CHALMERS

Small Earthfill Dams Operating in the Mining Industry

Conceptual Design

Master of Science Thesis in the Master's Programme Infrastructure and Environmental Engineering

JOHANNA LUNDIN

Department of Civil and Environmental Engineering
Division of GeoEngineering
Geology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2014
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Cover:
Two water storage reservoirs separated with a small earthfill dam, in the area of Boliden, Sweden (Private).

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Göteborg, Sweden 2014

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ABSTRACT

The mining industry produces large volumes of residue water and it is necessary to have systems to contain and treat the water. In the water treatment process small dam constructions, forming reservoirs, take a large part.

This thesis has intended to investigate the present small dams in five mines within the area of Boliden, Sweden. The considered constructions have been earthfill dams with heights between one to five meters, constructed with material found close to the mine. The investigation has concerned factors that contribute to the function and stability of the dam. Parameters determined to affect the stability has been slope stability and hydraulic gradient.

The conceptual model consists of two dam heights, three and five meters, and two different slopes, 1:2 and 1:2.5. There are four operating scenarios that have been analysed according to slope stability, these are: *steady state*, *steady state with load*, *rapid drawdown* and *rapid drawdown and load*.

Conclusions made are that for small earthfill dams it is essential for the stability of the dam to verify impacts of different material properties. Furthermore, a safe dam environment for small dams is similar with large dam and depended on clear directives regarding dam operation procedures.

Key words: *Earthfill Dams, Mining Industry, Water Storage, Hydraulic gradients, Slope Stability.*

Contents

Preface

This study has taken place in the area of Boliden County and the facilities of the mining company Boliden Mineral. The effort with this thesis has been carried out from June 2013 to December 2013. Together with Boliden Mineral and the author the work was initiated as a master thesis concluding the studies for a Master´s degree in Civil Engineering, within the department of Civil and Environmental Engineering and the division of GeoEngineering at Chalmers University of Technology.

Supervisor from the department of Civil and Environmental Engineering has been Johan Funehag. Johan have shown patience when introducing the world of technical writing for me. This study has been carried out together with Boliden Mineral with Camilla Årebäck as supervisor. Special thanks for making me feel comfortable, welcome and for interesting conversations concerning application areas of dam engineering. Also a special thanks to Johan's colleagues at the Tyréns office in Skellefteå for an office space and contributing with experience.

The extensive part of the field study as wells as reflection concerning dams and the operating in mining industry has been essential for the thesis. Special thanks to Camilla Årebäck and Michael Sandberg at Boliden Mineral for guiding and describing the process of construction of small dams within the mining industry.

Finally, it should be noted that this thesis would not have been possible without all the kind, wise and always cheering family and friends I have the opportunity to have in my life.

Boliden November 2013

Johanna Lundin

Notations

Roman upper case letters

A	[m^2]	The cross-sectional area through which Q flows
F	[-]	Factor for evaluation of freezing depth
H	[m]	Height of dam
H_{freeb}	[m]	Height of freeboard
H_{inc}	[m]	Height of inclination of reservoir surface
H_w	[m]	Height of reservoir
L	[m]	The distance through which the head is lost
L_n	[-]	Loading condition
Q	[m^3/s]	Discharge
R	[m]	Wave run-up
S	[%]	Compaction energy
V	[m^3]	Reservoir volume
Z	[m]	Freezing depth

Roman lower case letters

c	[kPa]	Cohesion
h	[m]	The total pressure head lost
h_p	[m]	Pressure head
i	[-]	Hydraulic gradient
i_c	[-]	Critical hydraulic gradient
k	[m/s]	Coefficient of permeability/ hydraulic conductivity
$k_{freezing}$	[m/s]	Coefficient for material property
n	[%]	Volume porosity
u	[kPa]	Porewater pressure
v	[m/s]	Discharge velocity
w	[%]	Moisture content
w_o	[%]	Optimum moisture content

Greek letters

Φ	[°]	Internal friction angle
γ_d	[kN/m^3]	Dry density
γ_w	[kN/m^3]	Unit weight of water
γ_T	[kN/m^3]	Total unit weight of soil
ρ	[kg/m^3]	Bulk density
ρ_s	[kg/m^3]	Compact density
ρ_w	[kg/m^3]	Density of water
σ_n	[kPa]	Stress condition
τ_f	[kPa]	Shear stress
τ_{fu}	[kPa]	Accessible shear stress
τ_{mob}	[kPa]	Mobilized shear stress

Abbreviations

ICOLD	International Committee of Large Dams
RDD	Rapid DrawDown
SWL	Still Water Level

1 Introduction

Dam constructions are found in civil engineering activities all over the world and have a long history within infrastructure development. Construction of dams is diverse and dependent on the purpose with the retention of water. Application areas in minor extent are water irrigation and agriculture purposes, and in larger extent hydropower or reservoir storage. Novak et al. (1990) define that the primary purpose of a dam construction is to provide "*a safe retention and storage of water"*.

Appearances of dams show diversity in geometry, material and application area (Vick, 1990). Dam constructions may be divided into two groups, dependent on the material used:

- Embankment dams. Embankment dams are constructed from earthfill and/or rockfill. Angular slopes forming a rather wide construction.
- Concrete dams. Dam constructed from concrete, construction appearance may vary from steep downstream sides and vertical upstream. It is possible to create more slender constructions.

In the Skellefteå area the metal company Boliden Mineral has been exploring and mining ore since the early 20th century. Five different mines are in operation today; Kristineberg, Kankberg, Maurliden, Maurliden Östra and Renström mines. Current production considers complex ore containing zinc, copper, lead, gold and silver. In total the production per year is 1.9 Mtonnes of ore and there are around 500 employees today.

Within the mining industry there are large tailings dams, reservoirs that contain residue tailings from the processing of ore. But there are also other application areas for dam construction within the industry. Newly constructed dams within the area of Boliden are earthfill dams from natural materials, preferable from the area close to the construction site. Soil material with different fractions and characteristics will form a united construction without any binding, only by compaction. The mining activity causes a lot of residue water. It is necessary to contain and treat the water, which is carried out by various methods. Minor dam construction forming reservoirs takes a large part of these processes. The water contained may be from the mine activity and activities in connection to the mine. Examples could be short time storage of residue water, sedimentation basins both before and after treatment facilities and collection of surface runoff.

The systems of the dams are continuously constructed due to mine production demands. One frequent problem has been extended seepage when the dam is taken into production. Problems may be due to variations in the material and performance during construction. Due to production processes there are frequently changing reservoir levels and the dams are exposed to various loading conditions over the entire life span. It is essential that the dam should provide a reliable system for the water treatment process during normal operating conditions. There is also a need to have evaluated the stability and reliability during extreme conditions. For larger dam constructions there are clear regulations and legislation for construction and operating, it has not been evaluated whether there is possible to apply the same regulation for these in relation small dams.

1.1 Aim of this Thesis

The aim of this thesis is to investigate the current constructions of small dams in the area of Boliden. According to the present constructions and materials, the investigation will concern function and stability of small dams operating in the mining industry.

1.1.1 Objectives of this Thesis

Variations in reservoir level have been considered to affect the stability of the slope and the hydraulic gradients within the dam. The following two objectives will be further investigated:

- The slope of the dam will be exposed to various pressures when the reservoir level is frequently changed. What material properties will govern the stability and conditions at which the slope is stable will be analysed.
- The hydraulic gradient within the embankment is affected by the variations in the reservoir level. The investigation will consider which material properties are governing the internal stability and when there may be a risk of failure.

1.1.2 Limitations

This thesis will only consider constructions with a height between one to five meters. The material properties used will be according to an extensive investigation of a till deposit by CM Tracing and Christer Mattsson (2007). In the case when there is a lack of information concerning material properties, present standards and characteristic values will be applied.

The areas of interest are assumed to have ground conditions with large depths of till. The characteristics of the foundation need to be determined for each individual construction site.

From the visits to the different sites the extent and conditions of small dam constructions have been obtained. The thesis have not contained any on-site testing, there have only been visible control and interviews with staff in the mines of interest.

1.2 Background

To understand the essential functions of earthfill dams and the demands within water treatment facilities in the mining industry, some theoretical parts have been generally described below.

1.2.1 Terminology of Embankment Dams

Embankment dams are constructed from both earthfill and a combination of earthfill and rockfill. The composition of a dam will be diverse and dependent on area of usage and surrounding environment. Some common embankment dam details are presented in Figure 1. The slope on the reservoir side of the dam is named the upstream slope and the one below the downstream slope. In Figure 1 the discharge system is located at the bottom of the downstream slope. This may be different for different dams, it is also possible to have discharge systems on the crest or further downstream the dam.

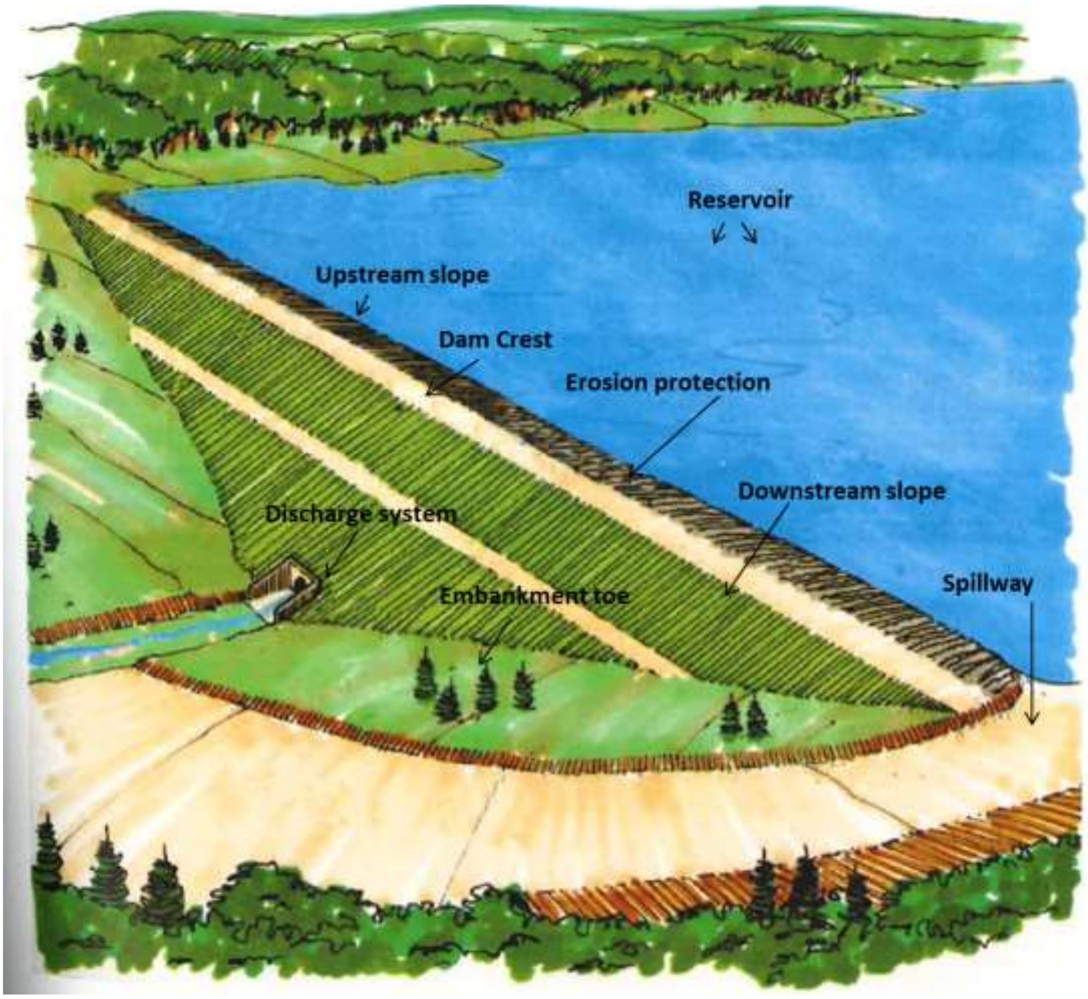
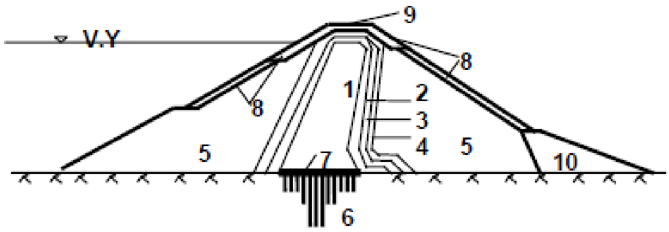


Figure 1 Embankment dam with some highlighted features (British Colombia, 1998).

To further understand what the different systems of a dam are and how they work, different features are described in Figure 2. Dam construction is to a large extent controlled by the interaction between different properties of dam features. Characteristics of certain interest have then been described more in detail below.



1	Core
2	Fine Filter
3	Intermediary Filter
4	Coarse Filter
5	Support Fill
6	Grouting
7	Surface Liner
8	Erosion Protection Material
9	Dam crest
10	Toe Reinforcement

Figure 2 Characteristic and details of an embankment dam (SveMin, 2012).

Core

The core consists of a less permeable material than the surrounding support fill to prevent seepage through the dam (Fell et al., 2005). The permeability will be governed by the material in the core. A dam consisting of core, support fill and other design features are referred to as a zoned dam.

Filter systems

The usages of filter and drainage systems have several purposes. They are used to prevent erosion of material within the construction, but also to collect eroded material due to seepage. The system will also function as a draining system decreasing porewater pressures and containing seepage within the construction (Fell et al., 2005).

There are different kinds of filter solutions and the material properties will be diverse depending on the position in the construction. Fine filters are found close to the core preventing seepage and collecting particles. Coarser filter will be placed outside the fine filter, collecting particles that manage to get through. The filter will have more permeable properties than the surrounding soil and contain drainage characteristics (SveMin, 2012).

Support fill

The material will function as the stability factor of the construction as well as surrounding and protecting other design features. Depending on the properties of the material, the support fill also prevents transport of eroded material (Fell et al., 2005). A dam consisting of only support fill is referred to as a homogenous dam.

Erosion protection material

The dam construction needs to be protected from damages caused by wave actions, freezing and surface runoff (SveMin, 2012). The extent of wave actions is dependent on the wind speed, reservoir length, the wave duration and the allocation of depth in the reservoir. The most common material for erosion protection material is a boulder sized material sometimes called riprap.

There are two methods of application systems. The erosion protection material is either dumped from the crest down on the slope. Or the material is dumped and later applied with the help of excavators. This is called an arranged erosion protection (SveMin, 2012).

Dam crest

The dam crest will be dependent on the composition of the dam. There should be a sufficient distance to the core and other frost sensitive materials to avoid problems with freezing. The width of the crest should provide space for the required transportation during construction and the life span of the dam (SveMin, 2012).

Toe bank

To improve the stability in a downstream slope sometimes a reinforcement of the toe is suitable (SveMin, 2012). The reinforcement consists of a boulder sized material and the intention is that it should work as a resisting force on the slope. It is important that the material has draining properties so the porewater pressure will not be built up in the dam.

Freeboard

The freeboard is defined as the distance between the reservoir level and the dam crest. The dimension of a freeboard needs to be sufficient to prevent damages on the dam caused by waves in combination with winds. The freeboard need to prevent overtopping, which means that water will be running over the crest. This may with high probability lead to failure of the dam (ICOLD, 1995). Figure 3 displays an illustration of an upstream slope where the wave run up height R is shown.

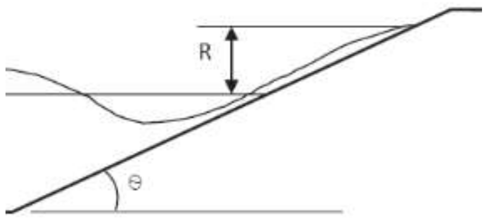


Figure 3 The freeboard represents the distance between reservoir level and the dam crest (ICOLD, 2005-2010).

Discharge system

The outlet from a reservoir is called discharge system. The capacity should be dimensioned to take care of the expected spillwater from the reservoir. But also to discharge additional water causing a potential safety risk due to high levels in the reservoir (ICOLD, 2005-2010). Discharge systems may consist of different solutions, for example: overflow thresholds, natural overflows dependent on the surrounding environment, pipes or conduits.

Foundation

According to SwedenergyAB (2012) the foundation of the dam must be "*designed for safe interaction with the foundation"* and "*be drained to eliminate the risk of leakage, internal erosion and instability"*. To determine what needs that have to be met considering foundation, the permeability of the material in the foundation has to be verified. GruvRIDAS (2012) states that if the foundation contains equivalent qualities as the embankment, the ground may be smoothened and compacted in the same manners as the embankment itself.

Independently if the embankment is to be founded on soil or rock, it is recommended to investigate the properties of the material (SveMin, 2012). Some construction examples of when a dam is founded on soil are presented below (Fell et al., 2005).

- General foundation excavation. The weak soils are removed in order to strengthen the bedrock until sufficient strength is reached.
- Cut off excavation foundation. Materials of high permeability below foundation level are removed to avoid uncontrolled seepage below the dam construction.
- Curtain grouting. Grout is injected into the rock foundation to decrease the permeability of the bedrock.
- Consolidation grouting. Injection with grout in the cutoff of the foundation is grouted to reduce the permeability. This solution is also called *Blanket Grouting*.

Transition Zone

Transition zones are found between for example downstream filter and support fill, support fill and coarser material at the downstream toe and erosion material as well as upstream support filling. The risk with these areas is the differential in settlements causing possible areas for internal erosion or deformations in the outer areas of the dam (Fell et al., 2005).

Liner System

Even if the dam is designed to be stable and fulfilling the construction features, there will always be seepage through the construction (Fell et al., 2005). To decrease or prevent this, a lining system may be used on the bottom and slopes of the construction. Consisting of a system of material preventing, collecting or decreasing leakage of both natural and synthetically materials. Geomembranes may be used to control and prevent leakage of residue water. Geomembranes consist of a rubber blanket and are within the mining industry used when there is a need for waterproof impoundments.

Regulations for disposals of waste are found in the Swedish Environmental code and further recommendations to this legislation are found in Handbook 2004:2. Geological barriers are without active measures and maintenance supposed to function during a long lifespan. When natural conditions do not fulfil this, counteractions must be taken. Recommendations from regulation according to Naturvårdsverket (2008) a liner system should consist of at least one meter thick layer and permeability according to Table 1.

Table 1 Limitation for permeability of a liner system according to regulation from Naturvårdsverket (Rättsnätet, 2001).

Deposited Material	Permeability		Thickness	
Hazardous waste	$<1,0*10^{-9}$	[m/s]	> 5	[m]
Non - Hazardous waste	$<1,0*10^{-9}$	[m/s]	> 1	[m]
Inconvenient waste	$<1,0*10^{-7}$	[m/s]	> 1	[m]

1.2.2 Loading Conditions to be considered for an Embankment Dam

When constructing a dam there are some parameters that need to be considered before choosing what kind of constructions to use. Novak et al (1990) claims that environmental aspects and regulations certainly need to be respected.

There are certain loads that affect the stability of the dam construction these may be divided into three groups; primary, secondary and extreme. Figure 4 displays an illustration of the different loading conditions on a dam construction. The proportions of the three loading categories will be unique for each construction.

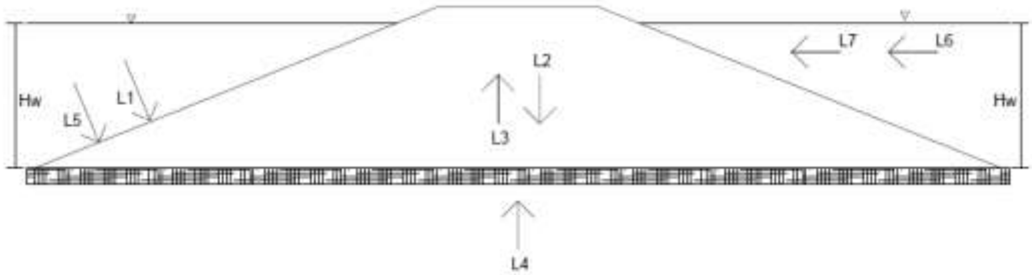


Figure 4 Example of loading conditions on a dam with reservoir levels on both sides.

Loading conditions according to Novak et al (1990) are presented below.

- Primary loads. The load of most importance for dam safety independent of type:
  - Water load. Hydrostatic distribution of pressure with resultant force, L_1.
  - Self-weight load. The unit weight of material, forming the resultant L_2, considered operating from the centre of a given section.
  - Seepage load. The unavoidable seepage through a dam in voids and discontinuities, will contribute to vertical loads. This may be seen as both internal and external loads, L_3 and L_4.
- Secondary loads. Universally applied loads from environment and surroundings:
  - Sediment loads. An additional hydrostatical load will be the accumulated materials or sediments will give the resultant L_5.
  - Hydrodynamic loads. Transient load formed by waves acting on the dam, L_6.
  - Ice load. Loads due to formation ice floe, L_7, during winter time. Freezing may have different consequences for concrete and embankment dams.
  - Thermal load. Internal changes due to cement hydration and cooling. Important when dealing with concrete dams.
  - Interactive effects. Possible internal changes in relative stiffness and diverse deformations within the construction.
- Exceptional loads:
  - Seismic loads.
  - Tectonic effects.

1.2.3 Hydraulic Behaviour in Soils

Dam construction is dependent on soil properties and the hydraulic behaviour of the soil. The governing factor for an embankment dam construction and a potential failure are to a large extent dependent on the porewater pressure. This needs to be considered through the process of construction and finally the lifespan of the dam. Terzaghi et al. (1996) describes three critical stages of certain interest to follow the porewater pressure conditions:

- Construction. During construction and immediately after completion.
- Full reservoir. With a full reservoir and when steady state conditions have been reach in the dam and foundation.
- Drawdown states. During and immediately after lowering of the reservoir level.

The total normal stress through a saturated soil consists of two parts. First the porewater pressure or what may be termed as the neutral stress, working in all directions with equal intensity (Terzaghi et al., 1996). Secondly this represents the excess over the normal stress and will consider only the solid phase of the soil, called the effective stress.

Cedergren (1988) states that a permeable material is one that is capable of being penetrated by another substances, usually a gas or a liquid. Jantzer (2009) describes the phenomena of the permeability of a soil by: "*…a material ability to transmit a fluid..".* A soil with voids filled with water is referred to as a saturated soil also called an undrained soil (Johnson & DeGraff, 1988). The opposite scenario would be if the voids of the soil are filled with air, called drained conditions. The movement or flow of water through the soil will be dependent on the permeability, called the coefficient of permeability. Darcy's Law are used to determine the coefficient, see equation 1.1.

$$k = \frac{Q}{A} * \frac{L}{h} = \frac{v}{i} \qquad (1.1)$$

An applied load on a soil will contribute to both compression and shear forces. Water will only provide resistance towards compression forces and resistance for shear forces will be dependent on the effective stress of the material (Johnson & DeGraff, 1988). The effective stress are dependent on the pore pressure, so when raising the pore pressure within the soil the pore pressure will increase causing an decrease in the effective stress. The critical point will be at the state where the effective stress is getting closer to zero. At that state the pressure within the voids will push the particles and lose contact and the resistance to shear forces are the least. The porewater pressure may be determined be the equation 1.2.

$$u = h_p * \gamma_w \qquad (1.2)$$

The hydrostatic pressure in a soil represents the energy level at that certain point when the water is motionless (Johnson & DeGraff, 1988). The energy level may be determined by using piezometers. If the piezometer indicates different energy levels, pressure head, it is called hydraulic gradient. The flow of water will contribute to seepage pressure due to the difference in total energy between two points. It needs to be determined whether the seepage pressure may potentially be high enough to move individual particles. This may potentially led to greater seepage pressure and higher flow velocities. Seepage pressure is determined by multiplying the hydraulic gradient and the unit weight of water.

1.2.4 Compaction of Soils

Johnson & DeGraff (1988) describes compressibility of the soil is the decrease in volume of a soil mass due to natural and artificial means. With artificial means one often indicates compaction. It might be performed by vibrating on top of a soil mass or loading and unloading of material. The intention is to decrease the volume of voids in the soil. The amount of compaction possible will to a great extent depend on the moisture content of the soil. Compaction is applied in all construction areas using soil material. The intention is to reduce permeability and increase the overall strength of the soil.

During construction the compaction is investigated to verify that the design specifications are met. Johnson & Degraff (1988) describes the present of water in the soil as an increase in resistance for particles to reorientation due to surface tension between the grains. But the frictional resistance may reduce due to water content in the soil. There is a need to find a level of water content where the maximum dry density are found, this level is called the optimum water content. Verifications may be performed by using standard Proctor compaction or modified Proctor compaction. This method will give the responding dry density in terms of different levels of water content and specified compaction energy. An example may be seen in Figure 5 where S represents the compaction energy.

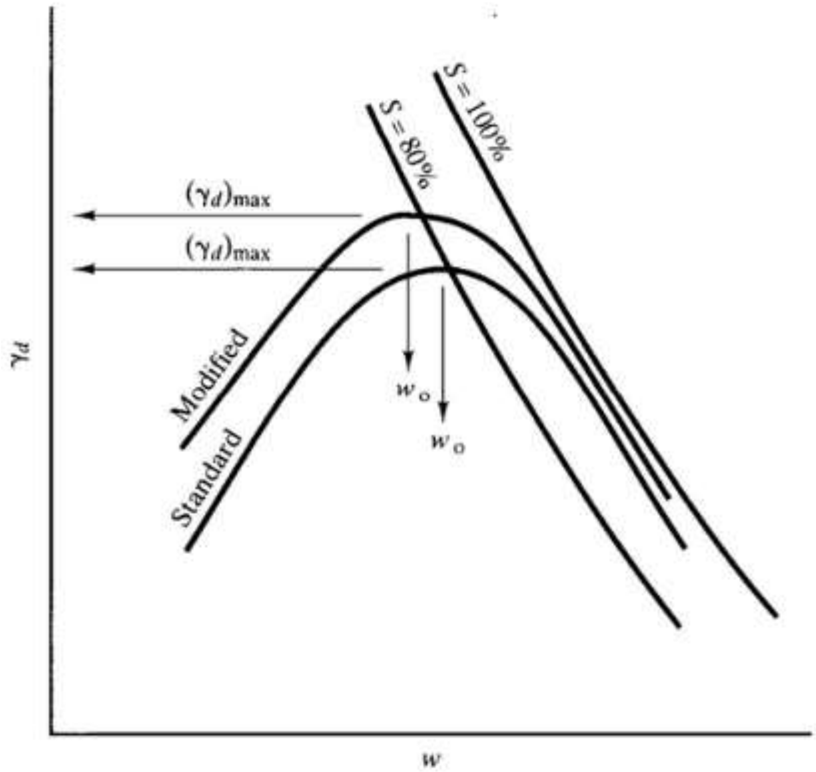


Figure 5 The responding dry density in relation to the moisture content of the soil and the compaction energy.

1.2.5 Shear Stresses in Soils and Till as Dam Construction Material

General assumption and main advantage of till as a construction material is relatively low permeability, high shear strength and low deformability in comparison with other fraction materials (Sherard, 1986). These qualities may be determined due to the broad range of grain size distribution together with a high content of fines. The composition of different grains depends on the rock of origin and the quality of the grains.

Shear strength are the largest shear stress possible to be obtained on a surface of a material (Vägverket, 1986). In friction soils, the maximum shear stresses are proportional to the normal stress towards the surface and the tangent of the friction angle. For friction soils the friction angle will be governing for the shear strength. The friction angle is not only material-dependent; it will also be affected by the stress levels in the soil. When the effective stress increases, the friction angle will decrease.

Slope stability is controlled by the shear stresses of the materials in the dam body and the foundation. For a homogenous dam the slope itself is the critical slip surface. To evaluate the failure criterion of a soil material, the Mohr-Coulomb failure criterion is used and the shear strength is determined according to equation 1.4 (Terzaghi et al., 1996).

$$\tau_f = c + \sigma * \tan \Phi \qquad (1.4)$$

Stress calculations in soils normally assume that the Mohr – Coulombs failure hypothesis is valid, see Figure 6. The failure criterion is determined by the effective strength parameters cohesion and frictional angle and the effective normal strength (Terzaghi et al., 1996). The intersection with the axis where σ=0 represents the cohesion of the soil. The line formed is the strength envelope for the material, which depends on σ_1 and σ_3. Using Mohr circles, the increasing σ_1 will gradually develop towards the strength envelop at the point where the circle tangent to the line failure occurs.

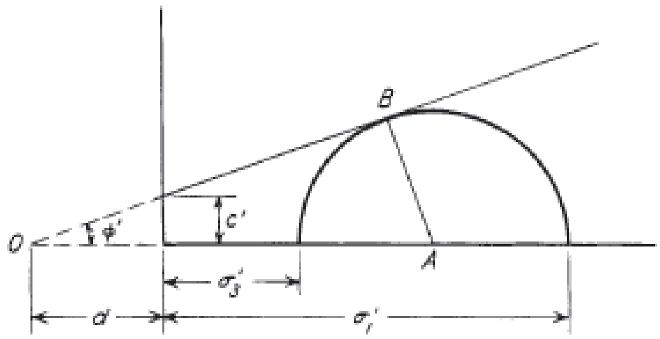


Figure 6 Mohr rupture diagram, the straight line represents the failure envelope (Terzaghi et al., 1996).

In relation to this the factor of safety may be determined according to the relation between, accessible shear stress appearing at maximum friction coefficient and the mobilized shear stress (Sällfors, 2001), seen in equation 1.5.

$$F = \frac{\tau_{fu}}{\tau_{mob}} \qquad (1.5)$$

Soil materials of silt, fine- and medium sand and silty tills have sometimes been found to be stable in more steeper slopes than the responding friction angle of the soil (Vägverket, 1986). This is termed as false cohesion and may be explained with the capillary tensile stresses which increase the pressure between the soil particles. Capillary stress in the water in connection with the particle´s contact surfaces causes a false cohesion in the material. When the soil is saturate, the capillary stresses disappear and the soil recovers its original friction angle.

According to ICOLD (1989), construction with till material is prohibited during freezing seasons. Even if there are measures taken to protect the material, the hauling, initial temperature, wind velocities are hard to predict. Till that has been frozen and then melted may lead to softening of the compaction, a reduction in shear strength and an increase in permeability. According to ICOLD (1989) there are two approaches that may be taken when constructing a dam in a till material and having winter conditions.

- All production will be completed when the ground freezes and material already on place should be covered to avoid frost penetration.
- If the work continuous even during cold period's actions needs to be taken, such as: adding chemicals, till in stockpiles, heated or stored water.

1.2.6 Critical Scenarios for Embankment Dams

According to ICOLD, (1995) the term failure is: *"Collapse or movement of part of a dam or its foundation, so that the dam cannot retain water"*. In general, a failure results in the release of large quantities of water, imposing a risk on the people or property downstream. There are two types of failures categorized by ICOLD (1974):

- Type1 - "A major failure involving the complete abandonment of the dam"
- Type2 - "A failure which at the time may have been severe, but yet has permitted the extent of damage to successfully be repaired, and brought into use again"

The most common mode for failure of a dam is overtopping of reservoir water (Fell et al., 2005). According to statistics the second most common reason for failure in earthfill dams is internal erosion by for example piping, a seepage path forming within the embankment. Piping may be initiated by backward erosion, concentrated leak or suffusion. In Figure 7 backward erosion are illustrated, to the left erosion on the downstream side of the core. To the right the process has continued and the formation of a pipe is displayed forming a path from the reservoir through the embankment.

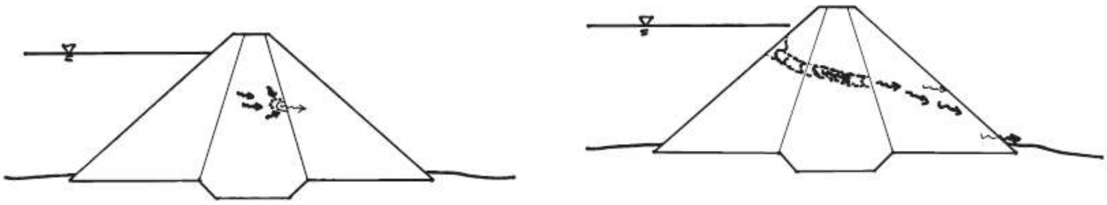


Figure 7 Example of backward erosion initiated in the core and backwards increasing (Fell et al., 2005).

According to Terzaghi et al. (1996) the critical states for an embankment dam do not only depend on the material, but also the boundary conditions for drainage when considering porewater pressure conditions. Concerning the effects on porewater pressure due to drawdown of reservoir level, called Rapid DrawDown (RDD), the reason for changes will be dependent on the compressibility of the different parts of the construction. In Figure 8 two situations for reservoir levels are illustrated, together with the responding flow net for each scenario. The figure to the left describes the flow of water through the dam and responding point in the filter toe. The scenario to the right describes when the reservoir has been rapidly emptied and the flow nets are divided between the upstream and the downstream slope.

Figure 8 Different scenarios illustrating change in flow net due to rapid loss of resisting load (Terzaghi et al., 1996).

The rapid loss of resisting load on the reservoir side will cause high porewater pressures in the upstream slope and increase the risk of failure depending on the extent of the effective stress. The dam consists of a fine, clean, well-compacted sand and foundation of an impermeable material. When the construction is exposed of a RDD of reservoir level, the behaviour of the flow towards the downstream flow will continue as before. But the upstream side will cause potential instability problems on the slope side. The pressure will sequentially decrease from the top line and downwards.

1.2.7 Regulation Concerning Construction of Dams

In Sweden today there are several different provisions applied to create a safe dam environment. The Swedish environmental code is one of the dominant ones regarding dam safety. The Swedish Association of Power Plants, *Swedenergy,* accepted the *Hydropower industry's Dam Safety Guidelines*, RIDAS in 1997 (SwedenergyAB, 2012). The latest revision was published in 2012. It is clarified that RIDAS should not be seen as regulation but as guidelines to a safer dam performance. The guidelines consist of two parts, first *Guidance* and secondly A*pplication Instructions*. According to the guidance dam safety is defined as: "*safety against the uncontrolled outflow of water from the reservoir (dam failure) that could result in damage or injury"*.

The dam owner is according to the Swedish Environmental Code responsible to safeguard against damages on public or private property or water conditions (SwedenergyAB, 2012). The RIDAS guidance is directed for the water power industry and initially the mining industry also used this publication. Nevertheless it was concluded that there where application problems to the facilities connected to the mining industry. The work with a unique guideline for the mining industry started, known as GruvRIDAS (SveMin, 2012). The foundation is still RIDAS but adjusted to be more suitable for the mining industry. The responsible agency for the publication is SveMin; *The Swedish Association of Mines, Mineral and Metal Producers*. However, GruvRIDAS (SveMin, 2012) take no consideration to whether the dam may be considered to be smaller than common dams within the industry.

2 Methodology

To be able to verify the stability of small dams the following methodology has been applied. The conceptual model describes the general dimensions and loading conditions of the dams according to the field study. There has been no on-site material sampling available for the mines. The properties of the material will be determined according to earlier material investigations in the Boliden area. The investigation has concerned till deposits aimed for an extensive dam construction in Boliden, carried out by CM Tracing and Christer Mattsson (2007). The investigation included sieve curves of different compositions of till and also laboratory tests regarding conductivity and additional hydraulic properties. The results have been analysed and the intention has been to find some general characteristics for the area.

2.1 Field Study to the Mines in Boliden County

Together with personnel from Boliden Mineral, the different mines of interest have been visited. The different dams in the mines show diversity in year of establishment, amount of constructions and area of usage. The intention with the field study has been to investigate the application area of the dams, the material used and the features needed for the construction to operate within the mining operation. Detailed information and documentation from the field study are found in Appendix A - Survey of Small Dams in Mining Areas of Boliden

The dams have been found to have some similarities. Materials used are to a great extent found in the area surrounding the mine. Primarily, different composition of till and then crushed materials to some extent. The heights of the dams are found to be between one to five meters in height. The dams operate as an individual construction or connected with one or more dams, forming larger systems consisting of several reservoirs.

There are diverse application areas for the dam constructions. For example short time storage of residual water from the mine, sedimentation reservoir connected to a treatment plant or mining activity, surface runoff or recycling of water. The dams show some diversity in appearance depending on their application areas. The short time storage reservoirs, with water pumped from the mine are stored for a short time before it is led to the treatment plant, or other application areas. Sedimentation basins are designed to keep sediments and wastes both before the water has been treated and after. The sediments are residues from the water treatment process. Treated water is finally released into an external reservoir or reused in the mining operation.

The characteristics of the sediments are that in saturated form they will be quite fluid, but when the sediments are drained they will instead be solid. The extensive amounts of sediments, in the sedimentation basin, demand a system for removal of the residues. One example would be two or more reservoirs working parallel. When one of them is emptied the other one is in production and vice versa. Sediments are then excavated with the help of excavators and dumpers to transport the material away from the site.

This demands that the additional water is drained or pumped away. This is a quite time-consuming and extensive process, but still a necessary part of the treatment process. Reservoirs for storage will often have, as mentioned, systems where the water is pumped away. The design of discharge systems is dependent on the reservoir level, as well as the amount of freeboard. Example when guidance in GruvRIDAS (SveMin, 2012) are hard to apply are the demand for a minimum freeboard of 2 meters.

From the visits on site and interviews, some areas of problem have been identified. For example there have been problems with large amounts of seepage through the dam in the earlier stages of production requiring reinforcement. In one of the areas by ice lenses have been discovered within the dam, caused due to production during wintertime. Stability problems in slopes have caused slope failure on the upstream side of the reservoir. The instability of the slope has appeared when the level in the reservoir has been lowered. The source of the problem has not been investigated, but solution has been to reinforce the slope and decrease the slope angle.

2.2 Literature Study

The aim of the literature study has been to understand the governing properties for a dam construction and the boundary conditions for a small dam operating in the mining industry. The literature study is presented in the introduction chapter and has together with the field study formed the foundation of the thesis.

2.3 Conceptual Model

The process of evaluating the present constructions in the area has been carried out in an iterative way. A general model has been applied to be able to verify the function of the dam and the numbers are based upon the field study. It is stated that the small earthfill dams consist of natural material with the following characteristics:

- Dam height of one to five meters
- Width of bottom 20 meters
- Length of bottom 100 meters
- Crest width five meters

The recurrent changes in reservoir level are applying high stress on the construction and will demand stability of the soil both internally and externally. To be able to evaluate the situation, a characteristic construction has been presented with water from the reservoir as the major loading condition, $L_{1,}$ and internal stresses due to hydraulic conditions within the construction, L_2. The reservoir levels are assumed to be full on both sides of the construction, see Figure 9.

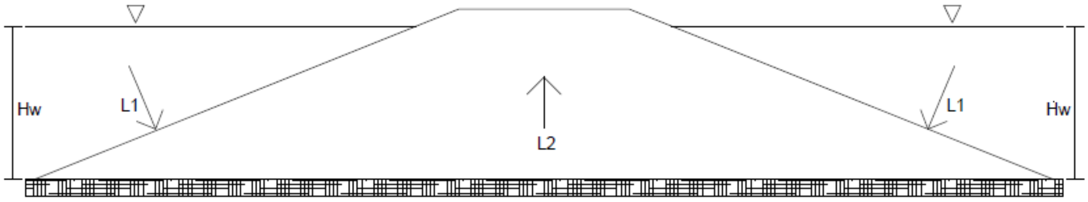


Figure 9 The assumed primary loading conditions on the general model.

There are four scenarios determined to be of certain interest for the stability of the dam; two normal operation scenarios and two extreme conditions.

- *Steady state*. The steady state conditions describe when the dam is in operation with reservoir levels on both sides.
- *Steady state and load*. Simulations have been carried out according to steady state operations and with an applied load of 20 kN/m^2 representing transport on the crest (Trafikverket, 2011).
- *RDD*. The extreme condition when one of the reservoirs is suddenly emptied.
- *RDD and load*. Extreme condition assuming that when the RDD occurs there are transports located on the crest of the dam.

2.4 Evaluation of Slope Stability

The conceptual design has been concerned when evaluating the slope stability, together with a sensitivity analysis considering material properties. The sensitivity analysis consisted of variations in cohesion and friction angle properties, in order to observe the proportions of changes in the factor of safety for the slope. Evaluation of slope stability was carried out according to the scenarios concerning the operation of the dam, described in chapter 2.3. According to GruvRIDAS (SveMin, 2012) the factor of safety should during normal operation fulfil a value of 1.5. For extreme conditions it is accepted to have a factor of safety of 1.3. Full reservoir level with a suddenly breach leading to lose of resisting pressure, represents an extreme case.

Stability analysis has been carried out by using the software GeoStudio 2007, which contains programs for solving different geotechnical problems. The program GeoSlope is a CAD software providing the possibility to analyse the factor of safety for rock and earthfill slopes. The Morgenstern –Price method have been applied and the porewater pressure conditions set by using piezometric line. The material model used will be Mohr – Coulomb. Applied material properties for each of the different dam components have been set concerning properties for unit weight, cohesion and friction angle. Procedures and specific properties regarding simulations in GeoSlope are presented in Appendix B.

Concerning slope stability the main interest has been the response of the construction according to variations in reservoir levels. The impacting properties have been found to be the friction angle and cohesion of the material. Though these have not been validated in material testing, there has been a need to find other ways to define these properties. Friction angle properties have been determined according to recommendations from a consultant (Carlsson, 2013) so as Trafikverket (2011).

Initially the cohesion was set to zero, representing the worst conditions for the slope stability. Then, by using various properties for the cohesion, the intention will be to get closer to an actual value of the present material.

The stability controls have been carried out with two different dam heights, of three and five meters, assumed to be representative for the entire height interval. Slope angles have been determined to be 1:2 and 1:2.5 in the different sites and the focus have been to analyse the stability of these two geometries.

Results from the analysis will be presented according to the factor of safety. There will be three material simulations, with different material properties. The first one have been based on recommendations of material properties from the consultant (Carlsson, 2013). In the second simulation some cohesion was applied in the material, assumed to be favourable for the stability of the slope. The third case was general values for the friction angle according to reference literature.

The freeboard levels impact on stability was initially investigated. Figure 10 display a comparison of two freeboard heights and the different geometries. The normal operation scenarios, *Steady state* and *steady state with load*, and the extreme conditions, *RDD* and *RDD and load*, defined in the conceptual model are also shown. The vertical axis represents the factor of safety and the horizontal the operation scenario and slope angles. Blue and green bars represent freeboard height of 1.0 meter and red and purple freeboard height of 0.5 meters. As can be seen freeboard height of 0.5 meters will provide a more unsafe solution, especially for the extreme conditions and the dam with slope angles 1:2. Hence, the following simulations are based on a freeboard level of 0.5 meters, simulating the worst case scenario for the dam.

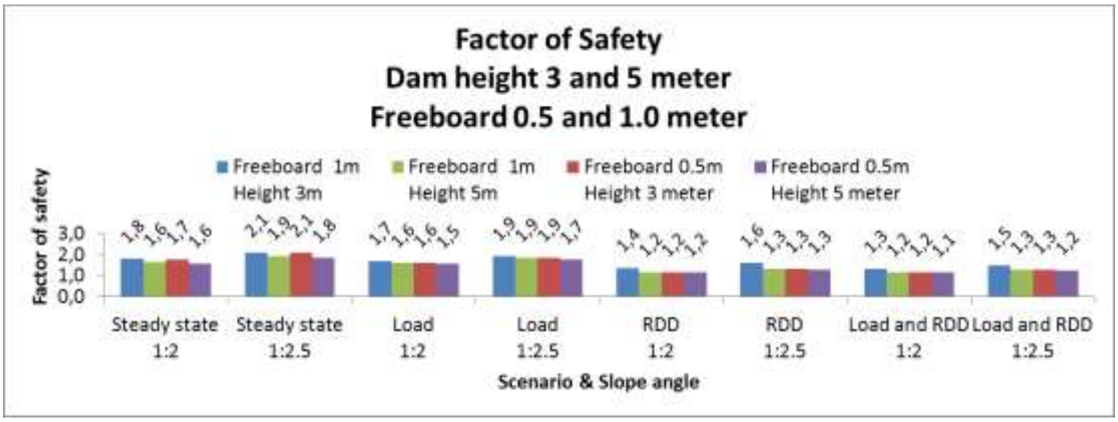


Figure 10 Variations in factor of safety according to the two freeboard heights.

2.5 Internal Seepage Load

To evaluate the conditions of the hydraulic gradient of the conceptual dam, the material investigation by Mattsson (2007) have been applied. Verified material properties together with standard values have together been used to determine critical hydraulic conditions.

To be able to verify if there is a risk for internal erosion within the dam potentially leading to failure, one important parameter is that in all embankment dams there will be a flow of seepage. The amounts depend on the permeability of the soil material and the performance of the construction. Despite, in most cases, the flow of water does not contribute to dam failure.

There needs to be a balance between the total stress concept, where the total stress is pushing the particles together, and porewater pressure, pushing them apart (Johnson & DeGraff, 1988). The critical hydraulic gradient i_c is defined as the state where the average seepage pressure is equal to the weight of the sand. Saying that the average seepage pressure will be equal to weight of the soil and the ratio will represent the critical gradient, equation 2.1 are used for evaluation. Input data and results of evaluation of the critical gradients are seen in Table 2.

$$i < i_c \qquad i_c = \frac{\gamma_T - \gamma_w}{\gamma_w} = \frac{(\rho_s - \rho_w) * (1-n)}{\rho_w} \qquad (2.1)$$

Table 2 Calculated properties according to evaluation of material sampling.

		Minimum	Maximum	Average	Unit	
Porosity	n	24%	21%	22%	[%]	(Trafikverket, 2010)
Bulk density	ρ	2,16	2,36	2,27	[t/m^3]	(Mattsson, 2007)
Compact density	ρ_s	2,65	2,70	2,68	[t/m^3]	(Trafikverket, 2010)
Density water	ρ_w	1,00	1,00	1,00	[t/m^3]	(Trafikverket, 2010)
Critical hydraulic gradient	i_c	1,26	1,35	1,31	[-]	(Johnson & Degraff, 1988)

The stability of the soil would be fulfilled if the factor of safety is minimum 2, see equation 2.2.

$$\text{F} = \frac{i_c}{i} > 2 \qquad (2.2)$$

2.6 Evaluation of Embankment Dam Features

The conditions of features on the constructions will contribute to the overall dam safety. Some of the characteristics will be evaluated and their function will be compared to the present conditions found in the field study.

2.6.1 Dam Crest

The dimensions have been based on a crest width of five meter, which was found to be sufficient for operating vehicles. Further parameters influencing the appearance of the crest is for example the geographical location, since there are several months of winter climate in the area of Boliden. There will be a risk of freezing of the material especially when the snow is removed from the crest. To avoid risk of damages when freezing there should be a sufficient distance between the dam crest and sensitive construction features like core, filter or drainage systems. The frost depth will be dependent on the material in the dam and the number of freezing hours in the area. In Figure 11, the variation in freezing hours in Sweden is presented. The freezing depth is evaluated according to the equation; $Z = k_{freezing} * \sqrt{F}$. The factor $k_{freezing}$ represent material properties. In the area of the existing mines there are three different zones for freezing hours, noted with the black circles.

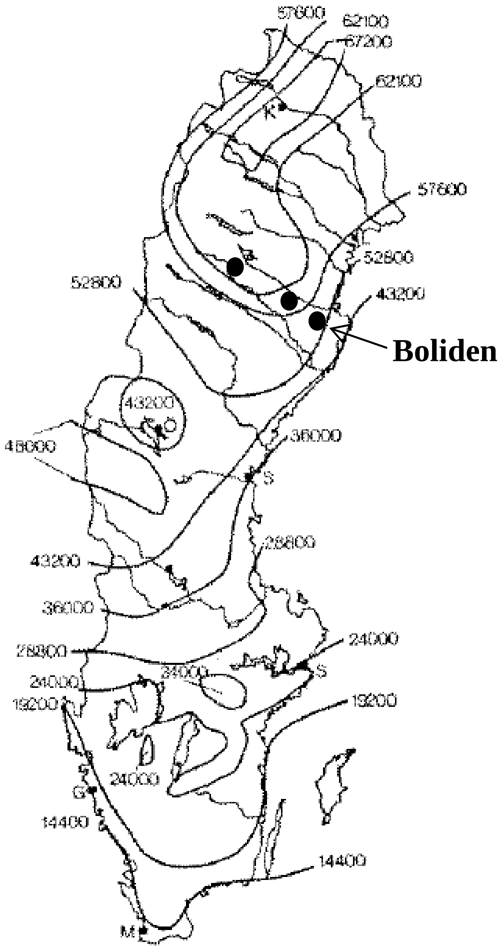


Figure 11 Map showing the variation of freezing hours in Sweden (SveMin, 2012).

2.6.2 Freeboard

Design of the freeboard should be determined with respect to wave run-up on the crest, causing erosion damages, and the wind set-up, contributing to high waves in the reservoir. These two design parameters are considered the most relevant for small dams according to ICOLD (2005-2010). Run - up defines the vertical height for the wave between the still - water level (SWL) and to the run up point on the crest. An illustration of a wave action on a dam slope is seen in Figure 12. The total amount of freeboard is determined by the sum of wave run-up and wind set-up height, see equation 2.3, during the possible worst conditions. The total amount of freeboard will be determined by the equation and geometry below (SveMin, 2012).

$$H_{freeb} = R + H_{inc} \qquad (2.3)$$

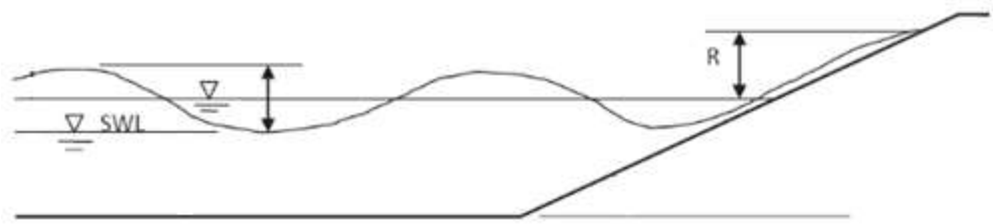


Figure 12 Illustration of parameters considered when determining the extent of freeboard (ICOLD, 2005-2010)

Alternative methods to determine the freeboard of a dam have been used by ICOLD (2005-2010). In this equation the total height of the dam and the reservoir volume are taken into account, see equation 2.4.

$$H_{freeb} = H^2 * \sqrt{V} \qquad (2.4)$$

Both of the methods have been applied and their respective results have been compared and evaluated together with other aspects considered relevant for the stability of the dam.

2.6.3 Discharge system

Design parameters for discharge systems will be considered according to experiences from the field trip. Design need to be both functional and provide a safe dam environment. Installation may be in both natural material so as in concrete or by different pipe constructions. The capacity needs to be fulfilled for both normal operating conditions so as in case of additional inflow due to extensive run off or defects in the primary spillway systems.

2.6.4 Erosion Protection Material

Due to the terrain in the area of interest, wind velocity on ten meters height above the reservoir level is assumed. The area is determined to be bare mountain and wind velocities of 25 m/s and the wind return time is set to 50-100 years are stated (SveMin, 2012).

Dimensions of the erosion protection material have been determined by Vattenfall (1988) by using the significant wave height and the angle of the slope. Recommended dimension of the erosion protection material will be two times the material diameter.

2.6.5 Lining System

Design of a liner system need to consider limitations concerning leakage as well as the processes connected to the function of the dam. Methods for evaluation have been practical once as well as technical aspects, to find the most suitable system according to production demands and current constructions.

3 Results

The intention of this thesis has been to verify governing parameters for stability of present small dams within the facilities of Boliden Mineral, Boliden. The two main objectives and the relevant design features considered have been evaluated.

3.1 Conceptual Design

Conceptual geometry of the dam seen in Figure 13 has been set according to information found during the field study and it represents one of the general dimensions of a reservoir surrounded with a dam construction.

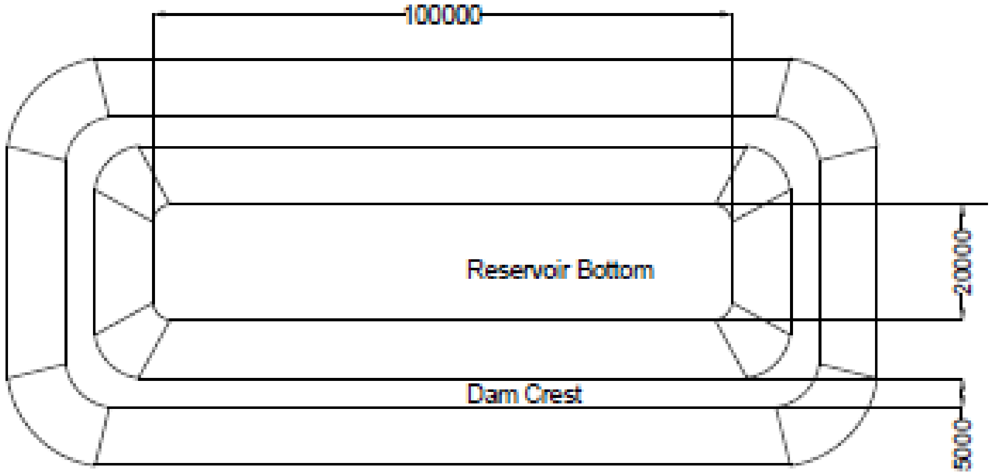


Figure 13 Conceptual geometry of the dam in a plan view.

The second alternative has been a construction with reservoir loads on both sides of the construction, which is assumed to have steady state conditions. This responds to a piezometric pressure head at an equal level through the dam, see Figure 14.

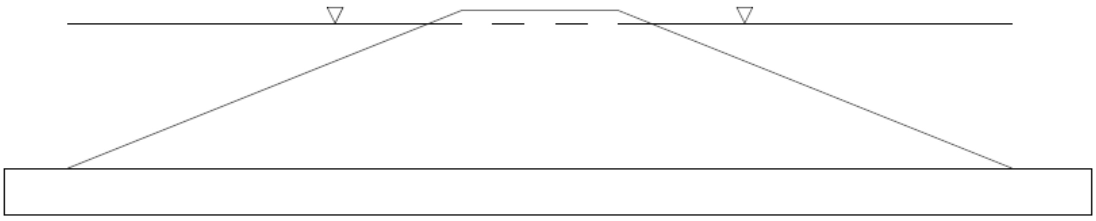


Figure 14 Steady state conditions with the piezometric head between the reservoirs.

3.2 Slope Stability

The slope of the dam will be exposed to various pressures when the reservoir level is frequently changed. What material properties will govern the stability and conditions at which the slope is stable will be analysed.

Results are presented according to the four scenarios stated in chapter 2.3. Each scenario has been tested according to stated variations in material properties: friction angle based on recommendations, applied cohesion and friction angle according to standards. As earlier stated in the methodology chapter, the freeboard height has been set to half a meter.

A sensitivity analysis was first done on a three meter high dam, see Figure 15. The different operating scenarios are presented next to each other with the slope angles 1:2 and 1:2.5. The different bars represent the different material properties, blue for no cohesion, red with an cohesion of 1 kPA and green for standard properties of friction angle.

For the normal operating scenarios, the factor of safety reaches the recommended values. Concerning the extreme scenarios there will be some issues for the slope angle 1:2 when applying a load together with a RDD. An increased cohesion results in a higher factor of safety and a decreased friction angle causes lower factors of safety.

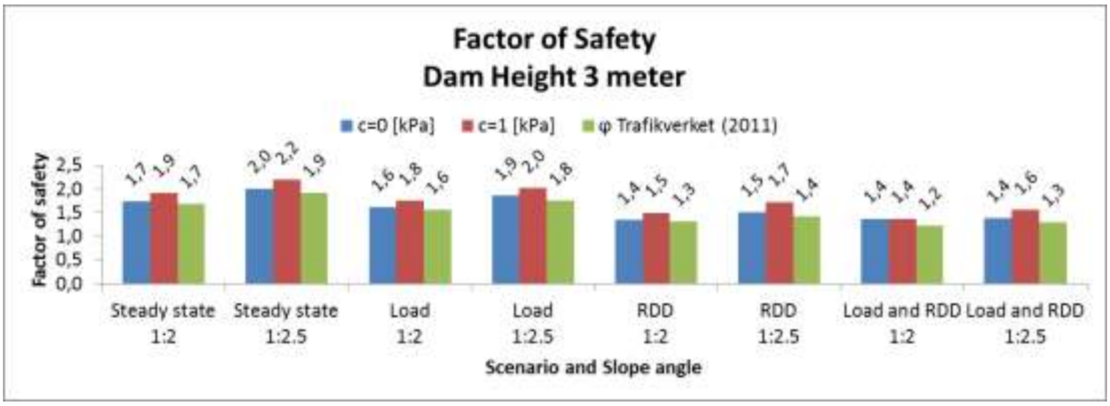


Figure 15 Factor of Safety for a dam of height three meter according to different material properties.

For a dam with the height of five meters, there will be an overall decrease in the factor of safety compared to a dam height of three meters. During normal operating scenarios there will be no problems with stability. Concerning the extreme cases there are some problems, especially in case of an RDD with an additional load, see Figure 16.

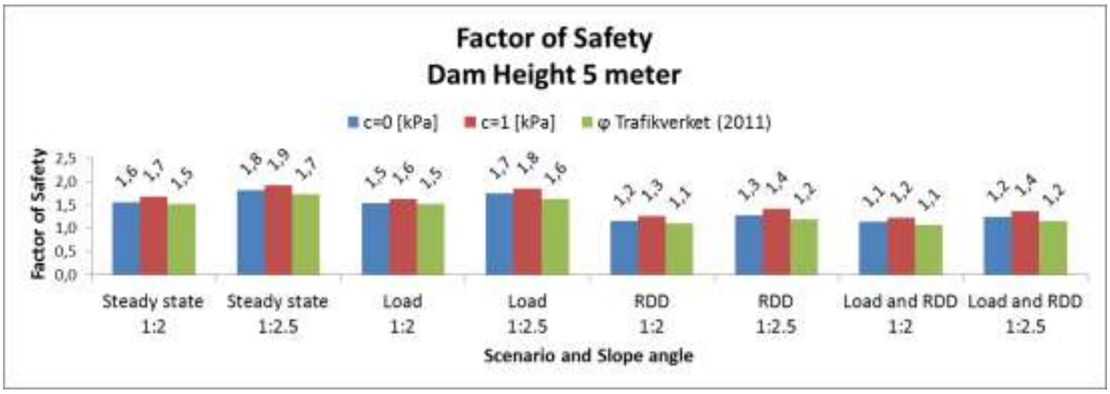


Figure 16 Factor of safety for a dam of height five meter, with different material properties.

The overall result of the stability calculations is that the geometry of the dam affects the stability. A dam with a height of three meters reaches recommended values for the factor of safety in almost all scenarios and for the five meter high dam there are some problems. Lowering the slope angle is favourable for the construction and will provide a better resistance against failure. In addition, as shown in Figure 15 and Figure 16, the factor of safety is changed if the material properties are altered.

3.3 Hydraulic Conditions

The hydraulic gradient within the embankment is affected by the variations in the reservoir level. The investigation will consider which material properties are governing the internal stability and when there may be a risk of failure.

Calculation show that the hydraulic gradient, determined in a laboratory, will be less than the evaluated critical gradient. Results are seen in Table 3. The minimum, maximum and average bars for hydraulic gradient represent the interval of laboratory results, compared to the critical hydraulic gradient evaluated according to the minimum densities and porosities. The ratio between critical hydraulic gradients and the hydraulic gradient are all above two, which indicates that the conditions in the dam are on the safe side.

Table 3 Comparison between the measured hydraulic gradient and the evaluated critical hydraulic gradient.

	Minimum	Maximum	Average	Unit
Critical Hydraulic gradient	1,26	1,35	1,31	[-]
Hydraulic gradient	0,42	0,52	0,46	[-]
Relation	**3,00**	**2,60**	**2,85**	[-]

3.4 Design Features

According to the present condition of the features and the function, the systems have been verified by calculations and with consideration to present recommendations.

3.4.1 Design of Dam Crest in Terms of Freezing Depth

Evaluations have concerned the three areas; Stekenjokk, Boliden and Kristineberg. Expected freezing depths are seen in the Table 4 below, results are displayed for both a homogenous dam and a zoned dam.

Table 4 The freezing depth in embankment dams in different geographic locations where mining activity take place within Boliden Mineral AB (SveMin, 2012).

	Homogenous Dam	Zoned Dam	
$Z_{Boliden}$	2,89	3,13	[m]
$Z_{Kristineberg}$	2,99	3,24	[m]
$Z_{Stekenjokk}$	2,82	3,05	[m]

3.4.2 Freeboard Capacity

According to evaluation by Vattenfall (1988) the dimension of the freeboard should be 0.3 meters. According to ICOLD (2005-2010) the dimension should be at least 0.4 meters. The diverse results may be described due to the difficulty to find balance between which parameter that will be of greatest importance for dam safety.

3.4.3 Discharge System

To achieve a steady outflow and a steady water level in the basin the discharge system need to be designed for the specific dam in question. The recommended design has been chosen to be a V-shaped outlet with a cover of erosion protection material, with the advantage of using the material found on site. The outflow should be constant and should not create too much turbulence and thereby affect the sedimentation process. To avoid risk of erosion damages, an erosion protection material should be applied.

According to the velocity of the water the dimension of the erosion protection material was set to 0-100 mm. This type of outlet is advantageous when doing visual inspections. There will still be a risk for erosion damages in the flow path but they will be easier to inspect. It will also be possible to detect potential erosion in the water when the water is lead above the construction and not through. Illustration of a section on the dam crest is presented in Figure 17 below. The reservoir level is rather low and the flow will be low in relation to the capacity. In the example there is also a metal plate on top of the discharge, allowing a transport path on the crest.

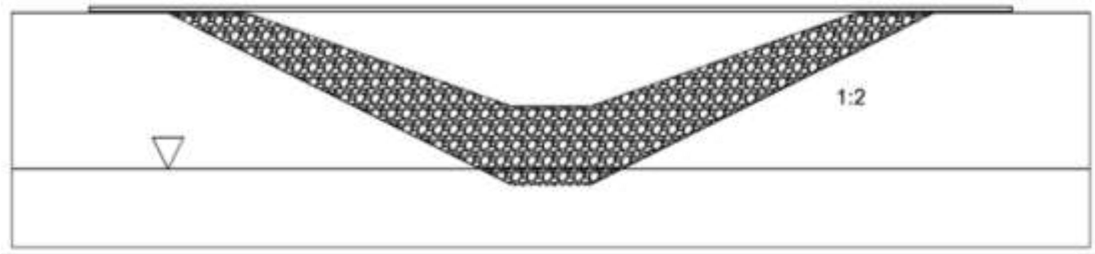


Figure 17 Section of the discharge system applied with an erosion protection material.

3.4.4 Erosion Protection Material

Evaluation of erosion protection material according to Vattenfall (1988) assumes wave action caused by wind action to be the primary threat for erosion damages. But for these rather small reservoirs, wind action may not be the primary source of damage. The purpose of the protection is primary to protect against ice loads and damages from machines. However, according to the general assumptions the dimensions of erosion protection material should be at least 0.6 meters. To prevent transport of material from the dam and through the erosion protection a filter could be applied, see Figure 18. The filter should be designed with respect to base material in the dam and connected with the material on the bottom of the reservoir.

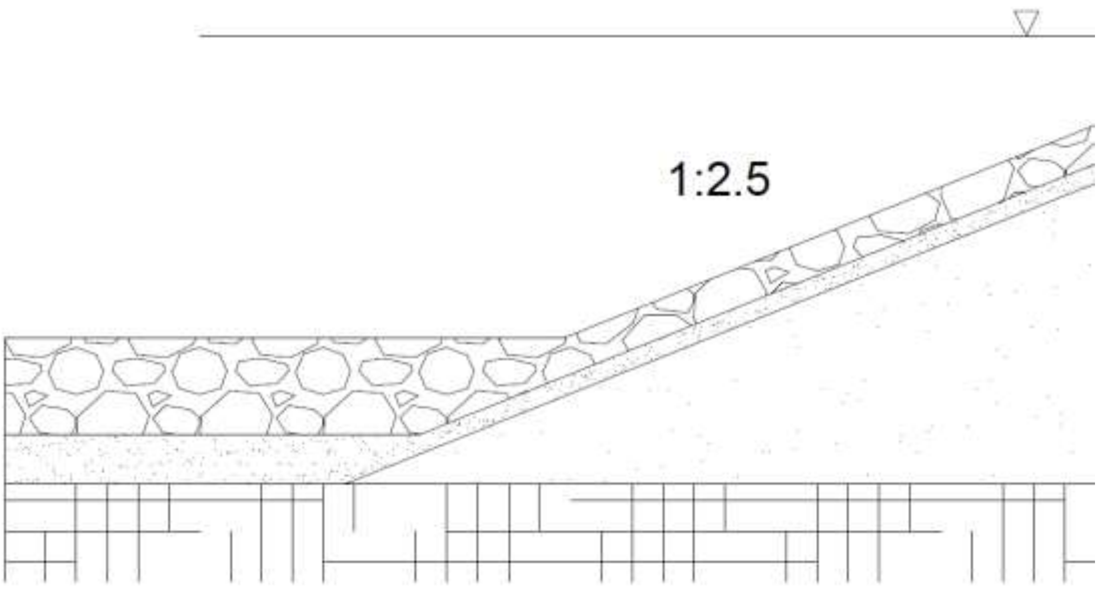


Figure 18 A system of filter and erosion protection material on the upstream side of the dam.

3.4.5 Lining System

Present conditions have been determined to be natural ground assumed to have the same characteristics as the construction material. The permeability has preferably been high, when there is a need to drain the reservoir from water. When using a geological liner system the suggestion would be to use a basic reinforcement of the foundation with a cover of erosion protection material to protect the clay soil layer, see Figure 19. This is important both for protection of the liner system as well as the dam material.

With a clay soil liner there may be difficulties using the same draining method as the present, other solutions for removing water needs to be applied. Geomembrane should be applied when there is a need for waterproof systems. Protection against damages on the geomembrane needs to be ensured and applied.

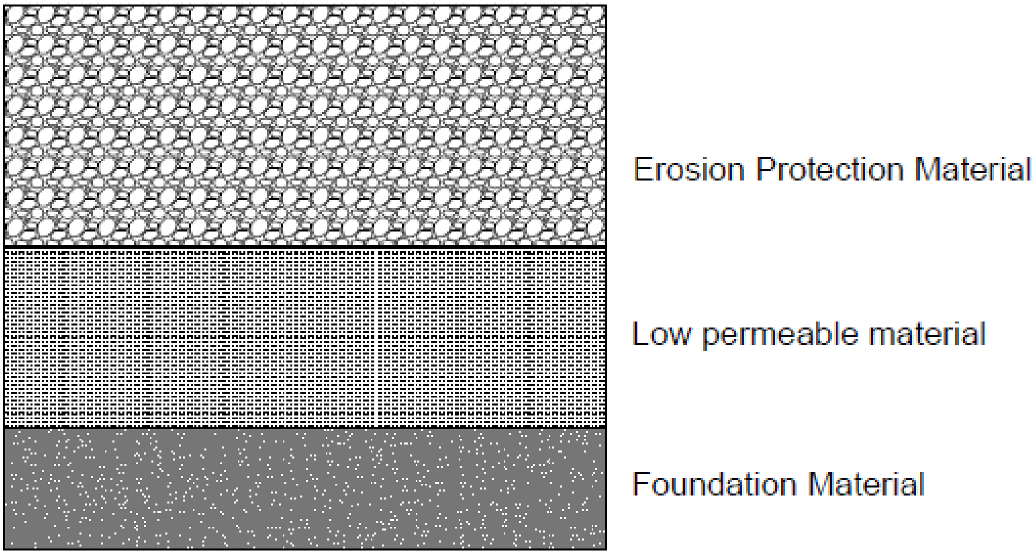


Figure 19 Natural foundation reinforced with a low permeability clay liner and erosion protection material.

4 Discussion

Providing a conceptual design for a dam for this rather diverse application area will contribute to some extent of assumptions and generalization. However, the results are a foundation describing the sensitivity and stability governing aspects, for these within the mining industry in proportion rather small dam constructions. Hence, the aspects considered to affect the stability the most seems to be the process and the operations surrounding the constructions. General evaluations of systems and stability have been done, there a no site-specific tests. The material investigation applied represented a specified area and have considered being representative. A generalization of the material properties was necessary, which should be taken into consideration when evaluating the results of the thesis.

The function of the dam and the demands on an easily operated and constructed product has been the main focus for these dams. Small dams operating in the mining industry are in some considerations exposed to larger loads and stresses of the material than larger dams with stable reservoir levels. Continuous changes in reservoir levels will cause a change in the conditions of the material within the dam even during stable conditions in slopes. Effects on the material behaviour in a long-term perspective are not investigated in this thesis. However, there is a need to verify if the material and the material properties will change over time. It is determined that there is seldom a defined life span for the construction. The dams are built without any reflection on if they should be operating for 10 years, 20 years or even longer. If an evaluation for expected effects on the material due to the variations in reservoir levels is determined there is possibility to see the status of the material and if there is an effect to the stability of the material.

Simulations concerning extreme conditions have been chosen to be a rapid drawdown of reservoir level. There is also another aspect, such as external conditions or weather conditions that would have been of interest to investigate. However, in this study the majority of the constructions have been considered not to be effect of extreme precipitation or surface runoff due, causing additional inflow to the reservoir. Also that it is not common with seismic actions. However, it is necessary to define additional aspects that may affect dam safety, such as external or site related consequences.

4.1 Sensitivity Regarding Material Properties

The intention was to investigate whether the differences in the material properties should affect the stability also for small dam constructions. Results from the investigation show that the slope stability will be affected from changes in the material properties however; the geometry will also be of importance. Even if there have been some stability failures in the area of investigation the main causes have not been found to be slope failures. This is why the material was assumed to have some cohesion, which would benefit the slope stability.

Some cohesion has been proven to have advantages for the slope stability, but an increase of cohesion may also contribute to a decrease of the critical hydraulic gradient. The risk for internal instability might be higher in a fine grained material. To contain stability for both slope stability and gradients within the construction, the critical properties for both parameters must be evaluated and taken into consideration when designing the dam.

Compaction of material will be of essential importance for the final properties of the material. In regulation and guidance for dam construction there are suggestions and directives for the process of testing results and follow ups on compaction may be somewhat hard to achieve in a practical manner. This is due to the volumes of construction material is rather small and the time of constructing a dam may in comparison be fast. There need to be other methods to determine that the compaction is sufficient, rather than having continuous testing during the construction.

The material properties of till will be affected of freezing actions during winter, in relation to the dam height the rather large expected freezing depths need to be considered. Procedure of removing snow from the crest should be considered when confirming the stability for a long-term perspective for the dam. Due to the continuously operating of the water treatment system and the non-acceptance concerning stop in production, the dams need to be accessed during the entire year. However, the removal of snow from the dam crest should to the utmost be limited, in order to protect the material from freezing damages.

4.2 Reflection on Appearance of Small Mining Dams

According to the field trip there are few directives concerning production guidance, operation procedures and inspection routines. Stability problems have been considered to be caused mainly by lack in experience and procedures concerning operating of dam systems.

The freeboard height has been determined to cause larger demands on stability when the reservoir level is increased. It is needed to have normal operation reservoir levels and also to determine a level where there is risk in dam safety. If the level in the reservoir start to increase it is possible to decrease the sensitivity and increase the dam safety, by having discharge systems with variable discharge capacities. Defects in the primary discharge system may cause rising levels in the reservoir. To provide a redundancy of the dam system, one solution would be to have a safety discharge system, an overflow spillway. The level of the overflow should be determined in concern to when there is a risk for stability problems in the dam slope.

The usage of geomembranes and different liner systems has been diverse for the constructions. The usage of geomembranes has not been considered for the stability calculations. Assumptions made have been that the stability of the embankment needs to fulfil similar stability demands as dams with liner systems in natural materials. Usage of both geomembranes and natural liner systems will contribute to a larger control of seepage of residue water. Systems where the water will be drained through the sediments and into the ground will not be functional with low permeable liner systems. Other methods for removing water from the sediments need to be determined. Removal of sediments will be more sensitive to avoid damages of the liner system. Both to protect the geomembrane and to avoid damages on the soil layers of natural liner systems causing potential leakage paths.

It was determined that in some cases there is a need to have waterproof construction. The usage of natural materials for these kinds of liner systems demands an extensive system of different layer compositions. There is a need to define when these situations may occur and to what extent it should be fulfilled. Whether it is according to legislation demands or company policies it would contribute to transparency within the decision making.

To find a more unified way of construction small dams within the company there are in fact clear directives in present regulation such as GruvRIDAS (SveMin, 2012). Whether the regulation is applicable in all areas could be further investigated but in some areas it has been determined to be possible. For evaluating material properties and features concerning safe operation there are possibilities to apply GruvRIDAS also for small dam constructions. Thought there may be difficulties when caring out continuously testing during construction, when the production is not as time consuming as larger dam projects. There need to be other methods to verify that the final construction will fulfil stated demands and provide a safe dam environment.

5 Conclusion

This thesis has been based on a field study in the area of Boliden. All the five mining sites have been visited to gather information concerning performance, function and environment of operating dams. To evaluate the condition of the dams and the performance regarding demands and stability, the general model was stated together with a conceptual design. The two loading conditions, water load and internal hydraulic load, were determined to be main parameters affecting the stability.

The material investigation and the verification of the material have led to a conclusion that the materials in the area are suitable for construction of small dams. It is also determined that the variation in the material properties cause instability problems for the dams. The results show that characteristics of the material will contribute differently to the stability. Materials with cohesion will benefit the slope stability but will increase the hydraulic gradient, which in turn may cause internal instability. Problems with stability for the dam of interest have been determined to be caused by lack of clear processing of the dams; both during construction and while operating the dams. This needs to be applied before the dams have been taken into operating.

The small dams operating in different water treatment facilities have been seen to be of low priority despite the importance of dams within the water treatment system. With this in mind, it is recommended to always have a redundancy in the systems to decrease the sensitivity in specific details in dam composition. For example, overtopping and leakage of untreated water or sediments may be avoided if spillways and seepage collection techniques are applied.

The verification of stability of small dams has been found to have similarities with the appearances from the field investigations. Constructions found to have stability problems have in some cases also been found on the sites. Determination and further investigation of material properties and the geometry of the dams will provide a safer operation of small dams within the area.

6 Further Investigations

To continue the verification of reliable design for small dams operating in the mining area of Boliden, there are some suggestions further investigations. Ageing of material due to continuously seepage and erosion of material may potentially cause stability problems. The amount and the consequences over time could be further investigated.

In areas where there is no relevant regulation available, development of other evaluations methods need to be stated. According to results and conclusions the overall solution to problems with dam safety, concerning small dams, would be to develop well-defined procedure planes and policies. This should be considered both during construction and operating of the dams.

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Appendix A - Survey of Small Dams in Mining Areas of Boliden

The first part of this thesis contained a field study to the mines operated by Boliden Mineral in the area of the Skellefteå fields, Västerbotten. In the following appendix some of the construction details will be further described as well as drawings and pictures from the areas of interest. The area and the mines are presented in Figure 20, where the pink marks represent the mines in question. The mines are located in Kristineberg, two mining sites in Maurliden, Renström and finally Kankberg. The area of Skellefteå and the mining areas are characterised by large areas of forest lands and wetlands. The smaller communities in the surroundings are Boliden, Norsjö and Malå, and the largest city in a close distance is Skellefteå.

Figure 20 The concerned area of investigation and the mining sites in question for this thesis.

Year of construction for the small dams varies between 1992 and 2012 and the reservoir volumes show wide diversity. The construction features are seen to be dependent on needs according to mining activities, year of production and material availability. Daily surveillance of the dams is carried out by operating staff in the mines. It is determined that the extent of dams has been developed as the mine production has developed.

As previously mentioned the different reservoirs operate in larger systems. Example of how the extent of a water treatment system may occur and the complexity are seen in Figure 21. The different reservoirs have different tasks and the amount depend on the extent of sediments and the need of closing some of the reservoirs when excavating residue material. The extents of a reservoir depend on the production need. The locations are particularly dependent on the function and on providing a safe production.

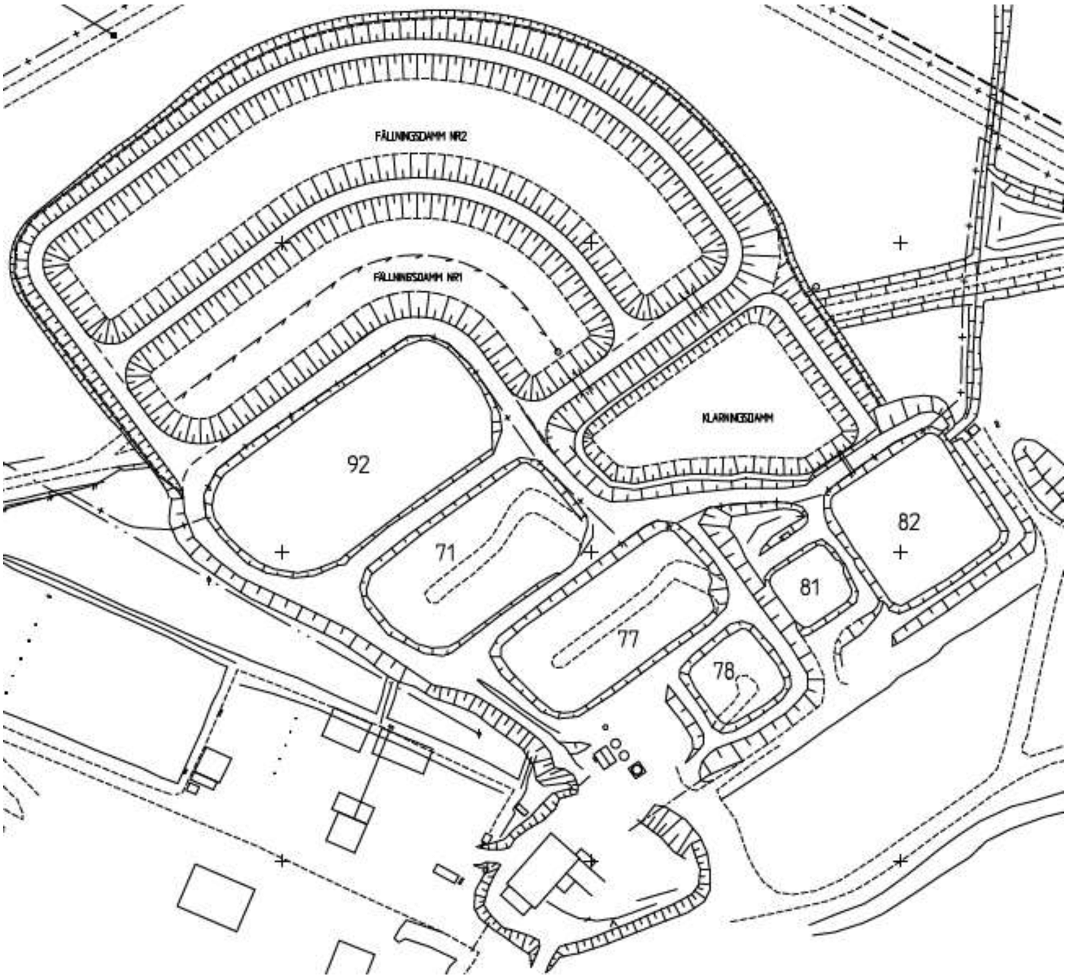


Figure 21 Example of a large system of reservoirs operating in one of the mines.

Below in Figure 22 one example of a storage reservoir is shown, the dam consists of two reservoirs working in a system connected with a threshold. The inflow is through a pipe from the mine and the outflow through a bottom pipe connected with the treatment plant. This dam has also been applied with an emergency threshold on the crest. The intention is that the water will be let out through the threshold and down on the downstream slope and connected to a screen trench. The reservoir is partly excavated and the height may be set to zero on two sides and filled earthfill embankment on two sides. This construction has been applied with a geomembrane liner; also the emergency threshold has been covered with geomembrane to avoid risk of erosion damages.

The extent of geomembrane differs among the sites and the opinion is that in some cases the usage of geomembrane is dependent on when the water have not yet been treated. The geomembrane appears to have been avoided when there is a need to empty the reservoir from sediments. When geomembrane have been used there is a system with a sludge pump to remove potential residues.

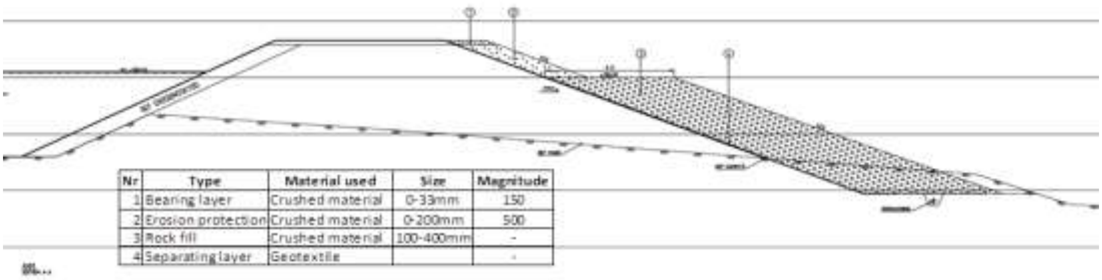
Figure 22 Water storage reservoirs connected with an overflow threshold.

Reservoir with the intention to contain sediments will occasionally be drained to excavate the material; the water will be percolated through the underground when the inflow of water is stopped. The process may appear differently due to the composition of the sediments. Removal may be carried out by excavator that is located on the crest of the dam and a dumper transporting the residues to a landfill for storage. If the location of the dam permits a tractor may be driven down in the reservoir provided that the sediments are stable. One example of a sedimentation basin is seen in the Figure 23 below. This is rather time consuming procedure and dependent on the permeability of the underlying foundation.

Figure 23 The sediments have been drained and waiting to be excavated.

There have been attempts to pump the sediments from a reservoir. By lowering the water level to somewhat above the surface of the sediments and then pumping the sediments away with for example a sludge vehicle. The water level may need to be lowered in several steps to contain the consistency of the sediment in a sufficient dissolved condition and to avoid pumping too much water.

The geometry of the constructions is as seen different according to application area and geometry. The heights have been determined to vary between 1-5 meters and the slopes from 1:5 to 1:2.5. Below in Figure 24 a drawing of a section from one of the sites is displayed. The construction consists of homogenous material and are reinforced with rockfill on the downstream slope due to instability and extended seepage.



Nr	Type	Material used	Size	Magnitude
1	Bearing layer	Crushed material	0-33mm	150
2	Erosion protection	Crushed material	0-200mm	500
3	Rock fill	Crushed material	100-400mm	-
4	Separating layer	Geotextile		-

Figure 24 Section of a dam, reinforcement with rockfill.

Discharge systems may due to the surroundings appear differently and there have been several solutions found in the sites. Below in Figure 25 the two basins are connected with pipes beneath the water surface. The construction consists of a till embankment with an erosion protection material on the reservoir side. This solution is rather common according to the field study. Disadvantages seen are though the limited possibilities to do inspections of the conditions of the pipe and the possible exposure of internal erosion in connection to the pipe.

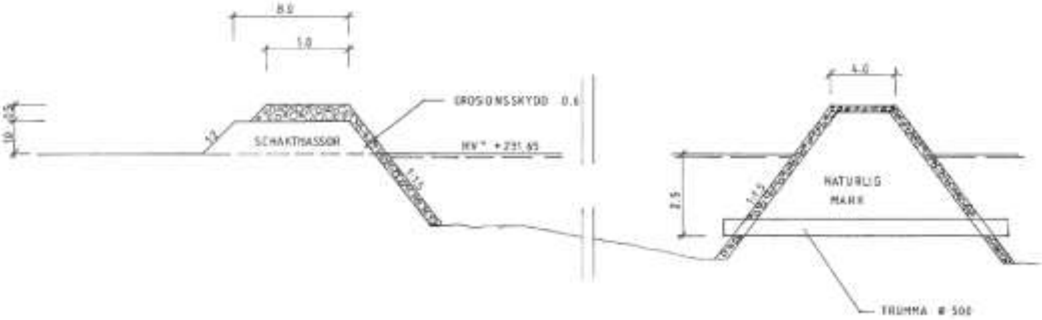


Figure 25 Section of two reservoirs operating as a system, connected with a pipe.

For the sedimentation reservoirs there are solutions with overflow dikes, plastic and concrete pipes through the dam other examples could be thresholds in both natural material and concrete. The solutions are dependent on the intention with the reservoir and the elevation of the connecting reservoir. Thresholds in till or concrete located on top of the crest have advantages in terms of inspections, as well as redundancy for dam safety if the level in the basin is increasing.

In Figure 26 a concrete threshold are shown, containing two levels with the possibility to increase outflow capacity when needed. In times of lower levels the velocity of the water will be kept high and prevent risk of freezing during winter time.

Figure 26 Concrete threshold in a dike connected from a system of reservoirs.

Reflections carried out from the field study have been that there are problems concerning the stability. In some cases there has been instability in slopes causing failures. Some of the sites have been described having high reservoir levels and an extended seepage have been noted. There are indicated problems concerning seepage through the constructions and also sinkholes have been found on downstream slopes. Sinkholes may be indications of process of internal erosion; the intensity of then erosion may led to stability problems and needs to be considered as a potential safety risk.

The extensive material investigation by Mattsson (2007) was initiated before the construction of a large dam for tailing deposits in the area of Boliden. In the investigation there were 165 test pits and 20 samples were sent to laboratory for grain size analysis. Five samples were also tested for hydraulic properties. Laboratory test was carried out according to Nippel permeameter and Universal permeameter. Conditions determined according to sieving of material have been considered in the evaluation of hydraulic gradients. The material assumed to be governing has been silty till and the amount of fines has shown to be diverse.

Appendix B - Slope Stability Simulation

GeoStudio 2007 is a CAD software used to solve different geotechnical problems. In this thesis the program GeoSlope have been applied to evaluate the slope stability, a program related to the Geostudio2007 software. In this appendix there will be more detailed presentation of the procedure concerning slope stability simulations. Initial approach has been to determine analysis type so as the evaluation methods of the slip surface.

The geometry of the dam was set according to definition in the general model presented in the Methodology chapter. Initially analyse type and porewater pressure conditions was applied, so as the slip surface approach example are shown below in Figure 27.

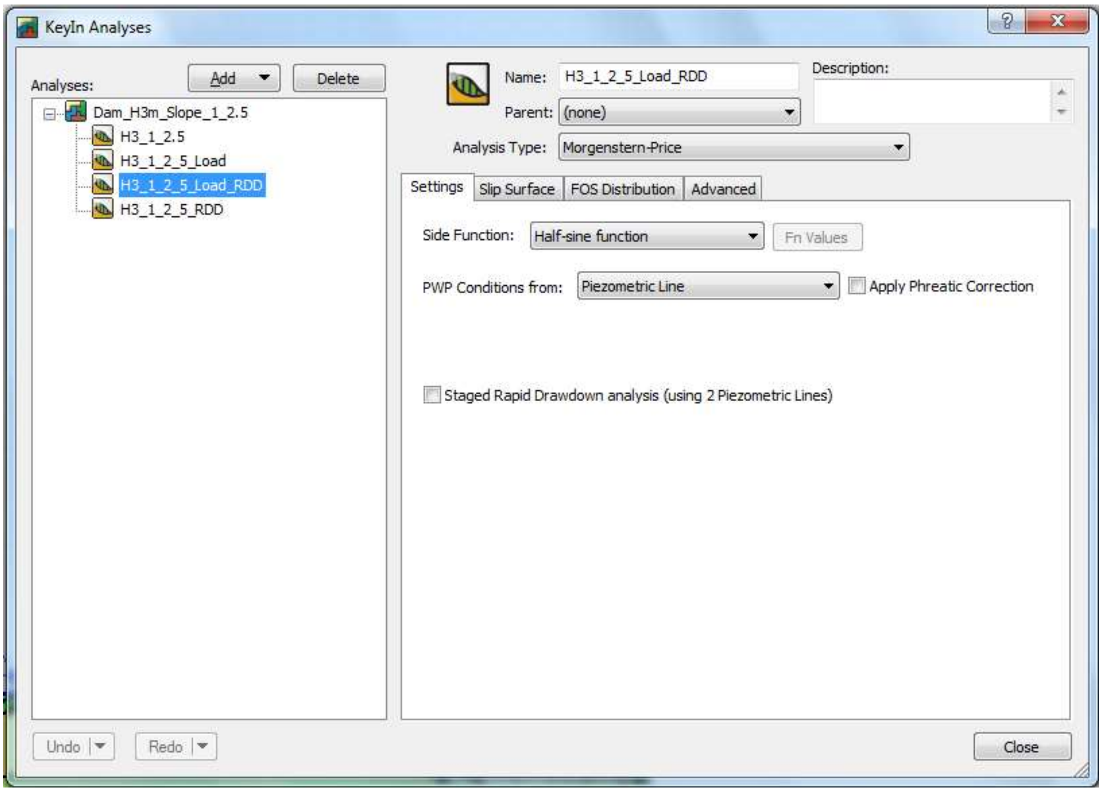


Figure 27 Input of analyse parameters and hydraulic conditions in GeoSlope2007.

The simulations have been applied with two meters of foundation material. This has been assumed due to that natural stored material will contain a higher unit weight and friction angle, than the disturbed material of the same origin. Material properties needed were unit weight, cohesion and friction angle. By first drawing the regions of the geometry of the dam and then applying the material properties for each of the parts, boundary conditions were set. Hydraulic conditions have been applied by the piezometric line, representing both the reservoir level and the conditions within the dam.

From the calculation the following illustration was displayed, see Figure 28. The dam below have a height of three meters and the slope angle have been set to 1:2. The piezometric line has been assumed to exit at the toe of the embankment with a full reservoir on the other side. The axis to the left represents the reservoir level and to the right the responding factor of safety is displayed.

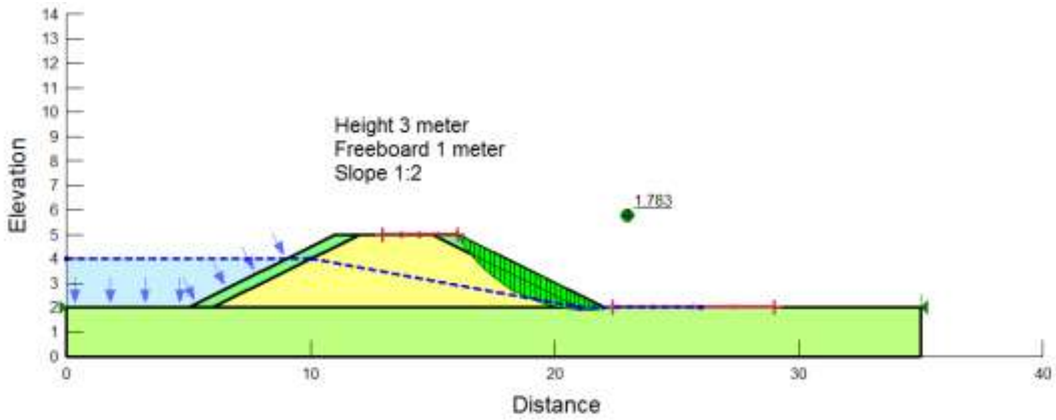


Figure 28 Illustration of the dam in GeoSlope2007 and the responding factor of safety.

The different scenarios, *steady state*, *steady state with load*, *rapid drawdown* and *rapid drawdown with load* have been applied for each of the geometries. For the program to respond for a scenario where a sudden rapid drawdown have occurred you need to find a point where the effective stress are zero. This is simulated by assuming steady state conditions on both sides of the construction and then on one side there is a rapid drawdown of the reservoir. The piezometric line has been added along the slope, this will display the exact moment where the gradient have not yet started to decrease within the construction. Responding to the moment where there is no resisting load on the slope and assumed to be the most critical moment.

In the Figure 29 below the extreme scenario when a rapid drawdown have occurred on one the right hand side of the dam. The dotted line represents the piezometric line and the solid line on the crest and at the dam toe indicates the entry and exit point of the expected failure zone. The expected factor of safety for this specific geometry and the stated boundary conditions are seen to the right in Figure 29.

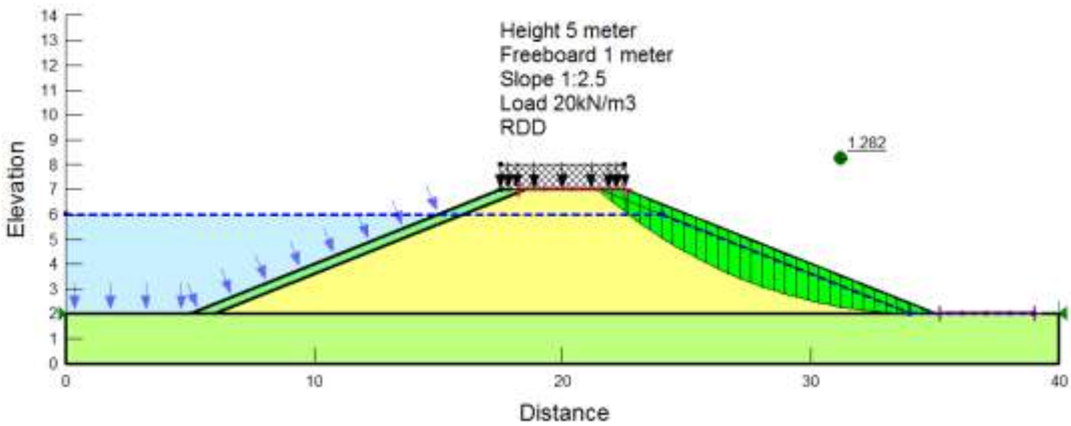


Figure 29 Responding factor of safety when applying load and simulating a rapid drawdown of reservoir.