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Geotechnical properties and possible geotechnical risks of young fine grain sediments in man made reservoirs

MASTER'S THESIS

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AFFIDAVIT

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Abstract

The accumulation of sediments is a concern regarding many reservoirs. Currently, there is limited available literature covering the geotechnical characterization of these sediments or the geotechnical effects and possible risks of current sedimentation mitigation methods. It is proposed that optimized mitigation methods for each reservoir will be best reached by considering the geotechnical behaviour of each reservoir's sediments separately. The characterization (limited to published data) of reservoir sediments undertaken in this thesis indicates that further investigations should be done before generalizing all reservoir sediments as a single deposit type. However, until individualized reservoir sediment characterization can be undertaken, there are indications that can be obtained by looking at other similar sediments, for example, marine, lacustrine or man made sediments, as proposed in this thesis.

Keywords: Reservoir sedimentation; Underwater sediments; Geotechnical properties; Sedimentation risks

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Kurzfassung

Die Ansammlung von Sedimenten stellt langfristig eine Problem für viele Stauseen dar. Derzeit gibt es nur begrenzt verfügbare Literatur über die geotechnische Klassifizierung dieser Sedimente oder die geotechnischen Effekte und mögliche Risiken aktueller Abminderungsmethoden. Es wird vorgeschlagen, dass optimierte Gegenmaßnahmen für jedes Reservoir am besten erreicht werden, indem man das geotechnische Verhalten der Sedimente jedes Reservoirs einzeln berücksichtigt. Die Beschreibung (begrenzt auf verfügbare Forschungsergebnisse) der Reservoirsedimente, die in dieser Arbeit durchgeführt wurde, deutet darauf hin, dass weitere Untersuchungen durchgeführt werden sollten, bevor alle Reservoirsedimente zusammen gefasst werden können. Jedoch, bis die individualisierte Reservoirsedimentcharakterisierung durchgeführt werden kann, kann man durch die Betrachtung ähnlicher Sedimente Hinweise erhalten. In dieser Arbeit werden Merres-, See- und künstliche Sedimente als Vergleichsmaterial herangezogen.

Schlüsselwörter: Reservoir Sedimentation; Unterwasser-Sedimente; Geotechnische Eigenschaften; Sedimentationsrisiken

Abstrait

L'accumulation de sédiments est une préoccupation au sujet de nombreux réservoirs. Actuellement, il existe peu de documentation disponible sur la caractérisation géotechnique de ces sédiments ou sur les effets géotechniques et les risques possibles des méthodes actuelles d'atténuation de la sédimentation. Il est proposé d'optimiser les méthodes d'atténuation pour chaque réservoir en tenant compte du comportement géotechnique des sédiments de chaque réservoir séparément. La caractérisation (limitée aux données publiées) des sédiments de réservoir entrepris dans cette thèse indique que des recherches plus approfondies devraient être faites avant de généraliser tous les sédiments de réservoir comme type de dépôt unique. Cependant, jusqu'à ce que la caractérisation individuelle des sédiments de réservoir puisse être entreprise, il existe des indications qui peuvent être obtenues en examinant d'autres sédiments semblables, comme les sédiments marins, lacustres ou artificiels, comme proposé dans cette thèse.

Mots clés: Sédimentation du réservoir; Sédiments sous-marins; Propriété géotechnique; Risques de sédimentation

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List of Symbols and Abbreviations

This list defines the symbols and abbreviations used in this thesis and provides an indication (in parentheses) of the section in the thesis where they are first used.

Symbols

A	[-]	Activity (of clay)	(4.4)
Cc	[-]	Compression Index	(4.4)
CF	[%]	Clay Fraction	(4.4)
CI	[-]	Consistency Index	(2.5)
e_0	[-]	Initial Void Ratio	(4.3)
LI	[-]	Liquidity Index	(4.3)
LL	[%]	Liquid Limit	(2.5)
OCR	[-]	Overconsolidation ratio	(3.1)
pH	[-]	potential of Hydrogen	(3.4)
PI	[%]	Plasticity Index	(3.2)
PL	[%]	Plastic Limit	(2.5)
SG	[-]	Specific Gravity	(2.4)
Sr	[%]	Degree of Saturation	(2.4)
S_u	[kPa]	Undrained Shear Strength	(3.2)
w	[%]	Water Content	(2.4)
γ	[kN/m^3]	Unit Weight	(2.5)
ϑ	[%]	Water Content by Volume	(2.4)
ρ	[Mg/m^3]	Bulk Density	(2.5)
ρ_s	[g/cm^3]	Particle Density	(2.4)

Abbreviations

ICOLD	International Commission on Large Dams	(1.1)
MFT	Mature Fine Tailings	(3.4)

1 Introduction

1.1 Background

This thesis presents the research undertaken to look into geotechnical aspects of the sediments accumulating in man made reservoirs. The man made reservoir involves a structure, usually a dam, to be built to close a natural space in such a way that water collecting in the reservoir can reach heights higher than would naturally be found. A natural reservoir may be found behind deposits, such as moraines from glaciers or large volumes of landslide debris, which act in a similar way to the dam. A lake can also be considered as a natural reservoir. The ocean at the end of rivers is the final reservoir.

In both man made and natural reservoirs, the water source for the reservoir is usually a water flow, of which the size determines the naming: creek, stream, or river for increasing flow. The reservoir thus collects water and any transported sediments. Once the reservoir is either at the desired height, for man made reservoirs, or reaches the lowest retaining height, for natural reservoirs, the water leaves the reservoir in a predetermined manner, usually an outlet (or in high flow times, also over a spillway) for man made reservoirs, or in the path of least resistance for natural reservoirs. There is a resulting effect that the reservoir acts as a sediment trap. In nature, this process occurs throughout geological time, and has created sedimentary deposits and rocks. In man made reservoirs, where the timescale is a fraction of geological time, the sediments also accumulate, and this is an important topic called reservoir sedimentation.

In this thesis, natural reservoirs are not considered, although the study of these reservoirs could contribute to the understanding of the behaviour of sediment accumulations. This thesis also concentrates on reservoirs where the retaining structure is termed a dam. There are thousands of such dams around the world, used for hydropower, water storage, irrigation and flood control. They have various features depending on the purpose, for example intake structures for hydropower, but they must all have features to allow for emergency release of water. The bottom outlet is a mandatory feature which is designed to allow the reservoir to be completely drawn down in the case of an emergency (Boillat & Pougatsch 2000). Due to its inherent function, it is located in exactly the location where sedimentation first occurs.

Reservoir sedimentation is one of the risks which dams and their reservoirs are designed to consider. Studies are made to gain an understanding of the extent of sediment transport which is likely to occur throughout the dam lifetime. This helps the designers understand how much sedimentation they can expect to occur, and often a dead storage is included in the initial design to accommodate the sedimentation. However, in some cases, whether due to insufficient investigation or unexpected conditions, the dead storage becomes filled up, resulting in further risks. For the reservoirs in which a filled dead storage is not yet a problem, the risks are still possible in the future, and as shall be seen, are significant. Thus every man made reservoir has risks associated with reservoir sedimentation.

Reservoir sedimentation is an issue because of the risks it poses to fulfilling the purpose of the reservoir and ultimately, the safety of the dam. The International Committee on Large Dams (ICOLD) has published numerous bulletins covering this topic (ICOLD 1999; ICOLD 1989; ICOLD 2009). In general, the risks of reservoir sedimentation include loss of reservoir volume (live storage), negative impact on dam safety by covering the bottom outlet, and damage to hydraulic structures, in the cases of hydropower reservoirs (Boes et al. 2014; Boillat & Pougatsch 2000). These risks are an important topic and are further discussed in Chapter 5: Possible Geotechnical Risks.

1.2 Research Question

When too much sediment has accumulated, and the risks are too high, (for example if the bottom outlet threatens to be covered by accumulating sediments) the sediments need to be removed. To optimize the process of removing or evacuating these sediments, it is helpful to have a good understanding of the problem and it is important to gain an understanding of the geotechnical properties in order to be able to apply it to the risks caused by these sediments. The importance of this situation is understood by those who have undertaken investigations to characterize the sediments, to expand the knowledge of their engineering properties, to test the effects of their various influences, and used this information to develop schemes on sediment removal, to evaluate hydraulic structure safety and to suggest dam operation recommendations to the dam operators (Lee et al. 2013; Mammou 1997; Sinniger et al. 1999).

The aim of this thesis is to gain an understanding of the geotechnical properties of reservoir sediments and to apply this understanding to risks caused by these sediments.

It is proposed to achieve this aim with the following objectives:

- To research, compile data and characterize reservoir sediments according to geotechnical properties based on the few available publications.
- To identify knowledge gaps in geotechnical properties and possible geotechnical risks of reservoir sediments.
- To address the knowledge gaps in part by characterizing underwater sediments from other settings.
- To characterize underwater sediments from other settings in order to explain, for instance, why the reservoir sediments left in place after dredging procedures are surprisingly strong.
- To research and compile data on slope stability in man made reservoirs and supplement this information with reference to landslides in marine sediments.
- To research the geotechnical effect of common reservoir management practices on reservoir sediment properties.
- To identify and clearly present possible geotechnical risks of reservoir sediments and how they relate to common reservoir management practices.
- To recommend future research based on remaining knowledge gaps, as it is understood that this thesis cannot address every aspect.

1.3 Structure of the Thesis

This thesis, its background and the questions to address have been introduced in this chapter. The following chapter, Chapter 2, will present the methodology used to answer the questions. It first presents methodologies that other researchers have used to obtain data with the purpose of annotating these methods in order to explain why that level of research was not feasible for this thesis. Chapter 2 also present the challenges encountered in compiling the information from numerous sources, and the assumptions used to face them. This is where the author presents definition discrepancies, explains the choices, and explain why the author's selection will be used throughout the thesis. Chapter 2 should provide the reader with a clear idea of the purpose of the following chapters and an understanding of why the thesis was undertaken in this way.

Chapter 3 presents the findings of the extensive literature search in a factual manner. As will be explained in Chapter 2, the sections of Chapter 3 are meant to introduce the various scenarios which have been found to relate to reservoir sediments. The reader will then also gain knowledge about geotechnical properties of the scenario sediments and the methods used to obtain those properties. Although the scenarios are described in a similar structure to make the information clear, they are not yet compared at this stage. This will follow in Chapter 4.

Chapter 4 examines the data presented in Chapter 3 with the purpose of finding similarities between the properties of the various scenarios so that the reservoir sediments can be considered to be better understood. In this process, the differences between the scenarios are also considered, with the result of illuminating some of the main influencing factors on the sediment properties.

Chapter 5 explores the risks mentioned earlier in the introduction. The opportunity is also taken to examine the risks of the sediments of the other scenarios. In essence, this chapter attempts to present a discussion about hydraulic risks and the intertwining geotechnical risks.

Finally, the conclusion in Chapter 6 ties the pieces together with a summary and will address the questions posed in the last section. It will also present an outlook for future work which could be undertaken to further advance the answers to these questions. As will be seen throughout this thesis, there are many factors to consider.

1.4 Influences Considered

As mentioned in the previous section, there are many factors that influence the properties of these sediments. To avoid possible confusion or misunderstanding about what has been considered or not, this section presents the influences considered and which ones were not. The ones not considered are covered in the outlook, Section 6.3, as ideas for future research.

In the next chapters, the following were considered:

- Clay minerals
- Water salinity
- These two topics combine to affect flocculation
- Thixotropy

In the next chapters, the following were only briefly mentioned and **not** addressed in detail:

- Sedimentation rate
- Spatial variability
- Organics
- Gas within deposits
- Depth of sediment samples
- Age

2 Methodology and Assumptions

2.1 Introduction

This chapter explains the workflow the author developed to answer the research questions. However, before getting directly into the work steps, Section 2.2 presents the involved testing and sampling methodologies other researchers used to obtain the kind of properties used in this thesis. The purpose of this section is to illustrate the complexity, the (time) costs, and the excellent laboratory conditions required to perform sampling and testing of a high quality, and that such high level of investigation was not in the scope of this thesis.

Once it has been established that this thesis is secondary research, mostly a literature review, Section 2.3 then delves into the workflow of this thesis: the literature search, the data collection, the associated challenges and assumptions, the comparisons made, and the discussion of possible risks. The reader should understand the reason for the structure of the next chapter.

The subsequent section, Section 2.4, then discusses the associated challenges (including inconsistencies) and the assumptions and simplifications made so that the reader can go into the literature findings of Chapter 3 with an understanding of the caution needed. These interpretations (challenges, assumptions and simplifications) are presented here in Chapter 2 to keep a clear distinction between them and the data in Chapter 3.

Finally, one of the challenges encountered is the assortment of terminology and definitions found throughout this research. As there is not always a standard definition for technical terms, these findings lead to choices. Section 2.5 presents them and explains why the author’s selection of terminology or definition, for example for clay and silt, will be used throughout the thesis.

2.2 Applied and Published Methods of Sampling and Testing

There are many researchers doing great work on the properties of underwater or soft sediments, and this is not a new topic of research. As this section will demonstrate, some great developments were made decades ago, and more recent research has built upon them to the point where this kind of work can be extremely sophisticated. It would be interesting to get into this kind of work, but there are so many factors affecting sediment properties that there is not enough time within a master’s thesis.

To begin with, sampling of underwater sediments is challenging, especially when the water depth is greater than 500m, because there is less control in the process and the sediments may be more sensitive to disturbance (Lunne et al. 1998). Samples, from both underwater and dry sediments) are usually taken from cores extracted using corers (tube sampling) or block sampling. The purpose of these careful methods is to provide sediments in a state as close to in-situ as possible (undisturbed), so that testing on them can provide relevant results. However, as Barros et al. (2009) established from their investigation (collecting undisturbed samples in seabeds 2000m below the water surface), one must recognize that an inevitable disturbance should be considered to have occurred, due to the enormous difficulty of this type of investigation.

Disturbance can occur from all stages from withdrawal, transportation, storage, handling, preparation for testing and the actual test. It can be classified as mechanical disturbance or stress disturbance (Carrubba 2000), where mechanical disturbance may be minimized, but stress disturbance is unavoidable. The minimisation of mechanical disturbance, the effect on the sample from the encompassing tube or sampler, has been tackled by countless researchers (Berre et al. 2007; Rochelle et al. 1981; Lunne & Long 2006; Emdal et al. 2016; Emdal et al. 2016; Lunne et al. 1998; Horng et al. 2010), with the result that there are now numerous samplers (block) and tube geometry considerations: Sherbrooke block sampler, Laval sampler, mini-block sampler, 54mm NGI piston sampler, 75mm Japanese piston sampler, tube geometry (proportions, angles, thickness, size). The Sherbrooke block sampler, has been shown to provide very high quality samples and most representative test results from its samples, and as such, it is considered to be the high quality standard to which all other sampling methods are compared (Long et al. 2010; Berre et al. 2007; Lunne et al. 1998). However the Sherbrooke block sampler is also costly and has high time requirements; thus it is mostly used for academic and research purposes (Emdal et al. 2016). As the block samplers are not suitable for routine investigations and are not used for underwater purposes, some of the other previously mentioned methods are more commonly used in underwater investigations. Also, as sample storage is a factor in sample disturbance, Rochelle et al. (1986) present a technique for long term storage considering temperature and moisture control.

Regarding stress disturbance, most sampling processes cause a reduction in stresses on the samples, and bring them into air contact allowing potential air entry (Hight 2003). When samples are obtained from depth, the stress relief causes expansion, which is a disturbance. For example, samples from 1500m water depth may expand up to 0.7%

(Lunne et al. 1998). Any gas within the pores can have an additional impact on the sample, as it expands when brought up to the surface, where there is less pressure. While it is unavoidable, stress disturbance is often addressed by investigating the effects, for example by quantification.

Many researchers (Bennett 1976; Long et al. 2009; Long et al. 2010; Carrubba 2000; Chung et al. 2002) have investigated methods of quantifying the disturbances occurring at various stages. These methods include the use of curves of void ratio versus pressure (logarithm), shear wave velocity and suction measurements. For example, Ravaska (2003) investigated the effect of disturbance on clay properties directly, by performing oedometer and permeability tests on undisturbed, remoulded and slurry-form samples of soft clays. He showed that the undisturbed samples, as compared to the two disturbed sample types, reached higher strains, had higher permeability, and had higher (2-3 times when at the overconsolidation pressure) coefficient of consolidation (Cv).

Another aspect is the difficulty and impracticability of obtaining undisturbed samples from material in a low plastic or liquid state (water content above the liquid limit), which is the case for many of these soft sediments. When sampling is no longer a practical solution, and even for many other reasons, one can consider in-situ testing. However, this also has challenges in underwater soft soils as demonstrated by the development of standard practice, such as Cone Penetration Testing (CPT), modifications to better assess these soils. For example, penetrometers with ball shape and T-bar shape tips are used to have extra sensitivity in soft soils, especially when fine interlayers of clay and sand occur (Lunne et al. 2011). In order to facilitate measurements at depth and in soft soils, Lee et al. (2013) included differential pressure measurements in their flat dilatometer and piezo-penetrometer tests. The differential aspect removed some uncertainty of measuring accurate pressures underwater (change of water depth had no effect) and in sediments (young ones with residual excess porewater pressure), and this method was shown to be effective (Lee et al. 2013).

Another option is to try to recreate the in-situ conditions in the laboratory, however this can only assess certain aspects at a time, not all influencing factors at once. For example, a recreation of sedimentation used salt water to mimic real situations where sediments fall through the fluid (Masin et al. 2003). It found that the salt water helps the clay sized particles to flocculate, and that the created structure seemed to be stable. However, it did not cater for real sedimentation rates and only considered one sediment composition, London Clay. In another case, in order to simulate the natural conditions of reservoir drainage consolidation, Mammou (1997) performed laboratory tests by mixing sediment and reservoir water (same salinity) to match the concentrations of inflows into the reservoir, and allowed to settle while the accumulating deposit was closely monitored. However, this could not account for seasonal fluctuations or other external factors, such as temperature and disturbances.

2.3 Workflow

As has been suggested in the previous section, an enormous amount of resources and access to a fully equipped laboratory is required for primary research. This was not available for this thesis, which has led the nature of this thesis of being secondary research. As such, the workflow started with an extensive literature search. The start of this topic is the Luzzone reservoir, as two publications about this reservoir were provided. One covered the physical properties of the sediments accumulated in the Luzzone reservoir (Sinniger et al. 1999), and the other discussed turbidity currents, which are formed from the density difference of sediment laden water flow into a reservoir and bring sediments (especially fines) farther into the reservoir (de Cesare et al. 2001).

The search began by looking for publications about reservoir sedimentation. (For this thesis, *publications* refer to the wide range of published documents, from journal articles, through conference proceedings, and theses to book chapters.) There is a lot of information on this topic (de Cesare et al. 2001; Hollingshead et al. 1973; Boillat & Pougatsch 2000), including a few ICOLD publications (ICOLD 1989; ICOLD 1999; ICOLD 2009) which helps to give a good overview of the topic and associated risks. However, as the subject of this thesis is the properties of these sediments, publications containing data on the properties were more specifically searched. These publications are not as readily available, and the data was mostly limited to information on the distribution of the grain sizes of the sediments. The number of publications which provided data on geotechnical properties of reservoir sediments was extremely limited. Thus this is highlighted as a knowledge gap in this field. An illustration of the proportions mentioned is shown in Fig. 1.

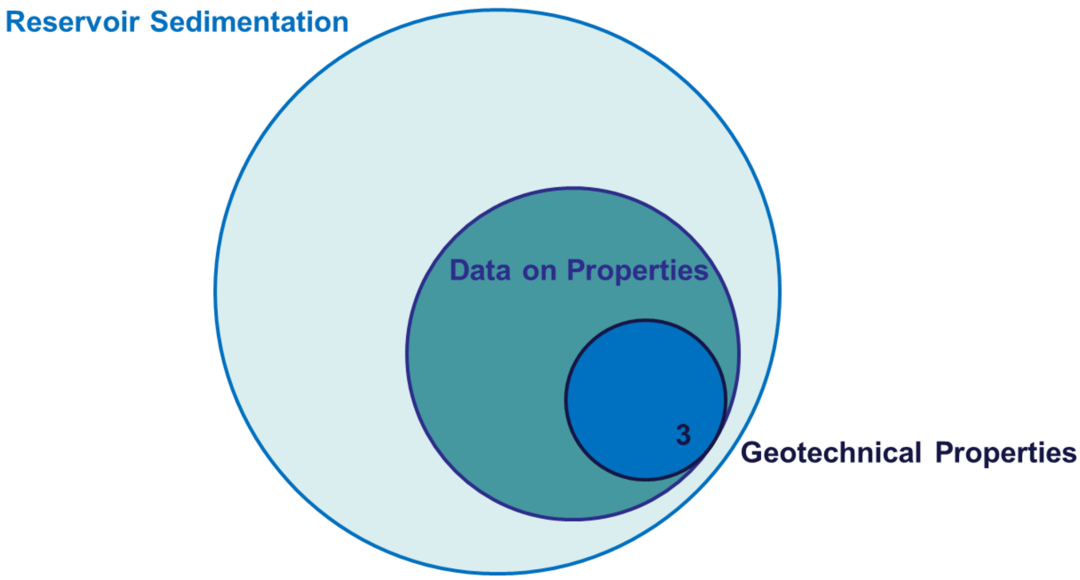

Fig. 1 Proportional distribution of available publications containing relevant geotechnical (numerical) data and more general publications

The three available publications include the Luzzone publication mentioned above; another publication in which Lee et al. (2013) investigate the Tsengwen Reservoir in Taiwan and address the exact topic addressed in this thesis: to characterize the sediments situated near a dam (and elsewhere); and a third publication examining the properties of sediments in Tunisian reservoirs (Mammou 1997).

In general, most information available for reservoir relates to the hydraulic engineering aspects, including turbidity currents and sedimentation rates. It is difficult to find data regarding geotechnical properties of these accumulated sediments as it seems very few are looking into this topic.

There was simply not enough data to adequately present anything of significance. Therefore, the search extended to looking for information about other sediments deposited underwater, of which there was certainly more information. The sources ended up being from all over the world. An example of the extent of countries, and the proportion of publications from a single country is shown in Fig. 2.

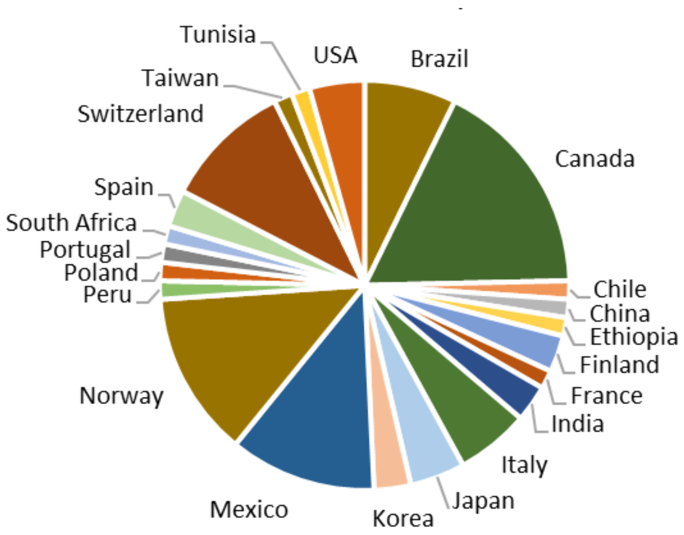

Fig. 2 Available sedimentation publications by countries and proportional distribution

This led to finding some similar settings and eventually distinguishing them into scenarios for the organization of data. The scenarios became named as reservoirs, marine, lacustrine and man made to represent the setting of the sediments. The inclusion of scenarios was determined based on the similarity to reservoir sediments (underwater deposition, particle size), and amount of published data. The scenarios are presented in further detail in Chapter 3.

It should be noted that at the beginning of the search, other conditions of similarity were considered such as sedimentation rate and depositional energy. They were dropped as criteria due to inaccessibility of their data and limited resources for this thesis. Initially, more settings were also considered, but they were gradually integrated into one of the four scenarios above or removed due to insufficient data.

The next step was to collect information on the methods used to collect the properties of the sediments and to collate the data on the properties. All properties of the sediments that could be found were collected, no matter the type. In the early stages, it was not known which properties would be the most relevant. The results of this step are presented in Chapter 3. Most of the data collated comes from the marine scenario, as shown in Fig. 3.

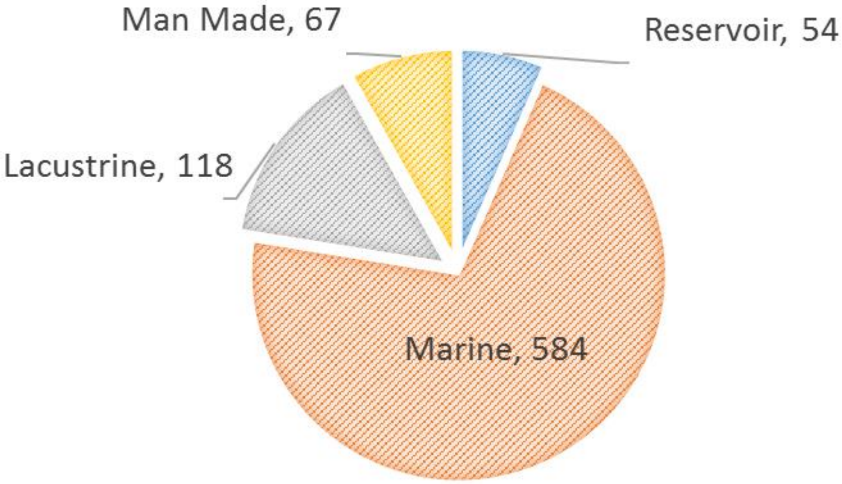

Fig. 3 Data (number of property values) by scenario

The available data have been consolidated into a spreadsheet for comparison and assessment. Assumptions and simplifications were required in order to use data presented in various formats. For example, data were simplified to single value inputs in the collating spreadsheet, to ease further analysis. The spreadsheet cells are colour coded according to the type of single value and what type of further information is lost in the process (see Appendix A). Assumptions are further elaborated in Section 2.4.

Once the data was collected into a spreadsheet, study of the data showed that some further properties could either be assumed, further discussed in the next section, or be calculated based on very simple relationships. For example, the liquidity and consistency indices can be calculated from the consistency limits (liquid limit, plastic limit) and water content. This allowed the wide range of data that filled the spreadsheet relatively sparsely to become a bit more complete. For those properties for which there was enough data, comparisons between scenarios were done and are presented in Chapter 4. The goal is to address whether the sediments of any other scenarios are comparable to reservoir sediments, as there is little geotechnical information available. Through the comparisons, similarities were found, and differences explained. From this newfound understanding, the next step progressed to the associated risks and how the two (understanding and risk) can be combined to better deal with reservoir sedimentation. This is presented in Chapter 5.

In order to better understand the details of, and to write about, sampling and testing methodologies, the author accompanied colleagues who were performing their own investigations via sampling, in-situ testing, transportation disturbance monitoring, and laboratory testing. This gave the author the opportunity to see and feel some of these sediments, and to experience some testing methods. These investigations' data have not been used in this thesis. Due to weather and time restriction, sampling for this thesis has not been carried out. However, a sampling and testing proposal can be found in Appendix B.

2.4 Challenges and Assumptions

This section presents the interpretations that were made so that the reader can distinguish between published facts, and assumptions by the author.

As previously mentioned, there are very few publications with data, and even then, these publications come with more complications. For example, the format of the data may be presented in tables, text or graphs, or the terms used for properties is not always the same: this is common in the geotechnics world; and inconsistencies were found both within and between publications. These inconsistencies include different methods used to determine same properties and translation errors. The following are some specific challenges:

- The publications do not always make it clear what method, what test, was used to obtain each value. This leads to the question of whether the same property can be compared across publications.
- More than one testing method may be used to determine a property value. For example, the clay fraction result will depend on the amount of dispersant used (Mishra et al. 2011), liquid limit determined by Atterberg or fall cone tests differ in value (Tanaka et al. 2012), and sensitivity (the ratio of undisturbed to remoulded soil strength) may differ according to the strength testing method (see next point) This presents concerns as to whether the same property can be compared across publications.
- For undrained shear strength in particular, the results are stress path dependent: the failure stress depends on the stress path followed until failure. This leads to the question of how to compare undrained shear strength obtained from different tests (and different stress paths) across publications.
- The authors of a publication may be writing in a second language to them, which can lead to an inaccurate translation. This is an issue when the translated terms used have a very specific meaning, likely not the intended one, as the term may not match the units provided for the term/property. For example, density is not the same as unit weight. This leads to the question of whether to go according to the term or the units.

In these cases, the author often inferred the general intent from the term, and used the units to interpret the intended property. To check whether the assumption is reasonable, the values were checked to reasonable values for the property for the material.

- In one case, two different publications presented some differing values of properties for the same deposits. As it is geologically likely (even certain) that a deposit is not entirely homogeneous, the differences are not of concern. Both values are valid (obtained through valid testing procedures), so the deposits are included twice in the spreadsheet to account for the variability. In another case, two investigations, about a decade apart and covering the same area, also had both their results included. They were initially only compared to give confidence to the first dataset, and then kept as both are valid and their results are from different investigative methods (Smith et al. 2010; Karakouzian et al. 2002). It is understood that this duplication of results creates a skew to averages and the data comparisons of Chapter 4. However, these are some of the few high data results found, and provide more confidence to the data ranges of the results.
- Many of the publications presented the data in a graphical form. In these cases, a best approximation of a representative value was made and the value's cell was colour coded accordingly. This is an important potential error source.
- For the data where multiple values were presented with depth, either in graphical or table format, a cut off depth of nine meters was decided: above it was considered data for the shallow sediments, and below nine meters was considered data for the deep sediments. The cut off was based according to difference in properties above and below, seen in the liquid limit and water content of Singapore marine clay (Bo et al. 2015), and in the unit weight and plasticity of Tsengwen reservoir sediments (Lee et al. 2013). The two sets were then included in the spreadsheet as two separate deposits. While this interpretation allowed the data to have more impact than a single value, the simplification effect results in the loss of trend information with depth, another important error source.
- When depths are not provided for samples, but values are given for an entire clay deposit, it is presumed that the authors of that data have taken sufficient samples at a range of depths and have confidence in their generalized data for the clay deposit.

The challenges were mostly dealt with by using assumptions and simplifications. For example, single values were approximated from graphical data, the intended meaning of some properties were interpreted in order to group some properties together through relationships, and reasonable clarifications were assumed for the inconsistencies. The goal was to produce a more complete data set. The following are some specific assumptions made regarding the data published by others:

- Assumed that the density of soil particles without pore space, termed particle density (ρ_s), equals specific gravity (SG), when ρ_s has units of grams per centimetre cubed [g/cm^3], and that researchers are defining particle density and specific gravity according to same testing methods. Thus values for these two properties were consolidated.
- Assumed that for underwater materials, when unit weights are given without further detail, they are assumed to be saturated.
- Assumed that gravimetric (by weight) water content is always used. If water content is referred to by volume (ϑ), the value is checked as to whether this truly is the case (volumetric water content cannot be greater than one and can be check by comparing to the liquid limit) and if so, it is converted to gravimetric water content (w) according to $w = \vartheta / SG$, where *SG* is specific gravity.
- Assumed that the degree of saturation (ratio of volume of water to volume of voids) of underwater sediments is 100%, when not provided. This is likely not technically correct: the only source which did provide a degree of saturation (Sr) had a value of 97% (Sinniger et al. 1999), and it is likely these sediments have some trapped air bubbles; however, without further information, the default for saturated sediments (Sr = 100%) in simplified geotechnics is used.
- When no further indication is given, property values, such as void ratio and unit weight are assumed to be in-situ. This is to distinguish from the rare cases when an indication is given, such as presenting void ratio at liquid limit.
- Assumed consistency limits (plasticity index and liquid limit) were determined according to standards specifying determination on the minus No. 40 (425 µm) sieve material. (ASTM 2010), and using the Casagrande cup and rolling thin threads. However, while these are the standards in North America, it is much more common in Europe to determine the liquid limit from the fall cone test (or cone penetrometer test), due to less subjectivity from the operator. Only some publications specify the method used, thus it is assumed that consistency limits determined from the two methods are similar enough that they may be compared and do not need to considered as two sets.

- Assumed the determination of clay size fraction was done in the same way by everyone, or that different methods (e.g. hydrometer versus laser) provide similar results: that the data collected is comparable. This is of importance, as flocculation occurs in these sediments, especially in marine environments, the use, and quantity, of dispersant has a large impact.

These lists give rise to the question of data confidence: caution should be exercised when using the data. There can be some discrepancies due to how the values are derived, the data it is not very precise, and there is some inaccuracy in the data.

2.5 Terminology

Another aspect that became apparent in the literature review was the variety in terminology: spelling, symbols and equivalent terms. There is no right or wrong in these varieties (although some may have strong opinions on this), but simply some differences in the geotechnics world. This section presents the differences, and the author's selection for use in this thesis:

- For the symbols used in this thesis, refer to the list of symbols at the start.
- The definition of unit weight (γ) as the weight (as a force) for a unit (volume) of soil will be used. This is as opposed to bulk density (ρ), which is the mass of the soil for a unit (volume) of soil. This thesis also applies the definition that particle density (ρ_s) in units of [g/cm3] equals specific gravity of particles (SG), and that both refer to the density of the solids of a soil.
- Water content, not moisture content, will be used. Water content (w) may be defined as gravimetric (by weight) water content (ratio of mass of water to mass of solids) or volumetric water content (see previous section). Only gravimetric water content will be used in this thesis.
- The term consistency limits will be used to represent the combination of liquid limit (LL) and plastic limit (PL). A synonymous term is Atterberg limits.
- Underconsolidated soils still contain excess porewater pressure and are not completely finished consolidating under the current overburden load (Karakouzian et al. 2002). This condition is mostly found in underwater fine grained soils where the dissipation of excess porewater pressure is very slow. Although there are some comments that the term should not be used, because it simply indicates unfinished consolidation, the term has been used in publications from 1979 (Sangrey et al. 1979) to 2015 (Wiemer et al. 2015) and will be used in this thesis.

- Soil states are defined by the relationship of the soil's water content to its consistency limits and are called liquid, plastic, semi-solid and solid (Craig 2004). In solid state, there is no volume change of soil even with increasing water content, until it hits the shrinkage limit. In the plastic and liquid state, volume varies with water content, and behaves plastically and as a liquid, respectively. They can also be defined according to the consistency index, CI = (LL – w) / (LL-PL), which simply indicates whether the water content is inside or outside the plastic behaviour state, as follows: liquid ($CI \leq 0$), plastic ($0 < CI \geq 1$), semi-solid and solid ($CI > 1$). In other words, these states represent the firmness of fine grained material. The term *soft* will be used to indicate fine grained soils in a liquid or low ($CI < 0.5$) plastic state; more specifically, the term *very soft* can be used for silts of clays with a consistency index less than 0.25 ($CI < 0.25$) (ISO 2004).

It should be remembered that these terms regarding liquidity and plasticity only apply to fine grained soils. Fine grained soils are comprised of clay and silt sized particles, but further distinctions into the terms clay and silt is not simple/clearly defined/consistent. There are often local names and local definitions and meanings. For example, in Austria, the local term *Seeton* (literal translation: lake clay) is used to indicate a soft fine grained soil, regardless of it being clay- or silt-dominated.

Even the definition of what consists of a fine grained size is not the same around the world. In North America, the ASTM standard is used, and fines are defined as material the No. 200 sieve (75µm). In Europe, soil is considered fine when the particle sizes are under 63µm (ISO 2004). Yet another definition can be found in the oil sands industry, where fines are defined as material passing a 44µm sieve (Beier et al. 2013) or 45µm (Suthaker & Scott 1997). Beier et al. (2013) clarifies, that the solids include fines (silt size < 44µm, clay size < 2µm) and residual bitumen.

The clay size is more globally consistent: it is defined as 2µm or less in British Standards (Craig 2004) and in the ASTM standards (ASTM 2016). The silt size is always considered the range between the clay size and fines size. Different properties, particle size distribution or plasticity, can be used to define a soil as a clay, but the chosen definition seems to depend on the user's background. For some, a clay must have its size fraction be greater than 50%, and for others, a clay simply must plot above the A-line.

The definition of a clay depends on the purpose and the user. The USCS definition, based on Casagrande classification and tied with the ASTM standard, is that a soil is a clay when 50% of the mass passes the No. 200 sieve (75µm), and it exhibits plastic behaviour within a range of water content, or plots above the A-line in the plasticity chart. When dry, this clay demonstrates considerable strength (ASTM 2010). Further definintion distinctions depend on the silt and coarse contents. According to British Standards, fine soils are termed silt or clay depending on the plastic properties (BSI 2015), which is conveniently determined from the plasticity chart: clays plot above the A-line, and silts (M) plot below.

In the research for this thesis, the definitions were often not stated. For example, the publication presents a clay, or a soft clay, but without clearly stating the definitions of those terms. However, sometimes authors called clay and silt mixes as clays, based on fraction size. The term fat clay, used in many publications, represents inorganic clay with high plasticity (Karakouzian et al. 2002). In a rare case, a publication about a marine clay gave a clear definition: the sediments had less than 50% clay size particles, but because their plastic behaviour plotted above the A-line, they were called a silty clay (Wu et al. 2015). This naturally shortened to the simpler term *clay*.

For the sake of comparison, it was assumed that any differences in results due to the variation of definition are subtle and the data comparison can be made. While the definitions are not always clear and stated, for this thesis, the author would like to clarify a few terms that will be used in this thesis. However, it should be noted that when a publication presented the term *clay*, it was assumed to be correct and was not modified when included in this thesis. For the other cases:

- The term fine soil will be used when a silt and clay distinction is not required or not possible and will be defined as a soil with more than 35% of the material being clay or silt size particles (when cobbles and boulders are removed), according to (Craig 2004).
- A clay will be defined as a fine grained soil with more than 50% clay size particles. It is assumed these soils will also plot above the standard A-line.
- A silt will be defined as a fine grained soil with a majority of silt size particles, and which plots below the standard A-line.
- Finally to avoid confusion, and according to Craig (2004), an alternative term, M-soil, will be used for fine grained soils with mostly silt size particles, but whose plastic behaviour plots above the standard A-line, due to the significant proportion of clay size particles.
- The representative letters will be according to the standard plasticity chart.

- Silting will be the accumulation of silts in a reservoir: a specific form of sedimentation.
- A soft fine grain soil (clay or silt) will be based on consistency as addressed previously: when CI > 0.5 and very soft when CI < 0.25.

3 Scenario Methods and Properties

This chapter describes in detail the scenarios previously mentioned: reservoirs, marine, lacustrine and man made in terms of setting, sampling and testing methods, and geotechnical properties.

3.1 Reservoirs Sediments/Deposits

This section describes the setting of reservoirs, some sampling and testing methods used to characterize sediments in reservoirs, and presents some deposited sediment properties. Reservoir often collect a wide range of grain sizes, from gravel to clay, which has been described by many publications (Bountry & Greimann 2009; Randle et al. 2010; Hollingshead et al. 1973; Scheuerlein 1990; Mammou 1997). This thesis only considers accumulated fines and does not consider suspended sediments.

Setting

Reservoirs are found around the world; for example, some of the reservoirs mentioned in this section are:

- Luzzone and Gebidem in Switzerland
- Magaritze in Austria
- Tsengwen in Taiwan
- Sidi Boubaker, Nebeur, Sidi Saad and Sidi Salem in Tunisia
- Matilija in United States of America (USA)
- Glenmore in Canada.

Reservoirs occur in various settings: alpine (Luzzone), fed by a glacier which impacts the sediment source (Gebidem, Magaritze), tropical climate (Tsengwen); and for various or multiple purposes: hydroelectric (Luzzone), city water storage (Glenmore), flood control and irrigation. In general, the setting gives indications of the characteristics of the sediments entering the reservoirs while the purpose of each reservoir dictates the type of operation and its impacts, which then relates to its risks and possible mitigation measures (ICOLD 2009). For example, the alpine setting tends to mean a lower yearly volume of sediment entering the reservoir and hydropower facilities usually mean the reservoir undergoes seasonal flows and water levels (Boillat & Pougatsch 2000).

Despite the importance of sedimentation rates for the characterization of reservoir sediments, this thesis does not include them because to include investigations (research) of these sedimentation rates (into a database) and their effect (correlations) on sediment characteristics would exceed the scope of this Master's thesis. However, researching sedimentation rates would be a logical and necessary continuation to understand the behaviour of these sediments in more detail. A good starting source for information on worldwide sedimentation rates of dammed reservoirs and spatial distribution of sediment aggradation is presented in (Boes et al. 2014).

The water depth of the reservoirs range from only a few meters at Glenmore (Hollingshead et al. 1973), 40m at Tsengwen (Lee et al. 2013), to over 175m at Luzzone (Sinniger et al. 1999).

Sampling and Testing

Sampling of reservoir sediments is mostly done by borehole drillings, as was done at Luzzone (Sinniger et al. 1999) and in dam removal projects (Bountry & Greimann 2009); the Matilija dam removal project had a drilling program of 18 boreholes and found no contamination (Bountry & Greimann 2009). The process of dam removal and its investigations also provide insight in reservoir sediments, because at all stages of a reservoir (planning, designing, building, maintaining, removing), similar techniques for understanding the sediments are used.

In some cases, draining the reservoir to potentially collect undisturbed samples is not an option due to water management concerns. Such an example is the Tsengwen reservoir in Taiwan, where geotechnical data was obtained by using in-situ testing rather than collecting undisturbed samples from material under 40m of water (Lee et al. 2013). Undisturbed sampling was also not possible due to the deposited material having a water content equal to liquid limit: the material verging to a liquid state (Lee et al. 2013). Lee et al. (2013) characterized the reservoir mud with a flat dilatometer and a piezo-penetrometer, as well as making excess porewater pressure measurements as it was not certain whether the young sediments had finished consolidating. The flat dilatometer results required interpretation and empirical equations. Some bailer samples were also taken to determine some basic properties in the laboratory.

At Luzzone, the sampling program entailed a collection of undisturbed and disturbed samples, from which specimens were taken on which to perform index property (particle size, unit weight, consistency limits) and strength (triaxial) tests (Sinniger et al. 1999).

The Casagrande cup and thin thread rolls are the conventional methods to determine consistency limits for fine grained material (either whole soil, or fine fraction), and were used for the consistency limit results from the Luzzone and Tsengwen reservoirs.

However, in his publication on geotechnical characteristics of sediments in Tunisian reservoirs, Mammou (1997) states that these methods are not suitable for sediments of significant clay content, which have liquid limits greater than 100%. Instead, he suggested, and used a relationship, involving the specific surface area of the sediments and amount of calcite, presented by Beaulieu in 1979. Mammou (1997) states that this method is simple and repeatable and that it determines consistency limits in precise enough (acceptable) manner, especially considering the sediment heterogeneity.

Mammou (1997) used X-ray diffraction on powders to determine the sediment mineralogy. Undrained shear strength of the intact sediments was done by the fall cone test, and was studied in remoulded samples as a function of water content with a shear vane. As was mentioned in Section 2.1, Mammou (1997) also simulated natural consolidation conditions of the reservoir.

Properties

The table showing an overview of the properties collected for this scenario can be found in Appendix A, Tab. A-1.

The Tunisian data are not presented in the table as it was not in format that allowed it to integrate into the system used for this thesis. However, the author presents very good findings, and they are included in this section.

The location of sampling becomes important considering that it is well documented that the sizes of the sediment particles decrease with distance from the inflow source into the reservoir (Mammou 1997; Bountry & Greimann 2009; Hollingshead et al. 1973). For the few reservoirs in this thesis for which data was included, the locations of the samples relative to the dam were not explicitly given: the samples from Luzzone and Tsengwen were near the dam. Thus due to insufficient description in the publications, this aspect has not been considered for this thesis, but should be investigated to fully understand the behaviour and risks of reservoir sediments.

The dam removal investigation at the Matilija reservoir (Bountry & Greimann 2009) provides a good description of the sediment distribution of a man made reservoir. The sediments are mostly sands and larger particle sizes as the fines passed by in flood flows. The distribution of sediments in the reservoir lead to the distinction of three zones, upstream channel, delta, and reservoir, each with rather characteristic particle size distributions (PSD). The distributions of the PSDs really prove that for this research of reservoir sediments, it is the reservoir part closest to the dam, which is most relevant as it has the finest particles, even if most of the fines wash over in the flood flows. In the

Luzzone reservoir, the sediments near the dam were found to be silt and sandy silt (Sinniger et al. 1999).

In the Sidi Saad reservoir (Tunisia), two rivers feed in and create an usual mix of sediments throughout the reservoir. In the Northern branch, sand is all the way to the dam, while the Southern branch displays typical behaviour of sands deposited before or at the entrance of the reservoir. The clay minerals of the clay fractions of sediments in both branches change in proportional composition as the distance to the dam decreases: the dominant kaolinite content and 20% illite gradually give way to an increasing (from 20% to 90%) smectite content (Mammou 1997). The variation in clay mineralogy within the reservoir is shown in Fig. 4 (from (Mammou 1997)).

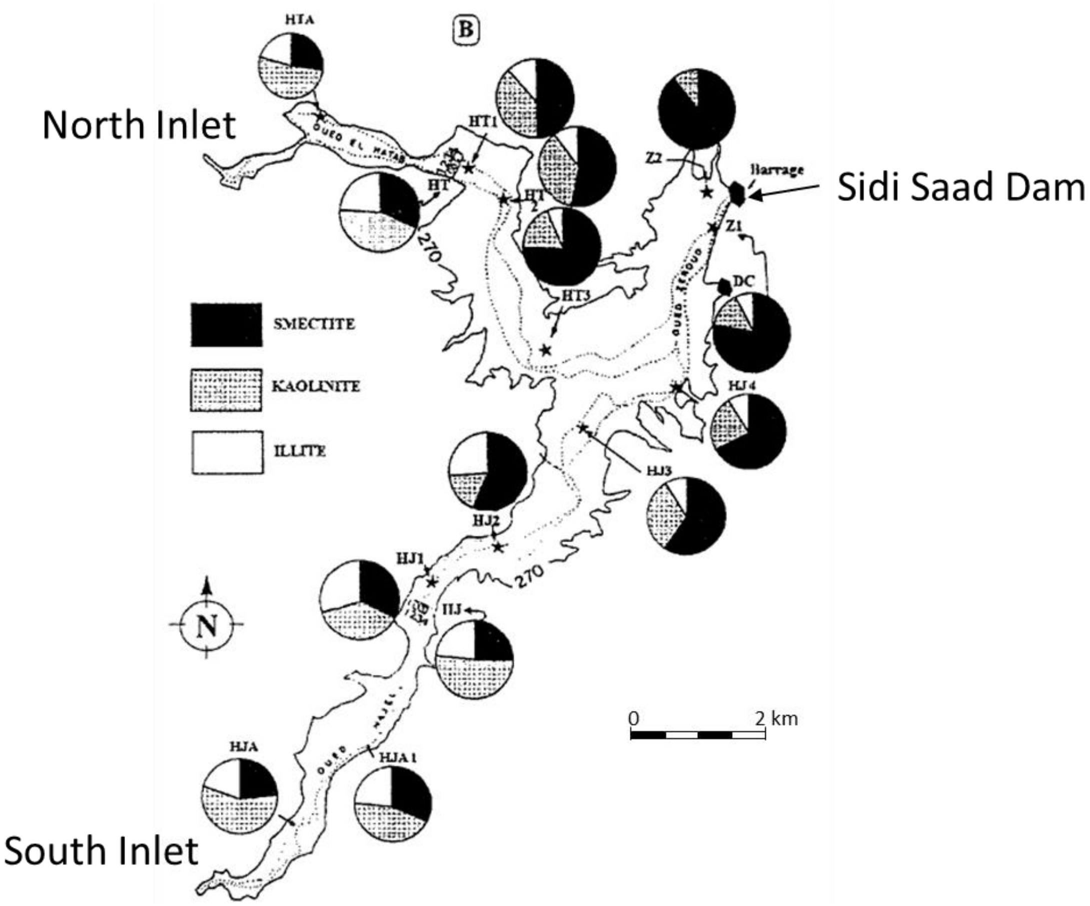

Fig. 4 Clay mineral distribution of the Tunisian Sidi Saad reservoir (after Mammou 1997)

As Lee et al. (2013) mention, the sediments near the dam have been transported by water, are usually the smallest of the reservoir, and are young, which lead to a deposit that is usually normal or underconsolidated. Thus the investigations of these sediments should include determination of the basic physical properties (plasticity, water content), as well as their state of consolidation (OCR) and density (unit weight). The results from this particular study in Taiwan did determine the above properties and showed that there were indeed still some excess PWP, indicating underconsolidation of the reservoir sediments.

A chapter in the ICOLD publication on sedimentation control (ICOLD 1989) provides insight into the density of accumulated sediments and factors affecting it, stating that reservoir operation is an influential factor (probably the most) because sediments subjected to long periods of (considerable or full) drawdown experience a greater amount of consolidation. This scenario is in contrast to is as opposed to a reservoir with stable levels, where the sediments are never dried out and do not consolidate to the same degree. The same chapter also presents equations for determining the initial density of reservoir sediments, which can account for time periods and more incoming sediment. This allows the user to estimate, based on the mass of incoming sediment, the volume the sediments will occupy in the reservoir after a 100 years of sedimentation.

Regarding the plastic behaviour, the Luzzone sediments plot below the A-line in the plasticity chart, indicating a silt that does not exhibit plastic or elastic behaviour. In three Tunisian reservoirs, the large majority of plasticity data points were above the A-line, indicating a clay, and varied between very plastic to plastic clays. Mammou (1997) explains this to be due to the reservoir heads catching the larger particle sizes, and the increase of smectites in the clays. Sediments from a same depositional event sort themselves in decreasing grain sizes, which is also seen in the corresponding increase of plasticity (Mammou 1997).

Flocculation has been found in the Tunisian reservoirs, and it is important to the properties of the sediments (Mammou 1997). The distribution of the particle sizes where determined for the sediments both before and after the addition of a dispersant, and it was found that flocculation changed the median particle diameter from 2-5µm to a bulk (70%) of particles having a diameter between 5 and 20µm (defloculated to bulk samples). The appearance of flocculation in sediments can occur for a range of particle sizes and seems to depend on clay mineralogy, salinity of the water, and organic and carbonate content. For example, the flocculation in the Nebeur and Sidi Saad reservoirs is linked to their salinity, the source of which comes from the reservoir banks or from floods, respectively. In another example, organic matter plays a large role, and carbonate content a partial role, in the flocculation found in the Sidi Salem reservoir. Further discussion regarding organic content is beyond the scope of this thesis, but Mammou (1997) does present more details on this subject.

Regarding strength properties, decompression in laboratory triaxial tests leads to a much higher cohesion due to negative porewater pressure (Boillat et al. 2000). Decompression on deposits in reservoirs occurs when lateral pressures on the deposits are reduced, such as by the removal of the sediments near the outlet. In the Luzzone reservoir, it was also found that of the slopes of these remaining deposits, some were much steeper (60 degrees) than the angle of repose of these sediments (32 degrees) (Boillat et al. 2000). Thus in these sediments, strength needs to be considered terms of both friction angle and cohesion.

3.2 Marine Sediments

This section describes the sediments and its various aspects from various marine environments, which include deep sea, delta, estuary, shelf, and deglaciation period waters. This section only presents a fraction of the amount of findings possible for the marine scenario. Due to hundreds (or thousands) of marine ports and decreasing barriers to sea resources, there is much research in this subject.

Setting

The deep sea situation is mostly investigated for offshore oil purposes. Barros et al. (2009) investigated marine clays, as stated by the author, of the Brazilian Bay, below water depths ranging between 600 and 2000m. Elsewhere in Brazil, Almeida et al. (2008) and Futai et al. (2008) collated numerous investigations of eleven Rio de Janeiro clays (stated by the authors), which are alluvia and marine sediments of the Quaternary Age. Most of them are no longer underwater and have varying details as to their setting, but apart from a couple of them, they are still considered very soft to soft clays. However, as they are coastal plain deposits, they all share a common feature: a sand layer underlies the clay layers, which may have an impact on the drainage path and consolidation rates of the clay layers.

Deltas are important features around the world, and understanding their sediments can be important for the oil and gas as they can reach far into deep water. The Gulf of Mexico and the Mississippi Delta in the USA has been extensively studied with regards to its sediments (Bennett 1976; Shephard et al. 1978; Quiros et al. 2003; Booth et al. 1977; Tompkins & Shephard 1979; Winters et al. 2008). Of particular interest here is research into the clay structure that develops in the shallower water depths (Bennett 1976). In Bennett’s study, the water depths were 67 to 73m (Bennett 1976) and the layers of deposition range in age from modern (at the top) to Pleistocene (sediment depths 85 to 150m).

Highly sensitive Singapore marine clay are estuarine deposits (Bo et al. 2015) and distinguished into upper, intermediate (desiccated crust of lower) and lower marine clay. Only the top 10m of the upper layer is considered in this thesis.

Many ports, such as Craney Island, are located in the environment where rivers are meeting sea. The sediments at Craney Island are both marine and fluvial-estuarine, depending on whether deposition was during glacial or interglacial periods (Smith et al. 2010).

The global water levels have fluctuated over the millennia in accordance with glaciations. During deglaciation periods, considerable sediments are deposited. In some cases, the water bodies change between marine and lacustrine environments, as was the case for the stratigraphy of sediments deposited in Finland (Messerklinger et al. 2003). Due to the long periods of constant glacier sources, thick layers of uniform clays can now be found in historical water bodies. Another great example of this clay is the Onsoy Clay in Norway, often investigated and used in research due to its high homogeneity (Long 2003).

Sampling and Testing

As these marine sediments are often in a liquid state, the testing and sampling of them have an increased difficulty. In the cases of offshore and delta sediments, these procedures need to be done underwater, and at high depths, also under high pressures. However, impressive equipment design has been accomplished in this field, due, in large part, to the oil and gas industry.

In the Brazilian basins, samples were collected from cores retrieved using Kullemberg and Jumbo Piston corers (Barros et al. 2009). In the Adriatic Shelf off of Italy’s Eastern coast, an investigation by Lanzo & Pagliaroli (2003) used a vibrocorer driven by self-weight. The Sherbrooke block sampler (Section 2.2) was used by Long (2003) to sample Norwegian Onsoy Clay.

For an excellent guide on deep sea in-situ geotechnical testing, see Lunne’s guidelines in which descriptions and notes based on experiences of the T-bar and ball penetrometers can be found (Lunne et al. 2011). At the Craney Island port, CPT testing was used and is described in publication by Karakouzian et al. (2002).

Once undisturbed samples were obtained from these investigations, the typical range of geotechnical laboratory tests was undertaken. For example, tests to determine physical properties (consistency limits, unit weight, natural water content) were performed for the previously mentioned investigations. The investigation by Lanzo & Pagliaroli (2003) used the DSDSS (simple shear) test in loading and unloading stages. In the Mississippi Delta, high magnification photos of clay were undertaken by Bennett (1976) to help determine the clay structure.

The methods to determine the in-situ undrained shear strength (Su) at Craney Island included vane shear test and cone penetration tests (CPTs). It was found to be critical to determine and use the correct empirical cone factor, which depends on the material, to calculate undrained shear strength (Karakouzian et al. 2002). As a later investigation at Craney Island found, the method of testing can have a significant impact on the results (Smith et al. 2010). They determined that using more ‘water based’ testing methods found the undrained shear strength profile to be 25 to 50% higher than had been determined from the investigation by Karakouzian et al. (2002), undertaken years earlier.

For the detailed investigation of the Singapore marine clays, bathymetric surveys, geophysical seismic reflection surveys (to profile the clay), both done considering tides, 50 boreholes, field vane, undisturbed samples, laboratory (oedometer) and X-ray diffraction (XRD) and scanning electron microscope (SEM) analysis for the mineralogy and photography were used (Bo et al. 2015).

Properties

The table showing an overview of the properties collected for this scenario can be found in Appendix A, Tab. A-2.

The sediments investigated in the marine settings presented above are mostly clays and some silts, as stated by the authors. The clays range from normally consolidated to overconsolidated with overconsolidation ratios (OCR) of less than 5 (Barros et al. 2009). It should be remembered that some of these clays are under up to 2000m of water, a vertical stress of 20 MPa. In the deltas, the environment is dynamic with significant river course changes over time, and thus the sediments stratigraphy may range from clays to sands.

The clays at Craney Island were considered as normally consolidated, until material for dikes and land reclamation were placed on top. Under the dykes, they are still considered underconsolidated even 50 years later. (Karakouzian et al. 2002). This can be seen by the porewater pressure (PWP) profiles, where the measured PWP is greater than the calculated hydrostatic pressure, indicating excess PWP, and unfinished consolidation (Karakouzian et al. 2002). As consolidation is still ongoing, strength measurements are only valid at the time they were taken.

In the clays of the Rio de Janeiro area, similar *OCR* values have been found, suggesting a similar stress history applies to this area. A consistently higher *OCR* (average 4) was found in the upper two meters due to desiccated crusts (Almeida et al. 2008). The publication says these are normally consolidated soils.

For the following compilation of data describing these marine sediments, attempts have been made to use comparable sediment layers if there was a choice. For example, the values from Bennett (1976) Mississippi Delta investigation are from the upper 30m of sediments. And as mentioned above, the dynamic delta environment means a range of sediments are deposited at a same location over time. Because of this range and the history of this location, a consistent sand layer at depth has been found in Bennett's investigation, and the 20m of silty clay layer on top of the sand has lower water content and indications of dewatering and consolidation processes. The whole profile, showing the properties changing with depth to 150m depth, can be found in his dissertation (Bennett 1976).

In general, the setting of marine deposits does guarantee a certain homogeneity, as similar fine grains continue to slowly settle. One publication did specify that there was not any systematic difference in clay property data (e.g., water content, plasticity) across the extent of the site (Smith et al. 2010). The publication goes on to explain that there is some variability, but to the same level (coefficients of variation) that most large sites have.

Other aspects of marine sediments are considered in these investigations, such as clay mineralogy, clay structure, particle interactions, irreversibility of properties, correlations of clay mineralogy and structure to physical and geotechnical properties. For example, due to the relative gentle deposition in salt water, a clay structure is developed and increases the sediment strength and stiffness properties (Bennett 1976). Once the structure is broken, the clay strength decreases (measured by sensitivity), and this process is often irreversible.

Salinity of the depositional environment (water within which the sediments are settling) is an important factor and may vary according to the marine setting. It has been shown that more flocculation and more structure strength occur with an increase in salinity (Wu et al. 2015). In deposits (soft clays) near the sea but no longer underwater, if the measured salinity is similar to that of the nearby seawater, it can be stated that the deposit is marine. However, it should be noted that reduced salinity may be measured as a result of salt leaching due to inflow of fresh water. This has been observed in Ariake clays in Japan, where salinity decreases with depth, due to fresh water flows near the surface (Wu et al. 2015). Severe salt leaching is also a process involved in the creation of *quick clays*, which are found in northern coastal areas of the northern hemisphere. Quick clays are known to be very sensitive, with sensitivity values greater than 30.

Singapore marine clay consists mainly of kaolinite, but also smectite and traces of mica (Bo et al. 2015). The clay fabric is described as open with “cardhouse” characteristics. It is mostly an inactive clay. It also exhibits a change of properties (liquid limit and water content) at an approximate depth of nine meters.

The Rio de Janeiro clays consists mainly of kaolinite, but either illite or smectite or both may also be found (Almeida et al. 2008). Organic matter (OM) is also found in these clays, giving a dark grey colour, and Almeida et al. (2008) showed a positive correlation to the water content (w) by $OM = 0.145*w – 1.41$. They found that 10% or less of organic content is enough to influence the behaviour, including compressibility and strength, of the Rio de Janeiro clays. Further discussion regarding organic content is beyond the scope of this thesis, but Futai et al. (2008) do present more details on this subject. For example, they studied these same Rio de Janeiro clays and stated that the presence of organic matter, and its associated fibres likely caused a scatter of friction angles found when correlating friction angle to plasticity index (PI). The scatter was more pronounced for the friction angles related to PI greater than 40%. For PI less than 40%, a good correlation was found.

3.3 Lacustrine deposits

Setting

Lakes are the natural equivalent of reservoirs: sediments are transported by and deposited in fresh water. The accumulated sediments become lacustrine deposits, which are either still underwater in lakes or have now become land due to changing lake levels over geological time.

Post-glacial lacustrine deposits are formed of sediments that were deposited as glaciers from previous ice ages retreated. The age of these sediments is temporally bounded by the age of the glaciers which produced the sediments and by the time when the deposit rose relative to the water level of the lake. In the central part of Switzerland, deposits from glacial melt-water lakes are common in valleys, and some are still located near major lakes, for example, Kreuzlingen near Lake Constance or Bodensee (Messerklinger et al. 2003).

Lacustrine deposits are not always consistent clays, as silt layers are often found within the deposits. While the clay is deposited in winter seasons, the silt layers are deposited during summer months when larger water flows occur. This creates a varved structure and leads to a significant anisotropy (directional dependency of properties) (Messerklinger et al. 2003). The approximate annual sedimentation rate of clay and silt into lakes producing the soft Swiss clays previously mentioned is 2 -3 mm (Messerklinger et al. 2003).

Sampling and Testing

In lacustrine deposits which are no longer underwater, it is somewhat less complicated to obtain undisturbed samples required for representative testing: the operator is not separated from the sampling apparatus and therefore can react to ground and sampling conditions. As mentioned in Section 2.2, numerous researchers have worked to develop sampling tubes, extraction techniques and specimen size preparation appropriate for undisturbed sampling of soft sediments, such as lacustrine sediments (Messerklinger & Springman 2009; Plötze et al. 2003).

Once undisturbed samples were obtained from these investigations, geotechnical laboratory tests (classification, fall cone, continuous loading oedometer, triaxial) were undertaken. The distribution of particle sizes between 700 and 0.2µm was determined using a laser light scattering apparatus (Plötze et al. 2003; Messerklinger et al. 2003). It should be noted that particles smaller than 0.2µm cannot be detected using this method.

These studies looked into the influence of clay mineralogy on the geotechnical properties. As such, the mineralogical composition was determined from X-ray diffraction (XRD) and Rietveld analysis, water uptake capacity was determined from the Enslin-Neff technique and the cation exchange capacity (CEC) was measured using some ion complexes (Plötze et al. 2003; Messerklinger et al. 2003)(Messerklinger et al. 2003). The CEC gives an indication of how much water can be chemically bound in the clay mineral interlayers, meaning that water content above this limit must be stored in the sediment voids as capillary water (Messerklinger et al. 2003) .The total water content, chemically bound and capillary, that can be stored by a clay deposit is indicated by water uptake capacity. After mechanically vibrating the sample, which decreased the porosity and the capillary water, the Enslin-Neff test was repeated with the result that the water uptake (as water content percentage) nearly matched the liquid limit determined by the Casagrande cup.

Cone penetration testing with measurements of porewater pressure (CPTU) was performed in the Swiss deposits and as can be expected, the tip resistance increased linearly with depth, indicating a normally consolidated clay deposit (Plötze et al. 2003).

Properties

The table showing an overview of the properties collected for this scenario can be found in Appendix A, Tab. A-3.

The table presents properties (specific gravity, friction angle, compressibility parameters, sensitivity, permeability, shear strength) for lacustrine deposits from Switzerland. In general, there is not much data published on the properties of lacustrine deposits. Therefore, most of the data presented here has been found in two publications (Messerklinger et al. 2003; Plötze et al. 2003).

The sediment properties seem to be influenced by the clay fraction, clay mineralogy and varving and to be correlated to mineral composition, cation exchange capacity and water uptake capacity (Messerklinger et al. 2003; Plötze et al. 2003). For example, liquid limit was positively correlated to water uptake capacity. Plötze et al. (2003) showed that the clay mineralogy has an impact on water content due to the better water uptake of certain clay minerals (Plötze et al. 2003).

3.4 Man made Deposits

Setting

Man made deposits in this thesis include tailings, industrial waste sludge, and dredged material. They are good to investigate as data has been collected in numerous projects around the world in order to better engineer the deposits of the project.

Industrial waste sludge encompasses tailings and mineral slurries from mining and industrial activity which needs to be stored in a safe manner.

For tailings from the oils sands industry, the process of extracting bitumen from oils sands and the resulting tailings is well explained by Beier et al. (2013). Thin fine tailings enter the settling ponds with solids content (solids) between 6 and 10% (1567 to 900% water content). It should be noted that solids content, a term used in oil sands tailings, is related to water content (w) by w = (1-solids) / solids. In these storage facilities, the fines fraction slowly (about two years) settle, resulting in mature fine tailings (MFT) with a solids content of 30% to 35% (water content of 186% to 233%). Suthaker & Scott (1997) defined immature fine tailings as having any solids content less than 30% (or water content greater than 233%). The MFT is allowed to settle further and consolidation is desired (and encouraged) in order to achieve regulated strength minimums. However, this settlement is extremely slow (in the order of decades), as the clay particles have a dispersed nature due to the oil extraction process. (Beier et al. 2013).

Dredging is the process of removing accumulated sediments from the bottom of a water body. In many ports around the world, this needs to be done to create enough water depth for large ships (Seng & Tanaka 2012; Sengul et al. 2016). Dredging can be done by mechanical or by suction processes. As it is often done in oceans or large connected water bodies, very large equipment can be used. There is a range of methods and equipment that can be used, and the best choice will depend on many factors, such as, soil type (van‘t Hoff & van der Kolff 2013).

Sampling and Testing

Undisturbed sampling is often not required of these materials as much of the testing of these materials done in the lab is done on remoulded or reconstituted samples, to mimic the deposition of the sediments in the field. In order to investigate the characteristics and the relationship between effective stress and behaviour of dredge material, Seng & Tanaka (2012) used remoulded samples of commercial and natural clays.

Villar et al. (2009) used standard soil testing procedures to investigate the particle size distribution, consistency limits and relative density of waste materials from different processing stages. They also considered the importance of the fluid, and its pH, by using water versus the original industrial liquids as the testing fluids.

In order to simulate the immature and mature oil sands tailings, Suthaker & Scott (1997) varied the water content (w) of their remoulded samples to suit: w = 300-400% to reproduce immature tailings and w = 100-200% to reproduce mature tailings; and tested their specimens from zero to 680 days, to simulate the couple of years it usually takes to achieve mature fine tailings (MFT) in the field.

Cavity expansion tests were done in Suthaker & Scott (1997)’s publication of fine tailings and other similar materials as a means to measure thixotropic strength with little disturbance. As thixotropic strength is the strength of a material that increases with time once agitation and disturbance of the material has ceased, any disturbance in the testing of in-situ strength is counterproductive. Suthaker & Scott (1997) found the cavity expansion tests were successful in estimating thixotropic strength as the strain rate was not affecting the strength. Suthaker & Scott (1997) also compared those strengths to ones determined from vane tests and viscometer tests (using T-bar spindle), however those tests were only done to check for similar trends in thixotropic ratio, as the values were of different magnitudes.

In-situ tests, penetration and field vane (FVT), are commonly used to assess the undrained shear strength of oil sands fine tailings (Beier et al. 2013). Strength is of significant interest as regulations require certain strengths to be reached after set periods of time. It has been shown that field vane tests provide the most reliable results, and are the most common method in oil sands tailings (Masala & Dhadi 2012)

Properties

The table showing an overview of the properties collected for this scenario can be found in Appendix A, Tab. A-4.

Villar et al. (2009) investigated bauxite (source of aluminium) mining and processing tailings, and found that flocculation is important and has a tendency to occur in this setting as chemicals are added. Their publication presents data that shows that standard soil testing procedures provide results which will not replicate the actual field behaviour of tailings material. They found the use of extremely basic (pH 14) industrial fluid as compared to water (pH 7) in some tests caused a different sediment behaviour and affected the results. For example, some testing procedures, such as heating is used for grain density and drying for plasticity, were developed for relatively neutral soils and are sensitive to highly basic sediments. In grain size distribution tests, the highly caustic (high pH) fluids created more flocculation, than neutral fluids, in the particles, although as can be expected, different flocculation behaviours were observed for fine and coarse sized sediments. The results showed the tailings as being either a sand or a clay, depending on the methods and fluid used. This is a significant finding. Data from this publication is not included as too many variables were considered, and there is not a consistent material which can be summarized (Villar et al. 2009).

Oil sands tailing deposits are only represented by a couple data points in this thesis, and in terms of plasticity, they plot above the A-line, as inorganic clays of intermediate plasticity. This is a similar result to the findings of Beier et al. (2013), who presented a plasticity chart plot of many test samples in oil sands that showed all points plotting above the A-line, and mostly as high plasticity clay (CH).

4 Comparison of Geotechnical Properties

4.1 Introduction

It was briefly mentioned in Chapter 2 that the scenarios were chosen based on similarity to reservoir sediments and amount of published data.

In the previous chapter, data for the scenarios were presented without interpretation. In this chapter, the data from the previous chapter are analysed and comparisons are made between the scenarios. The main idea is to show that sediments deposited in different settings have similar properties, thus reservoir sediments are better understood than initially thought.

The differences between scenarios are also discussed, and the properties used to show some of the main influencing factors on the sediment properties. This should then lead to ideas of what should be considered when investigating reservoir sediments for the purposes of risk analysis and mitigation, a topic of Chapter 5.

The scenarios presented are reservoirs, marine, lacustrine and man made. Reservoirs are included as this is the primary topic of this thesis. The marine scenario is mainly included as it involves fines settling underwater, and there is much more available data on these sediments. It is inclusive of a wide range of water depths. The lacustrine scenario is included because the sediments were deposited in the same setting as reservoirs, albeit in natural rather than man made basins. The man made deposits are included because they involve sediment and water depositions. These materials are often transported and deposited in a state of very high water content and it is this aspect which means it can be considered in this thesis as a comparison to reservoir sediments.

4.2 General Differences

As the scenarios will be compared at the property quantification level, it should first be clear what are the differences between them. Some of the scenarios' main characteristics that differ from reservoirs are presented in this section.

A big difference between reservoirs and marine sediments is that marine slopes often comprise large movements of material from shallow depths to deeper waters (Prior & Coleman 1982). So the sediments farther down slope may have undergone a second transportation.

The water depths of the scenarios are quite different, ranging from about 1.8km to no longer underwater, as seen in Fig. 5. The lacustrine sediments presented in this thesis were originally deposited below water, but were no longer underwater when the investigations took place. This is also the case for some of the marine and man made (dredged) sediments.

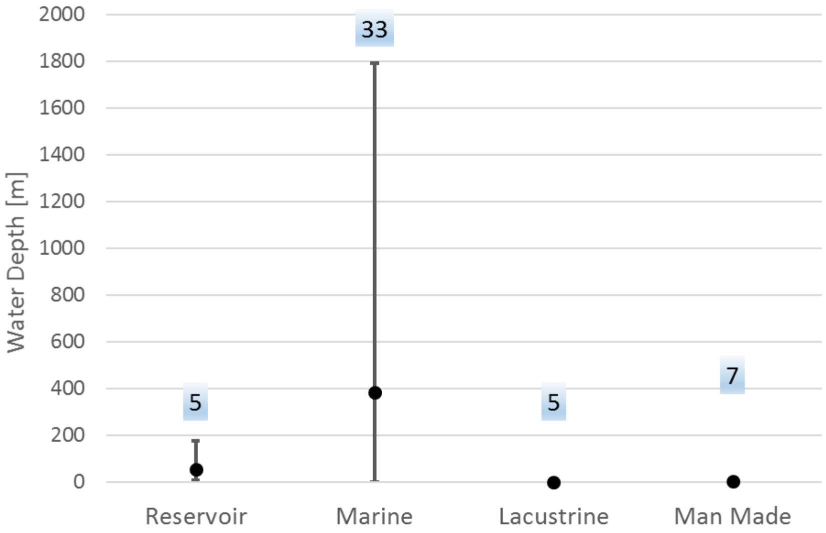

Fig. 5 Water depths for each scenario: average (dots), maximum to minimum extent, and number of data points (boxes)

Age has not been considered in detail in this thesis. However, the lacustrine sediments are no longer underwater and were produced by ice age glaciers, an indication that thousands of years have passed since deposition. Thus it is reasonable to state that the lacustrine deposits are much older than reservoir sediments, which can only be as old as the age of the dam. The age of marine sediments varies according to location (deep sea versus shallow river delta) and depth of sediment; most of the ones presented in this thesis are likely older than reservoir sediments. The age of man made deposits are in the range of reservoir sediment ages. Age plays a large role in properties that change with time, such as unit weight, strength, compressibility, which alter with self-weight consolidation.

Chemically, the scenario depositional environments are also not all the same. In general, marine sediments were deposited in salt water, while reservoir and lacustrine sediments settled in freshwater. While these are the endpoints, the findings showed there is a range of depositional water salinity. For example, reservoirs may have a higher salinity due to the geological content of the banks, and marine estuaries and shallow river mouths may have a diluted salt content due to the incoming freshwater. The salinity of the depositional fluid has an impact on flocculation and sediment clay structures. In terms of chemical content, man made deposits, such as oil sands tailings, may have processing residuals, and often have much higher water contents. Dredged deposits are often placed with additives to dewater and stabilize.

Waste and tailings sediments may be difficult to compare to reservoir sediments as many factors and influences must be considered. However, they are deposited as a slurry so their depositional consistency (solids liquids mix) may well resemble turbidity current mixes which are usually what bring the fine reservoir sediments near the dam. This comparison may be specifically for immature fine tailings.

Messerklinger et al. (2003) compared some marine (Finnish) and lacustrine (Swiss) clay deposits and presented a key characteristic difference due to their depositional conditions: the marine clays have a homogeneous composition and very open structure, while the lacustrine clays have a varved structure and thin interlayers of silt and clay due to differences in summer and winter depositions.

There are similarities between the scenarios, thus their inclusion, but it is good to remember some of the main differences as the properties are compared and explanations made.

4.3 Property Comparisons

In Fig. 6, specific gravity is similar across the scenarios, varying within 2.4 to 2.9. This is reasonable as 2.75 is typical for clay.

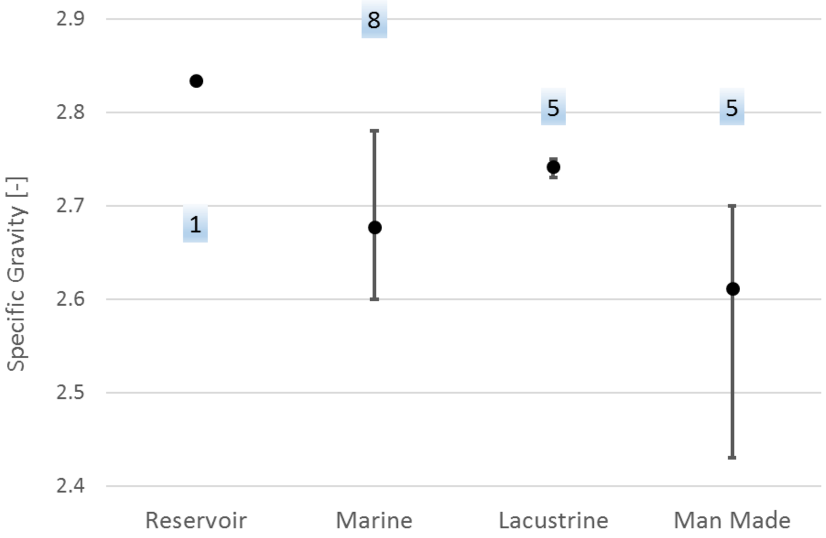

Fig. 6 Specific gravities for each scenario: average (dots), maximum to minimum extent, and number of data points (boxes)

Unit weight ranges between 12 and 19 kN/m3, as shown in Fig. 7. The lacustrine unit weights are higher, but their specific gravities (Fig. 6) are not higher; this is likely due to their years of consolidation which the underwater sediments cannot do as easily.

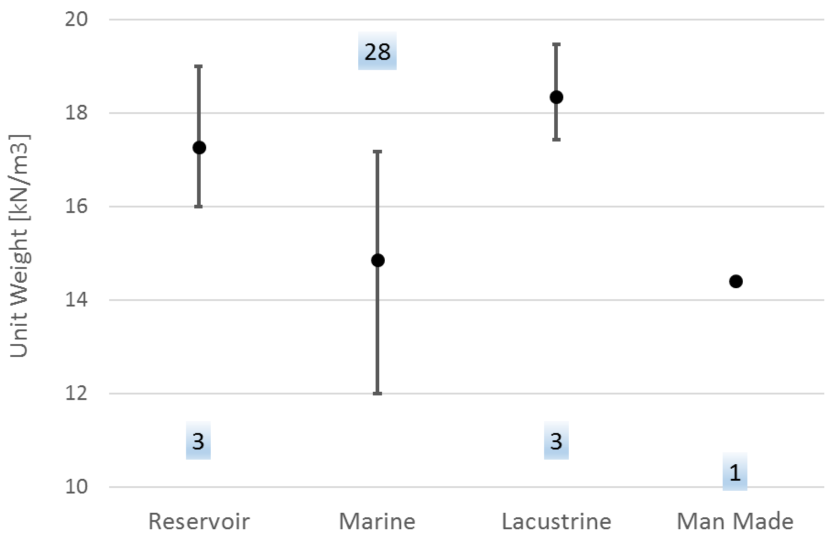

Fig. 7 Unit weights for each scenario: average (dots), maximum to minimum extent, and number of data points (boxes)

The following figure provides an indication of the clay and silt fractions in the sediments, grouped by scenario. The gaps to reach the 100% line represent the sand fractions. There is a significant amount of silt in the sediments, especially in the reservoir data. It should be remembered that most of the sediments mentioned in the publications were called clays by the authors, but they do not all have more than 50% clay fraction.

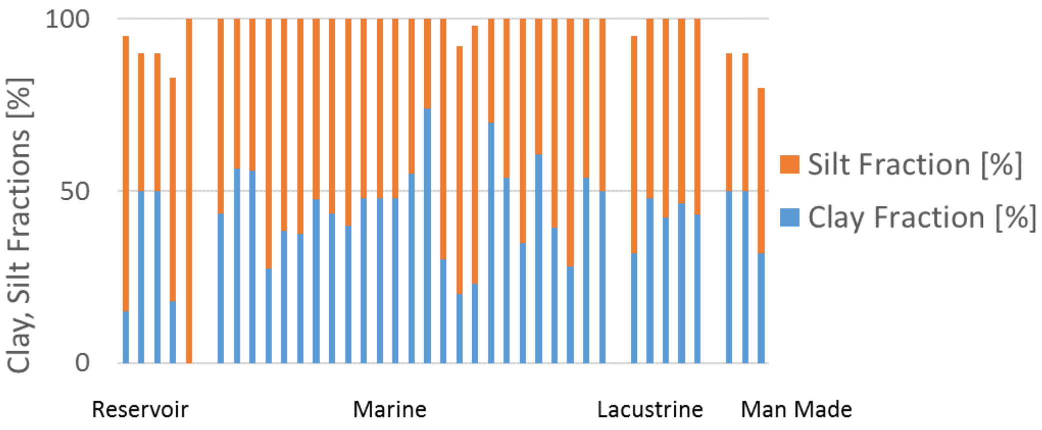

Fig. 8 Percentage of silt and clay sized sediments, grouped by scenario

It seems that the plasticity behaviour is also taken into account for the naming of the sediment deposits for each site. In the following Fig. 9, the plasticity chart shows that most of the deposits' plastic behaviour points are plotting above the standard A-line, which indicates a clay behaviour, shown with the letter ‘C’. The ‘M’ indicates silt, and the second letter in each label refers to the level of plasticity (Low – L, I – Intermediate, H – High, V – Very High, E, Extremely High). A note that the plasticity chart has been expanded to accommodate most of the data plotting off the standard chart size. There is a further man made point that plots off the chart, (with a LL of 250 and PI of 150, under the A -line.) The expansion has been done according to Note 8 of the ASTM D2487 (ASTM 2010), keeping the same axes scale and A-line slope. The U-line is empirically determined and designates the “upper limit” for natural soils; it delineates the line above which soil data points should not plot as it would indicate erroneous data. All data points are below the U-line. In general, all these sediments demonstrate similar plasticity behaviour, although the liquid limit range is quite wide. In this context, the reservoir sediments most resemble the lacustrine sediments.

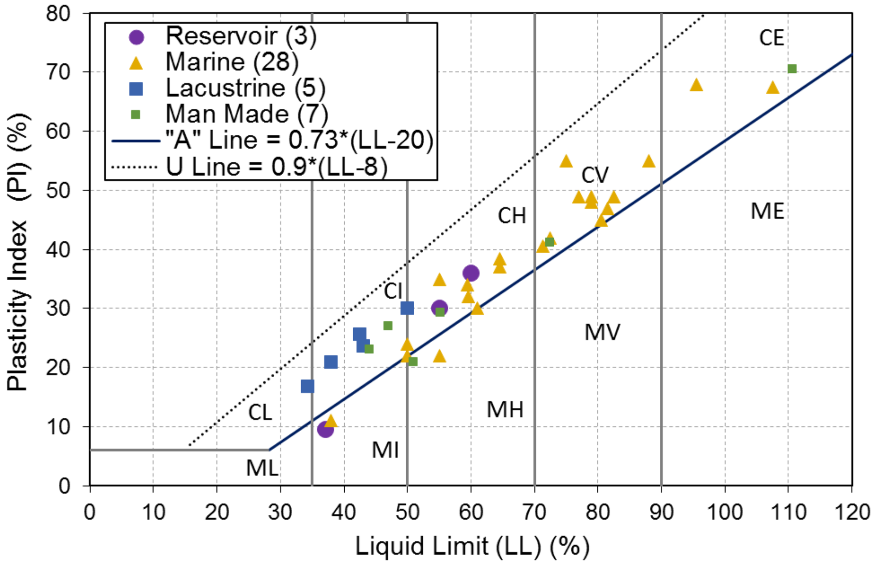

Fig. 9 Plasticity Chart for each site

Fig. 10 shows the natural water content (w) for each site’s sediments and how it sits relative to the plastic (PL) and liquid limits (LL) of those same sediments. It can be seen that all the sediments are near to or above the liquid limit, indicating a liquid state. The state is clearly presented when plotting the consistency index (CI) for the sediments, as shown in Fig. 11. Values below the zero line indicate the sediments are in a liquid state, and above the zero line and under one, they are in a plastic state. It can be seen that all the sediments presented here are in a liquid or low plastic state (CI < 0.25). In other words, these are very soft fine grained soils, as per the definition presented in Section 2.5.

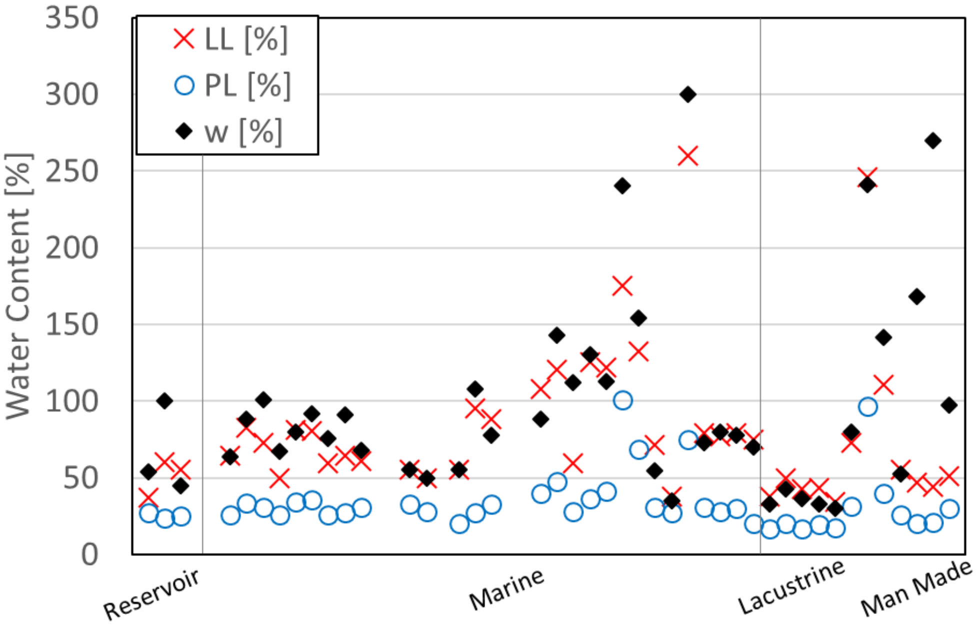

Fig. 10 Water content relative to liquid and plastic limits

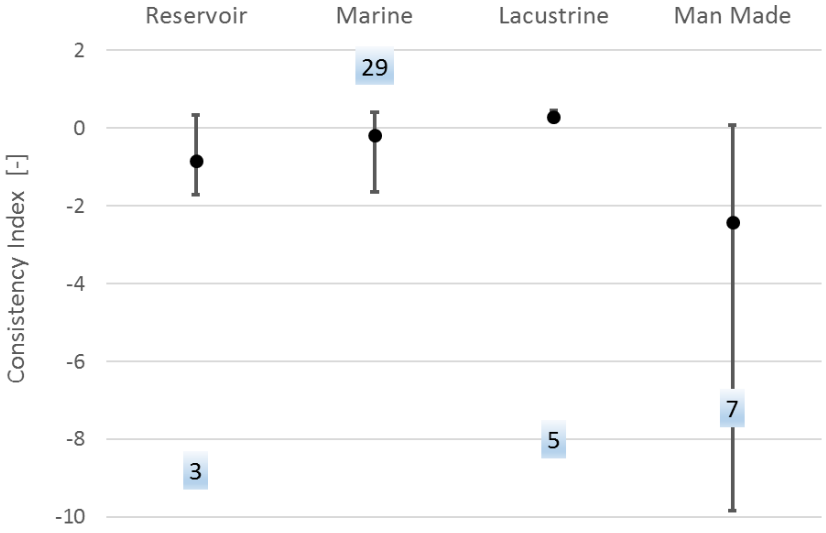

Fig. 11 Consistency indices (CI) for each scenario: average (dots), maximum to minimum extent, and number of data points (boxes)

In general, sediments in the liquid state indicate that they are from situated below water, and sediments in the plastic state are from land. However, the data collected in this thesis has shown numerous exceptions to this generality. The lacustrine deposits stand out in Fig. 11. They are no longer underwater, have lower water content and are in a plastic state rather than a liquid state. The same can be said for the few marine sediments which are no longer underwater. In the case of the reservoir sediments, the highest index is from the deeper (10-20m) sediments in the Tsengwen Reservoir.

Another soil index based on the consistency limits is the liquidity index (LI), defined by the following formula LI = (w-PL) / PI. Some liquidity indices were provided in the publications. These are compared to liquidity indices calculated according the above equation, in order to increase confidence in the general process used in this thesis. The comparison is shown in Fig. 12, and shows a strong linear relationship when the two outliers are discounted. It is reasonable to discount them as the values come from a publication that compared lacustrine deposits from multiple investigations: the consistency limits and the provided liquidity indices were not obtained from the same investigation.

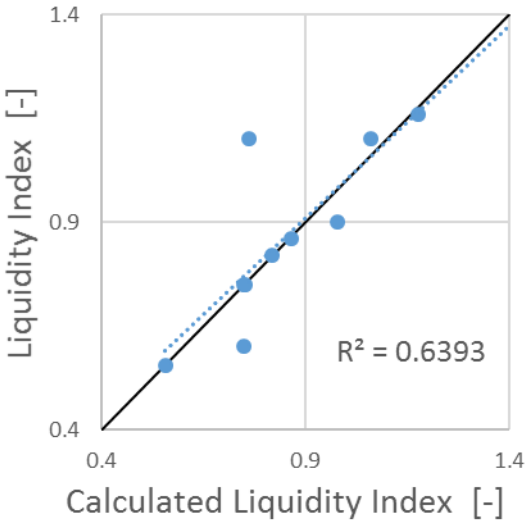

Fig. 12 Provided liquidity index versus calculated liquidity index

Fig. 13 compares void ratio and shows that the lacustrine deposits have a lower void ratio than the reservoir value, as they have consolidated more. The marine sediment void ratios are in general much higher, which is most likely due to with flocculation and the increased structure created by the deposition in salt water. In their comparison of marine and lacustrine clays, Messerklinger et al. (2003) presented that the marine clays are characterised by a flocculated particle arrangement, which leads to a very open structure, and rather high water content.

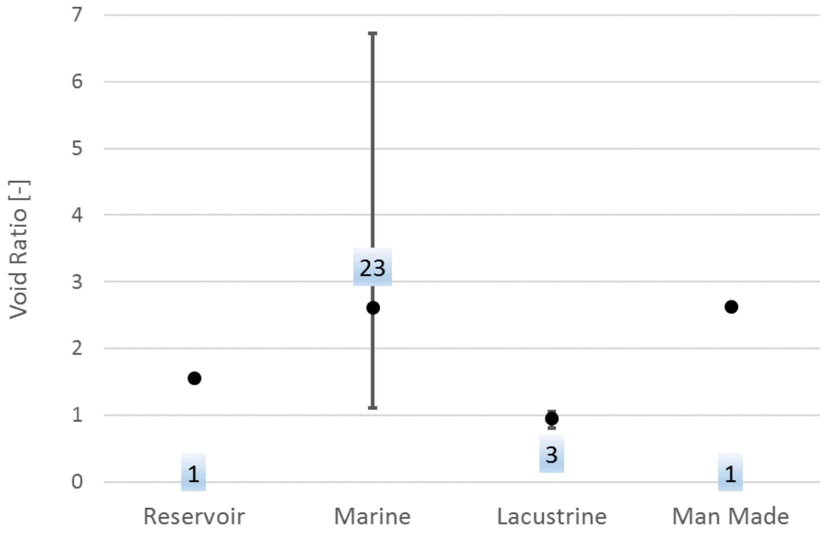

Fig. 13 Void ratios: average (dots), maximum to minimum extent, and number of data points (boxes)

As stated in Section 2.4, it was assumed that the provided void ratios were in-situ (initial) values when not otherwise indicated. Initial void ratio (e_0) was provided in some cases of the marine scenario, and defined in connection with the compressibility parameters (index (Cc) and ratio (CR)): $e_0 = (Cc / CR)-1$. Both in-situ and initial (indicated) void ratios were combined into one void ratio property. In order to increase confidence in putting the two together as one property, where data was available (nine marine sites (Barros et al. 2009)), initial void ratios were calculated from compressibility parameter sets (Cc and CR) and compared to the void ratios provided in the publication, as shown in Fig. 14. It is not clear what method what used by the authors to obtain their published void ratios. If they were calculated as above, then the differences in Fig. 14 may be due to the use of averages rather than individual results.

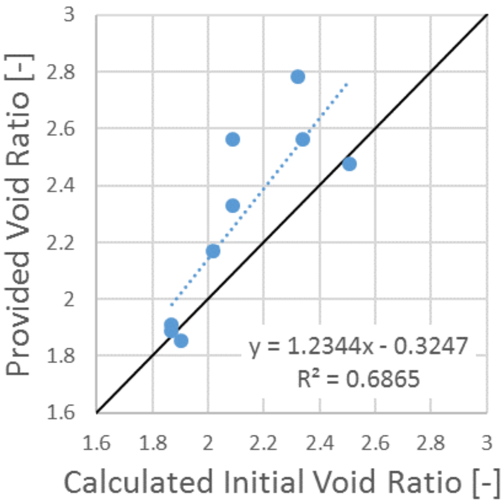

Fig. 14 Provided void ratio versus calculated void ratio

As is shown in Fig. 8, and in Fig. 15, the reservoirs sediments comprise mostly silt. This maybe be due to clay being suspended longer in water and thus more likely to be carried past the reservoir with flowing water. The low clay fraction and low plasticity behaviour of the Luzzone sediments has been explained by Boillat & Pougatsch (2000) as due to the poor vegetation of the sediment source (high altitude areas).

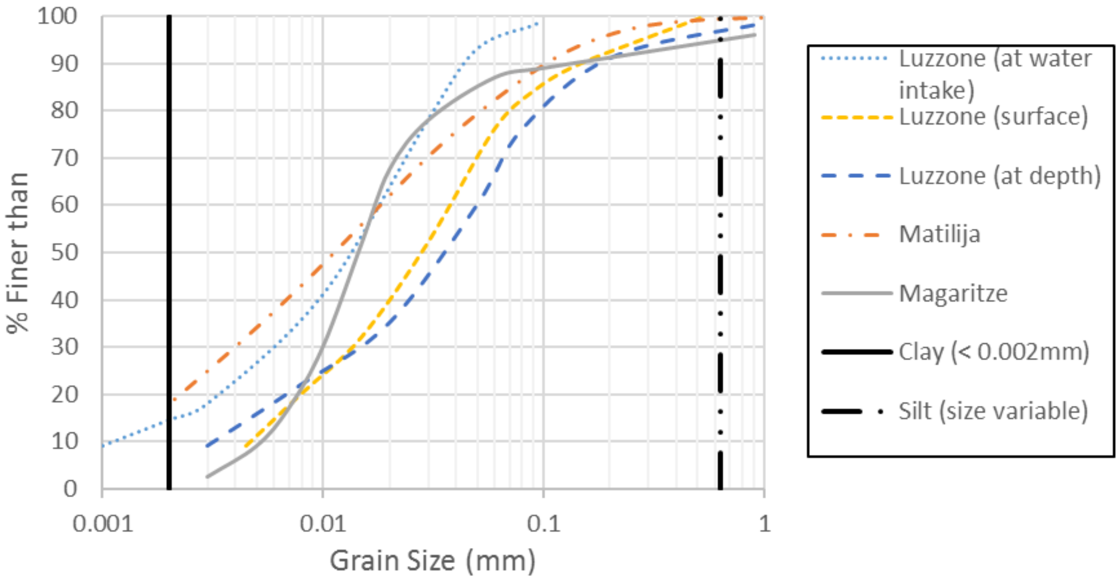

Fig. 15 Particle size distributions for reservoir sediments

4.4 Correlations

Geotechnical Properties

In this section, some geotechnical properties are compared to each other. The data points include all the available data from the four scenarios and they are given different markers to distinguish the scenarios in the graphs.

In Fig. 16, it can be seen that unit weight decreases as water content increases. This is to be expected as higher water content occurs with more pore spaces, and the density of water is less than that of particles. It can also be seen that the lacustrine points follow the same trend (shown as the dashed line) as the marine points.

Fig. 17 shows the relationship of undrained shear strength to water content and clay fraction. It can be seen that there is not a strong correlation. However, this is not too surprising as the undrained shear strength data values were collected from various sources using different methods and in tests following different stress paths. The non-correlation could also be an indication that there are not enough data points. This topic definitely warrants more research.

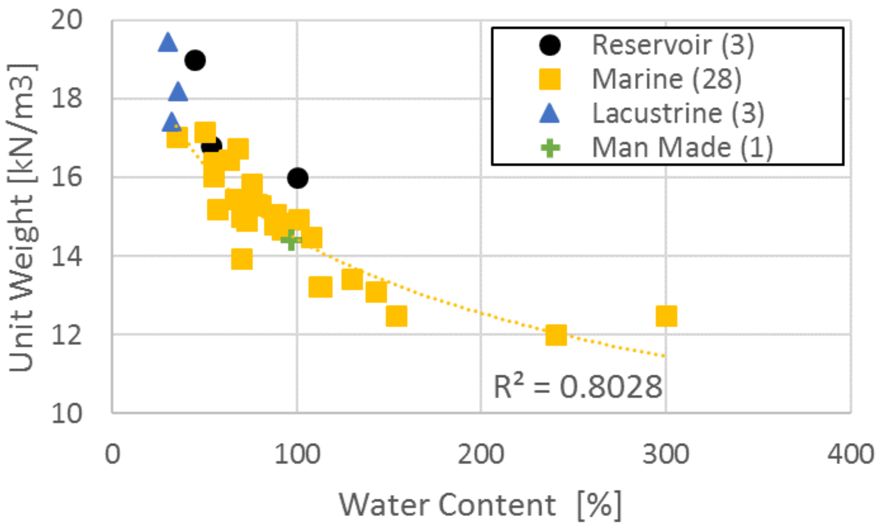

Fig. 16 Unit weight versus water content

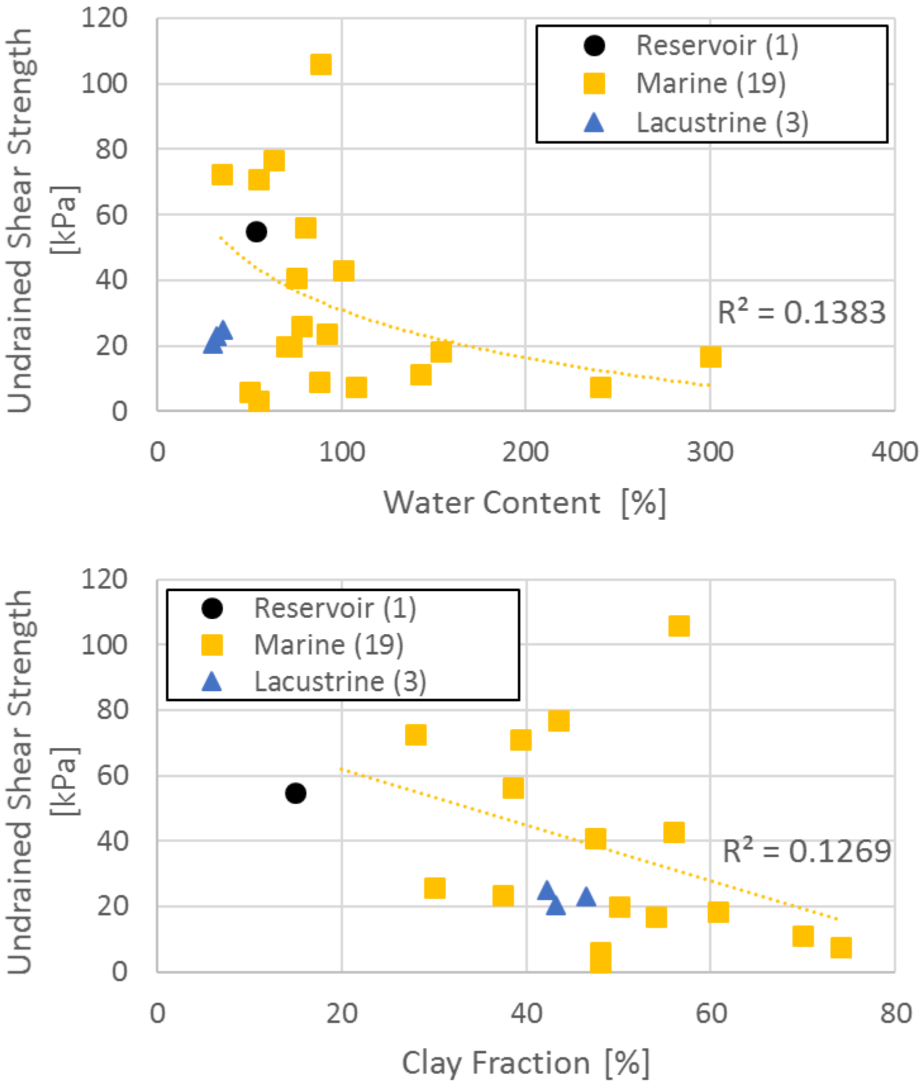

Fig. 17 Undrained shear strength versus (a) water content and (b) clay fraction

In the literature, a positive correlation between compression index and liquid limit has been documented (Tanaka et al. 2001; Tiwari et al. 2009). For data points collected in this thesis, Fig. 18 shows compression index relative to liquid limit. The line is the correlation between the two properties, established by Terzaghi. Comparing the data points to Terzaghi's equation, one can see a general alignment, when discounting the outliers. The outliers may be due to discrepancies in the various forms of compressibility parameters, and the different axes on which they are plotted. It has also been noted that compression index (Cc) is heavily affected by sample disturbance, which explain the differences (Tanaka et al. 2001).

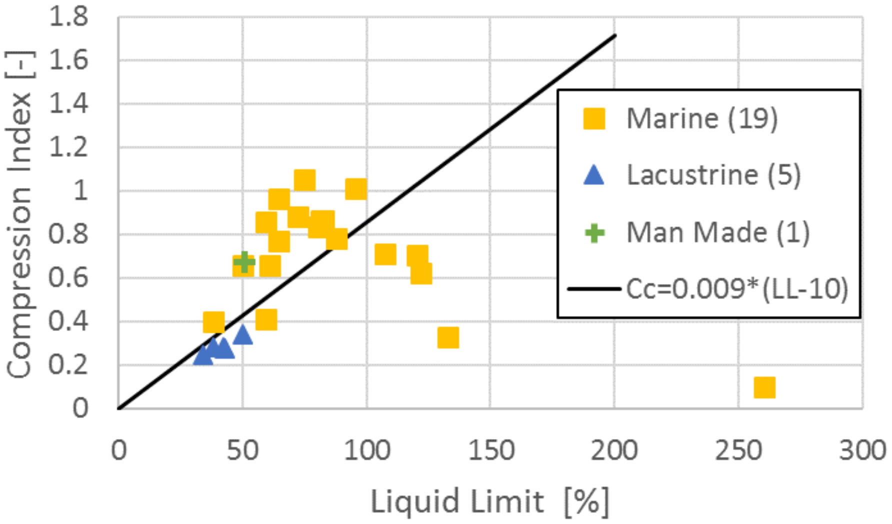

Fig. 18 Compression index versus liquid limit

Clay Influence

The influence of the clay fraction (as a percentage of soil) on the soil behaviour can be examined via the dimensionless activity (A) of the soil, defined as activity (A) = plasticity index (PI) / clay fraction (CF).

A plot of plasticity index versus clay fraction is shown in Fig. 19, and shows how the activity levels of the scenario data points. There is somewhat of a scatter in the marine data points, but the other three scenarios, reservoir, lacustrine and man made, all sit in the inactive zone.

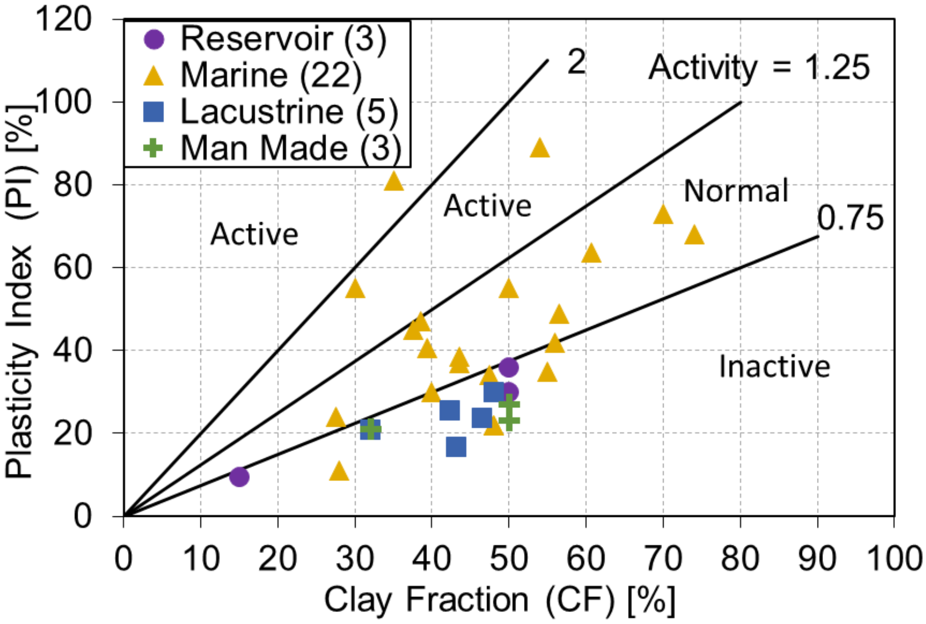

Fig. 19 Plasticity index versus clay fraction within context of activity

In another look at a consistency limit against clay fraction, Fig. 20 shows liquid limit versus clay fraction. There is not a strong correlation, although a slight trend shows that liquid limit increases with clay fraction.

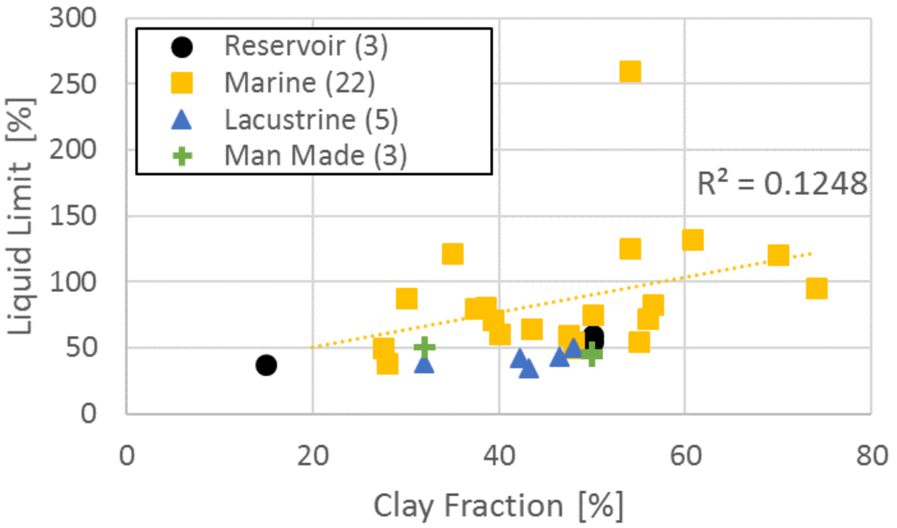

Fig. 20 Liquid limit versus clay fraction

A further look in clays leads to a discussion on the effect of different clay minerals. The main clay minerals found in these types of sediments are kaolinite, illite and smectite (or montmorillonite). They are briefly described as follows:

- Kaolin group – kaolinite – has a 1:1 structure: one tetrahedral sheet and one octahedral sheet. The combined sheet structures are connected to each other by relatively strong hydrogen bonding (Craig 2004, p.2). On its own, this clay mineral has a normal to inactive activity level (Ohtsubo et al. 2002).
- Illite group – illite – are similar to micas (sheet minerals) and have a 2:1 structure: one octahedral sheet sandwiched between two tetrahedral sheets. The combined sheet structures are connected to each other by relatively weak bonding of non-exchangeable ions (Craig 2004, p.2). On its own, this clay mineral has a normal activity level (Ohtsubo et al. 2002).
- Smectite group – montmorillonite – also has a 2:1 structure, although with a slightly different octahedral sheet. The combined sheet structures are connected to each other by a very weak bond due to the presence of exchangeable cations and water molecules. This clay mineral undergoes considerable swelling when in contact with water as additional water can be adsorbed between the sheet structures (Craig 2004, p.3). This clay mineral has an active activity level (Ohtsubo et al. 2002).

Chlorite and mixed layer clay variations were also mentioned a few times in the publications. Further details of clay minerals can be found in most geotechnical textbooks, for example Craig 's (2004 's) soil mechanics.

The impact of clay mineralogy on various geotechnical properties has been researched extensively. It has been found that consistency limits vary with clay mineral types and the percentage of their content in the soil. For example, kaolinite has lower consistency limits than illite, and smectite have the highest. This has to do with the their specific surface area and cation exchange capacity, or how much water each mineral can take into the structure (Chandra & Azam 2013). A correlation, found by Ohtsubo et al. (2002), of consistency limits to smectite content can be seen in Fig. 21, and shows that the East Asian marine clays with higher bulk smectite content have increasing liquid limits (Ohtsubo et al. 2002).

Compressibility parameters have also been found to be influenced by clay mineralogy. Tiwari et al. (2009) showed positive correlations of compression index and swelling index to the smectite proportion.

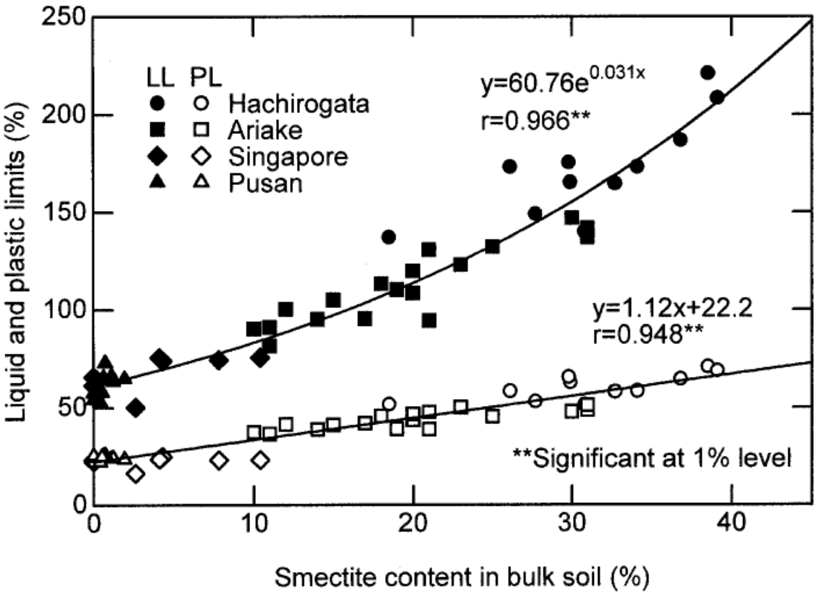

Fig. 21 Consistency limits as a function of smectite content in East Asia marine clays (Ohtsubo et al. 2002)

In clays, the undrained shear strength (Su) is due to cohesion. The cohesion may result from two mechanisms: attractive forces between particles or viscosity of water in the clay layers, that may operate independently or simultaneously. Sridharan et al. (2002) explain that the *Su* of kaolinite dominant soils is due to the first mechanism (attractive forces) while for montmorillonite dominant soils, *Su* is mostly due to the second mechanism (viscosity of clay layer water).

Undrained shear strength can also be examined in the context of thixotropy (a change in viscosity due to an applied stress), which is often done in the context of oil sands tailings (man made scenario). After sediments have been moved around (applied stress) and then left to settle, they may gain strength with time, simply by sitting in place with no additional stresses acting on them. This increase in strength can be expressed as thixotropic ratio: the ratio of the strength at a certain time versus the strength at the end of movement (start of settlement period) (Suthaker & Scott 1997). Fig. 22, taken from (Suthaker & Scott 1997), shows the thixotropic ratio three clay minerals and how they compare to fine tailings in oil sands tailings ponds. Bentonite may be considered as montmorillonite for comparison purposes. The graph shows that kaolinite (strength from first cohesion mechanism) does not gain any significant strength with time, while montmorillonite (strength from second cohesion mechanism) gains more than double its strength over a period of 200 days. Illite’s strength increase falls in between. This seems to indicate that the first mechanism (attractive forces) creating cohesion is less effective than the second mechanism (viscosity of clay layer water) in increasing strength with time.

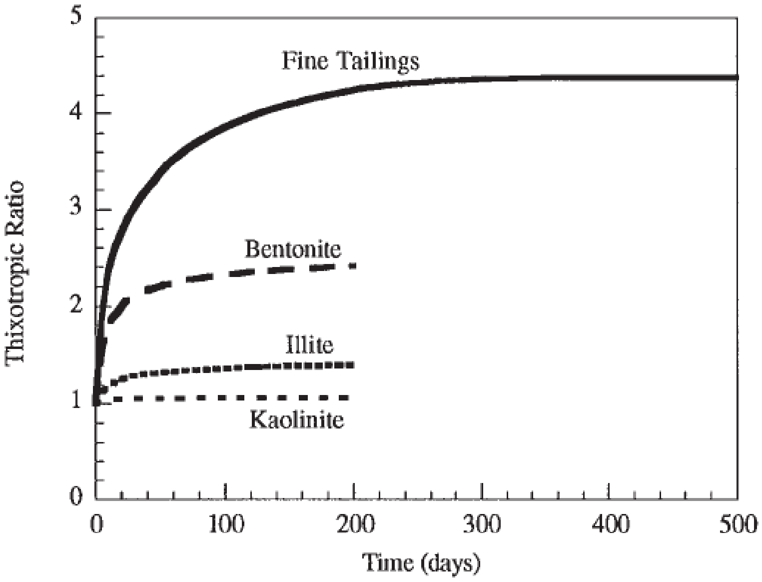

Fig. 22 Thixotropic ratio of clay minerals and fine tailings (Suthaker & Scott 1997)

Other minerals may also affect geotechnical properties of sediment deposits, for example calcite or carbonate. Messerklinger suggested that higher calcite content in Swiss lacustrine clays resulted in more clay minerals being cemented together, forming larger peds, and thus behaving more like silts. The lower calcite content of the Finnish marine clays (compared in the same publication) might mean fewer silt sized peds and thus more dispersed clay sized particles, increasing their sensitivity to destructurations (Messerklinger et al. 2003).

From the literature covered for this thesis, the available clay mineralogy data was collected and plotted in a ternary diagram, shown in Fig. 23. This does not include data from publications that only specify the predominant clay mineral, without giving any numerical indication of proportion. The three variables of the ternary plot are kaolinite, illite and smectite (also includes chlorite) and can be seen at the corners where their occurrence would be 100% of the total clay fraction. The data points represent the proportions of the clay fraction each clay mineral has of a site’s sediment. They are colour coded by scenario. The man made data points show low smectite content and have relatively low liquid limits (see Fig. 20). This is a possible finding that corroborates for the correlation of consistency limits and smectite presented earlier. However, there are too few data for representative analysis and the scarcity of available and reliable data means that any reliable conclusion for properties cannot be drawn.

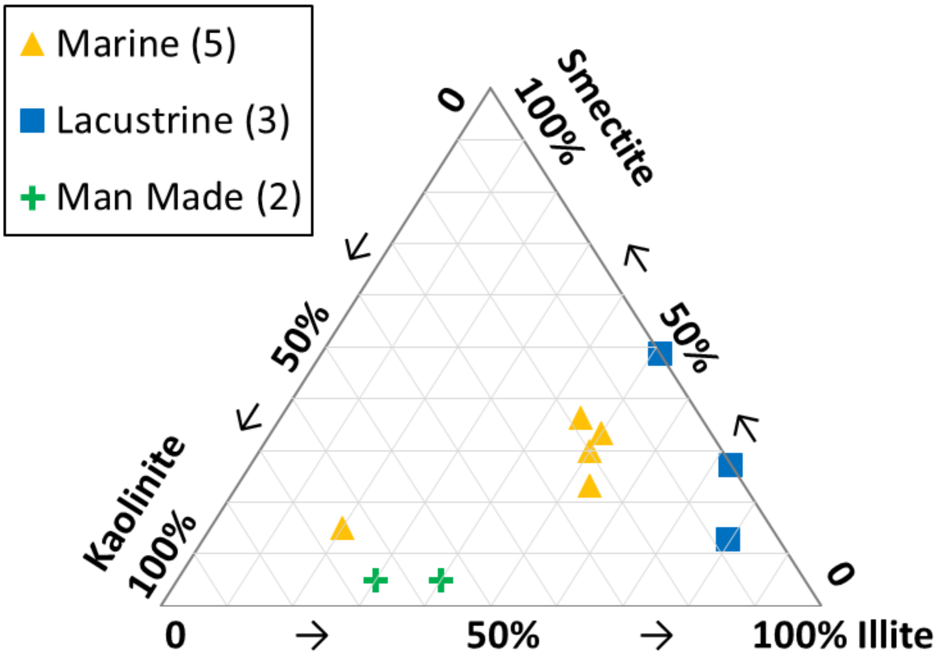

Fig. 23 Clay mineralogy ternary (kaolinite, illite, smectite (+chlorite)) diagram

4.5 Discussion of Comparisons

The purpose of Chapter 4 is to try to give some insights into the properties of underwater sediments. However, it has been based on a somewhat poor dataset and caution must be taken to avoid being misled by the comparisons and correlations; there are insufficient data points to present statistically significant results and interpretations.

Regarding the main scenario differences, one of the main ones is water depth. It is good to note the depths, however, in terms of soil behaviour, it is not of great concern: the water head is a total stress and soil behaviour is governed by effective stresses. Terzaghi has done a simple experiment to illustrate this concept (Ortigão 1995, p.42). The other main difference in scenarios is the chemical environment and chemical additives.

Based on graphs presented in Section 4.3, marine sediment properties seem to be the more applicable to those of reservoir sediments, as compared to lacustrine ones. The marine sediments are similar to reservoir sediments as they are still underwater while the lacustrine data are currently soft, plastic state land deposits. However, the marine sediments are influenced by salt. To better compare lacustrine sediments, it would be interesting to include some younger lacustrine deposits; ones that are still underwater.

In general, the man made deposits are characterised by high sedimentation rate, chemical influence, and often induced flocculation. This makes them less relevant for comparison to reservoir sediments. If further investigation into tailings materials is considered for comparison, it could be that ball mill tailings are most relevant as the process to create them involves a mechanical process rather than chemical.

While some correlations shown in this chapter attempt to replicate other published correlations, it should be noted that heterogeneity of the sediments studied may make not make the correlations evident, as (Mammou 1997) found in his investigations.

There are some interesting correlations to be made between clay minerals and geotechnical properties. However, it seems that there can be difficulties in accurately determining the clay minerals. In a few publications where the clay minerals were investigated, the authors have mentioned complications due to differentiating results (Sridharan et al. 2002; Covarrubias Fernandez 1994). As well, enough data points and range of soil compositions are needed to make general statements of clay mineral versus geotechnical property relationships (Ohtsubo et al. 2002).

It should be remembered that the data collected in this thesis indicated that there seems to be more silt in the reservoirs than clays (see Fig. 8, and in Fig. 15) and that the mineralogy may vary depending on location within the reservoir (see Section 3.1). Thus the effect of clay mineralogy on reservoir sediment properties may not be too significant. The main point is that every reservoir is individual in its particle size distribution, mineralogy and geotechnical properties.

5 Possible Geotechnical Risks

5.1 General

Thus far, the chapters have attempted to answer the aim presented in Chapter 1: how to gain an understanding of the geotechnical properties of reservoir sediments. This chapter looks to address the second part of the aim: how to apply the understanding (gained through the previous chapters) to the risks caused by these reservoir sediments.

A commonly used definition of risk is that it is the product of an effect (or consequence) and the probability (or likelihood) of that effect occurring. This scientific definition of risk requires a system (risk analysis) to quantify the effect, and has a certain probability of occurring. However, the term *risk* is also commonly used to indicate that an (negative) effect could happen: that the negative effect will occur with time or due to a particular action. It is a definition that relies on its negative connotation and is more synonymous with consequence.

If the scientific definition of risk is used, then the term *possible risk* is redundant, as a (scientific) risk is not certain, but it has a probability and thus it is inherently possible. However, in this chapter, and thesis, *possible risk* relates to the second definition of risk given above: the idea that it is a consequence. Thus *possible* is used to invoke the idea in the reader’s mind that there is only a likelihood of the risk to occur in the particular situation. Of all risks that theoretically could occur, the possible risks are only the ones which are considered relevant to the situation. For example, an asteroid falling into the reservoir is a risk not considered relevant in this thesis, and will not be considered as a possible risk.

The term *possible risk* is also used to indicate to the reader that while this risk is mentioned and it could happen, it is not suggested or guaranteed that it will happen; it is only a possibility. *Possible risks* are those risks that could, without certainty, occur in a situation, due to an action or with time.

This chapter and thesis aim to focus on the geotechnical aspects of reservoir sedimentations. However, it is difficult to separate the hydraulic aspects of reservoir from the geotechnical ones; they are interconnected due to the sediments being both a soil with geotechnical properties and fitting to soil mechanics, and a concern to the hydraulic design of a reservoir (dam, change of river morphology, equipment abrasion). Fig. 24 shows a general diagram used to illustrate these connections, as a possible circle of risk.

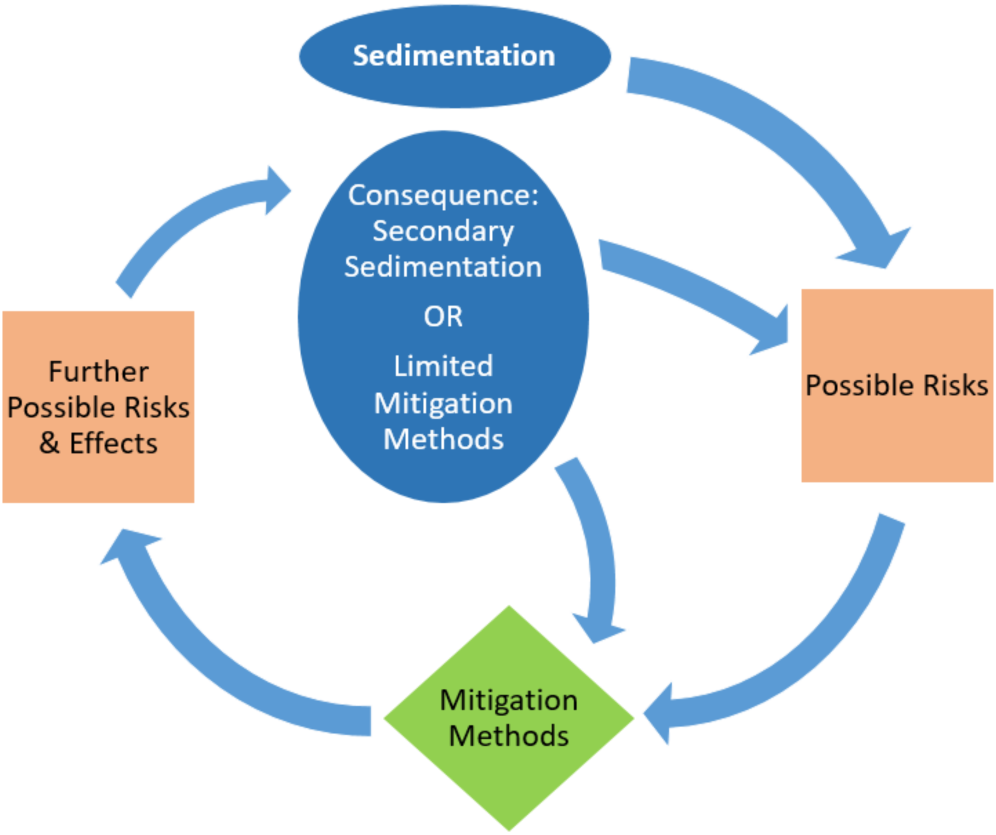

Fig. 24 Possible circle of risk: blue are driving factors, red are possible risks, and green is methods of dealing with the risks.

The possible circle of risk in Fig. 24 shows that reservoir sedimentation, as a driving factor, leads to possible risks, both hydraulic and geotechnical. Engineers resolve these risks by using mitigation methods. However, these mitigation methods may lead to further possible risks and effects, especially geotechnical ones. The further risks or effects may have a consequence, such as creating secondary sedimentation or limiting further mitigation methods, which are likely needed as the original sedimentation is an ongoing process. Secondary sedimentation is a term used in this thesis to differentiate from the traditional sedimentation term, and is further explained in Section 5.3.

In this chapter, possible risks due to sedimentation (right side of diagram in Fig. 24) and mitigation methods will be presented in more detail. Some risk and mitigation considerations specific to the other three scenarios (marine, lacustrine, man made), and relevant to reservoirs, are presented in Section 5.2. Finally, two examples are shown in Section 5.3 to illustrate the possible circle of risk for specific cases of reservoir sedimentation.

Possible Risks

As reservoirs are found around the world, they face different risks as the influencing conditions vary. For example, in Taiwan, a single typhoon event (causing intense rainfall and a lot of debris) caused 90 million m^3 of sediments to enter a reservoir, resulting in a 15% loss of volume over a few days (Lee et al. 2013). Another typhoon event in northern Taiwan caused a reservoir volume loss of 10% (Lee et al. 2013). This type of event is not found in Europe and thus does not affect European reservoirs. They may however, have risks relating to glacier sediments and freeze-thaw action. Gravel and sand that settle in mountain reservoir entrances may cause more problems than the fines distributing over the reservoir area (Scheuerlein 1990).

There is much discussion of reservoir sedimentation risks and associated possible mitigation measures to be found in publications within the hydraulic engineering field (Bollaert et al. 2014; Boes et al. 2014; Dysarz 2014; de Cesare et al. 2001; Weirich 2014b). There are also ICOLD publications that relate to this topic (ICOLD 1999; ICOLD 2009; ICOLD 1989).

The main possible risks of sedimentation in reservoirs are listed here:

- Covered bottom outlet: For safety, every dam has a bottom outlet in case of emergency, to release water from the bottom of the reservoir to avoid overtopping and to reduce pressure on the dam. Thus the bottom outlet is always at or near the bottom, which is also the first place where sediments will cover.
- Earth pressure on the dam: this extra pressure is sometimes unaccounted for in dam design.
- Volume loss which may impact the purpose of the reservoir. For example, more deposits in a reservoir means higher water levels during floods and reduced effectiveness: for the same amount of shore flooding, a lower flood can be withstood. This compromises the safety of the dam. (Bollaert et al. 2014)

The general theme is that the possible risks cause a reduction in safety. Too much of a reduction is not acceptable and so reservoirs have sedimentation management plans, which may involve one or more mitigation methods.

Mitigation Methods

The development of a reservoir's sedimentation management plan needs to account for the setting, forecasted sedimentation, upstream and downstream effects, local regulations and purpose in order to use the most appropriate methods. Sedimentation forecasting is an important hydraulic field that researches and models sediment sources, turbidity currents and sediment deposition patterns.

However, one should not think that reservoir sediment deposition patterns are static and that once known, further calculations can count on them being constant. It has been shown that the changing topography of a reservoir can itself dramatically alter the patterns of further sediment deposition (Weirich 2014a). It is important to understand reservoir sedimentation processes, a topic greatly covered in hydraulic engineering, and perhaps careful investigations of already existing sediment layers can help hydraulic engineers understand the past (and changing) deposition patterns. This may help to develop sediment management methods that might take advantage of changes in deposition patterns (Weirich 2014a).

Sediment management methods can be categorized into avoidance, mitigation and acceptance strategies. Avoidance strategies include engineering of sediment sources to reduce the incoming sediments or diverting (bypass tunnel) unavoidable sediments away from the reservoir. However, once sedimentation has already occurred to significant levels, mitigation strategies are needed and this is the category that will be elaborated on in this section. Acceptance strategies need to consider risk levels acceptable for all parties involved.

Mitigation methods are only presented here in broad general terms as this topic is more in the realm of hydraulic engineering and involve detail considerations such as allowable amount of sediments through pipes, abrasion of turbines (hydropower), and downstream river fish habitats. Further details can be found in the resources mentioned in the last section

Some general mitigation methods are listed here but their use depends on the facilities at the reservoir and dam:

- Flushing the sediments out, which is a complex operation and usually involves a full drawdown of the reservoir (Boillat & Pougatsch 2000);
- Sluicing the sediments in a water and soil mix, which does not fully drawdown the water level and is usually more localized; it is intended to keep the bottom outlet cleared and results in a cone shaped eroded sediment bed (Boillat & Pougatsch 2000);
- Dredging (mechanical) and either moving the sediments to other parts of the reservoir or removing them completely;

- Suction dredging (hydrosuction), which depends on the consolidation state of the fines;
- Using floods to pick up and move the sediments past the dam, either over spillway or through a bottom outlet;
- Monitoring, for example with bathymetry surveys to better understand the changing underwater landscape;
- Investigating the sediment properties to determine most reasonable long term solutions. This will likely be followed by one of the above methods.

The following table (Tab. 1) presents some examples of reservoirs and the mitigation methods used in their sedimentation management plan. The main risks they face are included to give context to the mitigation methods.

Tab. 1 Examples of reservoir mitigation methods

Reservoir	**Risks**	**Mitigation Methods**
Luzzone, Switzerland (Sinniger et al. 1999)	Volume loss Safety of outlet	Sluicing through bottom outlet Monitoring (bathymetry surveys)
Gebidem, Switzerland (Meile et al. 2014)	Excess earth pressure on dam Volume loss	Flushing once a year
San Dimas, South California (Weirich 2014b)	Volume loss	Flow Assisted Sediment Transport (FAST) method Mechanical excavation
Verbois & Chancy-Pougny, Switzerland (Bollaert et al. 2014)	Volume loss in sequential reservoirs	Flushing regularly usually Sequential flushing of two reservoirs using natural flooding events
Tsengwen, South Taiwan (Lee et al. 2013)	Volume loss	Investigating and characterizing the sediments located by the dam (and elsewhere)
Magaritze, Austria (Knoblauch 2017)	Covered bottom outlet Volume loss Earth pressure	Suction dredging, moving sediments to shallow part of reservoir and pumping through diversion gallery to another reservoir

For various reasons, there are times when risks associated with dams lead to the investigation of the dam removal option. In the United States of America, there are numerous dams which have undergone or are undergoing the process of determining its validity in remaining in place. For example, the Matilija Dam in California is being considered for removal due to its nearly full silting, concrete issues and to allow the return of fish (Bountry & Greimann 2009). However, one of the considerations in this process is how to deal with the sediments. In the case of the Matilija Dam, built in 1947, the reservoir became mostly filled up (approximately 90%) with sediments by the year 2009 (Bountry & Greimann 2009), thus nullifying the water storage purpose. In order to optimize the designs to manage the sediments, investigations are required to characterize them. The results can provide data to better understand other existing reservoirs with similar sedimentation.

5.2 Scenario Specific Considerations

To complete the picture of submerged sediments that the other scenarios have helped to develop, this section considers some of their risks and mitigation methods. As can be imagined, these considerations from the other scenarios are relevant to the risks and mitigation methods used in reservoirs. As will be seen, the common thread in these scenarios considerations is that a better understanding of the sediment properties is one of the first mitigation strategies to dealing with the risks and problems associated with those sediments.

Marine

The main risk in the marine scenario is the occurrence of submarine landslides, especially when offshore infrastructure, such as oil rig platforms, are in the area. This is especially relevant considering that it is estimated these submarine ones are that the largest landslides in the world; they are of large scale (kilometres), run out for kilometres and can trigger deadly tsunamis (Puzrin et al. 2016). They are generally characterized as a translational slide on low inclination continental slopes and have relatively shallow depths; all characteristics that are well suited to be modelled by the infinite slope model (Puzrin et al. 2016).

However, submarine landslides may occur by various failure modes (limited displacement, run-out, ploughing, spreading) and it is important to understand their mechanisms, to model them appropriately, and to forecast their occurrence (need to know possible triggers), all in order to better assess the extent of their impact on structures (Puzrin et al. 2016). In other words, the sediment properties should be characterized in order to assess the effect of triggers such as seismicity (earthquakes) and wave action on the stability of the submarine slopes (Lanzo & Pagliaroli 2003). More knowledge of the sediment properties allows geotechnical engineers to design more suitable and resilient structures.

There is a lot of information from numerous researchers who have, among other aspects of submarine landslides, undertaken investigation on shelf edge areas, utilized geophysical imaging, and developed analysis tools for quantitative risk assessment (Lee 2009; Twichell et al. 2009; NATO 1982; Biscontin et al. 2004; Nadim et al. 2007; Puzrin et al. 2016; Scholz et al. 2016; Locat & Lee 2002; Wiemer et al. 2015; de Blasio et al. 2005; Aarseth et al. 1989; Issler et al. 2005).

Lacustrine

Lacustrine deposits are often found in areas where civil works are most desired: large flat areas where water would have been found and are most likely still near water. Due to their relatively poor geotechnical properties, they are difficult to work with and adequate investigation is needed to mitigate the risks.

The hazards/risks include inherent slip surfaces in-situ and uncertainty in properties due to the varved structure and interlayers of clay and silt.

Man Made

Many dredged materials are dumped in storage facilities and research has been carried out to determine methods of optimizing, in terms of volume, these disposal areas (Van Impe et al. 2009; Seng & Tanaka 2012). As many disposal areas have limited space capacity, for example limited space near harbours, there are risks to the entire operation and for the safety of accumulated sediments which are often transported to their resting area in slurry form. A slurry has a very high water content (Van Impe et al. 2009), which is not suitable for storage.

Flocculants are commonly used to improve the geotechnical properties of the dredged material, such as reduce water content, increase permeability and increase strength. In their research, Van Impe et al. (2009) have tried adding additives, such as Greenfloc (anionic organic starch based polymer) to dredged material and industrial waste sludge to create a desired behaviour quickly.

In the optimization process, engineering design is carried out which requires the mining and industrial wastes to be characterized. The characterization is often done according to tests designed for natural soils and it has been found that these tests are not perfectly suited to handle the behaviour of the wastes which leads to results which do not match to field conditions (Villar et al. 2009).

5.3 Specific Examples

This section presents two theoretical examples to illustrate how the idea of a circle of risk (possible risks, mitigation methods, further risks and effects) can apply to reservoir sedimentation. In these examples, the possible risk is assumed to be a specific result. Two examples are obviously not enough to cover all permutations of risks, and mitigation methods, but they provide an idea of the complexities of managing reservoir sedimentation and show how some of the considerations from the other scenarios can also apply to reservoir sediments.

Example 1

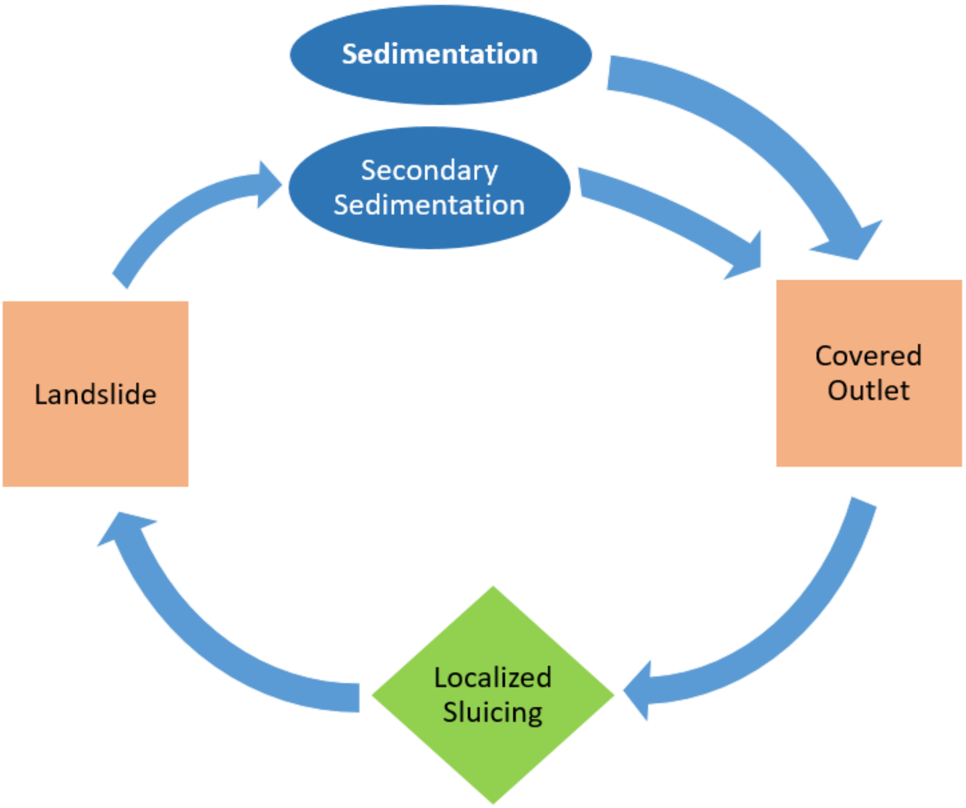

Fig. 25 Possible circle of risk - Example 1

The first example of sedimentation in a theoretical reservoir is illustrated in Fig. 25. As with the general example, it starts with reservoir sedimentation that leads to the bottom outlet being covered by too many sediments. This is not acceptable from the safety perspective, so the bottom outlet is opened as per the sedimentation management plan. As the sediments have not yet reached too great a depth and are not compacted, the effect of opening the outlet is that a mix of water and sediment is released from near the outlet. This is sluicing and is not done long enough to drain the reservoir, but it is successful in removing, by erosion, the sediments covering the outlet and near it.

The outlet is closed again, ensuring that it is properly sealed. Sinniger et al. (1999) mention that if the outlet is not properly sealed, water from the surrounding sediments will slowly seep through, which allows those sediments to consolidate as the excess pore pressure dissipates. Over some time, this leads to a solid plug covering the outlet, rendering it useless until it can be cleared, sometimes with explosives.

Should a survey of the sediment surface in the reservoir now be done, it would find a localized cone centred at the outlet, possibly with steep slopes. It is likely these slopes are much steeper than would naturally be allowed by only the friction angle of the sediments, as was mentioned for Luzzone sediments in Section 3.1. The apparent strength of the sediments in these slopes partially comes from a negative excess pore pressure (suction) occurring between the particles. With time, or with a trigger such as a seismic event, there will be a change in excess porewater pressure, leading to a reduction of the apparent strength and resulting in a landslide. Such a case has been reported by Bollaert et al. (2014), where a reservoir was undergoing sudden water level drawdown, which led to significant changes in porewater pressure within the sediments resulting in a 5900m^3 large landslide.

With coarser particles, such as sands, there is much less excess pore pressure that builds up after sediment removal, and thus landslide failure would not occur due to its loss. However, failure may still occur due to seepage forces of water going through the sediments or due to liquefaction of the loose saturated sediments if seismic activity occurs. Reservoir sediments are unlikely to consist of sands, but rather consist of a range of sizes. Therefore, the actual failure mechanism may be a combination of the above.

The resulting landslide has the consequence of quickly covering the bottom outlet with nearby sediments. In this thesis, the quick movement of sediments to cover another area is termed secondary sedimentation, to differentiate from the relatively slow original sedimentation from sediments settling out of suspension. The circle of risk of this example completes its cycle at the top, where yet again possible risks may occur due to ongoing and secondary sedimentation.

This example only covered a few aspects of sedimentation and its risks. Other aspects to consider include:

- Most of the submarine landslides aspects also apply here for these subaqueous reservoir landslides.
- In another worst case, the landslide could be huge and could mean a large force hits onto the dam.
- The larger the landslide, the greater the volume of water which will be suddenly displaced. This leads to potentially dangerous tsunami waves.

Example 2

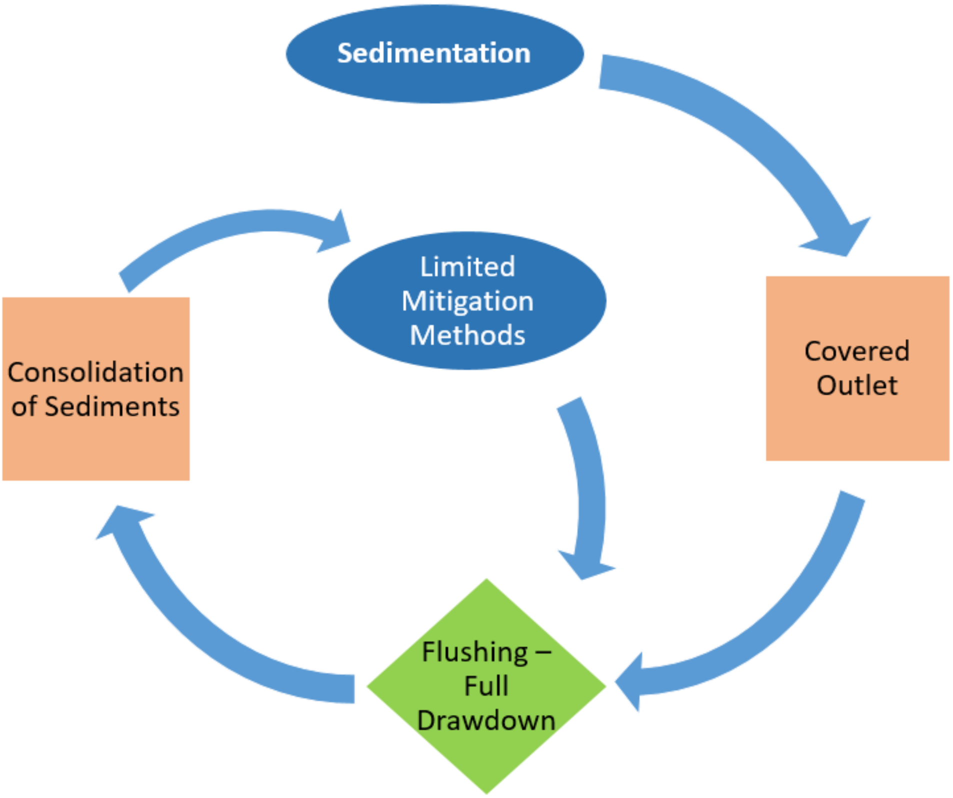

Fig. 26 Possible circle of risk – Example 2

The second example of sedimentation in a theoretical reservoir is illustrated in Fig. 26. Reservoir sedimentation is again the driving factor in the risk of the accumulation of the sediments covering the bottom outlet. This is not acceptable from the safety perspective, so a flushing event is undertaken as per the sedimentation management plan. This may include using the bottom outlet and any other opening in the dam that allows a water and soil mix to be carried passed the dam until the reservoir level is completely drawn down.

If successful, a large volume of sediment has been removed. However, it is unlikely that all the accumulated sediments were removed. Thus the remaining sediments are no longer underwater and can consolidate at a much greater rate than they could underwater. In soil mechanics, consolidation is often the desired effect because it results in a stronger and stiffer soil body. However, in this example, consolidation of the sediments has the consequence of limiting the choice of mitigation methods the next time sediment removal is required. Without much consolidation, newly deposited sediments have high water contents, are in a liquid state (water content greater than liquid limit) and very soft, and require less shear stresses for their remobilization (Mammou 1997). When these sediments undergo greater rates of consolidation, they have lower water contents, and require more shear stresses for their remobilization.

Some mitigation methods remove sediments by using moving water. For example, a common mitigation method is to use natural flood events to erode and carry away sediments in their already sediment laden waters. This process is easier when the sediments are softer, have higher water contents and their remobilization requires less shear stresses. These effects have been seen both in laboratory and sediment removal operations. In his publication, Mammou (1997) mentions that removal of sediments should be done right away in the case of smaller floods, and for big floods, removal should be done within a day of sedimentation.

This example only covered a few aspects of sedimentation and its risks. Other aspects to consider include:

- As mentioned in Section 3.1, the density of accumulated sediments is highly influenced by reservoir operation water levels (ICOLD 1989). This is also an effect of consolidation.
- There may be some reasons to prefer having denser sediments. If the situation requires to leave the sediments in place, it may be preferable for them to take up less room, to reduce the volume loss.
- For some reservoir investigations, the reservoir water levels could not be lowered which makes the investigation more challenging. However, this may be for the best if the sediment characterization, and the most appropriate mitigation methods are not yet known, as the methods are not limited by a less removable sediment deposit.

6 Conclusion

6.1 Summary

The subject of this thesis are the young fine grain sediments that accumulate in reservoirs (behind dams). The aim has been to characterize these sediments in terms of geotechnical properties and to use this understanding to discuss the risks they pose in a geotechnical context. The background to this subject and the objectives proposed to address the aim were provided in the introduction. Before delving into the characterization, the author presented the reader with the methodology used and the assumptions made to provide a clear context for the further content. The methodology included an explanation as to why this thesis has focused on secondary research findings and why the research for this thesis extended into the realms of other depositional settings, e.g. marine. In presenting the assumptions made, the author intends bring the reader’s attention to various terms that are not consistent in the geotechnical world.

The findings of the various depositional setting sediment characterizations are presented as methods and properties for four scenarios: reservoir, marine, lacustrine, and man made. The findings show that the marine scenario provides the overwhelming majority of data. This is due to the many projects, civil and resource based, which have been and continue to be done in deltas, seas and oceans around the world. These projects include rig platforms for oil and gas, reclaimed land in high population areas on coasts and improvements for ports. Comparisons of the data shows that there are some systematic differences and similarities between the scenarios, and that there are also some inconclusive correlations between geotechnical properties due to influences caused by predominant clay minerals and water salinity.

The second part of this thesis’ aim was to explore the risks posed by sediments accumulating in man made reservoirs, with an emphasis on the geotechnical aspects. The author found that the geotechnical aspects could not be cleanly disconnected from the hydraulic aspects and presented a view of their circular interconnections. This also brought sedimentation mitigation methods into the circle. The scenarios were used again to present the geotechnical risks and mitigation methods of their underwater sediments as considerations to improve the geotechnical understanding of reservoir sediments. Two theoretical examples were provided to tie together the circle of risk and the knowledge acquired from the other scenarios.

6.2 Research Question Addressed

The aim of this thesis was to gain an understanding of the geotechnical properties of reservoir sediments and to apply this understanding to risks caused by these sediments. It is the author's opinion that the aim was achieved, as explained below, although only within the context of currently available information. There are large knowledge gaps in this field and suggestions are provided below for future research. The following addresses the objectives presented in Section 1.2.

Reservoir sediments were characterized by geotechnical properties from three reservoirs. This provided too few data points for any conclusive determinations or statistical analysis. Thus there is a knowledge gap in reservoir sediment geotechnical properties because the values currently known cannot be checked to any significant dataset. In an attempt to provide a database for comparison, three other settings where sediments deposit underwater were defined and their data collected. They were termed scenarios, and including reservoirs became these four scenarios: reservoir, marine, lacustrine, and man made. The data on geotechnical properties were used to characterize all four scenario sediments. Through this process, some ideas came up which potentially explain why reservoir sediments left in place after dredging procedures are surprisingly strong.

While it is believed that slope stability is an important concern for reservoir sediments, there was only one mention of a slope instability in a man made reservoir. To shed some light on this important topic, the author has provided a summary of research on submarine landslides in Section 5.2 and presented an illustration of the effect in reservoirs in a theoretical example in Section 5.3.

In the theoretical examples of Section 5.3, some geotechnical effects, such as consolidation, of mitigation methods on reservoir sediment properties are presented. Reservoir sediments pose risk which cannot be clearly categorized as hydraulic or geotechnical. However, possible risks have been presented and linked to common mitigation methods via a circle of risk, which also brings in the previously mentioned geotechnical effects.

As was mentioned in Section 2.3, there does not seem to be much information or data regarding geotechnical properties for reservoir sediments. The author suggests that this thesis has provided reasoning as to why this topic should be covered in more depth. The next section provides some suggestions for future research that could address the knowledge gaps presented in this thesis.

6.3 Outlook

Many reservoirs are or will be at the state in which accumulated sediments are of concern. Based on limited reservoir sediment characterization done in this thesis, it seems that it will be difficult to generalize all reservoir sediments into one type, and proper mitigation methods will be best reached by an appropriate geotechnical understanding of each reservoir's sediments. However, until individualized characterization can be undertaken, looking at other similar sediments, for example from the marine, lacustrine or man made sediments, can help to understand reservoir sediments and give an indication of their behaviour.

As the issue of these sediments and their risks grows, the author envisages this thesis as a gateway to future research by showing, in this section, which gaps remain and what correlations may be made. The idea of this section is also to present ideas which were not covered, but are likely relevant or which potential influences should be ruled out as an important factor. The following topics are presented in no particular order:

- For monitoring, many reservoir operations undertake regular bathymetry surveys of the sediment surface, from which slope angles could be measured, and as Sinniger et al. (1999) state, the angle is the angle of repose of the material. This method could be used to assess the risk of landslides in the reservoir, once the critical angle of repose has been determined for the specific sediments.
- The local half-cone is the scoured hole in the sediments surrounding the bottom outlet after sluicing and is due to a localized removal of sediments. Methods to optimize the efforts required to increase the half-cone is a subject of research in hydraulic engineering (Dodaran et al. 2013; Meshkati Shahmirzadi et al. 2010). The methods include the use of a vibrator to loosen the sediments, which decreases the required shear stress for remobilization. As the vibration technique is essentially inducing liquefaction, and vibration (seismicity) and liquefaction are large fields in geotechnics, it is the author's opinion that geotechnical expertise could be used in the research for the optimization of the half-cone scouring methods.
- Investigations into the geotechnical properties of reclaimed land, such as artificial (man made) islands, were barely touched upon in this thesis. (Craney Island is reclaimed land, but the focus was on the underlying very soft clay.) However, there could be information from these island-making projects that relate to the reservoir sedimentation: sand is dropped into the water (young sedimentation), has slow (although faster than for clays and silts) sedimentation, deposits in very loose

structure (high void ratio), and requires ground improvement to improve its density. Therefore, further research should extend to investigate the development process and available geotechnical data of these artificial islands. Some existing islands or current projects around the world include: Donauinsel (Austria), various in Copenhagen harbour (Denmark), Nigehörn (Germany), Hong Kong International Airport (Hong Kong), Kansai International Airport (Japan), Maasvlakte (Netherlands), various islands in Singapore, Dubai Palm Islands (United Arab Emirates), Miami Beach Florida (United States).

- The potential influence of sedimentation rate on the geotechnical properties of the deposited sediments could mean that knowing the sedimentation rate would be a good prediction tool for the geotechnical properties. Comparisons of rates between scenarios may provide more confidence in which scenario is most appropriate to compare to reservoirs. Comparisons between rates in reservoirs may indicate which reservoirs are most similar and can have their properties predicted. A database of sedimentation rate should include information relating to it, such as the particle sizes involved, in order to then make reasonable comparisons. While this may seem daunting, reservoir sedimentation rates are usually known by hydraulic engineers and the distribution of particle sizes is really the only geotechnical property collected in reservoir sedimentation investigations. Thus this approach is one of the few research topics that would not require physical investigations. As mentioned in Section 3.1, a good starting source for information on worldwide sedimentation rates of dammed reservoirs and spatial distribution of sediment aggradation is presented in (Boes et al. 2014). The ICOLD organization has also already collated a lot of information relating to sedimentation rates, scaling, applications, names and locations around the world (ICOLD 2009).
- This thesis has mostly assumed that the sediment depositions are homogeneous. However, as with many sedimentary (not residual) soils, there is often spatial variability, leading to some heterogeneity. In reservoir sediments, this may due to different precipitation event, turbidity currents, or changes from mitigation methods (e.g. dredging or flushing). A possible result is that there are then sandy layers above and/or below clay layers. In the examples of Section 5.3, this may control the landslide mechanism of Example 1, and may increase the consolidation rates even without reservoir water level lowering in Example 2.
- As indicated in Sections 3.1 and 3.2, some investigations (Futai et al. 2008; Almeida et al. 2008; Mammou 1997) have shown that the organic content of the sedimentation deposit can have an influence on the geotechnical properties of the sediments. Many

reservoirs have their catchment basin (watershed) in areas of vegetation, likely resulting in some organic content entering the reservoir, and making the influence of organics on the properties a possibility.

- Continuing on from organics in sediment deposits, gas within deposits has been of interest to some researchers, mainly in the marine environment where methane gas has had time to generate. Biogenic gas in Holocene sediments has been found to affect the geotechnical properties of the sediments (Smith et al. 2010). Therefore, it might be important for the understanding of the sediment behaviour to investigate the effect of organic content and gas deposits in more detail.
- This thesis has compared data from various sediment deposits without much consideration of age or the depth as there was not always sufficient clear information on it. However, they likely have some influence on the geotechnical properties, and further research could clarify ages and depths for more relevant comparisons or rule them out as significant factors in reservoir sediments which may not be very old or very deep.
- External factors on reservoir sediments, such as low winter water levels in alpine reservoirs, freezing actions, storm surface wave activity, should be considered and possibly ruled out as influential. Earthquake activity is likely the most influential external factor on reservoir sediments and further research should investigate the effects it would have on these sediments and the possible damages that could result.
- Clay structure is important in sensitivity of clays, which is a measure of changes in strength, often due to changing environments of the clay. In this context, salt leaching and high sensitivity indicate quick clay. There are different methods to determine sensitivity: fall cone, or undisturbed to remoulded soil strength ratio from field vane, or laboratory tests. It would be important to investigate the clay structure and sensitivity of the sediments of interest, and examine possible connections to well-studied quick clays.
- Lee et al. (2013) describe the in-situ techniques (flat dilatometer (DDMT) and piezo-penetrometer) they used to obtain geotechnical properties of reservoir sediments (mud). They made an excellent case, in their publication, that their results are reasonable and their process is effective for characterizing very soft reservoir sediments. In this thesis, their resulting properties were compared to results from other similar settings and were not found to be askew. Thus the author of this thesis joins Lee et al. (2013) to suggest these methods be used in future investigations of this type.

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Appendices

Appendix A

The following property tables, for the four scenarios, use the colour code shown below:

Calculated values

Approximated from graph provided by source

Avg & +/- (Standard deviation) provided by source

Single value provided by source – I assumed to be Avg

Only Avg value provided by source

I **calculated avg from range** provided by source

Avg value & range (max, min) provided by source

Assumed

One test only

I **calculated avg** from some data provided by source

Single value provided by source – I assumed to be Avg or only 1 test??

Tab. A-1 Reservoir properties

Main Properties	Symbol	ID	1	2	3	4	5
Scenario	-	**1**	Reservoir[2]	Reservoir[3]	Reservoir[3]	Reservoir[4]	Reservoir[5]
Water Depth [m]	-	**2.2**	175	40	40	5	6
Clay Fraction [%]	CF	**4**	15	50	50	18	0
Silt Fraction [%]	MF	**5**	80	40	40	65	100
Sand Fraction [%]	SF	**6**	5	10	10	17	0
Saturated Unit Weight [kN/m3]	γsat	**9.1**	16.8	16	19		
Dry Unit Weight [kN/m3]	γd	**9.2**	11				
Unit Weight [kN/m3]	γ	**9.3**	16.8	16	19		
Specific Gravity [-]	SG	**10**	2.83				
Particle Density [g/cm3]	ρs	**10.3**	2.83				
Degree of Saturation [%]	S	**11**	97				
Void Ratio [-]	e	**12**	1.56				
Porosity [%]	n	**13**	61				
Water Content [%]	w	**14**	53.6	100	45		
Liquid Limit [%]	LL	**15**	37.1	60	55		
Plastic Limit [%]	PL	**16**	27.5	24	25		
Plasticity Index [%]	PI	**17**	9.6	36	30		
Calculated Liquidity Index [-]	LI	**18.2**	2.72	2.11	0.67		
Consistency Index [-]	CI	**19**	-1.72	-1.11	0.33		
Activity Index [-]	0	**22**	0.64				
Effective Friction Angle [o]	φ'	**27.1**	29				
Effective Cohesion [kPa]	c'	**27.2**	11				
Undrained Shear Strength [kPa] [1]	Su	**30.1**	55				

Notes

1 Su from Triaxial (UU) Test
2 Luzzone (Sinniger et al. 1999)
3 Tsengwen (Lee et al. 2013)
4 Matilija (Bountry & Greimann 2009)
5 Glenmore (Hollingshead et al. 1973)

Tab. A-2 Marine properties (continued on next page)

Main Properties	**Symbol**	**ID**	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Scenario	-	**1**	Marine[2]	Marine[2]	Marine[2]	Marine[2]	Marine[2]	Marine[2]	Marine[2]	Marine[2]	Marine[2]	Marine[3]	Marine[3]	Marine[4]	Marine[4]	Marine[4]	Marine[5]
Water Depth [m]	-	**2.2**	1145	1790	1435	1175	1305	1435	1450	1750	800	70	70	45	45	70	0
Clay Fraction [%]	CF	**4**	44	57	56	28	39	38	48	44	40			48	48	48	55
Silt Fraction [%]	MF	**5**	57	44	44	73	62	63	53	57	60			52	52	52	45
Sand Fraction [%]	SF	**6**															
Unit Weight [kN/m3]	γ	**9.3**	16.47	15.07	14.94	15.44	15.30	14.69	15.86	14.84	16.76	13.9	15.2	16.4	17.2		16.0
Specific Gravity [-]	SG	**10**										2.64	2.64	2.70	2.70	2.70	
Void Ratio [-]	e	**12**	1.86	2.57	2.79	1.91	2.33	2.57	2.17	2.48	1.89	2.33	1.96				
Porosity [%]	n	**13**										70	66				
Water Content [%]	w	**14**	63.5	88.3	100.6	66.9	80.1	91.8	75.9	91.4	68.1	70	57	55	50		55
Liquid Limit [%]	LL	**15**	65	83	73	50	82	81	60	65	61			55	50		55
Plastic Limit [%]	PL	**16**	26	34	31	26	35	36	26	28	31			33	28		20
Plasticity Index [%]	PI	**17**	39	49	42	24	47	45	34	37	30			22	22	22	35
Liquidity Index [-]	LI	**18.1**															
Calculated Liquidity Index [-]	LI	**18.2**	1.0	1.1	1.7	1.7	1.0	1.3	1.5	1.7	1.2						
Consistency Index [-]	CI	**19**	0.0	-0.1	-0.7	-0.7	0.0	-0.3	-0.5	-0.7	-0.2			0.0	0.0	0	0.0
Activity Index [-]	0	**22**	0.89	0.87	0.75	0.87	1.22	1.20	0.72	0.85	0.75						
Compression Index	Cc	**23.1**	0.77	0.865	0.88	0.66	0.865	0.835	0.86	0.965	0.66						
Initial Void ratio [-]	e0	**26.2**	1.91	2.09	2.32	1.87	2.09	2.34	2.02	2.51	1.87						
Effective Friction Angle [o]	ϕ'	**27.1**															
Initial effective vertical stress [kPa]	o'vo	**29.1**	52	79	59	19	101	84	70	19	27	30	100				
Initial stress for lab test [kPa]	0	**29.2**	233	354	148	19	201	84	141	39	54						
Undrained Shear Strength [kPa] [1]	Su	**30.1**	77	106	43		56	24	41					3	6		
Kaolinite [%]																	
Illite (Mica) [%]																	
Montmorillonite (Smectite) [%]																	

Notes

1 Su from fall cone, triaxial, direct shear tests
2 Brazil Offshore (Barros et al. 2009)
3 Mississippi (Bennett et al. 1976)
4 Adriatic Shelf (Lanzo & Pagliaroli 2003)
5 Finnish Clay (Messerklinger et al. 2003)

ID	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
1	Marine^5	Marine^5	Marine^5	Marine^5	Marine^6	Marine^6	Marine^6	Marine^6	Marine^6	Marine^6	Marine^6	Marine^6	Marine^6	Marine^6	Marine^7	Marine^8	Marine^8	Marine^9
2.2	0	0	0	0	0	0	0	3	1	0	0	0	0	0	4	5	6	5
4	74	30	20	23		70		54	35		60.7	39.4	28	54				50
5	26	70	72	75		30		46	65		39.3	60.6	72	46				50
6			8	2														
9.3	14.5	15.3			14.81	13.1	13.24	13.44	13.24	12	12.5	16.1	17.04	12.5	14.9			15
10	2.78	2.66																2.6
12	2.9	2.025			2.38	3.71	3.09	3.37	2.91	6.72	3.74	1.42	1.1					2.0
13																		
14	107.5	78			88	143	112	130	113	240	154	54.8	35	300	72.5	80	78	70
15	95.5	88			107.5	120.3	59.6	125.4	122	175.4	132.5	71.3	38	260	79	77	79	75
16	27.5	33			40	47	28	36	41	101	69	31	27	75	31	28	30	20
17	68	55			67.5	73.08	32	89	81	74.5	63.59	40.5	11	185	48	49	49	55
18.1	1.16	0.82													0.86	1.1	0.9	
18.2	1.18	0.82			0.71	1.31	2.64	1.05	0.89	1.87	1.34	0.59	0.73	1.22	0.86	1.06	0.98	0.91
19.0	-0.18	0.18			0.29	-0.31	-1.64	-0.05	0.11	-0.87	-0.34	0.41	0.27	-0.22	0.14	-0.06	0.02	0.09
22																		1.1
23.1	1.01	0.78			0.7098	0.7065	0.409		0.6256		0.3318		0.399	0.1				1.05
26.2					2.38	3.71	3.09	3.37	2.91	6.72	3.74	1.42	1.1					2.0
27.1	27.7	39			27	27.5				43	45	34	28	40				
29.1					178	157	199	134	113	120	88	145	102	150				
29.2																		
30.1	8	26			9	11.32				7.5	18.35	70.9	72.5	16.75	20			20
	18	17	23	20														66
	45	50	53	50														20
	36	33	23	30														15

Notes

5 Finnish Clay (Messerklinger et al. 2003)
6 Rio de Janeiro (de Almeida et al. 2008)
7 Craney Island (Karakouzian et al. 2002)
8 Craney Island (Smith et al. 2010)
9 Singapore Clay (Bo et al. 2015)

Tab. A-3 Lacustrine properties

Main Properties	Symbol	ID	39	40	41	42	43
Scenario	-	1	Lacustrine[1]	Lacustrine[1]	Lacustrine[2]	Lacustrine[2]	Lacustrine[2]
Water Depth [m]	-	2.2	0	0	0	0	0
Clay Fraction [%]	CF	4	32	48	42.3	46.5	43.2
Silt Fraction [%]	MF	5	63	52	57.7	53.5	56.8
Sand Fraction [%]	SF	6	5	0	0	0	0
Unit Weight [kN/m3]	γ	9.3			18.2	17.4	19.5
Specific Gravity [-]	SG	10	2.75	2.73	2.73	2.75	2.75
Void Ratio [-]	e	12			1	1.05	0.8
Water Content [%]	w	14	33	43	36	32.5	30
Liquid Limit [%]	LL	15	38	50	42.4	43	34.2
Plastic Limit [%]	PL	16	17	20	16.7	19.3	17.4
Plasticity Index [%]	PI	17	21	30	25.7	23.7	16.8
Liquidity Index [-]	LI	18.1	1.1	0.6	0.75	0.56	0.75
Calculated Liquidity Index [-]	LI	18.2	0.76	0.75	0.75	0.56	0.75
Consistency Index [-]	CI	19	0.24	0.25	0.25	0.44	0.25
Compression gradient	Cc	23.2	0.28	0.34	0.285	0.275	0.25
Swelling gradient	Cs	24.2	0.014	0.028	0.02	0.014	
Effective Friction Angle [o]	ϕ'	27.1	28	28	27.6	27.4	
Undrained Shear Strength [kPa] [1]	Su	30.1			25	23	21
Kaolinite [%]	0	0			0	0	8
Illite (Mica) [%]	0	0			51	73	79
Montmorillonite (Smectite) [%]	0	0			49	27	13

Notes

1. Su from fall cone test
2. Swiss Clay (Plötze et al. 2003)
3. Swiss Clay (Messerklinger et al. 2003)

Tab. A-4 Man made properties

Main Properties	Symbol	ID	44	45	46	47	48	49	50
Scenario	-	**1**	Man Made[1]	Man Made[1]	Man Made[1]	Man Made[1]	Man Made[2]	Man Made[2]	Man Made[3]
Water Depth [m]	-	**2.2**	0	1	2	0	1	1	0
Clay Fraction [%]	CF	**4**					50	50	32
Silt Fraction [%]	MF	**5**					40	40	48
Unit Weight [kN/m3]	γ	**9.3**							14.4
Specific Gravity [-]	SG	**10**	2.62	2.43	2.62	2.69			2.7
Particle Density [g/cm3]	ρs	**10.3**	2.62	2.43	2.62	2.69			
Degree of Saturation [%]	S	**11**							100
Void Ratio [-]	e	**12**							2.63
Water Content [%]	w	**14**	80	241	141.5	52.8	168	270	97
Liquid Limit [%]	LL	**15**	73	246	111	55	47	44	51
Plastic Limit [%]	PL	**16**	31	97	40	26	20	21	30
Plasticity Index [%]	PI	**17**	41	150	71	29	27	23	21
Calculated Liquidity Index [-]	LI	**18.2**	1.18	0.97	1.44	0.93	5.48	10.83	3.19
Consistency Index [-]	CI	**19**	-0.2	0.0	-0.4	0.1	-4.5	-9.8	-2.2
Compression Index	Cc	**23.1**							0.67
Kaolinite [%]							55	65	
Illite (Mica) [%]							40	30	
Montmorillonite (Smectite) [%]							5	5	

Notes

1 Japan Dredgings (Seng & Tanaka 2012)
2 Oil Sands Tailings (Suthaker & Scott 1997)
3 Craney Dredgings (Sengul et al. 2016)

Appendix B

Initial proposal for site and testing work

Sampling and Testing Proposal

A proposal, written by the author or this thesis, of what would be helpful to “see and feel” at reservoirs.

Prepared for the master’s thesis titled *Geotechnical properties and possible geotechnical risks of young fine grain sediments in man made reservoirs.*

Context

This has been written with the understanding that the complete solution of the problems associated with collecting good/undisturbed samples and representative laboratory work are beyond the scope of this thesis. It is acknowledged that difficult laboratory tests will not work well here (at TU Graz) and that I would not be happy with the process or results.

Learning of the aforementioned problems is proposed to be done through literature review and presented in Chapter 3 of the thesis. It will be interesting how others around the world deal with the problems of getting properties from their materials/sediments: what testing equipment they use, what lab tests they perform, what parameters they use, what kind of porewater pressure distribution they find.

One of the tasks brought up in the context of this thesis is for I to try to define what would be helpful to see and feel at reservoirs. This task was suggested with the knowledge of all parties that it would be unlikely that collecting undisturbed samples, (and consequently, any complex laboratory tests) or performing any CPTs (in general from a boat) would be possible. Based on the outcomes of this task, discussions are proposed to determine where any “see and feel” activities would be possible.

Proposal Summary

I would like to go out to at least two or three places (reservoirs, or any other relevant locations) to collect samples of sediments and bring them back to the lab to do some testing on them.

[I know this proposal is overkill, but it gave me the chance to put my thoughts and ideas in order, as well as give me practice in proposal writing.]

My reasons

From a more comprehensive perspective, as I am to write about everything I do for this project, the sampling and testing would provide more substance for the thesis and hopefully make it more interesting for the reader. I think it would also make it more interesting for me, and provide the advantage of creating a practical side to the thesis, which I believe will give me even more out of this thesis opportunity.

I believe that, in a way, this thesis has the potential to open the door to many ideas for following theses. The ability of my thesis to guide the next paths will be greatly enhanced by any concrete/hands-on work I can accomplish for my thesis.

From a more hands-on perspective, I would like to get a feeling, and some photos, of some of the material I am researching and discussing. Although even touching the sediments from one location would be helpful, I would prefer to see from multiple places for the opportunity to encounter more variety and to discover correlations.

It would be great practice to learn how to take these kind of samples, the difficulties involved and the material behaviour in sampling. This would help me to be able to write about sampling methodologies: where problems lie, and maybe how to overcome them. As previously mentioned, undisturbed samples are not easily possible and it is not my intention to attempt to take them. I believe I can still get significant value for my thesis from disturbed samples, because I would be able to see to what degree (for what tests) I can use such samples and I can at least get some indications of the sediment properties.

I also propose to do some tests on the samples. Once samples are taken, it will be interesting to ensure the samples are conserved adequately until testing. It would be very good for me to refresh my experience in certain soil tests and possibly see how some other tests work, all this in the context of another country's standards. With regards to sample disturbance, it is of no matter for some tests, which can still provide important and interesting data. Throughout the testing process, I can also learn more about which tests are suitable for various materials and how the material behaves, a great opportunity in itself.

I think there are numerous exciting possibilities that arise following the sampling and testing process, although I acknowledge that not all ideas/paths will be able to be followed. For example, maybe I can come up with an indication of what the actual material properties are based on through relatively simple observations like sampling and 'playing' with the sediments. Thus it would be great for me to do the sampling, and testing, myself. There is also the possibility that I could use the basic data acquired in this process to confirm/backup the literature research findings– and the data would also be valid and relevant even if they do not confirm/backup the literature. Overall, I think there would be value in any sort of results obtained through the sampling and testing process, positive or negative.

While I can see that these ideas can quickly escalate to very large amounts of work and time required, I do not want to limit or create barriers for myself. (Dreaming can be good, and motivating.)

Some specifics of what I want to do

I would like to go out to at least two locations, see the area and reservoir, try to take some samples, conserve and bring them back to Graz, do some testing on them, and assess the outcomes. I am open to the choice of locations as for most locations, some coordination will be required. I am also open to the timing of these trips and sampling, as winter is coming and other people are likely involved. It is option on my side to go on my own, with support, anywhere I can.

I have not yet specified my sampling methods, but I imagine I could try a few. Some possible ideas:

- simply use a bucket if it soft material,
- use a shovel for more firm material

- use the freeze coring technique (CO2 and fins, barrel or rods) – make the in-place water work to my advantage
- representative reservoir sediment samples can be taken with a bailer (a tool typically used to take water samples at designated depths) (Lee et al. 2013). So we could consider a bailer depending on where we are (this is probably more for BHs.)

For the process I am proposing, I would think sealed containers will be adequate to transport and hold the samples until testing. If there is no storage space at the Institute for the samples, I can keep them at my place.

I would like to use the soil mechanics laboratory at the Institute to undertake my testing. Depending on the type of testing, I would only need to be shown once and introduced to any software, if involved. The following tests are ideas of ones to undertake:

- Soil description and classification
- Atterberg Limits
- Particle Size Distribution (PSD)
- Hydrometer
- Angle of repose – based on particle shape [only for non-cohesive sediments]
- Measuring unit weight, porosity, degree of saturation? – can also attempt in the field
- Vane shear (for intact, fully-saturated, (soft) clays)? – can also attempt in the field
- Sensitivity to disturbances? [Disturbance effects being done by another student]
- Swelling test? [to test swelling, would first have to destroy sample (compress to reduce porosity, then remove overpressure) because in-situ conditions will be high porosity }
- Measuring shear strength parameters (direct shear, ring shear?)? [add to point below: not really possible (need undisturbed it seems), and triaxial test would better handle these kind of material, but I would hate this, and better to look at research. Also because of the consolidation phase in a triaxial, the sample will not at all be like in the field.]
- Not considering permeability or oedometer tests as do not intend to have undisturbed samples, nor considering compaction tests (Proctor) as not relevant to underwater sediments

For the more basic tests, as long as they are done properly, according to standards, the results will be valid and should be robust in further comparisons. It is acknowledged that complications in comparison may arise due to sample locations within a reservoir, as there can be a very large variability in sediment composition across a reservoir.

Ideas of possible correlations and conclusions

In this section, I describe some thoughts on possible correlations and conclusions that could be drawn from the previously proposed. I try to consider the various ways the results can lead. I have not yet read all the literature, and thus cannot yet comment on if anyone has already tried to make the following correlations, especially considering reservoirs from various industries.

First of all, I can compare my results across various reservoirs, and then to the data in literature. Any negative results could probably show that one really needs adequate efforts and money to get representative results.

I am considering a similar idea to how the RMR system works: try to get an idea of the rock (quality) based on only visual identifiers. I could try to come up with sediment properties and behaviour based on only visual or simple (or only quick field checks) tests. Although visual and field checks to estimate soil characteristics are the basics of geotechnical engineering, I would be trying to quantify this a little bit, say with Atterberg limits.

I would look for correlations between findings from literature, field observations and testing results. These could have positive or negative outcomes, but still lead to a conclusion. For example, I could compare my Atterberg limit results to other (literature) reservoirs or see if they correlate to visual observations, like difficulty of sampling, running through the fingers, and so on. If the results do correlate, then can ask if other values/characteristics also correlate, or not. I could try to find correlations between soil grading curves and any other characteristic of these reservoir sediments.

If I were to find that the results from disturbed samples make sense, then I could even question why one would need undisturbed samples at all. This may be more possible for sands and gravels rather than clays. For clays, where it is more likely that disturbance really does have an effect, the next question becomes: is there any possibility of quantifying the effect of disturbance? How much under- or over- estimation of properties occurs with disturbed samples compared to undisturbed or in-situ sediments.

I could compare the test results of drained and undrained disturbed samples (in which tests?) and see if there are any consistent relative differences which could also be found from undisturbed drained and undrained samples.

Conclusion

I am very interested in undertaking some sampling and testing of the sediments I am discussing in my thesis. It would make for a lot more involvement, and to start with, should this proposal or parts of it be accepted, the following are questions to address:

- Could I just go and get samples (can even do this on my own, with support)?
- Which sampling methods to use?
- How to transport (avoid vibrations?) and preserve the samples until tests? And where?
- Could I just do the tests myself? Any costs? Any restrictions on lab use time? A discussion with the lab manager will be required, and details of laboratory use (space, equipment, time) agreed upon.
- How many samples would be needed? How many tests? Any concerns about statistical significance? [don’t bother/worry about statistical significance as I would need lots of samples.]