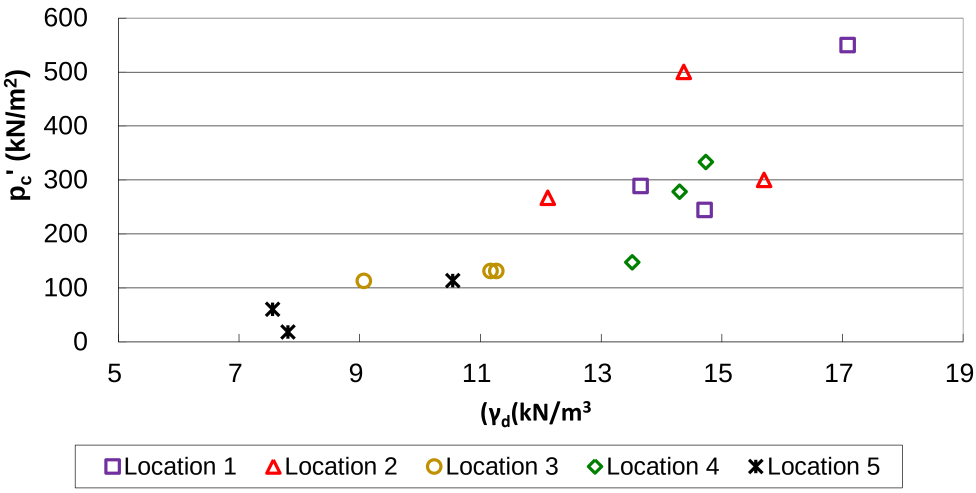
Distribution of Hydraulic Conductivity



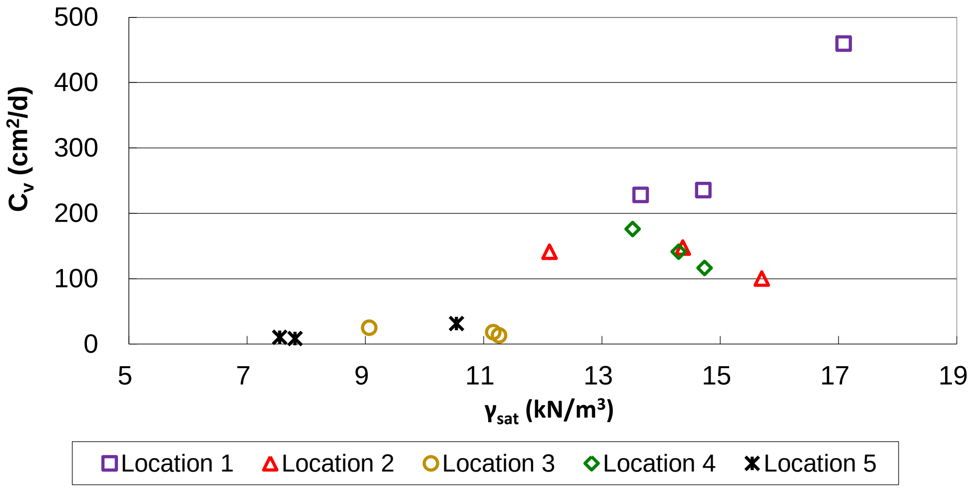
Relation between Dry Unit Weight versus Coefficient of Compressibility



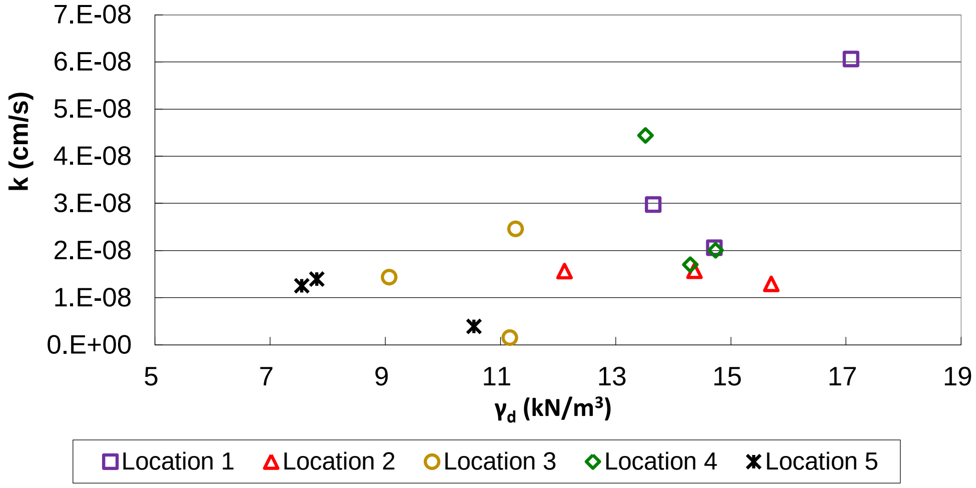
Relation between Dry Unit Weight versus Preconsolidation Pressure



Relation between Dry Unit Weight versus Coefficient of Consolidation



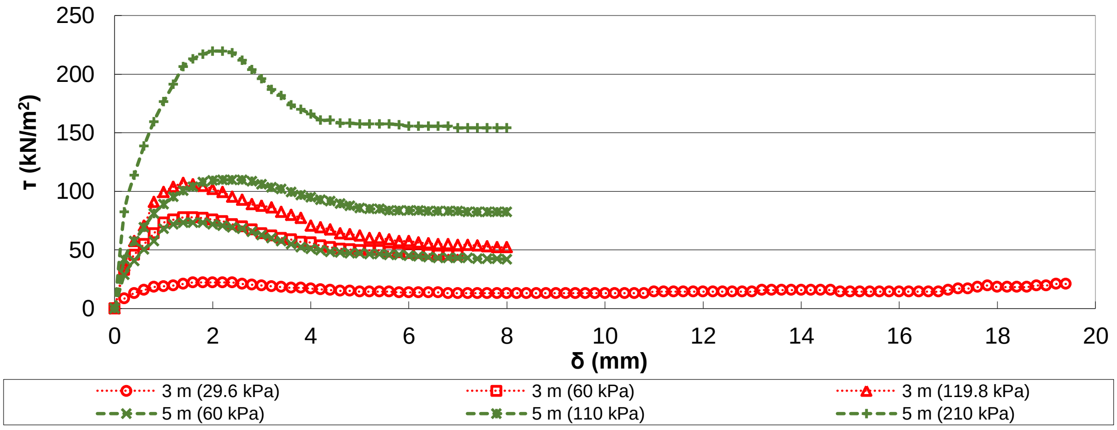
Relation between Dry Unit Weight versus Hydraulic Conductivity



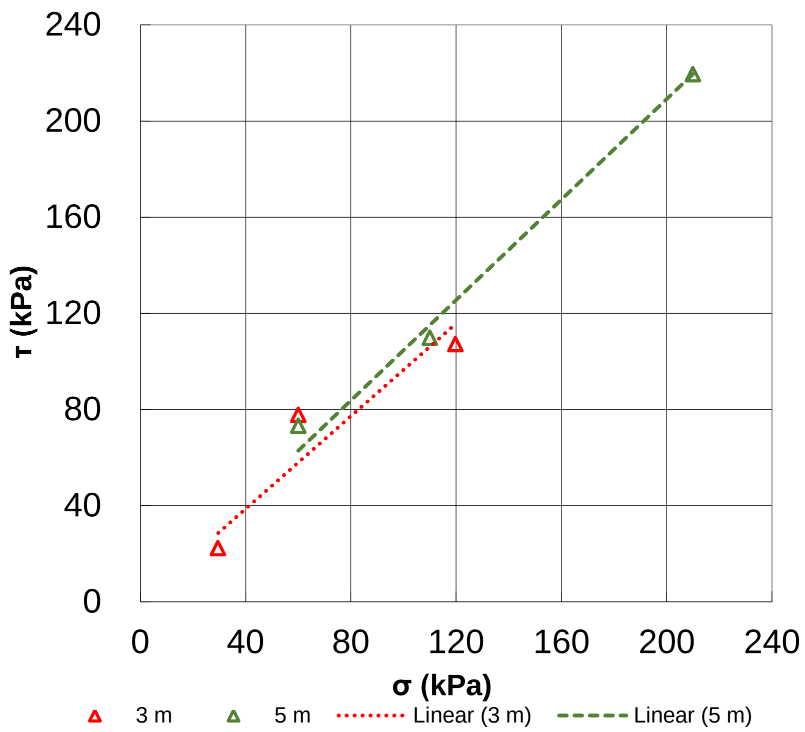
APPENDIX E

DIRECT SHEAR TEST RESULTS

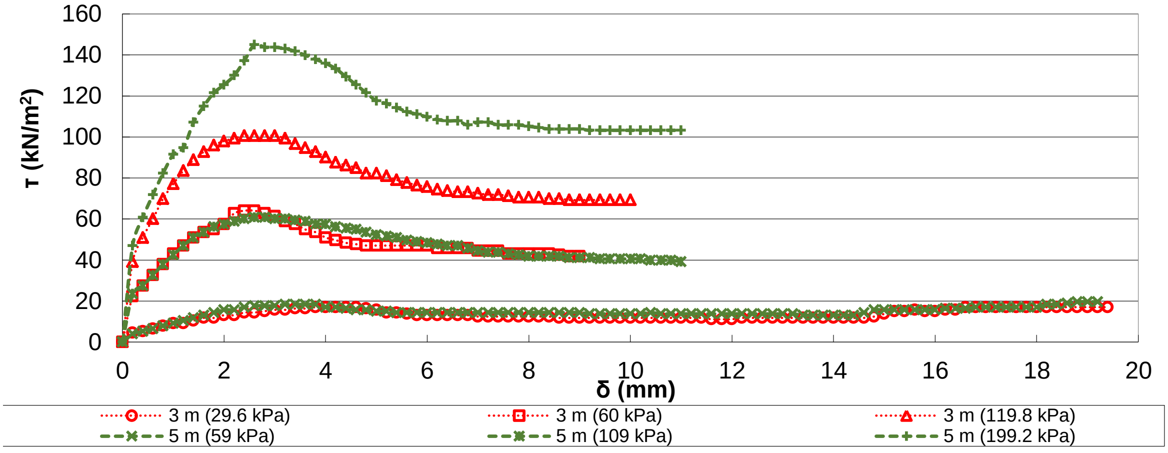
Shear Strength versus Displacement of Location 1



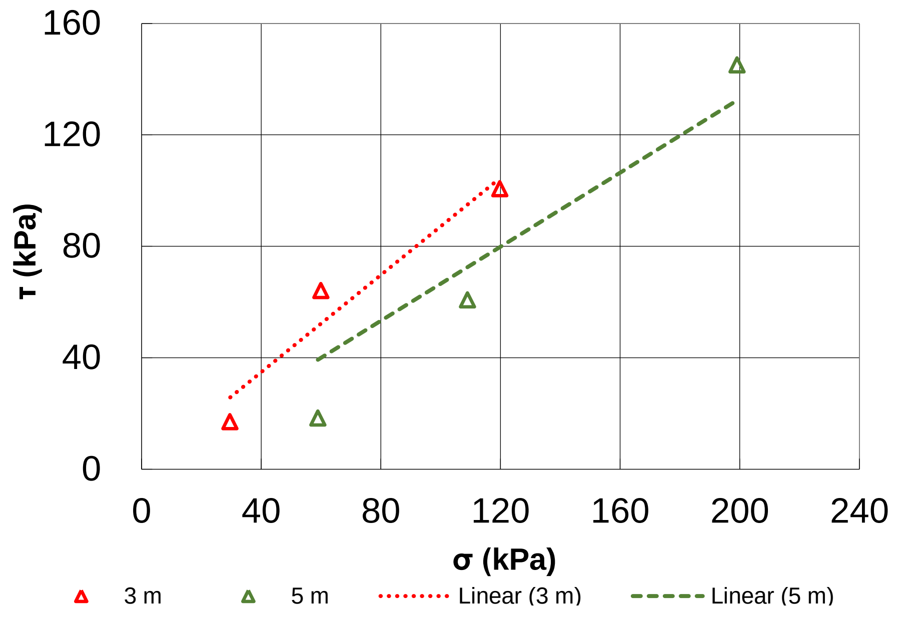
Shear Strength versus Overburden Pressure of Location 1



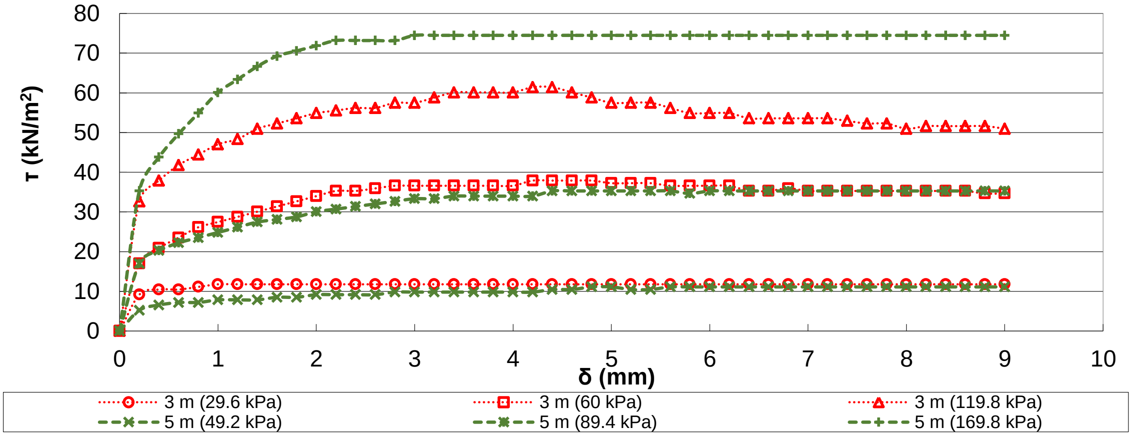
Shear Strength versus Displacement of Location 2



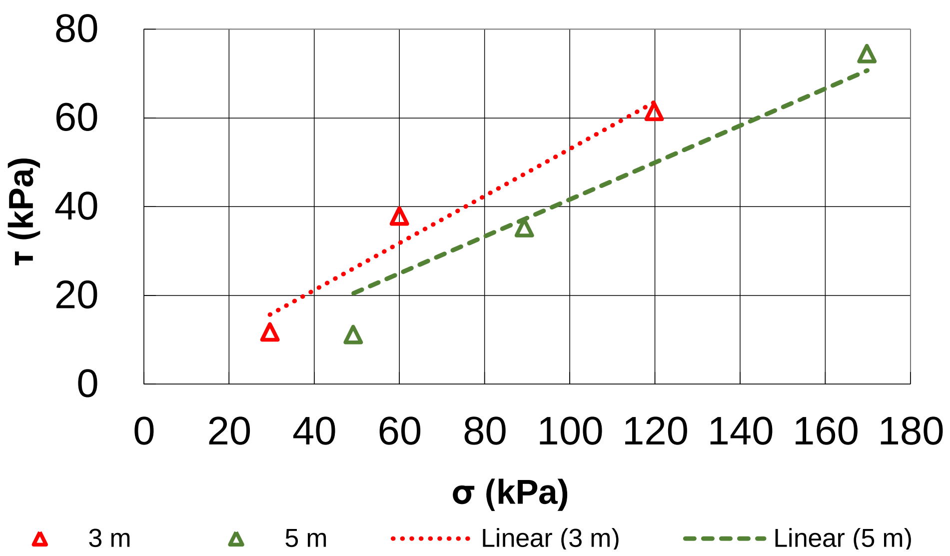
Shear Strength versus Overburden Pressure of Location 2



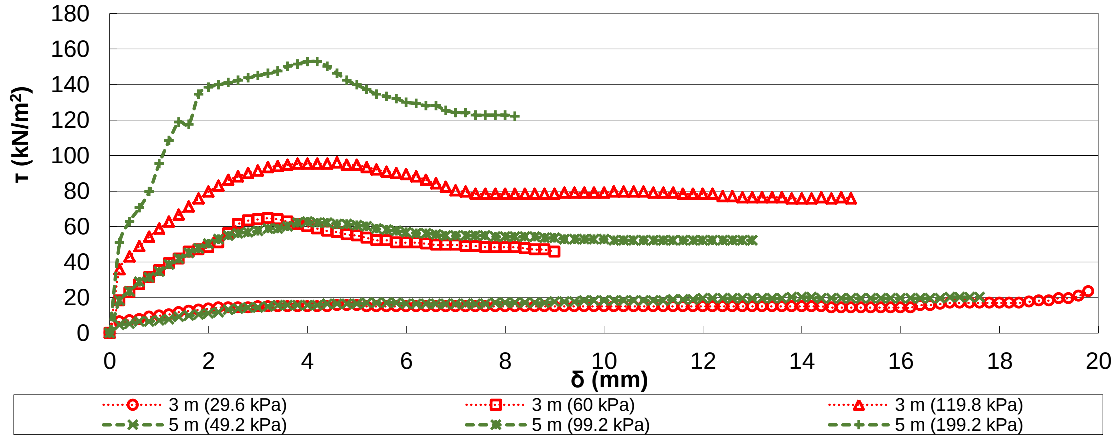
Shear Strength versus Displacement of Location 3



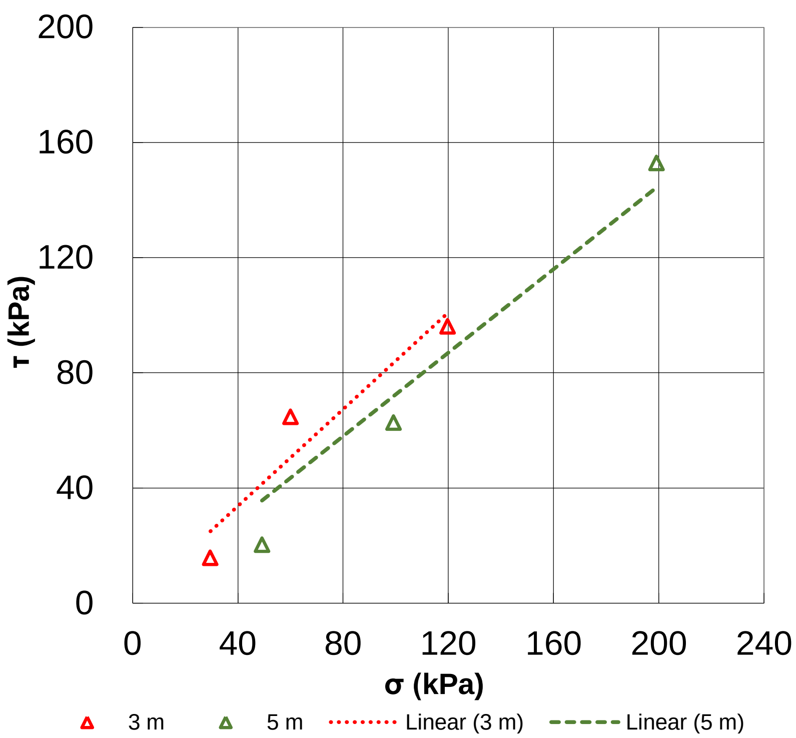
Shear Strength versus Overburden Pressure of Location 3



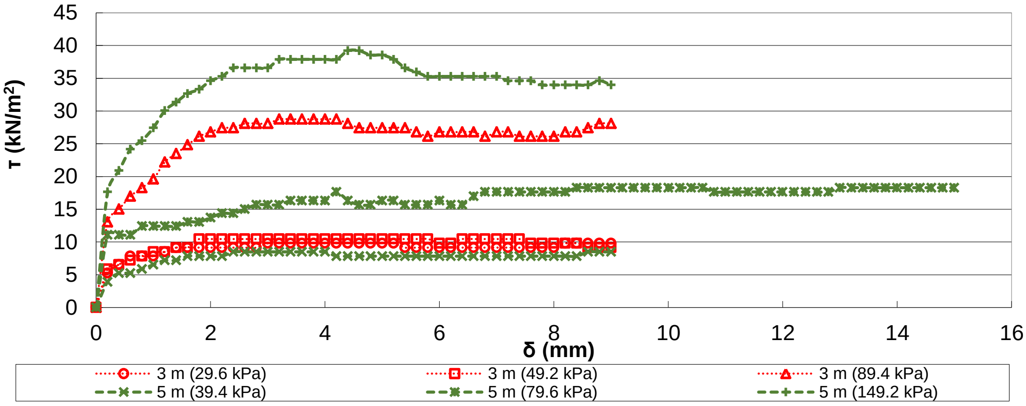
Shear Strength versus Displacement of Location 4



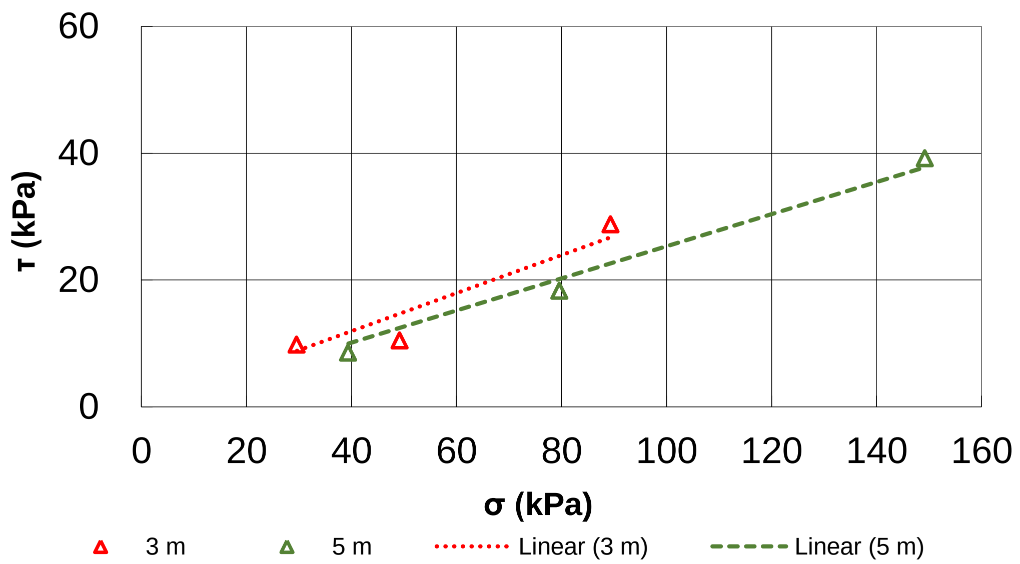
Shear Strength versus Overburden Pressure of Location 4



Shear Strength versus Displacement of Location 5



Shear Strength versus Overburden Pressure of Location 5



BIOGRAPHY

Fatin Adriati

Author was born in Pasuruan – East Java, Indonesia, June 4th 1989 as the youngest of 4 siblings. Currently, she lives at Dusun Melian Barat RT 7 RW 8 Desa Kejapanan, Gempol, Pasuruan – East Java, Indonesia.

She pursued bachelor degree in Civil Engineering Department, Faculty of Engineering, University of Brawijaya, Malang - Indonesia and graduated at 2012. Before continuing her education, she was able to work in a construction company and a consultant company. At 2014, author was accepted in Geotechnical Engineering Department, Faculty of Civil Engineering and Planning, Institut Teknologi Sepuluh Nopember (ITS), Surabaya – Indonesia which financed by Beasiswa Unggulan, Biro Perencanaan dan Kerjasama Luar Negeri (BU – BPKLN). During pursuing master degree in ITS, she had an opportunity to join JASSO Short-Term Exchange Program provided by Japan Student Service Organization (JASSO) in Kumamoto University, Kumamoto - Japan. She joined the program for one year, started from October 2015 until September 2016. At Kumamoto University, she continued her research regarding sediment material properties of Bengawan Solo River in downstream and estuary which had been started since second semester of her study at ITS.

Her interest in civil engineering, especially geotechnical engineering and her desire to keep learning, also grateful for great experience she gained, she wishes to be able to work at education field.

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