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INVESTIGATION OF PARTICLE SIZES, BEACH PROFILES AND COMPOUNDS IN TAILINGS DAMS

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MASTER'S DISSERTATION

INVESTIGATION OF PARTICLE SIZES, BEACH PROFILES AND COMPOUNDS IN TAILINGS DAMS

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Abstract

In mining for extraction of metals residues are often produced. A frequently produced residue is tailings, which potentially contains high amount of metals, soluble salts and acids. Therefore, it is often necessary to deposit, the tailings in stable impoundments, namely tailings dams, if not all tailings produced is used as backfill in mines.

In the construction of the tailings dam in Garpenberg, the method of construction is the upstream method. With this method tailings is utilized as construction material for the tailings dam's walls and as foundation material. In order to prevent formation of high pore pressure in the dam walls containing tailings it is recommended that the amount of fines (particles < 63 μm) is maximum 30 % of mass of tailings.

Samplings were performed in the surface and in trial pits to investigate amount of fines, metals and compounds in the tailings. A majority of tailings samples were sieved after prewashing of fines and also a small number of samples were wet sieved. The results indicate that dry sieving shows greater proportion of coarser particles compared to wet sieving for the same sample.

Coarser particles sediment closer to the discharge points and finer particles sediment further out in the dam. No distinctive increase of fines was seen 0-60 m from discharge points due to an inhomogeneous sedimentation of particles. Although, in most of the samples taken 120 m out it was found that the amount of fines exceeded the 30 % limit. The conclusions that can be drawn are that in area of 90-120 m from the discharge points fines can exceed the 30 % limit and sedimentation of particles larger than 63 μm primarily occurs between 0-100 m.

The investigation of metals and compounds resulted in various amount of them with an indication that larger amount of metals were found in samples taken closer to the discharge points.

A relationship between relative particle size and position along a beach was used to roughly predict where a specified relative particle size is found. However, no relationship could be found which is possibly explained by irregular flow of slurrys and limited sampling.

Beaches in the tailings dam were surveyed with GPS and the results show typical beaches that form due to segregating slurrys by the utilization of spigots. The inclinations of the beaches were approximately 1 % or less. No distinctive dimensionless beach profile was found due to spread in the results. Results have shown that the majority of the profiles are concave. With the use of a dimensionless beach profile potentially better assumption of beach inclinations can be performed.

Sammanfattning

I gruvdrift för att extrahera metaller produceras oftast restprodukter. En vanligt förekommande restprodukt är anrikningssand som potentiellt kan innehålla höga halter av metaller, lösliga salter och syror och därför oftast måste deponeras i stabila gruvdammar, om inte hela mängden anrikningssand används till fyllnad i gruvor.

I uppbyggnaden av gruvdammen i Garpenberg används uppströmsmetoden. Med denna metod utnyttjas anrikningssand i byggnation av dammvallar och som grundläggningsmaterial. För att hindra uppkomst av höga portryck i dammvallar bestående av anrikningssand rekommenderas att finjorden (partiklar < 63 μm) maximalt är 30 % av anrikningssandsmassan.

Provtagningar i gruvdammen utfördes i ytan och i provgropar för att undersöka innehåll av finjord, metaller och föreningar.

Anrikningssandsprover som togs torrsiktades efter borttvättande av finjord och ett mindre antal av proven våtsiktades också i Bolidens laboratorium. Resultatet från siktmetoderna indikerade att torrsiktning med förtvättning resulterar i större andel grövre partiklar jämfört med våtsiktning för samma prov.

Grövre partiklar sedimenterar närmare utsläppspunkterna medan finare partiklar sedimenterar längre ut, men på grund av en inhomogen sedimentering av partiklar fanns inte en tydlig ökning av innehållet av finjord 0-60 m från utsläppspunkterna. Emellertid hittades i prover 90-120 m ut finjord överstigande 30 %, vilket kan bero på att partiklar med större storlek än 63 μm primärt sedimenterar i området 0-100 m.

Undersökningen av metaller och föreningar visade varierande mängd av dem i proven med indikation att större andel metaller i anrikningssanden finns närmare utsläppspunkterna.

Ett samband mellan relativ partikelstorlek och läge längs slänten användes, för att grovt kunna uppskatta var en viss relativ partikelstorlek hittas. Men inget samband fanns vilket kan förklaras av varierande flöden av slurrys samt begränsad provtagning.

Utvalda slänter i anrikningsdammen i Garpenberg inmättes med GPS och resultaten visar typiska slänter för separerande slurrys med lutningar på omkring 1 % och mindre, då deponering sker med spigotter. Ingen entydig dimensionslös släntprofil för de undersökta slänterna hittades, vilket kan bero på spridning i resultaten. Resultaten visar att majoriteten av slänterna är konkava. En slutsats som kan dras är att med användning av en dimensionslös släntprofil kan eventuellt bättre antagande om slänters form göras.

Preface

I had the great opportunity to perform my Master's Dissertation in conjunction with Sweco Tailings Dam division and Boliden Garpenberg. I am very pleased for the opportunity to work with these companies and I am thankful for all knowledge they have contributed with.

I am very thankful for all the help and good suggestion I got from my supervisors Roger Knutsson at Sweco and Professor Ola Dahlblom at Department of Construction sciences at Lund University, Faculty of Engineering (LTH).

In February 2013 at LTH's Branschdagen, I came in contact with Johanna Ekstedt, who was the first I came in contact regarding a Master's Dissertation with Sweco. I wish to thank her for the help to come in contact with Elin Wormeester, at that time operational chief at Sweco's department Tailings Dams. During the spring 2013, I had foremost contact with Elin regarding this Master's Dissertation and I wish to thank her for her commitment in this thesis.

Furthermore, I want to thank Boliden for the availability to execute this Master's Dissertation and for their helpfulness when I was at Garpenberg during field work. I also want to thank the staff at Boliden’s laboratory for help with interpreting the results from samplings, conducted at Garpenberg.

Lastly, I want to thank my family that has supported me during my student time.

Table of Contents

Symbols

A	Relative particle size ratio
C	Dimensionless coefficient
D	Particle size found at a distance from point of deposition (mm)
D_{50}	Particle size when 50 percent is passing (mm)
e	Void ratio
F	Distance of a travelled particle (m)
G	Relative density
g	Acceleration due to gravity (m/s^2)
H	Length of beach profile
i	Gradient of beach
k	Hydraulic conductivity (m/s)
L	Distance of particle movement (m)
M	Dimensionless tailings property constant
M_s	Mass of solids (g)
M_w	Mass of water (g)
n	Porosity (%)
S	Degree of saturation (%)
t_s	Time for settling (s)
v_h	Vertical velocity (m/s)
v_v	Horizontal velocity (m/s)
V	Volume (m^3)
V_a	Volume of air (m^3)
V_s	Volume of solids (m^3)
V_V	Volume of voids (m^3)
V_w	Volume of water (m^3)

w	Water content (%)
W_1	Mass of empty pycnometer dried and cleaned (g)
W_2	Mass of pycnometer and dried soil (g)
W_3	Mass of water and soil in pycnometer (g)
W_4	Mass of pycnometer and distilled water (g)
x	Distance from discharge point to decant pond (m)
y	The elevation from discharge point to decant pond (m)
β	Dimensionless beach concavity constant
δ	Sheet flow height (mm)
κ	Intrinsic permeability (m^2)
μ	Dynamic viscosity (Pa·s)
ρ	Density (kg/m^3)
ρ_b	Bulk density (kg/m^3)
ρ_d	Dry density (kg/m^3)
ρ_s	Particle density (kg/m^3)
ρ_w	Density of water (kg/m^3)

1. Introduction

1.1. Background

In mining operations for extraction of metals from ore, there will often be produced residues. Commonly, a large quantity of these residues is produced by extraction plants and they are often referred as tailings and its sizes depend greatly on what type of ore that is processed. It is imperative to deposit these tailings in an environmentally safe approach, because of the potentially high content of metal compounds, acids and soluble salts. Therefore, impoundments are built namely tailings dams, which store the tailings and prevent them from intoxicating surrounding areas. In order to build economically, safe and environmentally effective tailings dams it is necessary to determine the particles sizes, the mechanical properties of the tailings and their behaviour during and after deposition, to ensure stability of tailings dams. The mechanical properties of the tailings and its particle sizes are of special interest, if the tailings are intended to be utilized as construction material, which tailings frequently is used as, in the upstream construction method (ICOLD, 1996).

In mining operations, depositing of tailings is performed and consequently, methods of deposition of tailings are developed. A regular method to deposit tailings is with hydraulic deposition, which implies transportation of tailings mixed with water called slurry, from extraction plants to a point or points of discharge in a tailings dam. The locations of the points of discharge vary depending on the method utilized for deposition, although they are commonly situated either on the walls of a dam or in the centre of a tailings dam. The slurry flow due to gravitation from discharge points to the area with least height. The position with least height is often situated in the centre or edges in a tailings dam. Simultaneously, during the flow of slurry aggradations and sedimentation of particles will occur and form inclined surfaces in the tailings dams referred as beaches (ICOLD, 1996).

A typical view of tailings dams is that they contain material of negligible value. Nevertheless, reassessments of tailings dams are being made and are in some cases, considered valuable. This is the case, especially for old tailings dams where deposition of residues from mining has taken place under several decades (Lottermoser, 2010).

In old tailings dams, the probability is higher to find metals, which have not been extracted, because extraction plants operate within certain recovery rates. Techniques to increase these recovery rates progress and potentially in the future it is possible to extract more precious metals from the deposited tailings. In addition, it is an environmental value to extract as much metals as possible in order to potentially use tailings as resources instead of deposit them as waste (Lottermoser, 2010).

1.2. Problem Description

Sweco is a consultant for Boliden and has recommended a maximum limit of the fines content (particles < 63 μm) that can be accepted, in usage of tailings, as construction material for the tailings dam's walls and as foundation material for the expansion of the dam. Sweco's recommended limit is 30 % (in terms of mass). The limit was established in order to prevent formation of high pore pressures in dam walls. High pore pressures in dam walls affect the stability of the dam and the pore pressures are recommended to be controlled, by among others maintaining amount of fines below 30 % in the tailings used as construction material.

Sweco attends continuously, during the construction and rise of the tailings dam in Garpenberg. Regularly, controls of the tailings used in dam walls are performed, to ensure that the limit of fines is not exceeded. However, at present time it is not fully understood where tailings with fines below 30 % is found.

1.3. Purposes and Aims of Study

Purposes

- Investigate where the amount of fines (particles <63 μm) in tailings exceeds 30 %.
- Increase the understanding of how beaches form in the tailings dam at Garpenberg depending on the present utilized deposition method with spigots.
- Determine if there is a relationship between a dimensionless beach profile and the beaches in the tailings dam at Garpenberg, for ability to assume inclinations of them.
- Investigation of contents of metals, compounds and particle sizes in the tailings at different distances from discharge points of tailings.

Aims

- Revaluation of the tailings contents as assets in respect to the investigation of contents of tailings.
- Investigation of how deposition from different areas of the tailings dam such as tips, corners and straight lines affects the formation of beach inclinations.
- Investigate if there is a relationship between relative particle sizes and positions along a beach, to possibly use this relationship for assumptions where a relative particle size is found along a beach.

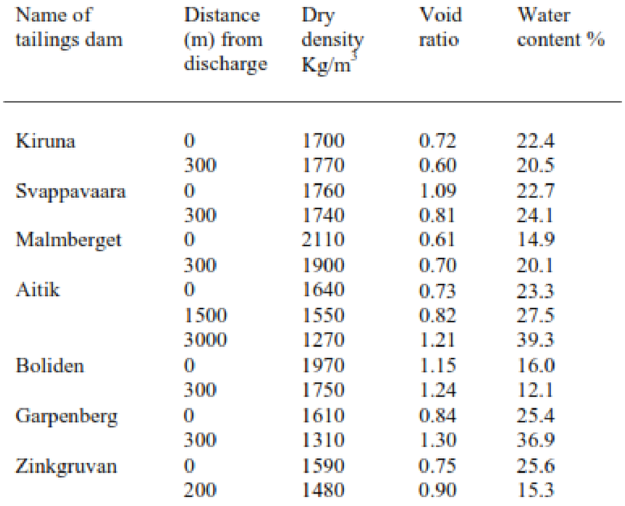
1.4. Limitations

Investigations of beaches are limited to those formed in air due to unavailability to perform sampling and survey in the area of a pond. Merely the proportion of fines are investigated and not the particle size distribution in the fines. This limitation is conducted with consideration to which particles, the most of the dam walls consists of namely sand, and therefore it is not of relevance for this study to comprehensively investigate the fines content.

1.5. Previous Studies

A general investigation of some of Sweden's operational tailings dams have been performed by Bjelkevik & Knutsson (2005), where among others, the tailings dam in Garpenberg were investigated. Several properties were studied at each of these dams and some results can be seen in the Table 1-1. Typically, for most of these tailings dams, the particle size distributions have shown that particles closer to the discharge point are larger in size. The majority of tailings particle sizes are in the range of silt to fine sand. As seen in Table 1-1, the dry densities for Garpenberg were found to be in range of 1300-1600 kg/m^3 and samples were taken at distances 0 and 300 m from the discharge points.

Table 1-1: (Bjelkevik & Knutsson, 2005 p.123).



Name of tailings dam	Distance (m) from discharge	Dry density Kg/m^3	Void ratio	Water content %
Kiruna	0	1700	0.72	22.4
	300	1770	0.60	20.5
Svappavaara	0	1760	1.09	22.7
	300	1740	0.81	24.1
Malmberget	0	2110	0.61	14.9
	300	1900	0.70	20.1
Aitik	0	1640	0.73	23.3
	1500	1550	0.82	27.5
	3000	1270	1.21	39.3
Boliden	0	1970	1.15	16.0
	300	1750	1.24	12.1
Garpenberg	0	1610	0.84	25.4
	300	1310	1.30	36.9
Zinkgruvan	0	1590	0.75	25.6
	200	1480	0.90	15.3

2. Tailings Dams

2.1. Extraction Plants and Making of Tailings

Tailings are created through crushing and grinding of rocks that potentially have some amount of metals that has not been possible to extract. Typically, recovery rates of metals can vary greatly depending on which extraction technique is utilized, and therefore more or less metals can be extracted. With high metal contents in the ore, it can be sufficient to utilize merely crushing and grinding of metals in mills, cf. Figure 2-1, instead of chemical extracting of metals. However, chemical extracting techniques typically impacts more on the environment compared to only using mills and can require precautions in use (Blight, 2010).

Figure 2-1: Mills in the extraction plant at Garpenberg (H. Aitahmed-Ali (Boliden), personal communication, 2013-10-31).

When using chemical extraction techniques of metals, it is conducted among others with sedimentation and flotation basins, Figure 2-2. To extract more metals from the ores, the material undergoes several processes that foremost start with crushing the ore to smaller particles using steel balls in mills. Several mills can be used to increase efficiency of crushing and to control the crushed particle sizes. It is often of great interest to crush the particles to a certain size, which contributes to greater extraction of metals (Boliden, 2013).

In the extraction process of metals it is essential to have water available. Large amount of water is required for cooling mills and to transport particles in the extraction processes. In the flotation basins, the extraction of metals is accomplished by adding chemicals. This is done in order to produce mineral compounds with higher content of metals (Boliden, 2013).

Figure 2-2: Sedimentation basin in the extraction plant at Garpenberg (H. Aitahmed-Ali (Boliden), personal communication, 2013-10-31).

The processed ore is transported to the sedimentation basins where flocculated particles with higher densities are recovered in the bottom of the basins and then gathered for further extraction in smelters. The smelter is the last step, there segregation of particles takes place and metals are extracted. Metal contents and particle sizes, are controlled regularly. If there are noticeable high contents of metals or excessively large particles, those are to be returned through pipes either to the flotation process in Figure 2-3, to the mills or to the sedimentation for reprocessing (Boliden, 2013).

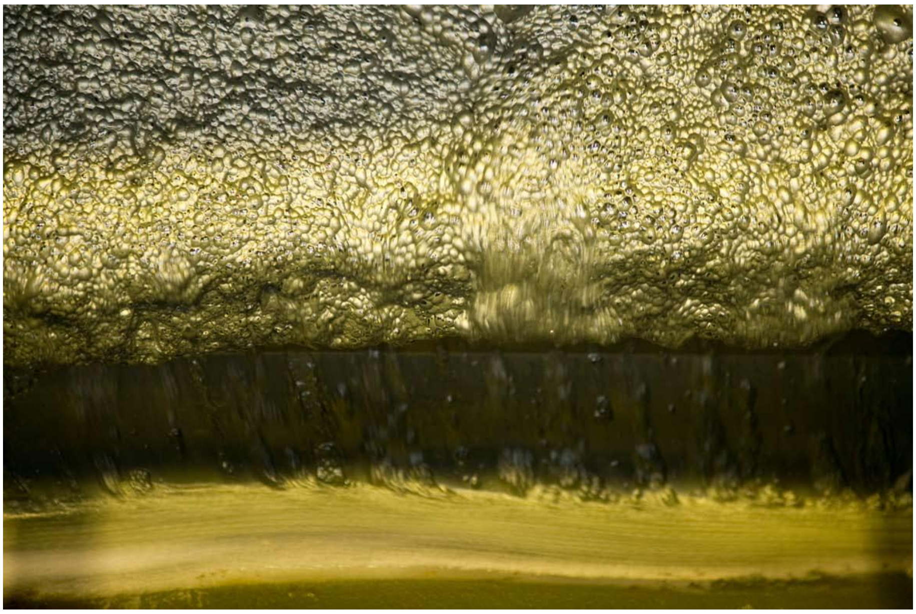


Figure 2-3: Floatation process for extraction of metals in the extraction plant at Garpenberg (H Aitahmed-Ali (Boliden), personal communication, 2013-10-31).

During all steps in the metal extraction process residue materials with low metal content are removed and transported with pipes to a paste plant or to a tailings dam or both (H Aitahmed-Ali (Boliden), personal communication, 2013-10-31).

Paste plants are often used in addition for removal of waste material and for usage of paste as back filling in underground mining areas. In paste plants water is removed from the slurry which creates slurry with high particle content (paste). Increase of particle content is achieved in a cyclone where excess water is recovered as overflow in a thickener, as in Figure 2-4 (Bell et al., 2005).

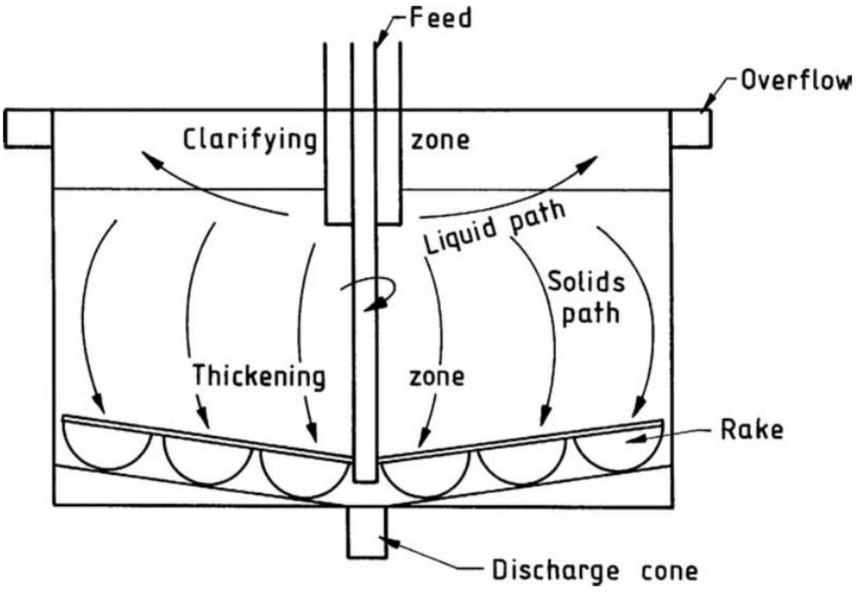


Figure 2-4: Explanation of a thickener (Bell et al., 2005 p. 768).

2.2. Methods of Deposition

Open end discharge

Open end discharge is a well used deposition technique, where slurry is transported in pipes from the extraction plants to the discharge points. It is occasionally necessary to pump the slurry from extractions plants to the impoundment, because of height differences. The slurry is discharged as in Figure 2-5 with one discharge point, which produces large amount of supernatant water. Both, the supernatant water, amount of discharge of slurry and velocity of the slurry impacts on the settlement time of particles (Blight, 2010).

Figure 2-5: An open end pipe at the Garpenberg tailings dam 2013-09-03.

Spigots

A common method for deposition of tailings is the usage of spigots. The method involves delivering of tailings in slurry through a pipe, from the extraction plant to the impoundment. The pipe surrounds the impoundment and spigots are usually connected to the pipe at equal spacing to each other, around the impoundment as in Figure 2-6. The spigots are used for the discharge of tailings and they are pipes of smaller dimensions with a common inner area of around 1 dm^2, but can vary. In addition, the increased number of smaller sized outlets (the spigots), reduces the velocity of the deposited tailings and enhances the ability to spread the tailings, evenly around the impoundment. The reduced velocity of the slurry reduces also the time for settling of coarse grains. This enhances segregation and sedimentation of coarser particles from slurry and ability for reclamation of coarse tailings closer to the discharge points. Spigots are frequently used in conjunction with an open end discharge in the end of the pipeline, connected to the extraction plant (Blight, 2010).

The whole impoundment is normally not under deposition. Instead, the impoundment is divided into sections, where some sections are under deposition and others are under drainage, and are left to consolidate, before next deposition of tailings (ICOLD, 1996).

Figure 2-6: A spigot at the Garpenberg tailings dam 2013-09-03.

Spray bars

Spray bars are similar to spigots, but the spray bars are made of casing tubes with small holes seen in Figure 2-7. Spray bars have a much smaller spacing than spigots and the spray bars can be positioned around 0.5 to 1 m between each other, but it varies. This method enhances ability to evenly deposit the tailings throughout the impoundment and to decrease the velocity of the slurries. Spray bars are frequently utilized when weathered types of rocks are mined, typically where extraction plants produce a greater deal of fines (Blight, 2010).

Figure 2-7: Spray bars during deposition (Blight, 2010 p. 314).

Cyclones

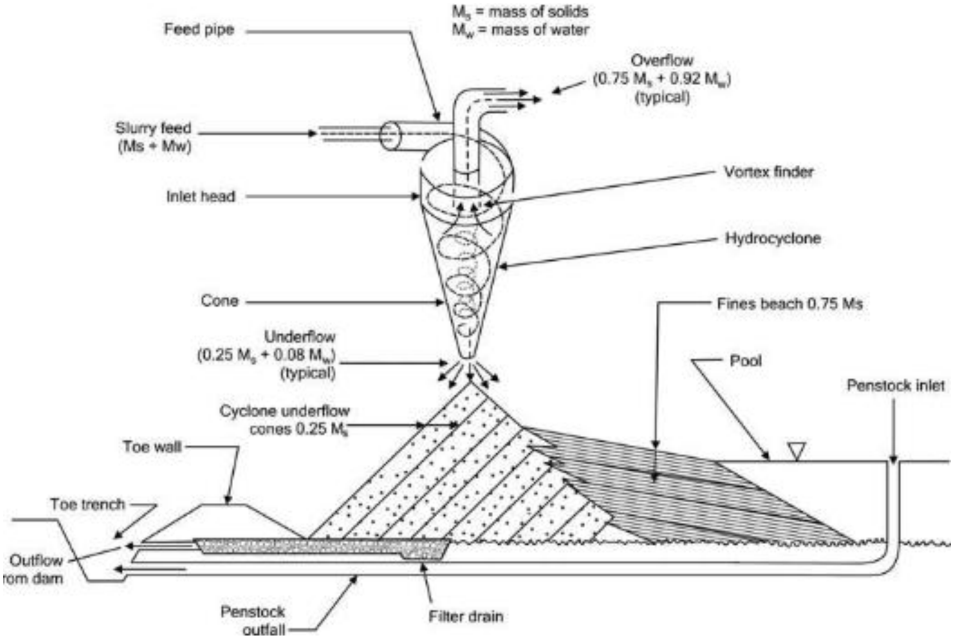


Figure 2-8: Cyclone (Blight, 2010 p. 318).

Cyclones are used to decrease the amount of water from the discharged tailings, increase density and produce a coarser deposit. Cyclones are spiral shaped cones where coarse and denser particles flow into the core of the cone by a cyclone, where the tailings are discharged as underflow in the end of the cone through a hole, as in Figure 2-8. In the meantime transportation of light fine particles and water occurs in the upper and larger part of the cyclone as overflow, which is connected to a pipe. The pipe distributes the overflow with lighter particles for deposition at a certain intended location (Blight, 2010).

Use of this method increases the ability for extraction of coarser particles, which can be reused as building material. The particles found outside discharge points of cyclones are more controlled of coarseness than for spigots. This technique can greatly increase ability to reuse water from slurries, which is important in arid climates, because of water demanding, extraction- and deposit-techniques (Blight, 2010).

Factors that impact on selecting a deposition method

In order to choose an appropriate method of deposition, several site investigations are required to be performed among others the following:

- The type of ore mined and particle sizes that are produced from extraction process.
- Investigation of hydrology.
- Intended building method of the tailings dam.
- Calculations of the amount of discharged materials.
- Investigation of the area around the placement of the tailings dam.

When combining and evaluating these items, the most convenient method of deposition can be determined. In addition, it is as well a matter of expenses regarding materials, installations and maintenance that have to be considered. Evaluations of different methods of deposition can as well lead to those already utilized techniques to be changed to others that are more effective (ICOLD, 1996).

2.3. Methods of Construction (wall raising)

Approaches of the construction of tailings dams have developed into three typical methods, which will be described more thoroughly.

- Downstream construction method
- Centre line construction method
- Upstream construction method

Downstream construction method

In order to construct a tailings dam according to the downstream construction method it is necessary, for each rise of height of the impoundment, to construct the tailings dam outwards, which can be seen in the Figure 2-9 (a). It implies that for a downstream construction method it is vital to have sufficient area for the expansion outwards. Furthermore, for the utilization of this construction method, additional materials for the expansion of the tailings dam is required for each rise of height of dam, which greatly enlarges the expenses, if inexpensive materials nearby are rare (Blight, 2010).

Centre line construction method

The utilization of the centre line construction method implies for each rise of the impoundment that its walls expand upwards through the centre line of the impoundment's walls. This can be seen schematically in the Figure 2-9 (b), this method is a combination between up- and downstream method and it is therefore built partly on tailings, which requires satisfactory properties of the tailings. Moreover, the stability is less for this method than for the downstream method (Blight, 2010).

Upstream construction method

Tailings dams constructed with the upstream method are constructed with either permeable or impermeable dam walls with suitable material properties. When the impoundment expands further, the dam walls are constructed inwards and upwards on previously deposited tailings, as Figure 2-9 (c). This decreases the effective volume of the impoundment as the walls continues inwards.

Previously deposited tailings are regularly used as building material for the ongoing construction of the impoundment. However, an aspect to be taken into account is the frequency of seismic activity. In case of seismic activity and with utilizing of the upstream construction method, there is an obvious risk of dynamic liquefaction. Liquefaction can endanger the stability of the dam and in worst case cause collapse of the dam. Liquefaction occurs due to inability for excesses water to be expelled and forces water and particles to behave as a thick moving fluid. Furthermore, it is a key aspect to investigate the distribution of grain sizes of the tailings, which will be built upon, for maintaining stability of the impoundment. In addition, with the use of this method, the expenses can decrease, due to construction with previous deposit materials (Blight, 2010).

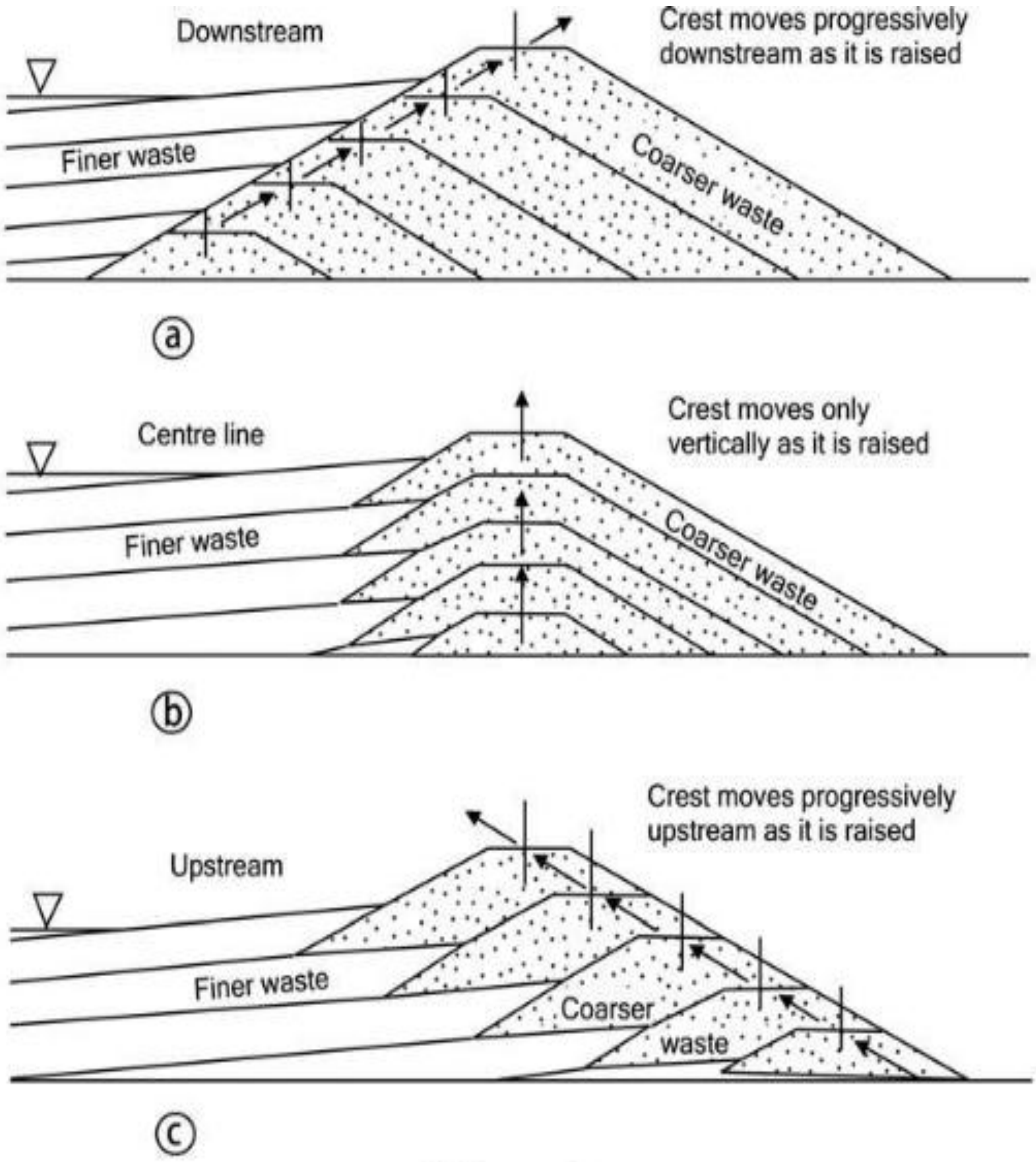


Figure 2-9: Downstream, centre line and upstream construction method (Blight, 2010 p. 282).

3. Theoretical Background

3.1. Hydraulic Fill

3.1.1. Phase Relations

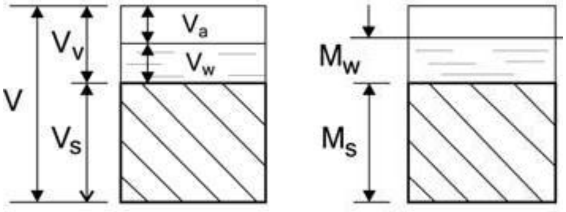


Figure 3-1: Phase relations (Blight, 2010 p. 91).

Normally, in all soils there exist particles and voids. The voids are commonly more or less filled with water and may also contain gas, normally air. The Equations (1)-(9) describe some general phase relations in soil and can as well be used for determination of phase relations for tailings.

The mass of a soil is the sum of mass of water and solids

$$M = M_W + M_S \tag{1}$$

However, there is as well air, but its mass is insignificant compared to the mass of water and soil, which is sketched in Figure 3-1 to the right.

The dry density is the ratio of the solid mass and the total volume

$$\rho_d = \frac{M_S}{V} \tag{2}$$

The bulk density is the sum of mass of solids and water over the total volume

$$\rho_b = \frac{M_S + M_W}{V} \tag{3}$$

The particle density is the ratio of the mass of solids and the volume of the solids and also equal to the relative density times the density of water

$$\rho_S = \frac{M_S}{V_S} \tag{4}$$

Relative density *G* is the ratio of the unit weight of solid and unit weight of a liquid

$$G = \frac{\rho_S}{\rho_W} \tag{5}$$

where the liquid used foremost is water at 4 degrees Celsius (Julien, 2010).

A property of special importance for tailings is the void ratio, which is related to the porosity. In associations with tailings, the void ratio is more used than porosity. The void ratio describes the ratio between pores and soils which is of interest, due to relations with parameters such as friction angle, hydraulic conductivity and deformation attributes (Bjelkevik & Knutsson, 2005).

The void ratio is the ratio between the volume of voids and solids, in a given total volume

$$e = \frac{V_V}{V_S} = \frac{V_a + V_W}{V_S} = \frac{n}{1+n} \tag{6}$$

The porosity is the volume of voids divided by the total volume

$$n = \frac{V_V}{V} = 1 - \frac{\rho_d}{\rho_S} = \frac{e}{1-e} \tag{7}$$

In order to calculate the porosity from tests performed at the tailings dam in Garpenberg, it is required to investigate the dry density and relative density.

Degree of saturation is the ratio of the volume of water and the void volume

$$S = \frac{V_W}{V_V} \tag{8}$$

The water content is the ratio of the mass of water and the mass of solids

$$w = \frac{M_W}{M_V} \tag{9}$$

Soils with high void ratio have increased risk of looseness, which is relevant if the material is used as construction material. In addition, using tailings as construction material requires decreased void ratio and higher dry density, which implies need of compaction of tailings, to preserve stability in the tailings dam walls (Blight, 2010).

Permeability

Permeability describes the ability for a fluid to flow through a porous material. In tailings dams, the permeability typically decreases further in towards the centre of the pond, depending on the particle sizes along the beach and the pore volume (Blight, 2010). However, where layers of particles with fines, potentially appear, the permeability can vary a great deal in both vertical and horizontal direction (Verruijt, 2010).

Hydraulic Conductivity

In regard to tailings, hydraulic conductivity is more used compared to permeability. Hydraulic conductivity is similar to permeability. Both, take into account the properties of the fluid and sediments. Whereas, intrinsic permeability κ only takes into account the properties of the rock in which a fluid passes (Kuo, 1999). Hydraulic conductivity is given by

$$k = \frac{\kappa \rho g}{\mu} \tag{10}$$

Consolidation

Consolidation is a vital component in management of tailings. Terzaghi (1936) was the first person to describe and evaluate effects of consolidation. Consolidation appears as a process of gravitation and earth pressure together with permeability. The pressure, forces particles closer to each other, which results in decreased pore volume. Depending on the permeability of the soils, the consolidation takes more or less time. Typically, for clayey soils, the permeability is low, which increases the time for the soil to consolidate. The consolidation is exponential and therefore soils are seldom fully consolidated (Verruijt, 2010). Consolidation also applies for tailings. However, several notations regarding the consolidations in tailings have to be taken, which is as following:

- Hydraulic conductivity varies in vertical and horizontal direction.
- Large strains occur in the tailings.
- Occurrence of layering and particularly layers of clay.
- Strains in horizontal direction.

These assumptions do not fit well to Therzahgi's (1936) one-dimensional consolidation theory. Therefore, solutions have been derived, which can cope with large strains.

It is often wanted, to deposit as much tailings as possible, which may imply a fast wall rising rate. Consolidation correlates to the wall rising and is a factor among others that determines how fast walls can be raised. Typically, wall rising figures varies greatly from dam to dam and are often calculated in metres per year with FEM-modelling software (Blight, 2010).

As soon as the slurry is discharged through the spigots, a process of consolidation and dewatering begins. As slurry continuously is discharged can in some cases deceleration of the consolidation process occur as a result of that excess water maintains pore pressure high (Blight, 2010).

3.1.2. Sedimentation and Segregation

Sedimentation

When slurries are deposited in an impoundment a flow of water mixed with particles and potential adhesives flows towards the centre of the impoundment to the pond, where velocity of the flow decreases, due to friction effects. After deposition of slurry from discharge points the vertical velocity of particles forces the particles to sediment. This occurs for larger denser particles first, whereas fine particles can be held in suspension for considerable time and settle first after reaching the steady part of the pond in an impoundment (Blight 2010).

Segregation

Generally, slurries are either described as segregating or non-segregating. The slurries which are described as segregating have typically soil content between 10 and 25 %, but vary greatly. Segregating slurries starts to segregate directly after discharge through spigots or open ended pipes. The segregation affects the coarseness along the beach which implies that particles with higher densities and volume settle near the discharge points and particles with less density and size settles further out from discharge points. Furthermore, segregating slurries typically create flat beaches with beach slopes with possible inclinations of approximately 1 % or less (Blight 2010).

Slurries that are non-segregating have greater soil content and behave more like thick fluids. Non-segregating slurries are created by thickening them through removal of water, to increase the soil content. However, minor segregation has been observed directly after discharge of non-segregating slurries. Non-segregating slurries have uniform segregation over the length of the beach.

Typically, the thickened slurries create steeper beaches with slopes in a range of 2-4 %. The solid content of the non-segregating thickened tailings lies between 40 and 60 percent, but varies.

It has been referred by researchers that a threshold appears for when the slurry enters from segregating to non-segregating slurries. However, for the ability to create non-segregating slurry, it is concluded that removal of water is necessary (Fitton, 2006).

3.2. Pore Pressure

In the case of construction of dams and rise of dam walls, depending on the size of particles, excess pore water pressures may develop in fine grained soil, especially for silt and clay particles. Therefore, it is convenient when constructing dams that coarser particles are deposited closely to the impoundment walls and that finer particles are retained, in the inner part of impoundments.

The phreatic surface in an impoundment with permeable dam walls can be maintained at lower levels by adding drainages in the walls. These drainages contain materials with large permeability, in order to prevent high pore pressures, near dam walls.

Excess pore pressure can occur in static loading foremost in silty and clayey soils. However, when dynamic loading occurs liquefaction can take place in the fine sand, due to inability for the excess water to dissipate at a required rate. The tailings together with the water then potentially behave as a thick slowly moving liquid, which could greatly decrease the stability of the dam and in worst case cause, a dam failure (Blight, 2010).

3.3. Alluvial Flows

The slurry discharged from a spigot or open end pipe flow in the most convenient way down to the point with least height, which is where the decant pond starts. Delta resembling paths are created along the beach until the decant pond, which is seen in Figure 3-2. The paths are created depending on the particle sizes, the particles specific densities and the velocity of the slurry. The flows are usually laminar for discharge of tailings from spigots, although turbulent flows occur. Turbulent flows occur more frequent in use of the open end pipe discharge method.

Beneath the discharge point from either spigot or open end pipe a pool is created, which absorbs energy and decreases the velocity of the slurry according to Blight (2010).

Mohrig & Parke (1998) states that alluvial flows formed by the deposition of tailings, can potentially be predicted. They developed a method to predict alluvial flows from equations for natural sedimentation from alluvial flow deltas. However, simplifications are required and are necessary to be made, for manageable calculations of the prediction.

Figure 3-2: Delta created by flow from spigots at Garpenberg tailings dam C, 2013-09-03.

3.4. Particle Sizes

Particle sizes along the beach depend on the substances which tailings consist of, on the rocks mined and the extraction technique of metals etc.. According to Blight et al. (1985) it is possible to roughly predict the particle sizes along the beach if certain properties of the tailings dam are identified.

Blight & Bentley (1983) states that particle sizes at distance from the dam walls can roughly be calculated with the Equations (11)-(15), by following Graf‘s (1971) sedimentation and flow equations:

The settling velocity v_v^2 is calculated as

$$v_v^2 = \frac{4(\rho_s - \rho_w)gD}{\rho_w} \tag{11}$$

where the density of the slurry is ρ_s, the density of water is ρ_w, the grain size is D and the gravitation is g.

Time for settling of particles is t_s

$$t_s = \frac{\delta}{v_v} \tag{12}$$

where δ is the depth of slurry and v_v is the vertical velocity of a particle.

The distance of a particle travelled along a beach is denoted F

$$F = v_h \cdot \frac{\delta}{v_v} \tag{13}$$

where v_h is the horizontal velocity of settling particles.

The horizontal velocity v_h is calculated as

$$v_h = C(\delta i)^{2/3} \tag{14}$$

where *C* is a coefficient and the gradient of the beach is i.

The predominantly particle size *D* at distance *F* is calculated as

$$D = \frac{C\delta^{3/2} i^{1/2}}{\frac{4(p_S - p_w)g}{p_w} F} \tag{15}$$

Experiments were conducted for investigation of best fit of data. From the empirical experiments Blight & Bentley concludes that instead of Equations (11-15) a rough prediction of specified relative particle sizes along a hydraulic fill beach can be made accordingly with the simplified

$$A = \frac{Mx}{H} \tag{16}$$

$$A = \frac{D_{50}(\text{at X down the beach})}{D_{50}(\text{of maximum grain size})} \tag{17}$$

where *H* is the distance of the beach, A is the relative particle size, *X* is the distance along the beach and *M* depends on properties of the tailings dam such as the particles sizes, type of deposition technique and length of beach (Blight & Bentley, 1983). In order to retrieve the property M from the tailings dam it is required field sampling and usage of Equation (16).

In the Figure 3-3, Blight (2010) determined the particles sorting that occurs on a diamond tailings dam's beach and observed some scatter. He states that the scatter that is seen in the Figure 3-3 can possibly be derived to turbulent flows of slurries on the beach.

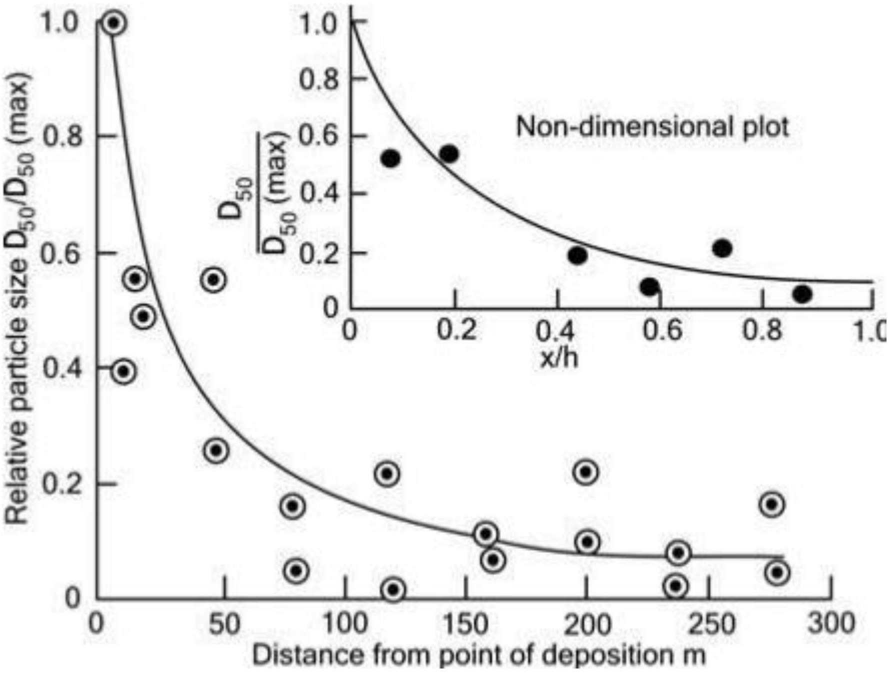


Figure 3-3: Particle size distribution measured on the beach of a diamond tailings storage (Blight 2010, p. 297).

3.5. Beach Profiles

According to Blight (1994) all tailings dams' beaches form a dimensionless profile if the length and elevation from the discharge of the tailings to the decant ponds are known. The profiles of beaches in tailings dams have generally a concave shape. In addition, other profiles as convex shapes are as well found when investigating beach profiles.

Research concerning prediction of tailings beaches slopes from small scale laboratory constructed beaches has been less successful (Blight, 2010).

Jewell (2012) states that established beach slope prediction methods are currently not that accurate, they are instead implemented by corporations as the best there is and should be used with good sense. Depending on if the slurries are deposited over or underwater, different beach inclination appears, with typical steeper beaches forming underwater (Qiu & Sego, 2006)

It is of relevance to predict the slopes of the beaches, for calculations of storage volumes in the progress of designing a new impoundment (Blight, 2010).

Blight (1994) has from Melent'ev's (1973) work established the Master Beach profile through empirical testing on dams with different tailings properties, which is given by

$$\frac{y}{H} = \left(1 - \frac{x}{L}\right)^{\beta} \tag{18}$$

where β is a concavity parameter, H is the vertical distance of the beach to the pond, y is the height difference between the discharge point and the pond, x is the horizontal distance along the beach and *L* is the horizontal distance between discharge point and pond, which is graphically seen in Figure 3-4.

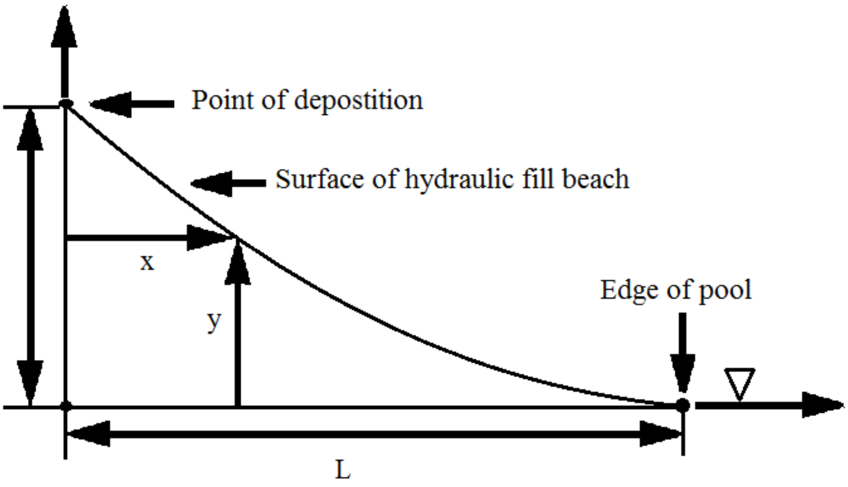


Figure 3-4: Beach profile (Blight, 1994 p. 38).

In Figure 3-5 points measured at beaches of gold, copper, platinum and diamond tailings are shown, where they are compared with dimensionless beach profiles and their concavity parameters. Variation of the measured points in the beaches occurs depending among others on the solid concentration of the slurry and the type of discharge method (Blight, 1994).

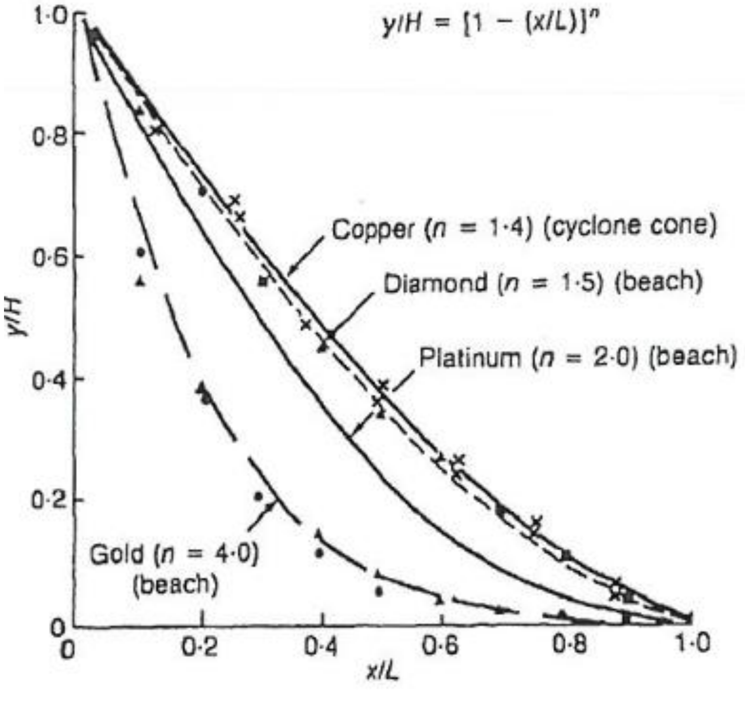


Figure 3-5: Dimensionless profiles compared to measured beach inclinations, where n is equal to the concavity parameter β (Blight, 1994 p. 32).

4. Case Study Garpenberg Tailings Dam

4.1. Background Garpenberg Tailings Dam

Mining has commenced in Garpenberg since the 11th century. However, not until the late 19th century, the mining operation grew to a large scale and increased greatly. The main metals extracted from the ore body are zinc, silver, lead and some minor amounts of copper and gold (Boliden, 2013).

Since the mining in Garpenberg commenced, the production of residues such as tailings have been ongoing and discharge of tailings in the tailings dam in Garpenberg started in 1960 (Wormeester 1, 2011).

The tailings dam in Garpenberg has an area of approximately 0.85 km^2 and an overview of it is seen inFigure 4-1. The deposited tailings in 2013 is approximately 622 200 m^3 and the mined ore is in the order of 1.4 million tons. However, a new extraction plant is under construction, which will increase the capacity of the amount of ore processed to approximately 2.5 million tons, annually (Boliden, 2013).

Overview of the tailings dam:

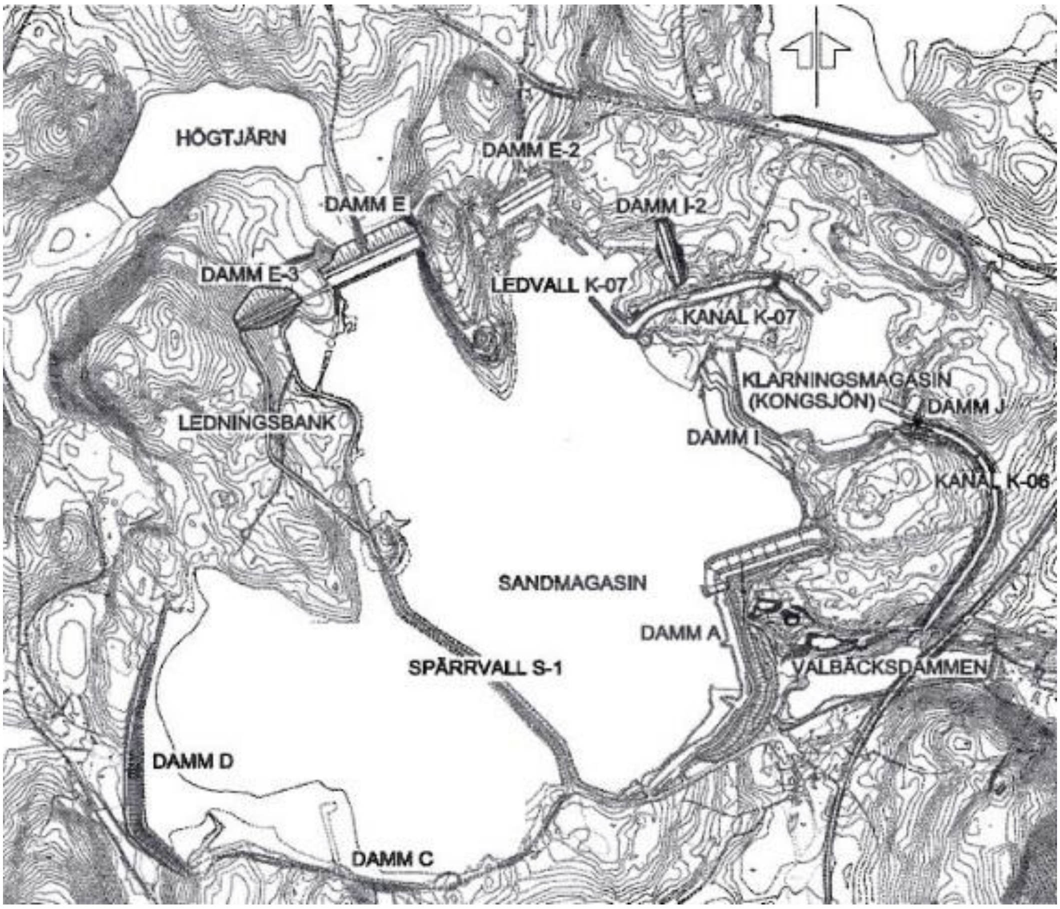


Figure 4-1: Garpenberg tailings dam (Wormeester ;1, 2010 p. 1).

4.2. Methods of Deposition

In Garpenberg, different deposition techniques have been utilized. In the beginning of mining operation in Garpenberg the general technique was to pile the residues. However, as the mine expanded, a larger area was required for the discharge. When the deposition of tailings eventually grew in size this created a large amount of water in the impoundment, which had to disperse by seepage or evaporation and therefore a spillway was built. Before 2009, the method of deposition used was open ended discharge and thereafter deposition with spigots began. With the use of spigots a large area was possible to be discharged. Moreover, the upstream construction method could later be utilized by reuse of tailings with sufficient particle sizes for the tailings dam's rise of dam walls (Wormeester ;2, 2011).

4.3. Methods of Construction

Generally, construction of tailings dams in Sweden was performed through replication of the construction of water dams and earth filling dams. Those dams were characteristically built with an impermeable core of moraine and with rock fill or other support fill, surrounding it (Jantzer, Bjelkevik & Pousette, 2002). Tailings dams have generally a spillway or a decant tower where water is removed. The water can be transported further to basins for sedimentation of particles and potential purification, before returning the water to nearby rivers and extraction plants (Blight, 2010).

A great deal of the Swedish tailings dams were built in the middle of 20th century and are still in use, due to comprehensive legislation and environmental duties to overcome, before even planning, for the construction of a new tailings dam. As a typical Swedish dam, Boliden's tailings dam at Garpenberg was created with a middle core of an impermeable moraine. The tailings dam was initially built with the use of downstream construction method. However, using this method demanded more materials for each increase of height of walls. Therefore, Boliden investigated if the upstream method could be implemented. Tests for the usage of upstream construction method commenced in the early 21th century and later it was concluded that the upstream method could be used. Since 2009, the upstream method has been the construction method and tailings on site have been used in the construction of the tailings dam's walls (Wormeester ;2, 2011). Figure 4-2 shows a cross-section of the tailings dam in Garpenberg with a typical core of moraine.

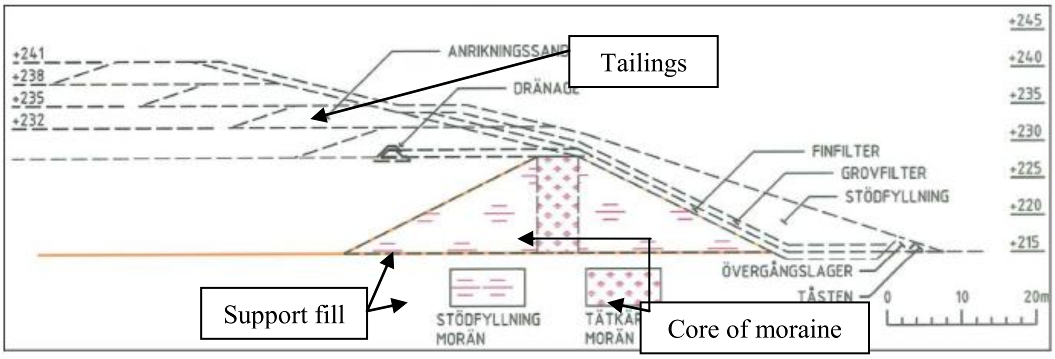


Figure 4-2: A cross-section of one of the tailings dam at Garpenberg (Wormeester ;2, 2011 p. 3).

5. Experimental Methods

5.1. Field Work in Garpenberg Tailings Dam

5.1.1. Sampling Disturbed Samples

Field work was performed during August and September 2013 in Boliden's tailings dam at Garpenberg, where samples were taken in trial pits and in the surface of the beaches. The positions for samplings were surveyed with a GPS and can be seen in Figure 5-1.

Trial pits were dug with an excavator and the rest of the samples were taken by hand. The Garpenberg impoundment is surrounded by six different dam sections (A, B, C, D, E and I), where tailings carried in slurries are discharged through spigots and an open end discharge. Between dam C and B in the middle of the impoundment there is a connection, where as well discharge of tailings through spigots have been done. However, as the rise of the impoundment continues this connection will disappear and the whole dam will be formed more or less like a ring. Samples were taken orthogonal from the potential start of discharge point at the dam walls and in lines, which can be seen in the Figure 5-1. Zoomed views of the different dam sections are seen in Figure 5-2-Figure 5-4.

The samples taken by hand were aimed to penetrate the overlaying newest deposited tailings, at a depth of approximately 10 cm below surface. This was conducted to decrease influence in the samplings by smaller particles, which might have been deposited in the surface, through winds.

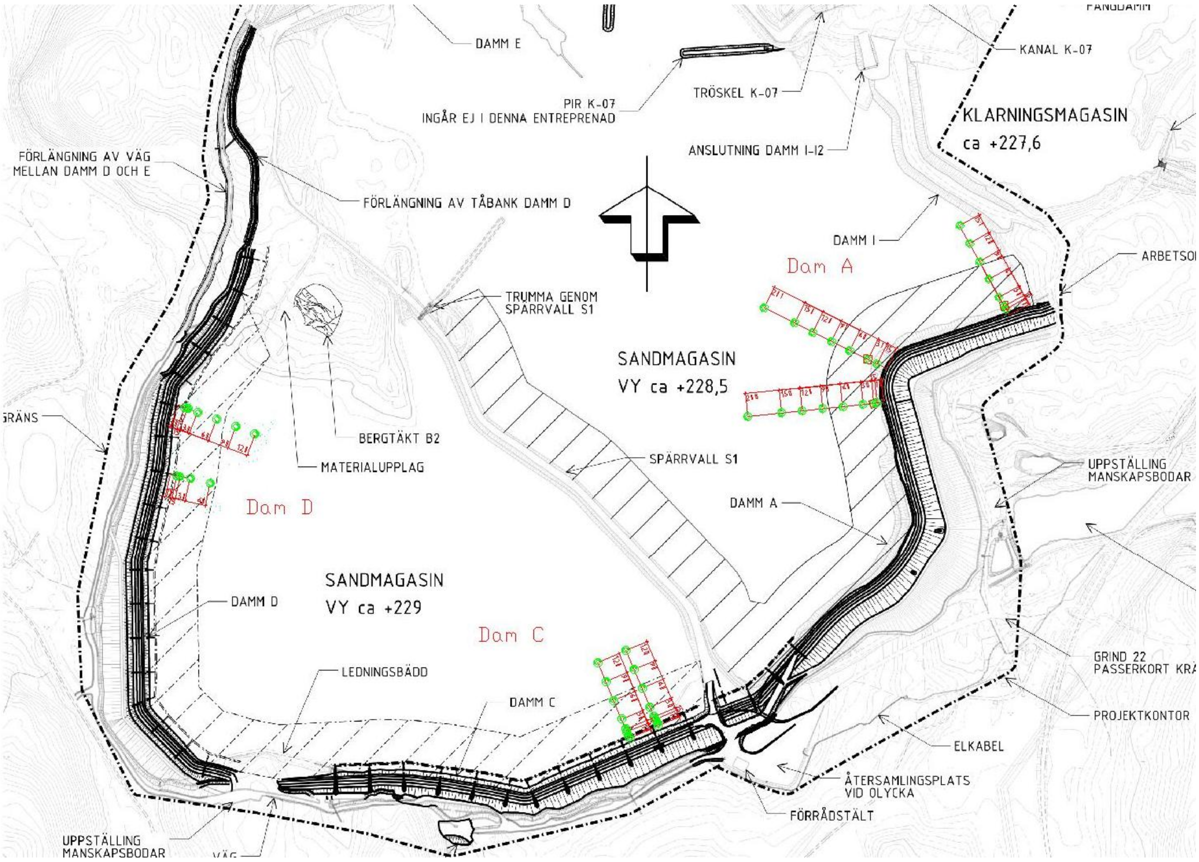


Figure 5-1: Samplings performed at selected positions at Dam A, C and D.

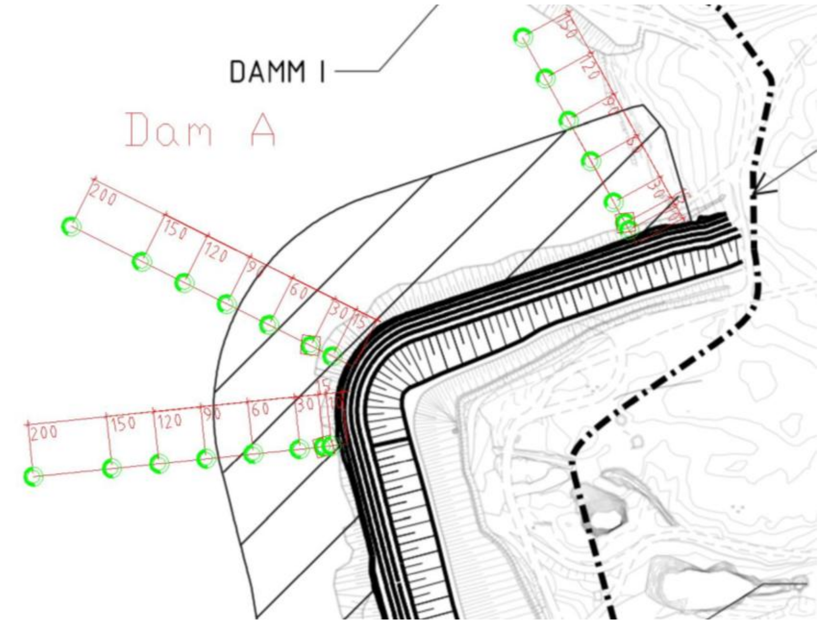


Figure 5-2: Zoomed view of performed samplings at dam A, lengths in metres.

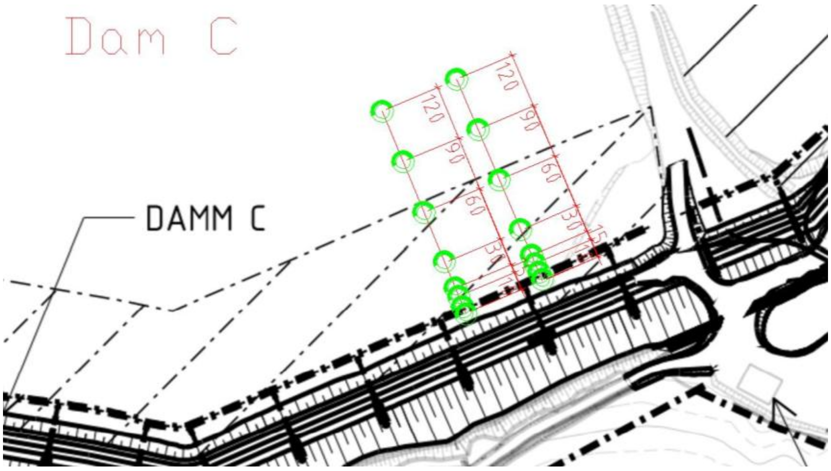


Figure 5-3: Zoomed view of performed samplings at dam C, lengths in metres.

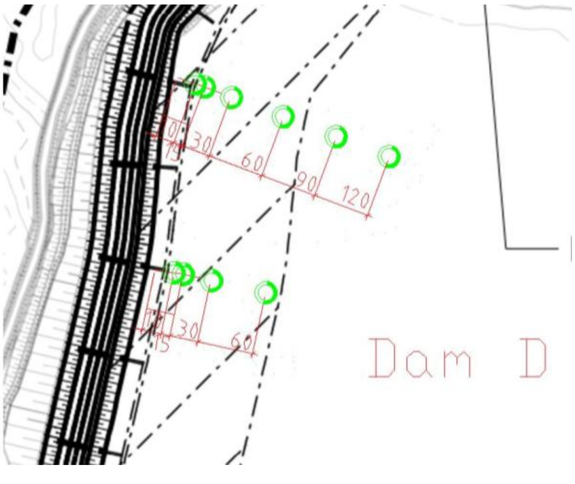


Figure 5-4: Zoomed view of performed samplings at dam D, lengths in metres.

Trial pits

Investigation of bulk density was conducted through excavating three trial pits. Figure 5-5 taken on site shows an ongoing excavation of a trial pit in dam A section 0+400. Layering is observed in a trial pit at dam A section 0+575 as darker areas that are of thickness 5 to 10 cm, the layers likely consist of clay, silt and particles <63 µm, seen in Figure 5-6. Layering is created, mostly depending on the flow from spigots and potentially by the closure of the spigots and by weather conditions, which imply decreased velocity of the slurry and aggradations of fines close to the discharge points.

Figure 5-5: On-going excavation of a trial pit in dam A 2013-09.

Figure 5-6: Layering in trial pit at dam A 2013-09.

Almost all samples taken on site were ocular examined and determined of its contents through sight. The most soils were of sand and fine sand, but 90-120 m out from discharge points differences in particle sizes are visually seen. When the tailings were excavated, the tailings also behaved differently. The tailings further out than 90-120 m, could if they were vibrated behave as a thick fluid and liquefy. This can imply that the tailings have high water content and that it consists of a greater proportion of fines.

When the spigots are closed, the flow of slurry energy dissipation appears which contributes to sedimentations of finer material closer to the dam walls. Moreover, at 250 m out in the impoundment there are large amounts of aggradations of particles less than 63 µm.

During summer months, when the sun shines, the evaporation increases, which has the potential of increasing the appearances of dry cracks in the impoundment, as seen in Figure 5-7. These cracks are partly filled by tailings, when a new deposition of tailings takes place which causes inhomogeneous tailings deposit (Blight, 2010).

Figure 5-7: Dry crack in surface of the tailings dam approximately 250 m out in dam A 2013-09.

Figure 5-8-Figure 5-15 show where samples of tailings were taken in dam C. Samples were taken at distances of approximately 5, 10, 15, 20, 30, 60, 90 and 120 m from discharge points. What is noticeable is that at a distance of approximately 60 m, the tailings particles are harder to see by the eye. At approximately 90-120 m it can be seen that when those samples were taken the tailings were more or less saturated. The distances from the walls were measured with a measuring tape with length of 50 metres. Therefore, it is seen in the Figure 5-8-Figure 5-15 that the measuring tape does not show 60 and 90, instead shows 10 and 40 m, due to splicing.

Figure 5-8: 5 m from dam wall 2013-09.

Figure 5-9:10 m from dam wall 2013-09.

Figure 5-10: 15 m from dam wall 2013-09.

Figure 5-11: 20 m from dam wall 2013-09.

Figure 5-12: 30 m from dam wall 2013-09.

.

Figure 5-13: 60 m from dam wall 2013-09.

Figure 5-14: 90 m from dam wall 2013-09.

Figure 5-15: 120 m from dam wall 2013-09.

5.1.2. In-situ Density

During week 34 and 36, 2013, the in-situ density was determined with a balloon test apparatus, in preferred positions at dam A.

The approach for utilization of a balloon test is first to create a flat surface on the tailings, Figure 5-16. Thereafter, the balloon test shall be placed on the plane area and water is pumped through a plastic pipe from the cylinder containing water into a balloon, to determine the initiate volume ($V_{Initiate}$). Then, a hole of approximately 10x10x8 cm^3 is dug under the apparatus and the material from the hole is stored in a plastic bag, which will later be weighed (M) and dried (M_d), Figure 5-18. After the hole is dug, the balloon is inserted in the hole and the volume of the hole is determined by filling the balloon with water (V_{Hole}), Figure 5-17.

Figure 5-16: Flat area in a trial pit.

Figure 5-18: Hole dug under the balloon densitometer.

Figure 5-17: Volume of hole under the balloon densitometer was determined.

The densities can then be determined:

$$\rho = \frac{M}{V_{Hole} - V_{Initiate}} \tag{19}$$

$$\rho_d = \frac{M_d}{V_{Hole} - V_{Initiate}} \tag{20}$$

5.1.3. Data survey – Beach Shape

With use of a GPS, coordinates for the surface of the beach was surveyed and the surface was modelled in the Bentley MicroStation application InRoads. In Figure 5-19-Figure 5-21 shows the beaches at dam A, C, D which was surveyed by GPS. It was aimed to survey as much as possible of the beach. However, in some cases the tailings in the beaches were very saturated, which prevented walking further out towards the pond and survey.

Figure 5-19: Beach at dam D section 0+850, 2013-09.

Figure 5-20: Beach at dam C section 1+850, 2013-09.

Figure 5-21: Beach at dam A profiles of section 0+575 and 0+450, 2013-09.

5.2. Lab Tests

5.2.1. Gradation Test

Sieve analyse was performed on 60 samples by first prewashing the samples and then sieving with the dry sieving apparatus in Figure 5-22. Sieving was performed according to SS-EN/ISO 14688-2. Prewashing was conducted to remove fines and detach them from coarser particles, by scrubbing the samples in a 63 µm mesh. Washed and scrubbed samples were dried 24 hours before conducting sieve tests. The measuring device used was calibrated before weighing, for optimised measuring and each test was sieved 20 min.

Figure 5-22: Sieving apparatus and meshes, 2013-09.

The sieve at Sweco field laboratory used by the author was able to sieve fractions of 0.063, 0.125, 0.250, 0.500 and 1 mm.

The sieve at Boliden laboratory was able to sieve fractions of 0.063, 0,090, 0,180 0.250, 0.500 and 1 mm. Particles less than 0.063 mm were gathered, and sorted by sedimentation, which determined particles of sizes 0.020 and 0.045 mm (H. Aitahmed-Ali (Boliden), personal communication, 2013-10-31).

Particle sizes over 1 mm could be determined, by the laboratories. However, the insignificant amount of these particles, made it unnecessary to examine them.

5.2.2. Water Content

Samples of tailings where dried 24 hours in an oven 105℃, before conducting sieve analyses and the water content could be determined by weighing the specimens before and after drying.

5.2.3. Pycnometer Test

With the use of a pycnometer, the relative density of the tailings samples can be determined. The procedure determining relative density with a pycnometer is as following:

Firstly, determine the mass of the pycnometer bottle (W_1), the volume inside it and the mass when the bottle is filled with distilled water at 20 ° C (W_4). Then, dry approximately 30 g of the tailings specimen and pour it down the pycnometer. Thereafter, measure the mass of the bottle and dry specimen (W_2). Then, fill the pycnometer with distilled water, to approximately three fourths of the bottle and put it on a heating plate. On the heating plate, the specimen shall boil for some minutes, as seen in Figure 5-23. This is performed in order to remove entrapped air. Then, the specimen shall cool down during a few minutes and after that, distilled water shall be poured to the top of the bottle and a lid shall be put on. The specimen shall then be left to settle for at least 24 hours and occasionally distilled water is required to be filled to the top of bottle, if air bubbles appear under the lid. Finally, when the specimen has had enough time to settle, the mass of pycnometer with its contents of soil and water is to be determined (W_3). It is essential that air entrapped under the day is removed and more water is poured up to the top of the pycnometer to be able to determine the relative density.

$$G = (W_2 - W_1) / [(W_4 - W_1) - (W_3 - W_2)] \tag{21}$$

The scale which was used was calibrated with a documented mass of 46.3 grams and a mass of 2000 grams. However, an error was found for 2000 grams mass with a fault of 0.7 grams. It was then controlled, that the deviation was linear and it was therefore neglected, when Equation (21) was used.

Figure 5-23: A pycnometer on a heater, 2013-10.

5.2.4. Particle Content

With the assistance of Boliden's laboratory staff, analyses of contents in different fractions were identified. The contents that could be identified were iron (FE), sulphur (S), silver (Ag), zinc (Zn), copper (Cu), lead (Pb), silicon dioxide (SiO_2), magnesium oxide (MgO), manganese (Mn). Analyses were performed on a total of 9 samples at Boliden's laboratory with fraction analysis method (H Aitahmed-Ali (Boliden), personal communication, 2013-10-31).

The procedure of determining particle contents is as following; Staff at Boliden laboratory weighed 100 g of each sample, then the sample was sieved with water using a sieving apparatus. Particles were thereafter collected in sieve meshes and particles smaller than 63 µm were collected and determined by sedimentation analysis. Samples were taken from each sieve mesh and were crushed, grinned and mixed together with adhesives to form brickets. The brickets were then x-rayed in a fraction analysis apparatus. By x-raying the brickets, the amount of atoms of the materials in the brickets could be found and measured (H Aitahmed-Ali (Boliden), personal communication, 2013-10-31).

6. Results

6.1. Grain Size Distribution and Particle Size Prediction

Grain Size Distribution

Results from the sieve analyses conducted by the author and Boliden (A. Lindh, personal communication, 2013-10-02) clearly show increased amount of fines between 90-120 m from the discharge point.

In Figure 6-1-Figure 6-6, the blue rectangular areas represent the 30 % recommended maximum limit of fines, in tailings used as materials in dam walls. Where the curve is over the corner between the horizontal and vertical light blue area, it implies that the 30 % limit is exceeded. Moreover, it is clearly graphically seen, in Figure 6-1–Figure 6-6 that the amount of grains less than 63 µm is altered roughly between 90-120 m out from the discharge point. The 3-D graphs have been constructed through curve fitting of sieve test results. Figure 6-1-Figure 6-3 show results of sieve tests conducted by Boliden (A. Lindh, personal communication, 2013-10-02) and Figure 6-4-Figure 6-6 show results of sieve tests performed by the author.

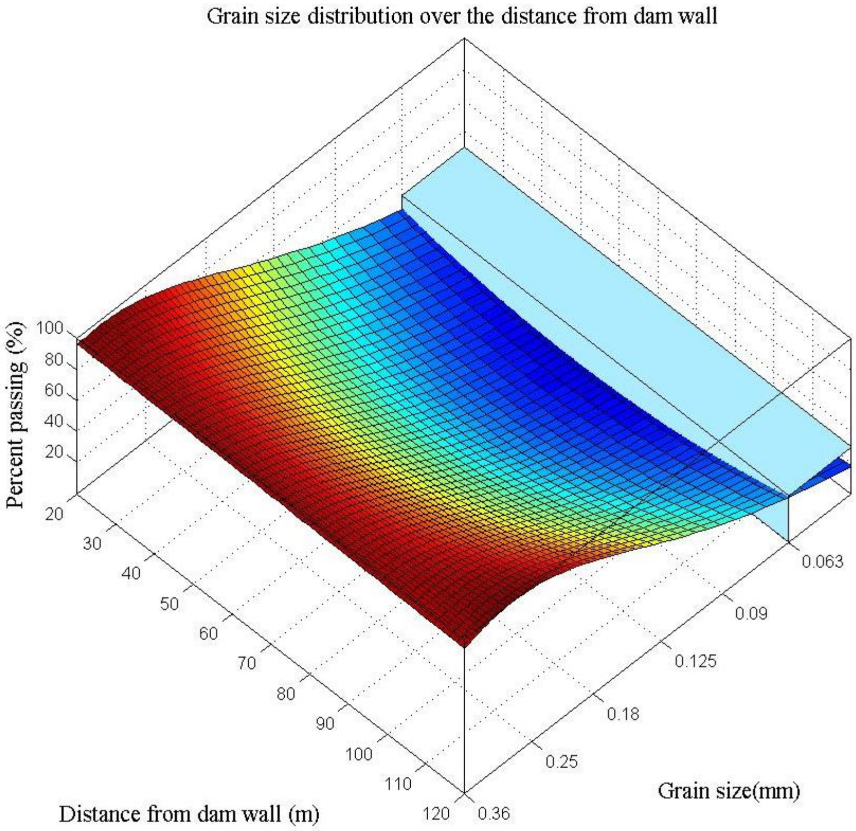


Figure 6-1: Grain size distribution over the length, section 0+375 at dam A (wet sieving).

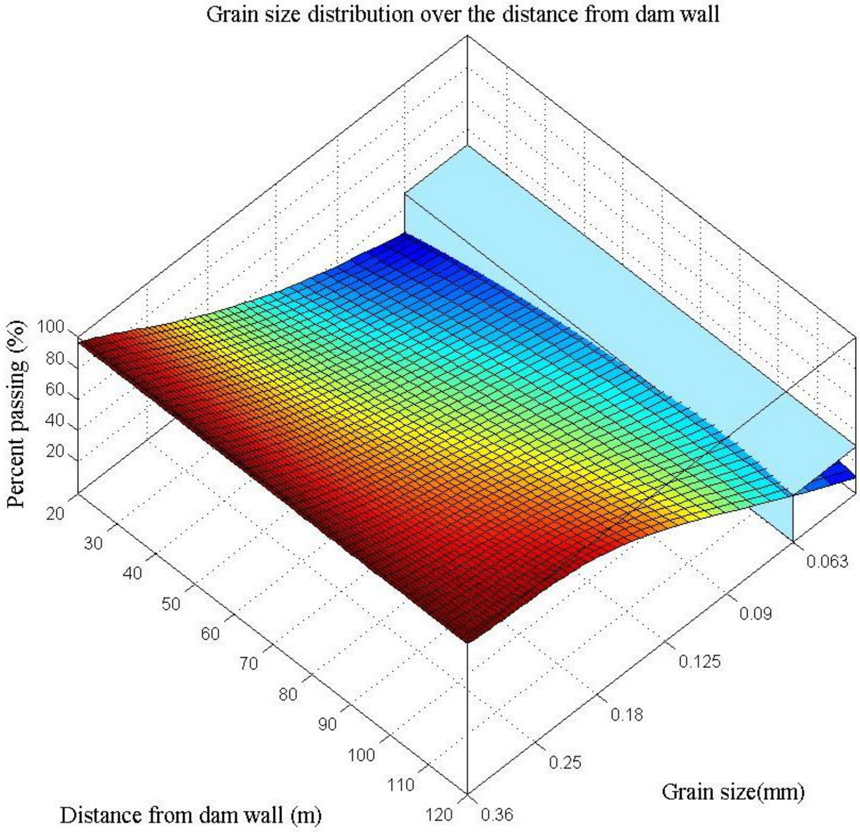


Figure 6-2: Grain size distribution over the length, section 1+750 at dam C (wet sieving).

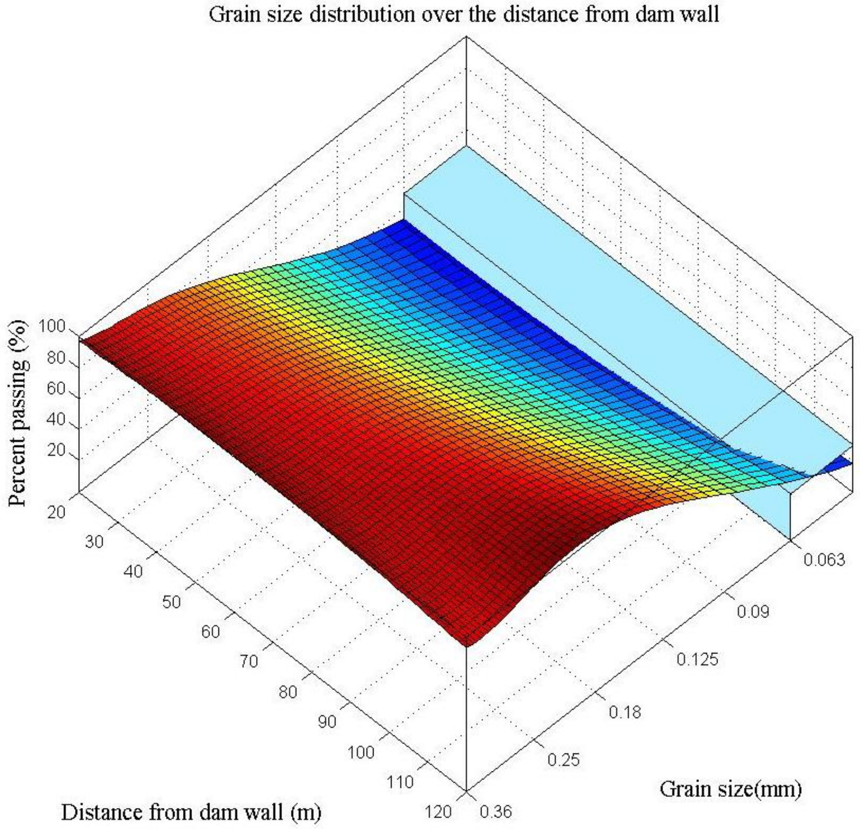


Figure 6-3: Grain size distribution over the length, section 0+850 at dam D (wet sieving).

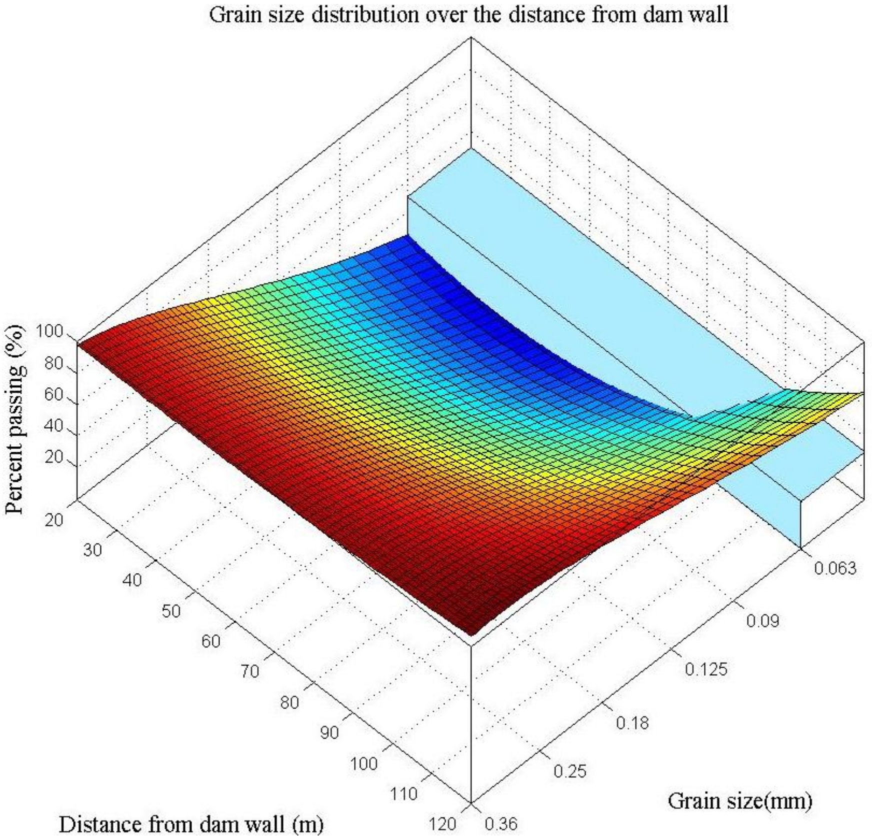


Figure 6-4: Grain size distribution over the length, section 0+375 at dam A (dry sieving).

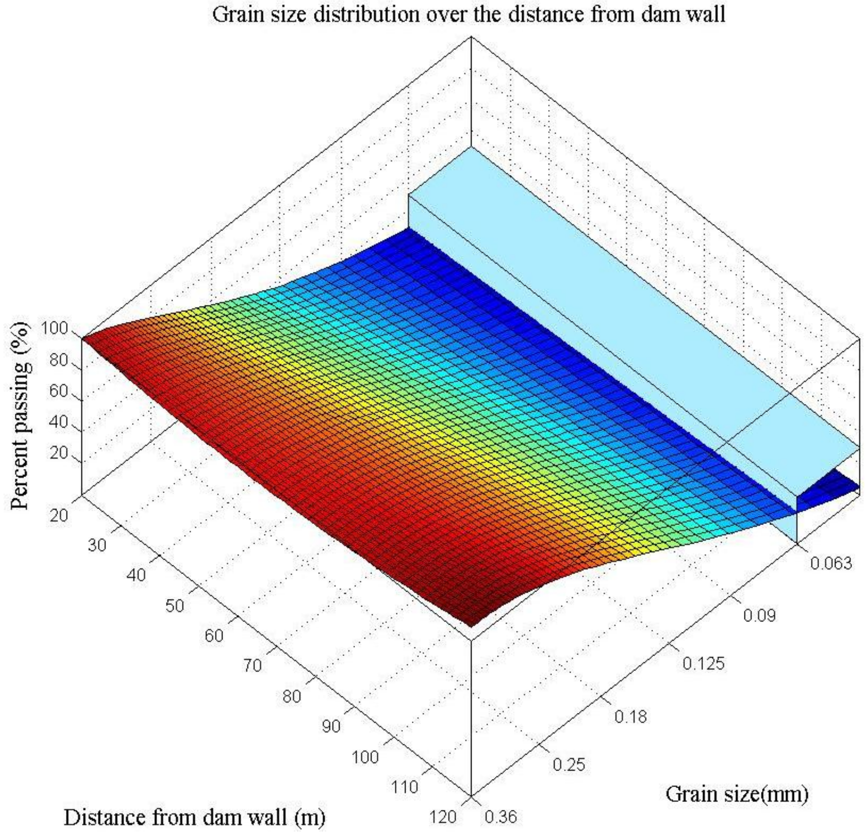


Figure 6-5: Grain size distribution over the length, section 1+750 at dam C (dry sieving).

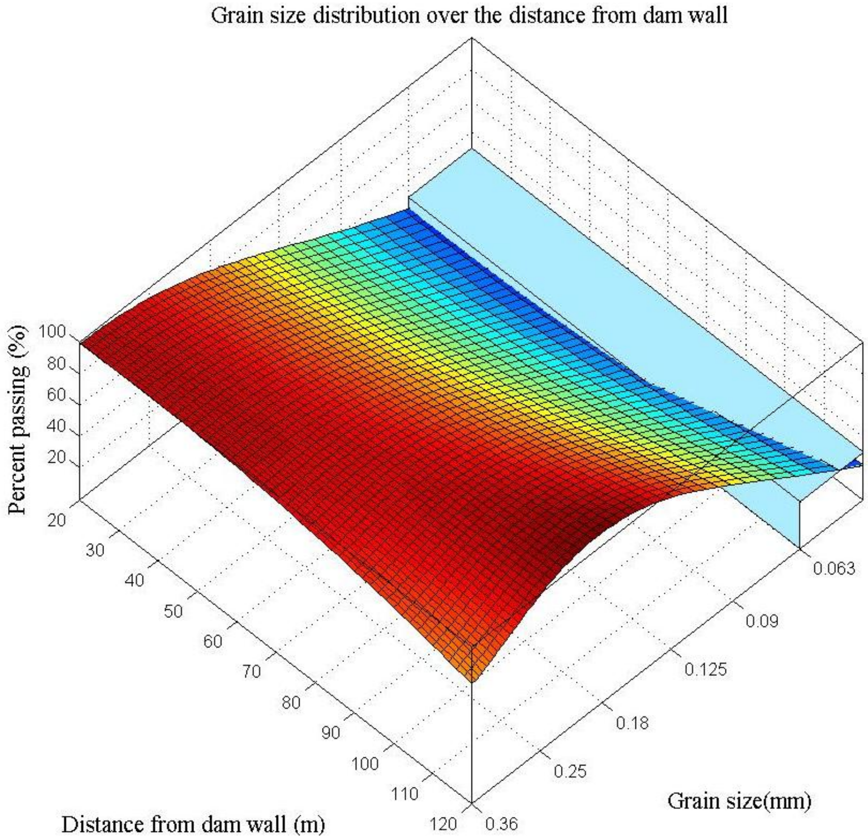


Figure 6-6: Grain size distribution over the length, section 0+850 at dam D (dry sieving).

Results of grain size distributions of samples are seen in Figure 6-7-Figure 6-9, in 2D-graphs, sieved by Boliden (A. Lindh, personal communication, 2013-10-02) and by the author. Differences are seen in the results depending on usage of different sieving methods.

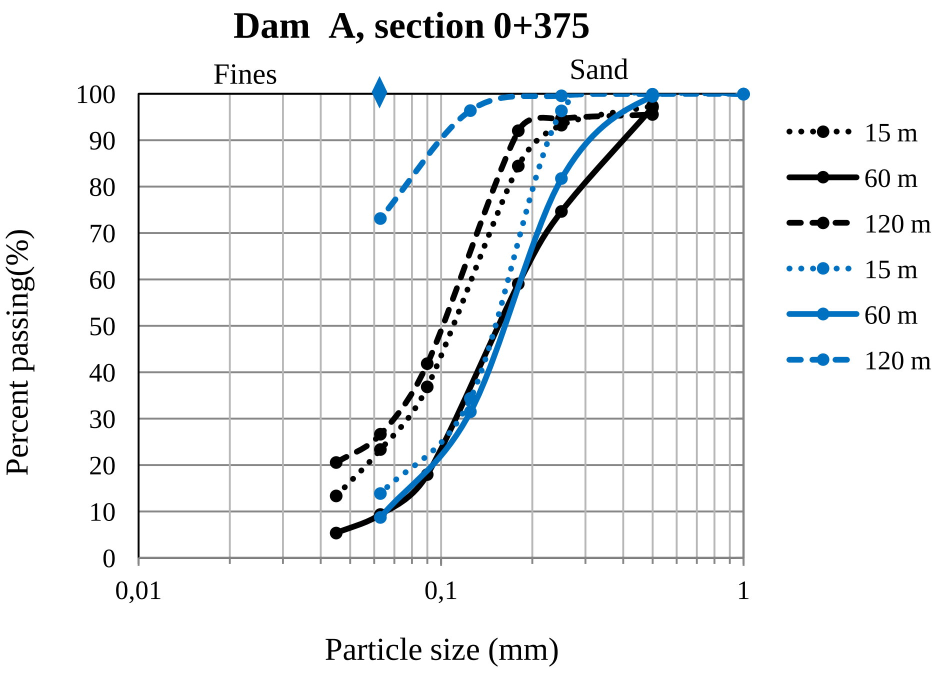


Figure 6-7: Difference in grain size distributions, where black colour represent tests by Boliden (A. Lindh, personal communication, 2013-10-02) and blue by the author.

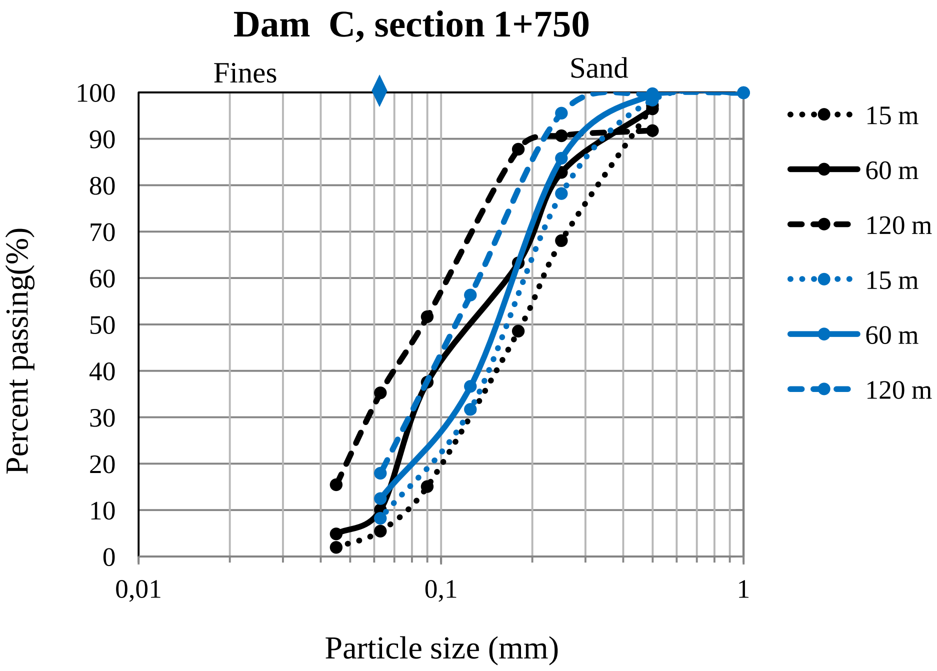


Figure 6-8: Difference in grain size distributions, where black colour represent tests by Boliden (A. Lindh, personal communication, 2013-10-02) and blue by the author.

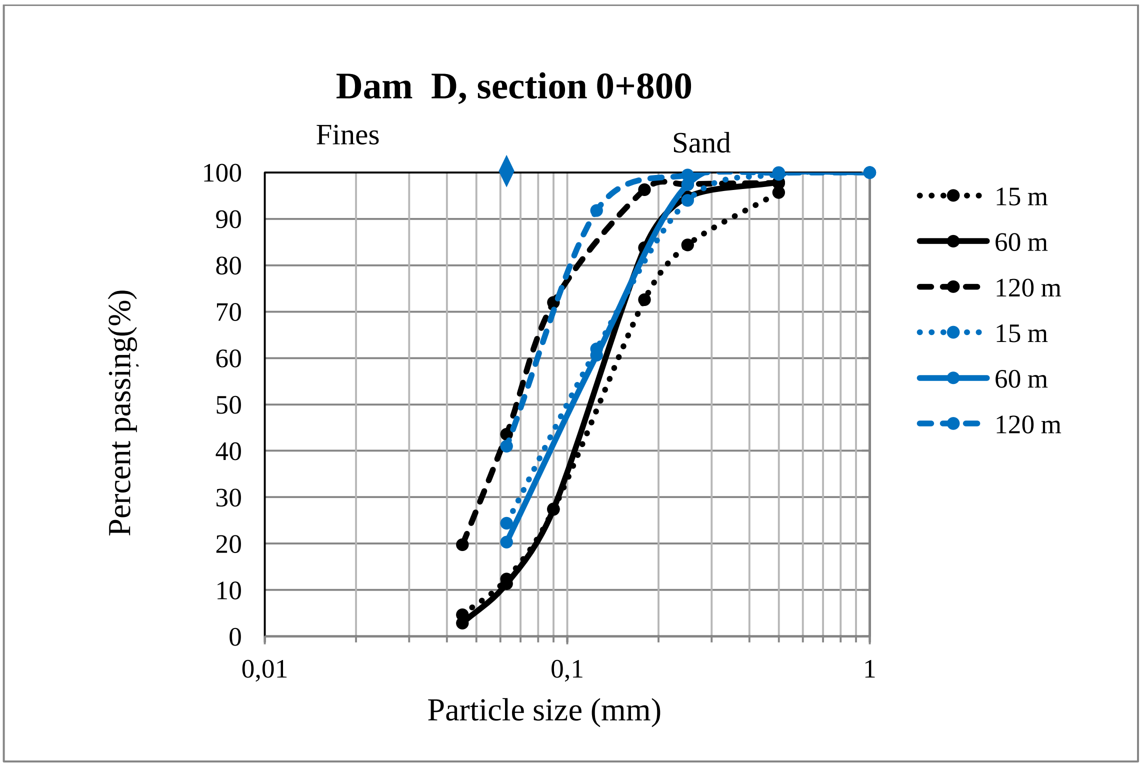


Figure 6-9: Difference in grain size distributions, where black colour represent tests by Boliden (A. Lindh, personal communication, 2013-10-02) and blue by the author.

Tests of grain size distribution were performed on 60 samples and the results of these can be seen in appendix 10 Figure 10-1-Figure 10-7. Results of the sieve tests show that coarser particles were found closer to the discharge points.

Particle size prediction

Tailings property *M* was approximated through Equation (16) for Garpenberg tailings dam section C. Dam C was used depending on the least interference effects, owing to newly deposited beach, at the time of field work. It is seen that a scatter appears in the results in Figure 6-10 around the blue line, which represents the approximated relative particle size found at a distance *x* m from the discharge point. The constant *M* for dam C was found to be 1.13.

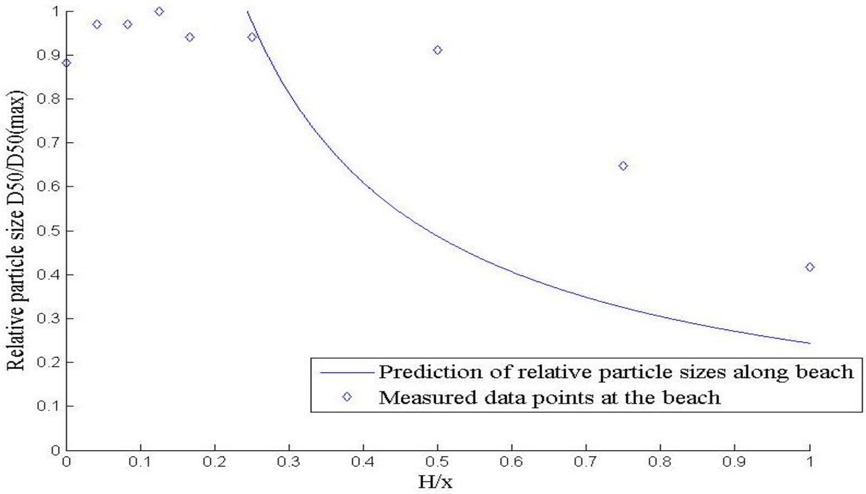


Figure 6-10: Relative particle size along the distance of dimensionless beach, where the diamonds represent the relative particle sizes indicated through tests of samples and surveys. The line is the assumption of relative particle sizes along the beach as a result of the approximated tailings property *M*.

6.2. Grain Contents

Figure 6-11-Figure 6-19 show results of the fraction analyses conducted by Boliden laboratory staff, which was communicated through personal communication with A. Lindh 2013-10-02. The results show that the tailings contain to a great extent of silicon dioxide, which is a natural component in the rocks mined at the site. The results show that there are percentages of metal in all samples taken in the sections of the tailings dam. Where the slopes of the curves are horizontal in Figure 6-11-Figure 6-19, the maximum percentage of metals, in the samples, depending on mass are reached and where the curves are steeper, the more percentages of metals or compounds are found in that particle size.

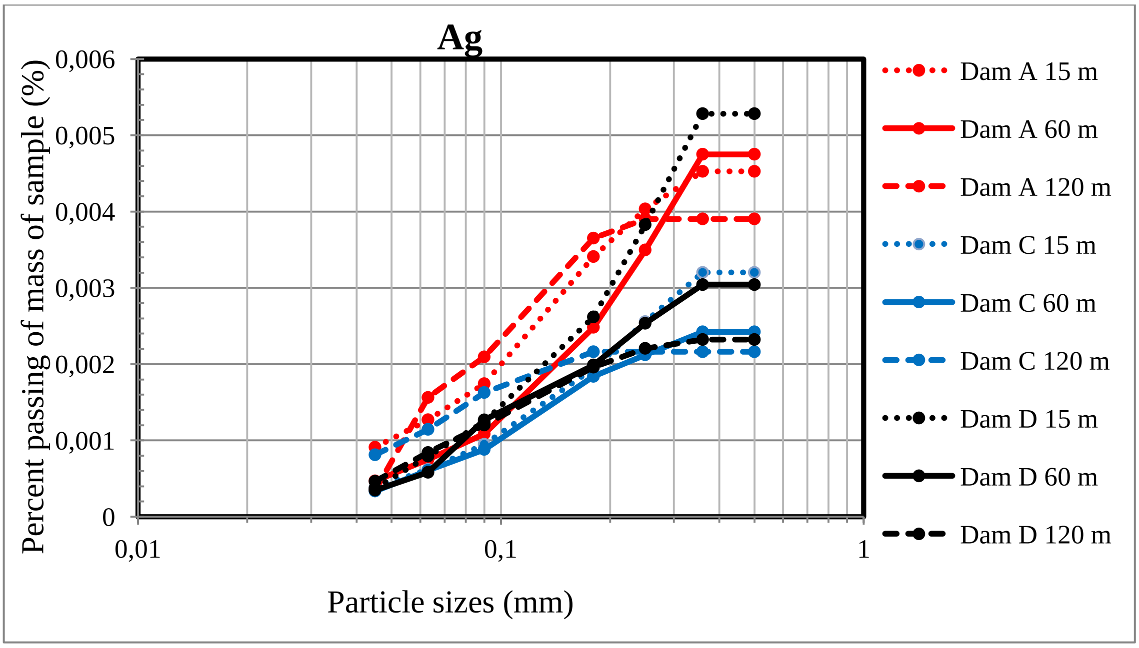


Figure 6-11: Contents of Ag in particle sizes in percent of mass of sample.

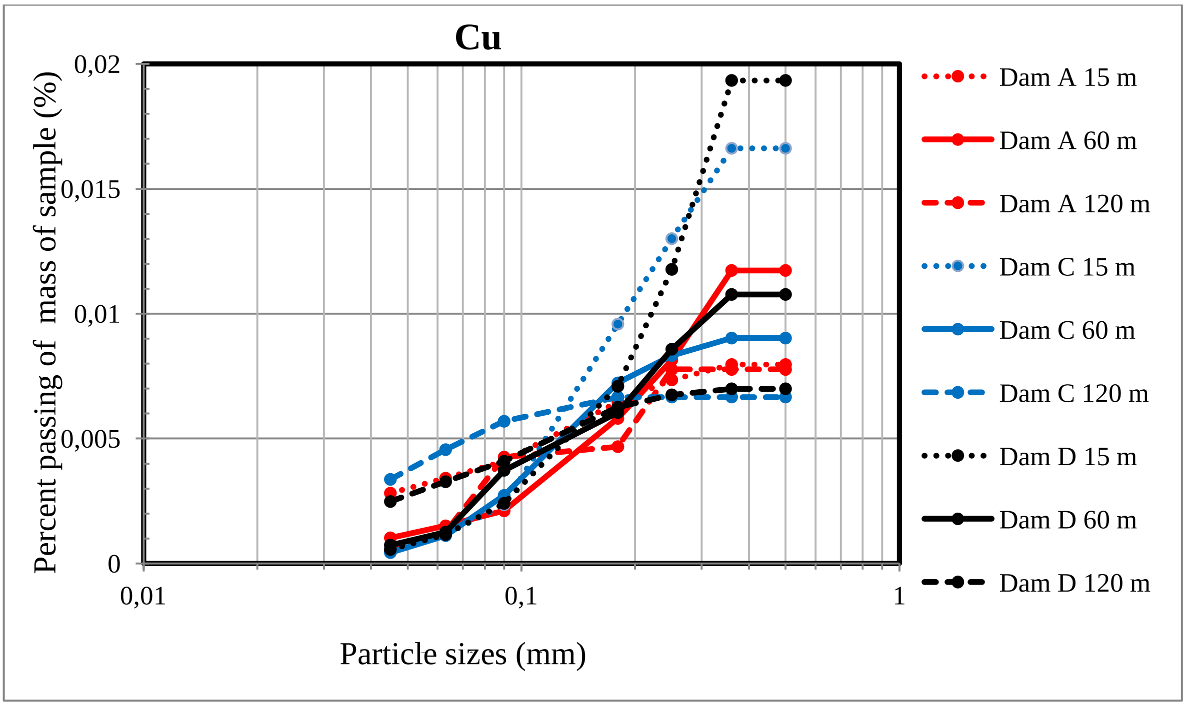


Figure 6-12: Contents of Cu in particle sizes in percent of mass of sample.

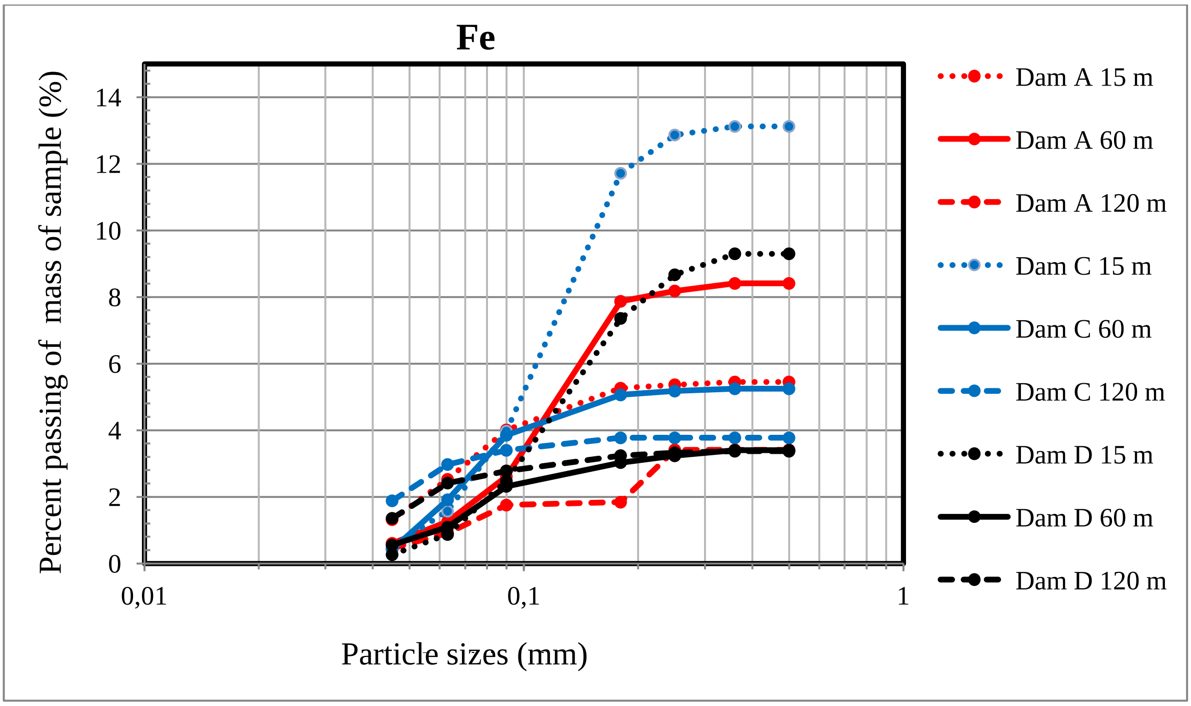


Figure 6-13: Contents of Fe in particle sizes in percent of mass of sample.

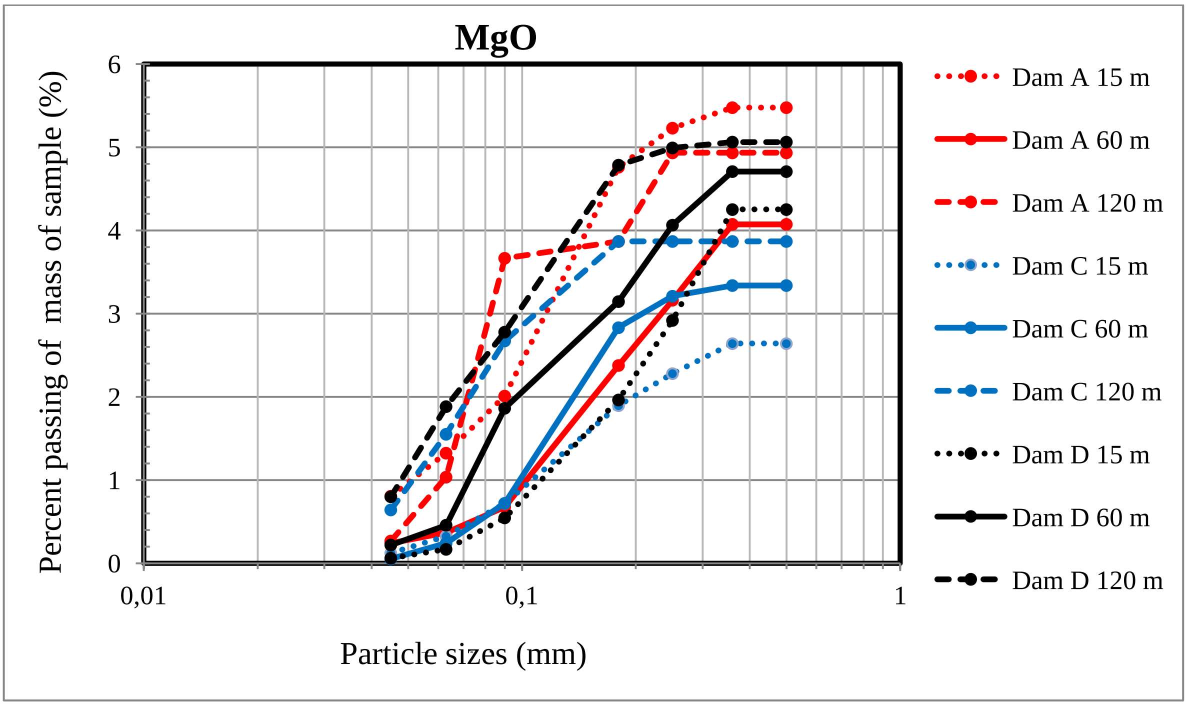


Figure 6-14: Contents of MgO in particle sizes in percent of mass of sample.

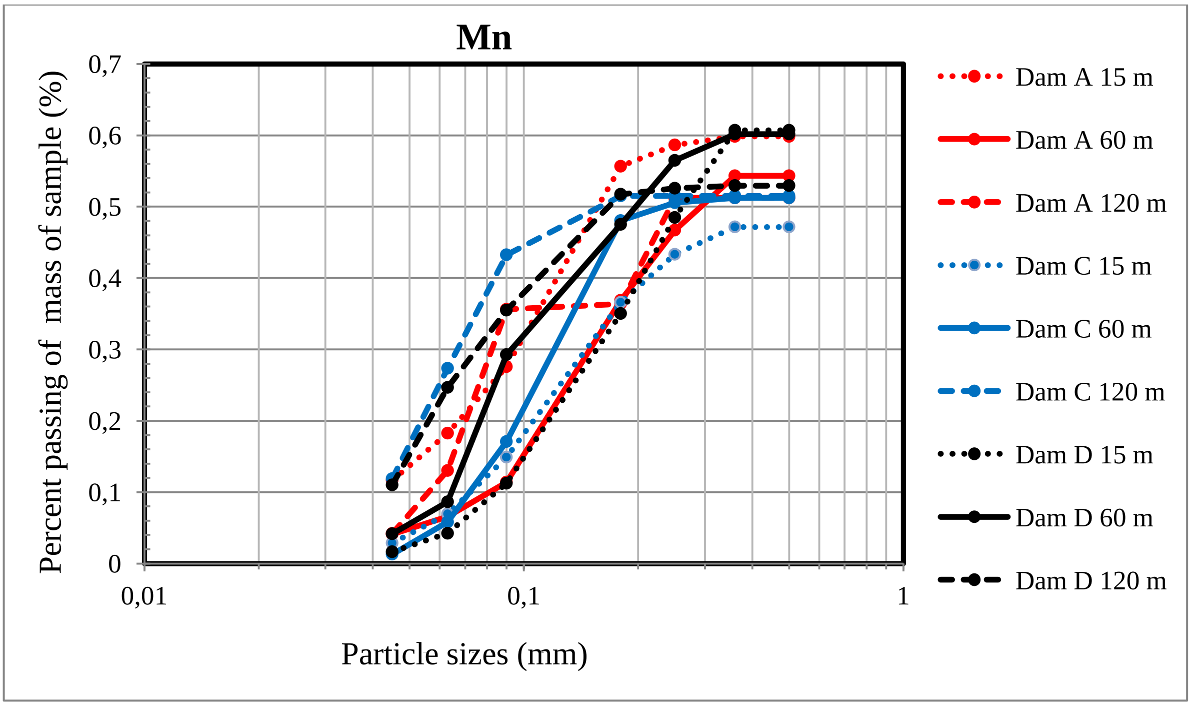


Figure 6-15: Contents of Mn in particle sizes in percent of mass of sample.

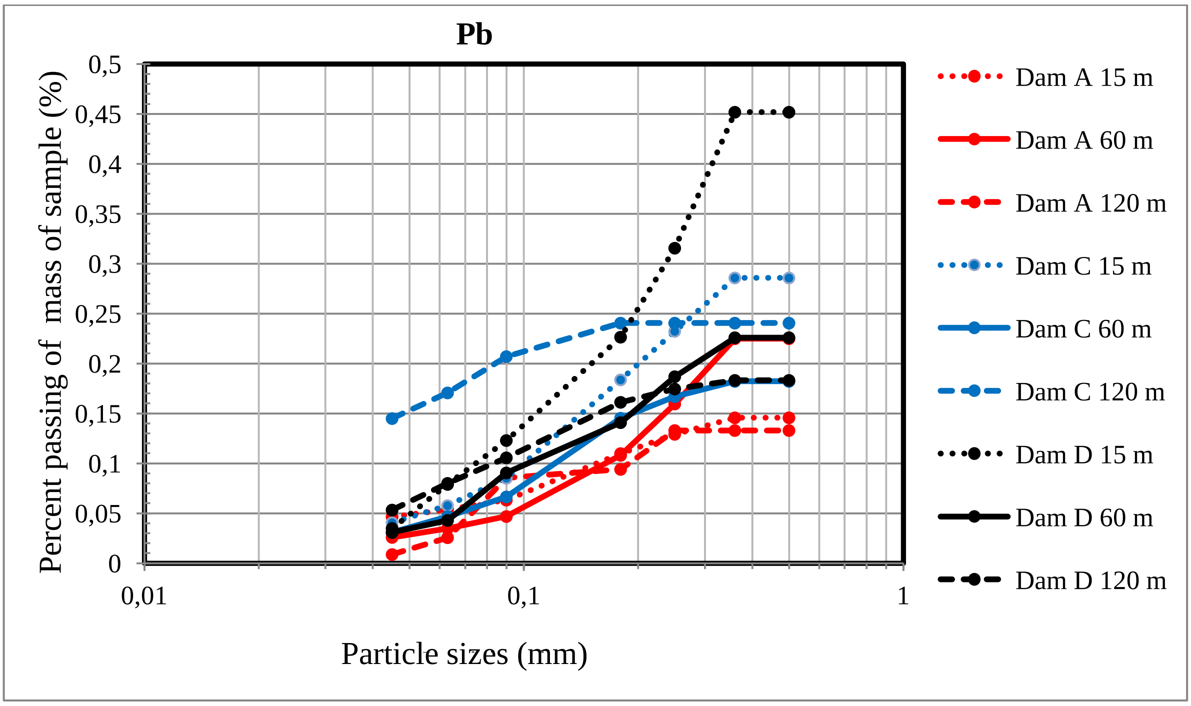


Figure 6-16: Contents of Pb in particle sizes in percent of mass of sample.

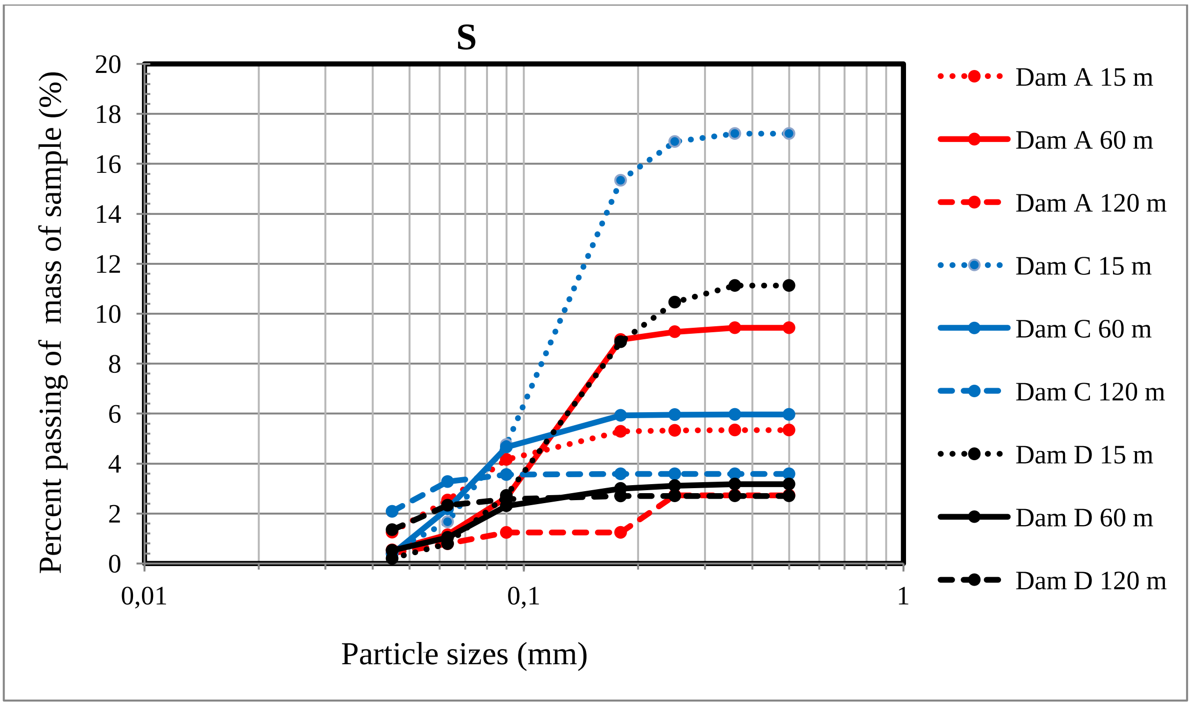


Figure 6-17: Content of S in particle sizes in percent of mass of sample.

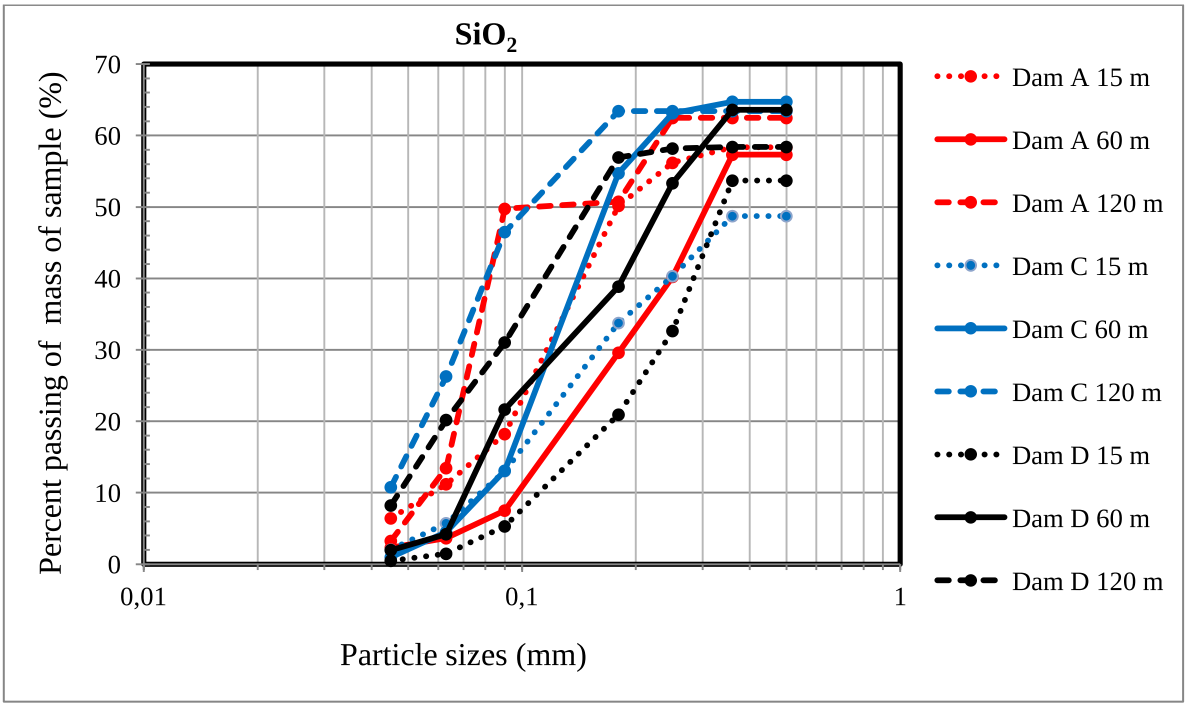


Figure 6-18: Content of SiO_2 in particle sizes in percent of mass of sample.

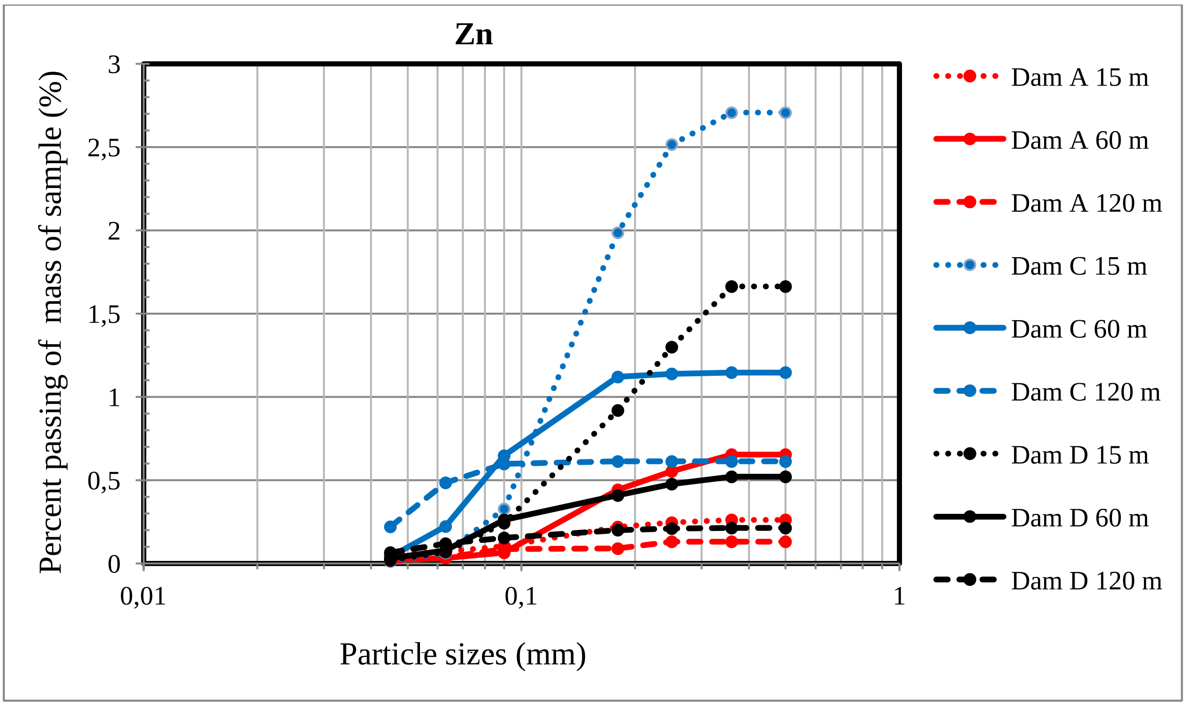


Figure 6-19: Content of Zn in particle sizes in percent of mass of sample.

6.3. Phase Relationships

Results from balloon tests are shown in Table 6-1-Table 6-3. The observations made are that the bulk and dry densities at the surface at nearly all locations for the balloon testing are greater, than in the rest of the tests beneath the surface. There are as well a small number of noticeable differences in the results. More detailed explanations of these results are found in the chapter "Discussion".

Table 6-1: Dam A, section 0+375, 15 m.

Dam A. section 0+375, 15 m	Depth Surface	Depth 1 m	Depth 2 m	Depth 3 m
Bulk density (kg/m^3)	1620	1470	1540	1640
Dry density (kg/m^3)	1560	1270	1270	1560
Particle density (kg/m^3)	-	2820	2840	2870
Porosity (%)	-	55	55	46
Void ratio	-	1.15	1.23	0.84
Water content (%)	3.77	15.89	21.34	5.39

Table 6-2: Dam A, section 0+400, 30 m.

Dam A. section 0+400, 30 m	Depth Surface	Depth 1 m	Depth 2 m	Depth 3 m
Bulk density (kg/m^3)	1750	1590	1720	1510
Dry density (kg/m^3)	1700	1530	1670	1410
Particle density (kg/m^3)	-	3280	3040	3150
Porosity (%)	-	54	44	55
Void ratio	-	1.15	0.81	1.23
Water content (%)	2.96	4.31	2.81	6.91

Table 6-3: Dam A, section 0+575, 15 m.

Dam A. section 0+575, 15 m	Depth Surface	Depth 1 m	Depth 2 m	Depth 3 m
Bulk density (kg/m^3)	1500	1790	1640	1890
Dry density (kg/m^3)	1430	1750	1580	1780
Particle density (kg/m^3)	-	3190	2880	3080
Porosity (%)	-	45	45	42
Void ratio	-	0.82	0.82	0.73
Water content (%)	5.38	2.62	4.04	6.22

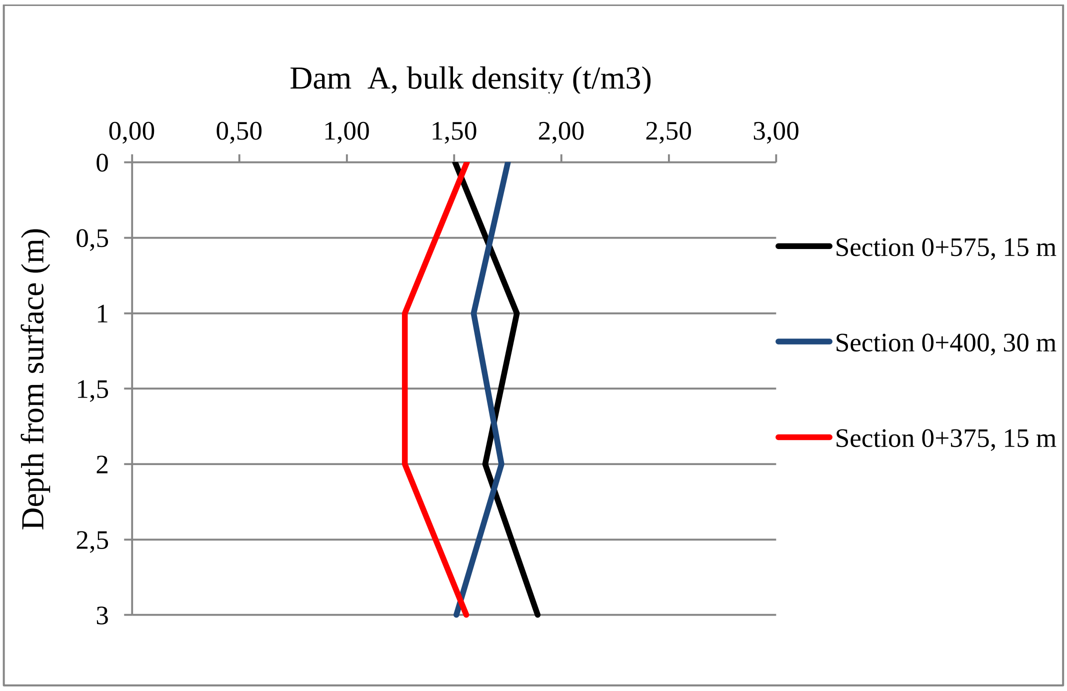


Figure 6-20: Bulk densities from balloon tests at Garpenberg tailings dam.

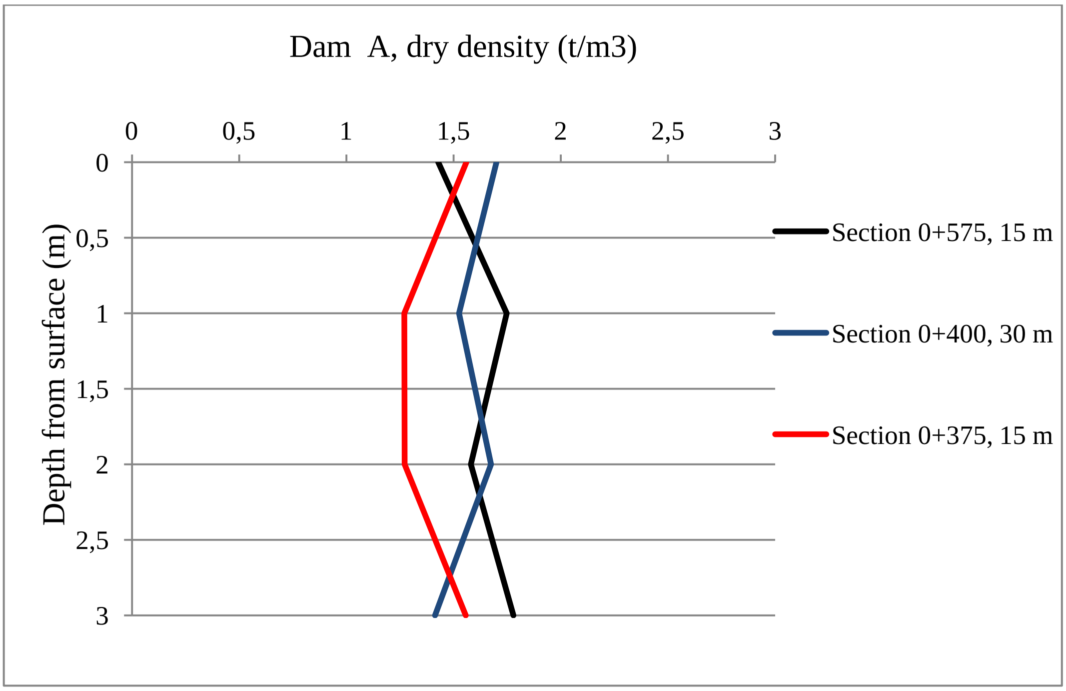


Figure 6-21: Dry densities from balloon tests at Garpenberg tailings dam.

6.4. Beach Slopes and Dimensionless Slopes

The beaches at the tailings dam in Garpenberg were surveyed for selected locations and these can be seen in Figure 6-22. The results from these sections correspond to available data concerning beach slopes. The shapes are foremost concave and the slopes are steeper in the beginning of the beaches from the discharge points. The surveyed beaches resulted in beach slopes of approximately 1 % and less. It is observed through the survey that dam D's slopes differ from other beaches, due to flatter beach at dam D. The results in Figure 6-22 show that the section 0+400 at dam A differs from the other slopes in dam A.

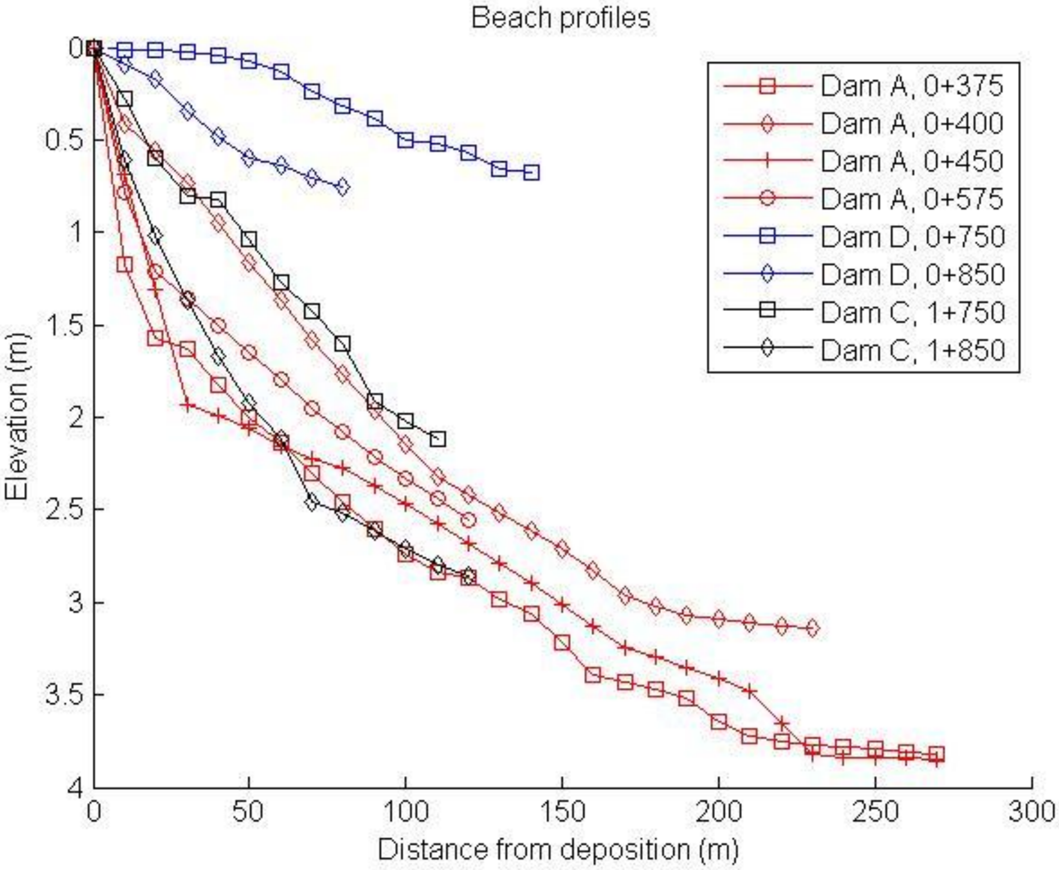


Figure 6-22: Beach profiles at Garpenberg tailings dam.

Concavity parameters have been approximately found through fitting beach slopes to dimensionless beach profiles using MATLAB. Table 6-4 shows the approximated concavity parameters and Figure 6-23-Figure 6-25 show dimensionless beach profiles compared to surveyed beach slopes. A couple of concavity parameters are missing in Table 6-4, because it was not possible to find them.

Table 6-4: Approximated concavity parameters for surveyed sections at Garpenberg tailings dam.

Best fit concavity parameter	
Dam	β
Dam A, 0+375	2
Dam A, 0+400	≈3
Dam A, 0+450	≈3
Dam A, 0+575	-
Dam C, 1+750	1.3
Dam C, 1+850	2
Dam D, 0+750	-
Dam D, 0+850	-

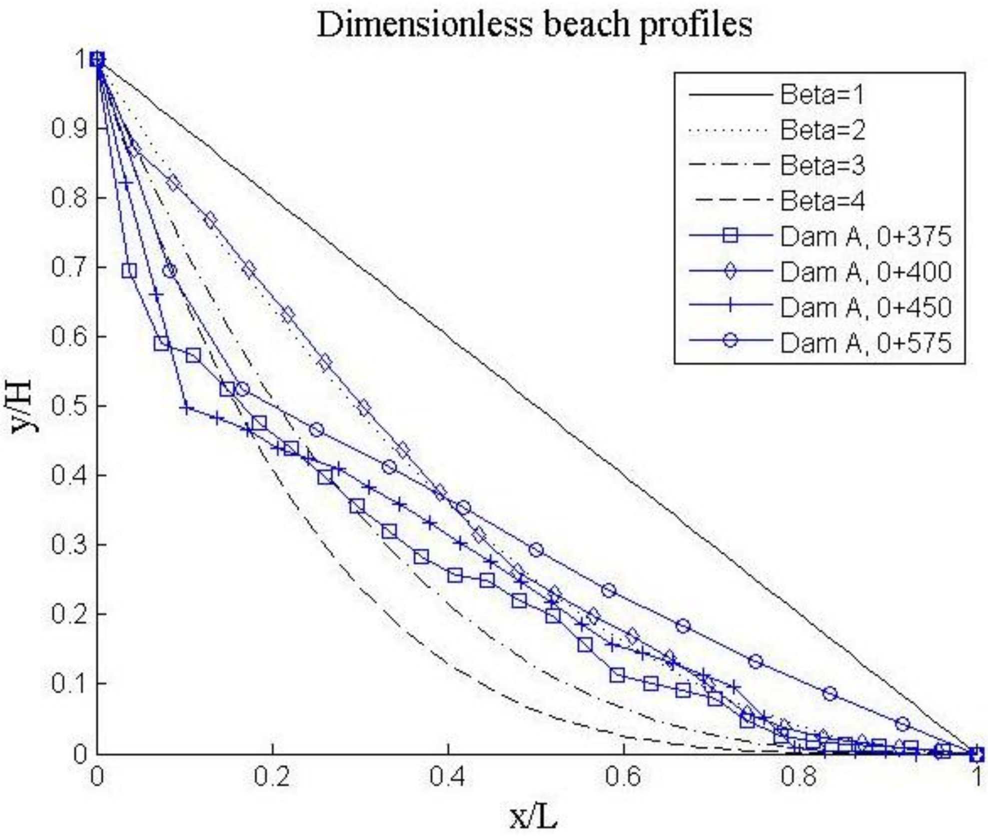


Figure 6-23: Dimensionless profiles compared to surveyed beaches at dam A.

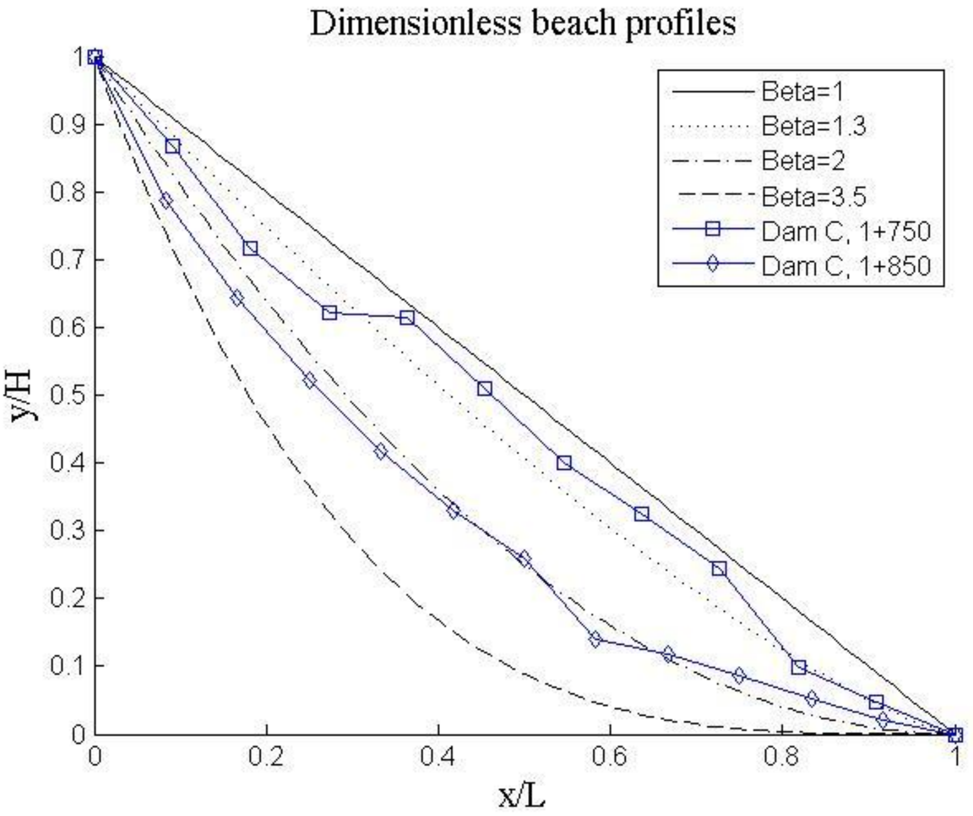


Figure 6-24: Dimensionless profiles compared to surveyed beaches at dam C.

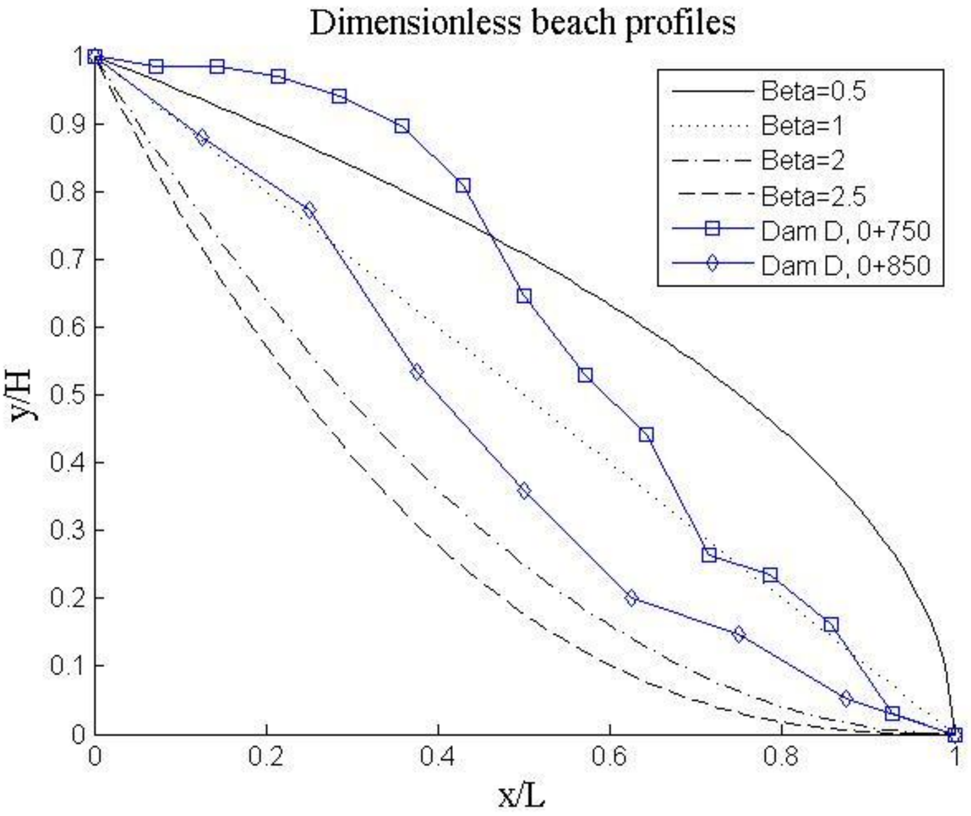


Figure 6-25: Dimensionless profiles compared to surveyed beaches at dam D.

7. Discussion

7.1. General

Grain size distribution

Results have shown that grain size distributions differ depending on which sieve analysis method is used. The differences in the dry and wet analyses can be seen in Figure 6-7-Figure 6-9. The observed differences are not considerably large. However, an indication through comparing the analyses is that using the dry sieving method rather than wet sieving method shows smaller amount in some grain sizes. The differences in grain sizes are foremost between fractions passing 250 and 125 µm, minor notice can be taken to the difference of the grains passing 63 µm, which is the limit between fines and fine sand.

If the difference in sieving tests is a common occurrence, it must be considered that analyses that have been performed potentially have resulted in slightly less reliable values. It can as well be noted that if less reliable values have been determined, the dam walls constructed with tailings, could potentially have more amount of fines than assumed. It is of interest to be able to use the sieving method that shows the most reliable results. However, it cannot be stated which sieving method is the most accurate and more tests are required to be performed, to determine statistically that the dry and wet analysis give excessively large differences in results. The difference in the results Figure 6-7-Figure 6-9 is potentially caused by fines attached to fine sand particles, when conducting dry sieve analyses. Even though, the samples were scrubbed, attached fines could have prevented the fine sand and sand particles to pass a sieve, which they would have passed, without fines attached. Moreover, another cause of the difference in grain sizes is potentially that samples taken, separated in the plastic sample bags, which implies that the samples tested do not represent the sample in total. Another potential explanation is that the sample was taken in a thin layer of particles sizes <63 µm that appeared due to closure of spigots.

One particularly observed grain size distribution is a sample sieved by the author at dam A section 0+375 (120 m from discharge points), which shows a considerable amount of fines. It is possible that this sample is not representative for the tailings found at 120 m and it could be explained by segregation of particles in the sample bag.

From the sieve analyses conducted by the author and by laboratory staff at Boliden (A. Lindh, personal communication, 2013-10-02), it is clearly shown evidence of that after 90 m from the discharge points, the amount of soils under 63 µm increases significantly. A possible explanation for this appearance is that each year Boliden reclaims deposited tailings from the dam sections, which then are transported to where a rise of dam wall is proceeding.

Typically, it is of importance for Boliden to be able to reuse as much tailings as possible in the dam walls. Therefore, each year the reclamation of tailings is stopped at around 90-120 m from the dam wall, due to the large amount of fines, which creates a discontinuity of the beach. By stopping approximately at 90-120 m out from the discharge points a depression of two to three metres depth from dam wall to the discontinuity is created. This depression is relevant due that it potentially correlates with encountering finer soils at 90 to 120 m from dam walls. Additionally, the disadvantages with a depression 90 m out and 2-3 m deep are that more fine particles might settle and enhance settling of fines, which decreases the hydraulic conductivity. The lower hydraulic conductivity could potentially result in larger excess pore pressures, closer to the dam walls. Furthermore, what can be imagined is that these walls of tailings, which are unintentionally constructed, due to discontinuity in reclamation of tailings potentially effects the grain size distribution and also on the flow of slurries. The slurries are prevented from flowing to the pond. Potentially, if paths are created through the discontinuities, the slurries may reach the pond and result in settling of fines further out in the basin. In addition, possibility for reclamation of tailings, within the recommended limit further out from the wall could potentially increase by creation of these paths.

It is of relevance to have knowledge of the grain sizes, due to ability to reuse the material, in the further rise of dam walls, with the upstream method. A more accurate understanding of where tailings with sufficient properties segregate would ease the construction of the walls, by better assumptions on where to excavate the tailings. However, depending on the flow of slurries, an inhomogeneous layering and segregation of particles occurs, on the beach. Therefore, it is difficult to state exactly where tailings with sufficient properties exist, but it was found that the amount of fines exceeds the recommend 30 % limit in the interval 90-120 m from dam walls. It is therefore suitable that before reclamation of tailings to take samples in the area of 90-120 m, to investigate how far out from the discharge points the reclamation is to be performed.

The light blue areas in the Figure 7-1-Figure 7-3 represent the established recommended limit of 30 percent fines. If the curves exceed the intersection of the corner of the light blue vertical and horizontal rectangles, it implies exceeding of the recommended 30 % limit.

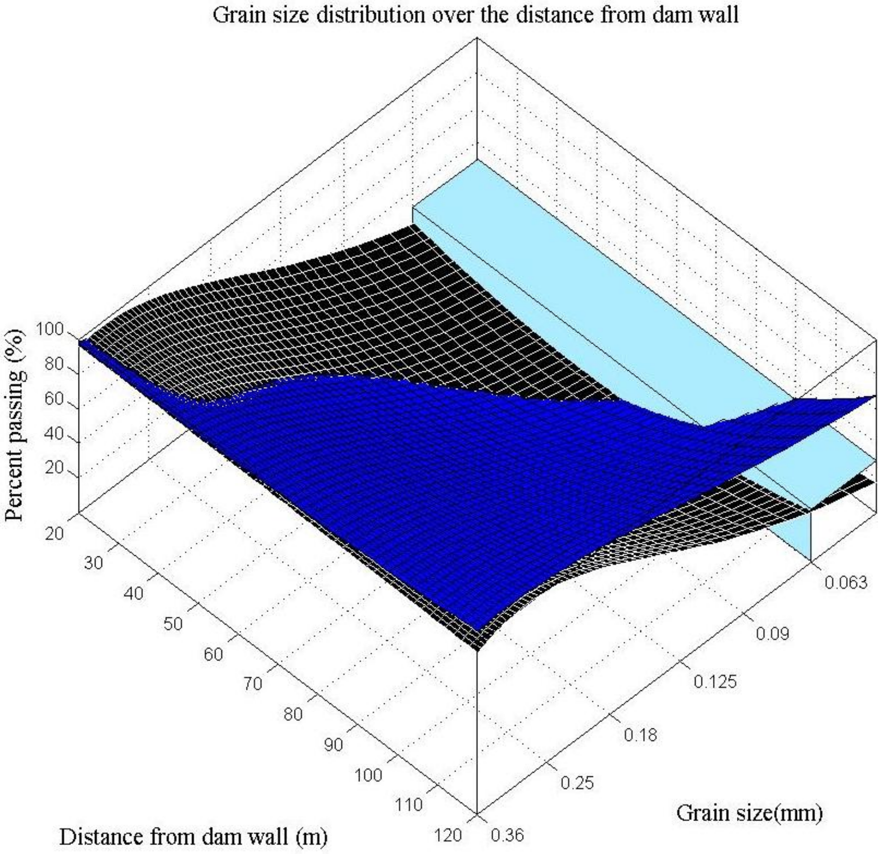


Figure 7-1: Difference in grain size distributions at dam A 0+375, where black chequered colour represent tests by Boliden (A. Lindh, personal communication, 2013-10-02) and blue by the author.

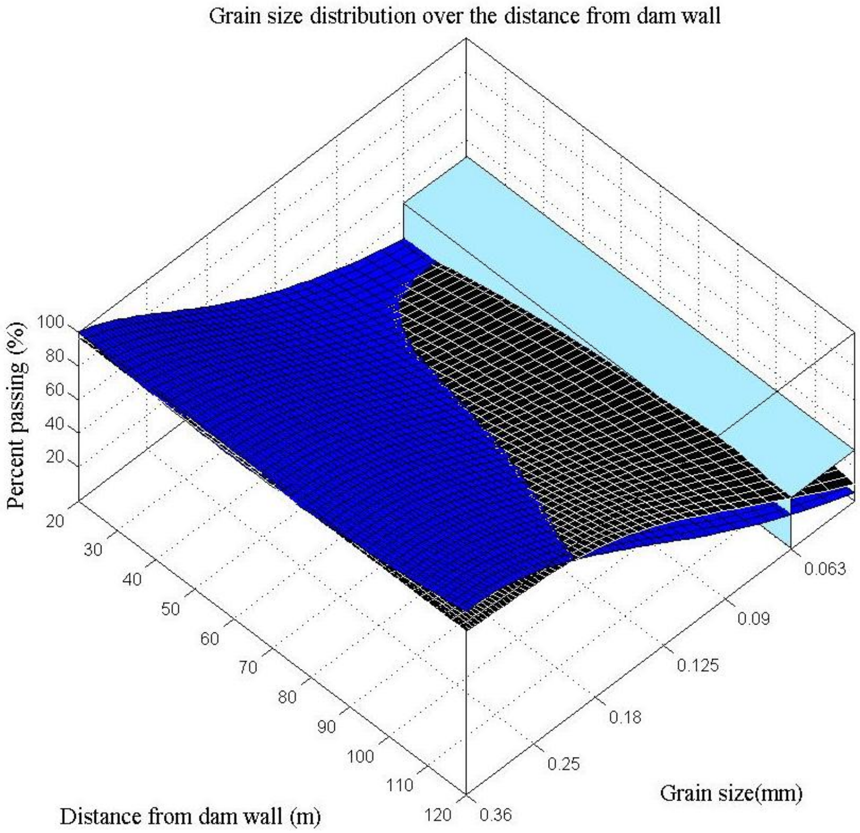


Figure 7-2: Difference in grain size distributions at dam C 0+800, where black chequered colour represent tests by Boliden (A. Lindh, personal communication, 2013-10-02) and blue by the author.

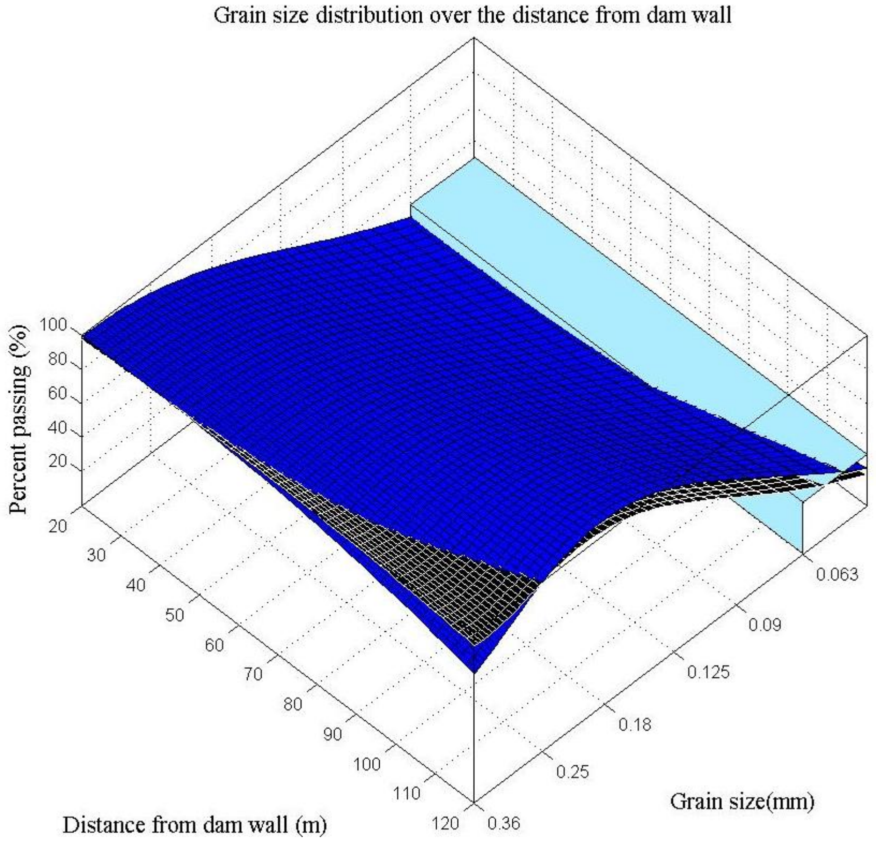


Figure 7-3 Difference in grain size distributions at dam D 1+750, where black chequered colour represent tests by Boliden (A. Lindh, personal communication, 2013-10-02) and blue by the author.

Particle size prediction

The particle size prediction coefficient *M* was assumed with Equation (16). A great deal of scatter can be seen in Figure 6-10. The scatter can probably be explained Blight & Bentley (1983), which state that scatter, may appear due to turbulent flows. This can also explain why the first 0 to 30 m differs a great deal, between assumptions and results. To conclude, the empiric formula by Blight & Bentley (1983), showed no relationship with the measured values at dam C section 1+750, which is observed in Figure 6-10. Why no relationship was found can be explained by limited sampling, inhomogeneous flow of slurries and inhomogeneous settling of particles.

Differences in areas of the dam

One of the aims of this Masters's dissertation was to examine how different locations and areas of the beach affect the particle sizes on the beach. Depending on that the tailings dam in Garpenberg is a work place, the scheme for sampling at the site was revised several times. Therefore, possibility for determining and specify different locations' properties were not as comprehensively performed as aimed for. Instead, more concern was given to straight lines in the tailings dam. Nevertheless, one tip at dam A, section 0+400 was investigated and some conclusions were made.

- The tip showed a flatter beach profile than the straight lines at dam A. Less material deposition appears on section 0+400 depending on the curvature of the wall, as can be seen schematically, in Figure 7-4. The lines in Figure 7-4 (to the left) represent where spigots are positioned with a distance of approximately 25 m between them. Furthermore, what is concluded by Jewell (2012) is that more spigots in the vicinity of each other create steeper beaches. This is observed in Figure 7-4 (to the right) by comparing section 0+400 with the other sections at dam A. Furthermore, there was not found any apparent differences in grain size distributions by comparing samples taken from the tip and samples from straight lines of the dam's curvature.

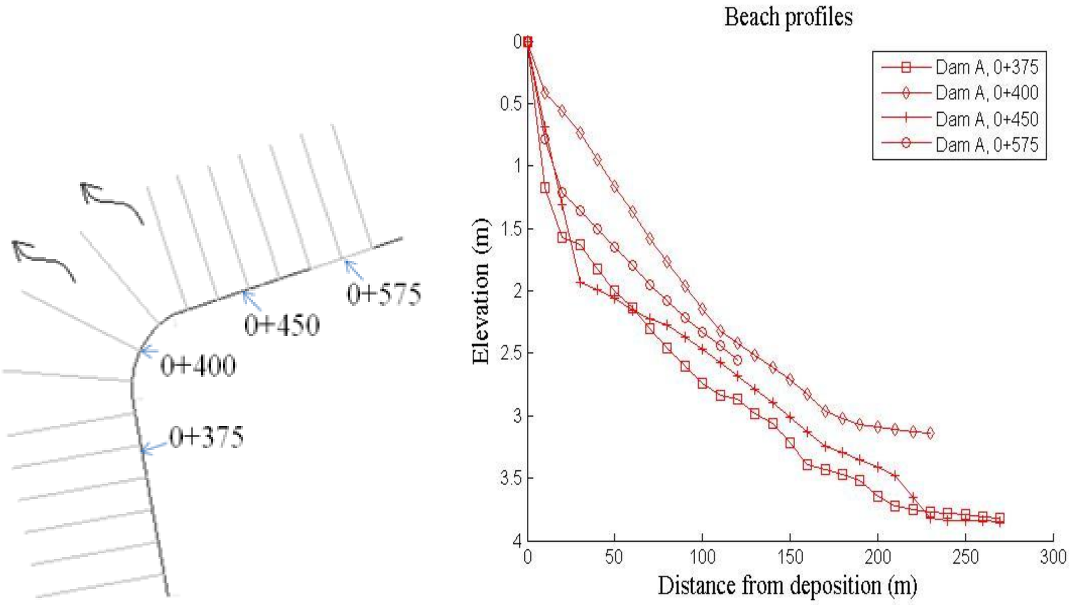


Figure 7-4: Dam A (the tip), overview to the left and beach profiles of sections to the right.

Phase relations

What can be stated about the phase relations is that some results correlate to previous performed tests performed by Bjelkevik & Knutsson (2005). For example the samplings at 0 and 300 m showed dry densities of 1300-1600 kg/m^3, which can be compared to samples taken at surfaces at dam A at 15 and 30 m from dam wall. Samples taken by the author showed dry densities in range of 1400-1700 kg/m^3 seen in Figure 6-21.

Table 6-1-Table 6-3 present results of particle densities which if compared to the metals and compounds particle densities and their percentage in samples in Table 10-2 indicates a minor overestimation of particle densities found, in trial pits. There is inhomogeneous aggregating of particles on the beach that potentially can explain why some of the specific densities are larger than others. Furthermore, as can be seen in Figure 6-20-Figure 6-21 the densities in the surfaces are higher for both dry and bulk densities, than on depth. This could be caused by dumpers that have been driving on the beaches in the tailings dam, to reclaim tailings. Additionally, in one case for the section 0+375 an excavator was used with forks on the dipper. The forks ripped the surface, where the balloon tests were performed, which could have affected the results in that trial pit. One particular result of the particle density in 1 m depth at section 0+400 shows a rather high value, which potentially is not accurate. On the other hand, depending on inhomogeneous segregation of particles on the beaches, the value is not an impossible value.

There is potentially normal scatter in results depending on the inhomogeneous sedimentations and segregation of particles, which leads to different results overall. There is also when using the balloon test in field a scatter depending on the correctness of the instrument. Therefore, it can be noted that there is no typical enlargement of the bulk and dry densities on depth and a spread in results of approximately 10 percent is observed.

7.2. Beach Slopes

After evaluation of the surveyed beach slopes at the Garpenberg tailings dam, it can be concluded that they are typical slopes created by segregating slurries, with a solid content of 10-25%. The inclination of the beaches is of ranges approximately 1 percent or less. The slopes differ depending on where the discharge was made and the largest difference observed was for the slopes at dam D compared to the other beach slopes. Another slope that differs compared to the others was the slope at dam A section 0+400, which is the section on the tip.

Concavity parameters were estimated which can be used in prediction of slopes at Garpenberg if the length from the plunge pool to the pond and the height difference are both known. However, some dimensionless profiles and their concavity parameters were not possible to be found which might be explained by limited surveying of beaches.

The flatter beach at dam D might be explained by closure and starting of spigots before deposition on another area. This would have decreased the velocity of the slurries and affected the beach at dam D, due to discontinuity of flows of slurries, during a short time period.

It is important to predict slopes for the planning of new tailings dams especially for calculations of storage volume and capacity. The dimensionless profile depends on tailings dams that already exist and therefore does not serve the purpose for prediction beach slopes for new tailings dams. However, beach slopes can be predicted at the tailings dam in Garpenberg, by using the estimated concavity parameters. The results have shown a great deal of variety in the approximated dimensionless profiles and concavity parameters, which potentially can cause incorrect assumptions. However, by performing additional surveys of the beach slopes, the spread in results could potentially decrease.

Sweco currently assumes that the beach inclinations in the tailings dam at Garpenberg are linear (R. Knutsson personal communication, 2014-01-14) although results have shown that the majority of beach slopes are concave. Therefore, by using dimensionless profiles better assumption of the beach slopes can potentially be performed.

7.3. Mineral Contents

In the future, closed tailings dams such as the tailings dam in Garpenberg could potentially be assets, due to various extraction techniques. There are examples of waste mine deposits that have been reworked in order to extract more metals, because of better extraction techniques.

There exists among others an extracting technique as heap leaching, where flocculants and reagents of dissolvent of metals components are deposit on the tailings in order to extract metals. However, the technique would require recovery of leachates and processing of the leachates even after the heap leaching would stop, due to ongoing extraction and possible seepage of potentially harmful contents, to surrounding areas. Although, it would be a great environmental gain is if as much metals as possible could be extracted from tailings for the ability to use it as possible components in concrete or fillings (Digby et al., 2002).

In Figure 6-11-Figure 6-19 it can be seen that there exist metals which have not been extracted. The largest amount of metals exists in the limit of fine sand, which is not unexpected, depending on that the largest amount of particles in samples taken, were in that range. There is an indication by observing the results in Figure 6-11-Figure 6-19 that more metals exists in the tailings closer to the dam walls. In regards to the contents of metals in the tailings, the prices of the metals are a key aspect if it would indeed be affordable to reprocess the tailings (Lottermoser, 2010). To conclude more tests are required to be performed to investigate contents of metals in width, depth and also if it is possible to extract the remaining metals in the tailings.

7.4. The Utilization of Spigots in Garpenberg

The method of utilizing spigots at the tailings dam shows a good process of separation of particles in sand to fine sand fraction, seen from the results in Figure 10-1-Figure 10-7. The flows of slurries from spigots create deltas where particles of more significance as construction materials for dam walls aggregate. The particle segregation appears to be as indented out to 90-120 m from discharge points and particles larger than 63 µm primarily settles in between 0-90 m. Nevertheless, areas with higher amount of fines were found between 90-120 m. These areas exceed the recommended limit that Sweco's tailings dams division established to ensure that sufficient tailings particle sizes are used in the continued rise of the dam. An aspect to consider is that if higher amount of fines segregate and sediment closer to discharge points than expected, tailings used in dam walls can have fines proportion exceeding the 30 % limit.

As the dam's enlargement proceeds inwards, towards the centre of the impoundment, the possibility increases that deposited tailings are built upon tailings that have not appropriate properties. In the Garpenberg tailings dam, there exists a spillway, where water is designed to flow towards. Potentially, fine particles flow with the water to the spillway, where in the vicinity of the spillway a great deal of fines could potentially aggregate. Therefore, it is potentially necessary, in the future design of rise of the dam wall, to introduce another method of deposition to prevent fines to segregate and sediment in the vicinity of the spillway. In order to prevent formation of high pore pressures in the dam walls that potentially affects the stability of the dam.

8. Conclusions and Future Investigations

Conclusions

- Coarser particles segregate closer to the discharge points. However, no typical enlargement of the amount of fines was found between 0-60 m, due to inhomogeneous sedimentation and segregation of particles.

- The amount of fines increased significantly at 90-120 m from dam walls. In some cases there were found samples that exceeded the recommended limit 30 %.

- Various metals were found in the tailings samples. The contents of metals vary in the samples with an indication that more percentages of metals where found in samples closer to the dam walls.

- An indication that dry sieving performed on the same sample shows smaller amounts of some particle sizes than wet sieving.

- The beach slopes at the tailings dam in Garpenberg were in the most cases concave.

- Using the estimated dimensionless beach profiles rather than a linear assumption of the beach profiles could potentially improve the assumption of inclinations of beaches, at the tailings dam in Garpenberg.

- No relationship was found between prediction and measured values by using the empirical formula by Blight & Bentley (1983).

- It was found that dam walls with a curvature shows flatter beaches compared to straight ones due to less material deposition.

Future investigations

- Investigations of how moraine piles affect the sedimentation and segregation of particles, by sampling in the vicinity of the moraine piles.

- Investigations of sieve analyses for more accurate results of field sampling.

- Investigation of the segregation and sedimentation that appears due to reclamation of tailings, from discharge points to 100 m out in the dam.

- The flow of slurry through spigots was not modelled and therefore further analyses regarding flow from spigots might be necessary, to further understand the sedimentation and segregation processes that occur in tailings dam at Garpenberg.

- Investigation if it is possible to extract remaining metals from the tailings.

9. References

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10.Appendix

Grain size distribution analyses from sections in dam A, B and C in Figure 10-1-Figure 10-7. As can be seen, the smallest sieve was 63 µm and therefore, the curves stops there, depending on uncertainty of how the curves stretches towards zero.

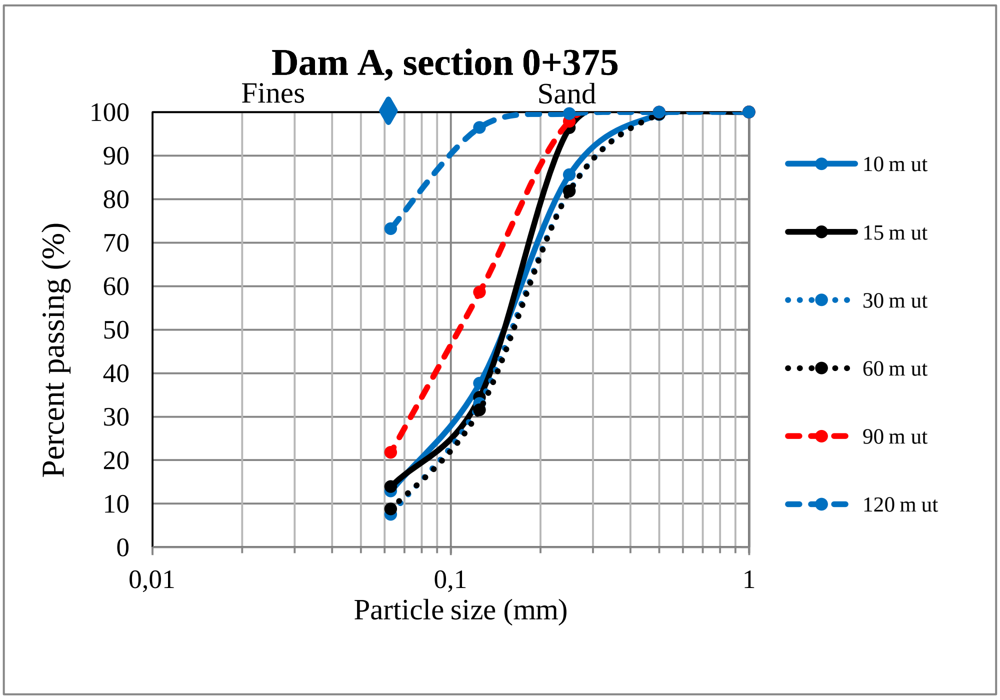

Figure 10-1: Grain size distribution dam A section 0+375.

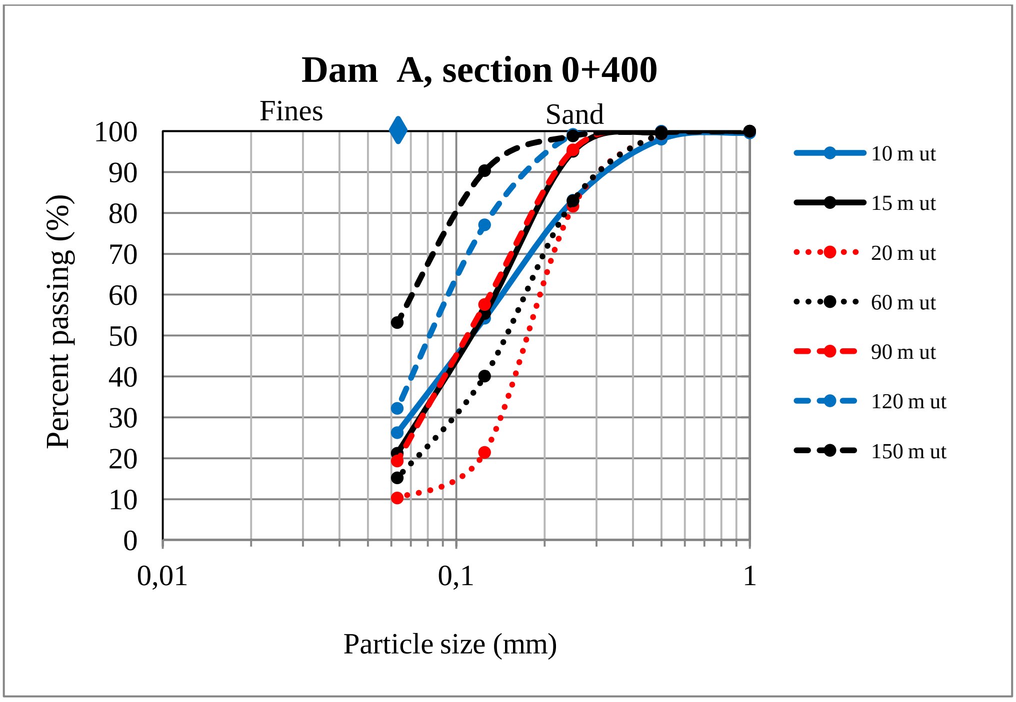

Figure 10-2: Grain size distribution dam A section 0+400.

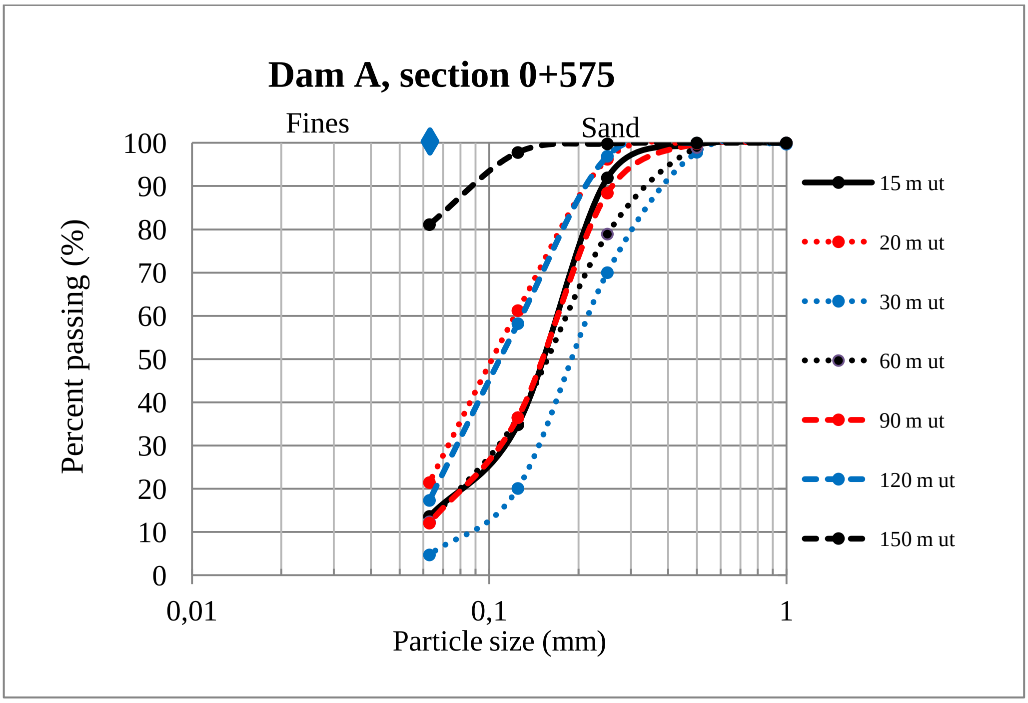

Figure 10-3: Grain size distribution dam A section 0+575.

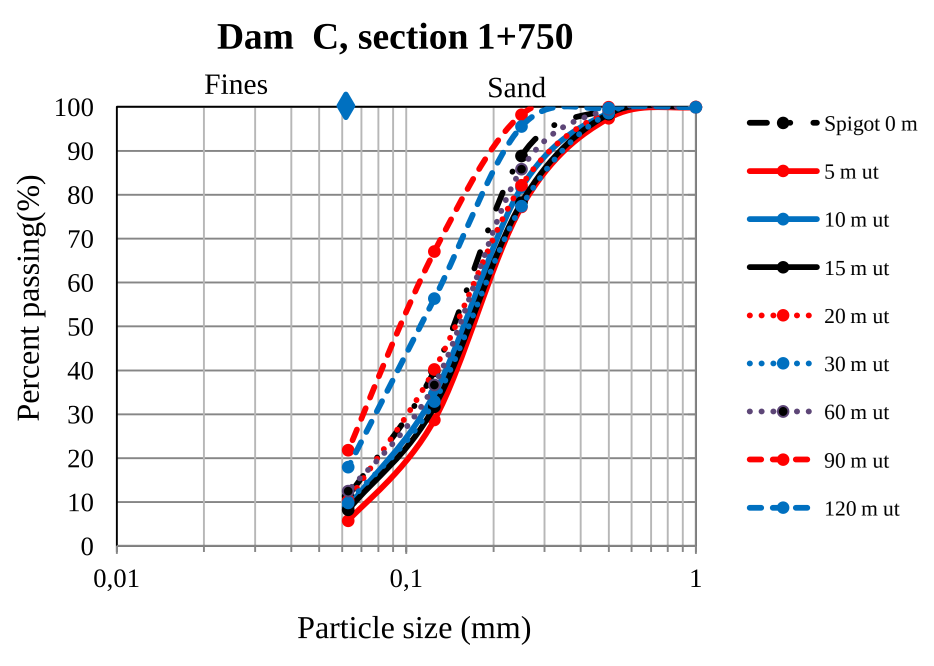

Figure 10-4: Grain size distribution dam C section 1+750.

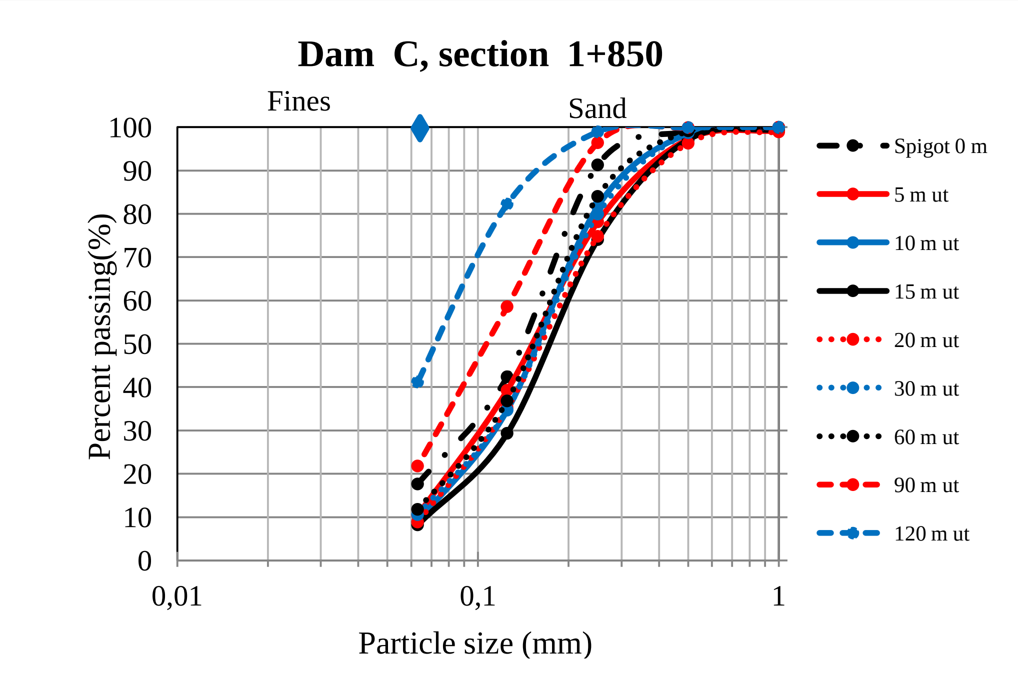

Figure 10-5: Grain size distribution dam C section 1+850.

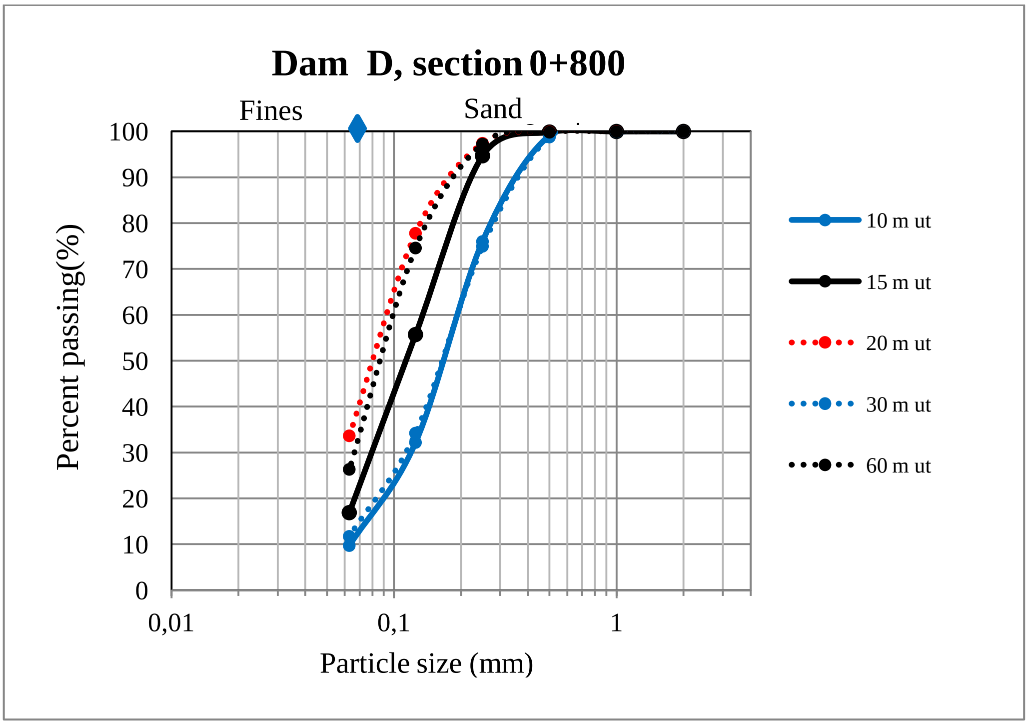

Figure 10-6: Grain size distribution dam D section 0+800.

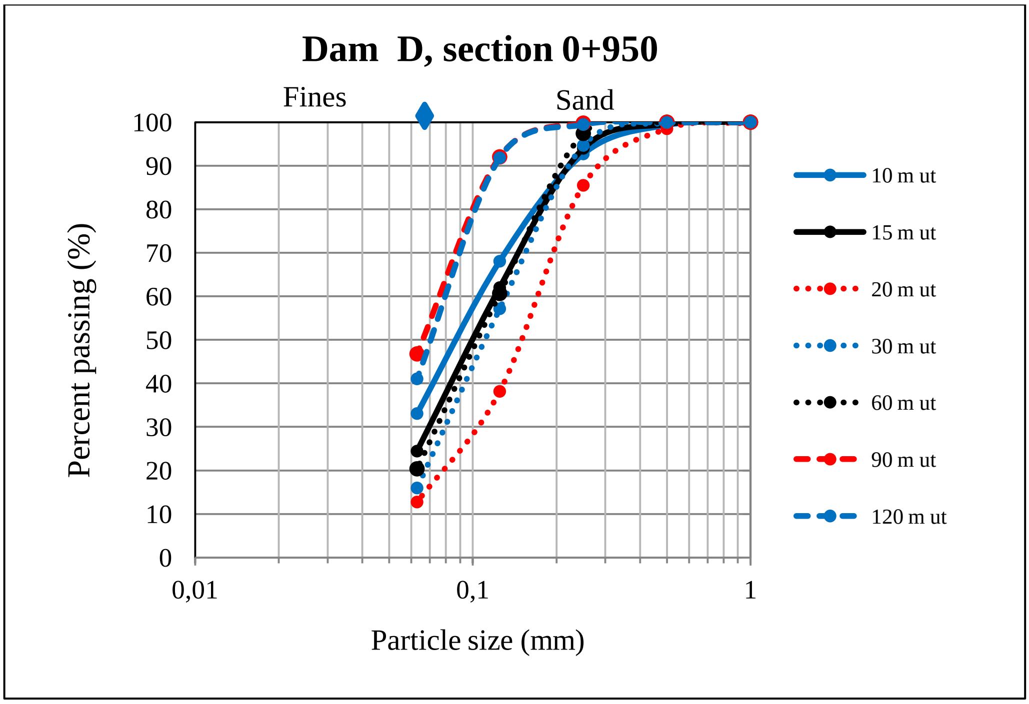

Figure 10-7: Grain size distribution dam D section 0+950.

Table 10-1: (A. Lindh, personal communication, 2013-10-02).

Dam	Position	Mass	Proportion (%)					
	m	g	0.250 mm	0.180 mm	0.090 mm	0.063 mm	0.045 mm	rest
A	15	100	4.1	8.8	47.6	13.5	10	13.4
A	60	100	22.4	15.6	41.1	8.6	4	5.4
A	120	100	0.9	2.6	50.2	15.2	6.1	20.6
C	15	100	29.1	19.5	33.5	9.6	3.5	2
C	60	100	13.7	19.5	25.7	27.5	5.2	4.9
C	120	100	1.1	2.9	36.1	16.4	19.8	15.5
D	15	100	11.3	11.8	45.2	15	7.7	4.7
D	60	100	3.2	10.9	56.3	16.1	8.5	2.9
D	120	100	0.3	1.1	24.3	28.4	23.8	19.8

Table 10-2: Contents of metals and compounds in samples (A. Lindh, personal communication. 2013-10-02), metal and mineral densities (Julien, 2010).

Dam A	Mesh mm	%	%	%	%	%	%	%	%	%
		Ag	Cu	Zn	Pb	Fe	S	Mn	MgO	SiO_2
15 m from wall	0.250	0.0120	0.015	0.41	0.404	2.01	0.36	0.29	6.01	52.58
	0.180	0.0071	0.010	0.30	0.219	1.18	0.45	0.34	5.33	68.46
	0.090	0.0035	0.005	0.24	0.098	2.63	2.36	0.59	5.78	67.12
	0.063	0.0035	0.005	0.25	0.070	11.00	12.06	0.69	5.08	51.97
	0.045	0.0036	0.006	0.18	0.073	12.11	12.85	0.66	5.17	47.74
	Rest	0.0068	0.021	0.39	0.347	9.81	9.33	0.87	6.02	47.94
60 m from wall	0.250	0.0056	0.016	0.45	0.292	1.01	0.71	0.34	4.07	76.30
	0.180	0.0065	0.015	0.71	0.330	1.99	2.01	0.63	5.03	68.11
	0.090	0.0034	0.009	0.92	0.149	12.80	15.38	0.62	4.14	53.75
	0.063	0.0039	0.007	0.37	0.139	15.78	17.39	0.56	3.59	44.99
	0.045	0.0070	0.012	0.27	0.224	16.22	15.14	0.62	3.20	33.70
	Rest	0.0087	0.019	0.39	0.480	11.19	10.01	0.76	4.43	42.48
120 m from wall	0.180	0.0097	0.016	0.14	0.333	3.36	0.10	0.30	7.77	38.42
	0.090	0.0031	0.006	0.10	0.119	1.67	0.90	0.45	5.24	72.29
	0.063	0.0035	0.005	0.15	0.111	3.03	2.46	0.58	5.05	67.10
	0.045	0.0057	0.008	0.20	0.144	7.43	6.77	0.69	4.39	53.33
	Rest	0.0059	0.015	0.20	0.189	7.63	7.24	0.72	5.17	56.91

Dam C	Mesh mm	%	%	%	%	%	%	%	%	%
		Ag	Cu	Zn	Pb	Fe	S	Mn	MgO	SiO_2
15 m from wall	0.250	0.0050	0.026	1.25	0.468	2.17	2.29	0.42	4.58	72.33
	0.180	0.0062	0.024	1.95	0.457	6.72	8.13	0.69	4.90	60.06
	0.090	0.0041	0.014	2.02	0.309	14.58	18.37	0.71	4.23	46.67
	0.063	0.0047	0.013	1.81	0.458	16.7	20.11	0.73	3.94	39.98
	0.045	0.0120	0.017	1.44	1.260	17.34	16.90	0.74	3.04	27.78
	Rest	0.0187	0.028	0.89	1.745	13.15	9.93	0.82	3.07	24.40
60 m from wall	0.250	0.0037	0.016	0.32	0.285	1.20	0.46	0.27	4.70	74.99
	0.180	0.0028	0.013	0.35	0.236	1.04	0.58	0.46	4.71	74.18
	0.090	0.0028	0.009	0.57	0.196	2.78	2.70	0.71	4.99	66.97
	0.063	0.0025	0.009	0.67	0.173	4.46	4.60	0.75	5.11	63.44
	0.045	0.0045	0.010	0.91	0.233	10.28	9.97	0.86	4.58	42.88
	Rest	0.0071	0.015	0.61	0.629	11.31	10.69	0.85	4.48	40.31
120 m from wall	0.250	0.0105	0.022	0.29	0.784	4.18	0.07	0.34	6.34	19.70
	0.180	0.0085	0.017	0.32	0.459	2.96	0.18	0.29	7.14	42.93
	0.090	0.0021	0.006	0.13	0.154	1.27	0.35	0.45	5.56	71.75
	0.063	0.0022	0.005	0.21	0.156	2.23	1.50	0.66	5.46	66.17
	0.045	0.0019	0.004	0.27	0.135	5.35	4.94	0.69	5.47	60.44
	Rest	0.0030	0.016	0.42	0.344	8.74	8.71	0.71	5.16	53.04

Dam D	Mesh mm	%	%	%	%	%	%	%	%	%
		Ag	Cu	Zn	Pb	Fe	S	Mn	MgO	SiO_2
15 m from wall	0.250	0.0057	0.032	1.69	0.473	2.28	2.84	0.34	3.19	74.42
	0.180	0.0052	0.029	4.49	0.412	9.74	13.15	0.57	3.26	55.57
	0.090	0.0022	0.016	3.67	0.218	17.13	23.41	0.48	2.60	45.89
	0.063	0.0022	0.008	1.76	0.183	16.02	20.61	0.53	2.63	48.55
	0.045	0.0031	0.007	0.66	0.223	13.66	15.39	0.53	2.65	48.20
	Rest	0.0081	0.013	0.26	0.863	11.02	10.22	0.61	2.57	43.08
60 m from wall	0.250	0.0094	0.022	0.25	0.478	2.14	0.25	0.21	4.02	50.28
	0.180	0.0026	0.010	0.17	0.198	1.07	0.28	0.23	3.47	77.12
	0.090	0.0017	0.008	0.84	0.140	2.15	2.25	0.55	3.75	73.95
	0.063	0.0017	0.010	2.64	0.123	12.03	15.37	0.70	2.99	53.40
	0.045	0.0032	0.008	2.15	0.185	17.54	21.23	0.53	2.20	41.39
	Rest	0.0116	0.015	1.34	1.068	14.53	13.15	0.45	1.79	33.56
120 m from wall	0.090	0.0022	0.004	0.06	0.138	1.54	0.12	0.34	4.92	69.67
	0.063	0.0017	0.004	0.40	0.128	1.50	0.99	0.56	3.95	71.15
	0.045	0.0014	0.005	1.11	0.108	4.58	5.01	0.65	3.82	65.15
	Rest	0.0041	0.017	1.11	0.732	9.50	10.52	0.60	3.24	54.45
Particle density (kg/m^3)		10500	8900	7100	11300	7900	1960	7470	3580	2630