Experimental Assessment of Contact Erosion in Embankment Dams with Glacial Till Core

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Master programme in Civil Engineering, with specialization in Mining and Geotechnical Engineering

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Preface

The research work presented in this thesis report has been carried out at the Department of Soil Mechanics in the Lulea University of Technology. The input and suggestion received from all the people directly or indirectly related to this thesis have been enormous.

I want to thank Vattenfall Research for their generous funding and infrastructure support to carry out this work. I am incredibly grateful to Johan Lagerlund from Vattenfall Research labs in Älvsby, Sweden for his continued support and continuous strive for perfection.

I am forever indebted to the department of Soil Mechanics and my Supervisors Professor Jan Laue and Ingrid Silva without whose support and motivation, this report could not have seen daylight. I would also like to acknowledge the support of Karina Tommik, Tarun Bansal, Gurmeet Shekhar, Per Gunnvard and Jasmina Toromanovic for their continuous assistance throughout the length of the project. I would like to acknowledge the special role of Associate Professor Hans Mattsson for introducing me to the subject of soil mechanics and dams. His enthusiasm, his passion and drive to see the students succeed in the field of geotechnical engineering helped me remain motivated throughout the project timeline.

At last, thanks to the efforts of Thomas Forsberg in bringing the entire project into fruition through his expertise in geotechnical laboratory work.

Chinmoy Pattanaik

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Luleå, Sweden
Abstract

Contact erosion is an internal erosion mechanism which happens inside an embankment dam at the contact zone between core and filter or core and foundation under the condition of the tangential flow of water parallel to the contact zone. It can initiate under normal reservoir loading conditions or in aggravated cases of higher hydraulic loading due to flood water storage. The long-term effect of this process can be the genesis of a pipe leading to the potential development of sinkholes, clogging of filter drains causing structural instability. As this process develops and progresses deep inside a dam body, it is essential to study the mechanism more closely.

In this report, laboratory method was used to test for contact erosion on a plexiglass apparatus replicating a small-scale dam cross-section. Two types of glacial tills were used to construct the core with varying degrees of compaction on top a filter layer composed of gravel. Testing involved: (i) allowing water to flow through the filter layer parallel to the contact zone between the soil layers, and (ii) monitoring of pore water pressures and turbidity of the outflowing water on the downstream side to check for eroded particles.

Key findings of experimental work were the description of geometrical configuration between filter and base soil, and inflow water velocities which cause initiation of contact erosion. Effects of base soil layer compaction and filter layer design along with the geometrical properties of the base soil on contact erosion and structural stability were summarized. Contact erosion can lead to the development of backward erosion piping and sinkholes if left unchecked or undetected.

Results indicate that Terzaghi’s filter criteria need to be breached for contact erosion to initiate. Geotechnical factors like fine-grained particles content, the degree of compaction play a significant role in dam’s ability to arrest contact erosion. Thickness of the filter layer directly influences the stability of the core soil layer. The primary advantage of performing these lab tests is that they are much cheaper and faster to process and analyze as compared to field measurements.
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<th>Description</th>
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</thead>
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<tr>
<td>JS</td>
<td>Glacial till soil sample with 19% fine-grained particles content</td>
</tr>
<tr>
<td>IS</td>
<td>Glacial till soil sample with 31% fine-grained particles content</td>
</tr>
<tr>
<td>$D_{\text{max}}$</td>
<td>Maximum particle size of filter. (mm)</td>
</tr>
<tr>
<td>$D_{\text{min}}$</td>
<td>Minimum particle size of filter. (mm)</td>
</tr>
<tr>
<td>$d_{\text{max}}$</td>
<td>Maximum particle size of base soil. (mm)</td>
</tr>
<tr>
<td>$d_{\text{min}}$</td>
<td>Minimum particle size of base soil. (mm)</td>
</tr>
<tr>
<td>$d_{10}$</td>
<td>Grain size corresponding to 10% mass passing the sieve for base soil. (mm)</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>Grain size corresponding to 30% mass passing the sieve for base soil. (mm)</td>
</tr>
<tr>
<td>$d_{60}$</td>
<td>Grain size corresponding to 60% mass passing the sieve for base soil. (mm)</td>
</tr>
<tr>
<td>$D_{15F}$</td>
<td>Grain size corresponding to 15% mass passing the sieve for filter. (mm)</td>
</tr>
<tr>
<td>$d_{85b}$</td>
<td>Grain size corresponding to 85% mass passing the sieve for base soil. (mm)</td>
</tr>
<tr>
<td>$C_U$</td>
<td>Coefficient of uniformity</td>
</tr>
<tr>
<td>$C_C$</td>
<td>Coefficient of curvature</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Moisture Content (%)</td>
</tr>
<tr>
<td>$Y_U$</td>
<td>Maximum Dry Unit Weight (kN/m$^3$)</td>
</tr>
<tr>
<td>$i$</td>
<td>Hydraulic gradient</td>
</tr>
<tr>
<td>pp1</td>
<td>Upstream side piezometer tube reading</td>
</tr>
<tr>
<td>pp2</td>
<td>Downstream side piezometer tube reading</td>
</tr>
<tr>
<td>$\rho_t$</td>
<td>Bulk density (t/m$^3$)</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Dry density (t/m$^3$)</td>
</tr>
<tr>
<td>USBR</td>
<td>U.S. Bureau of Reclamation</td>
</tr>
<tr>
<td>USACE</td>
<td>U.S. Army Corps Engineers</td>
</tr>
<tr>
<td>ICOLD</td>
<td>International Committee for Large Dams</td>
</tr>
<tr>
<td>ILH</td>
<td>International Levee Handbook</td>
</tr>
</tbody>
</table>
1.INTRODUCTION

1.1 Background

Embankments dams made of earth fill core can be susceptible to internal erosion of either the embankment and foundation or both making it one of the primary reasons for dam failures around the world (ICOLD, 2015). According to USBR and USACE, internal erosion is a generic term used to describe the detachment and transportation of soil particles by the passage of water through a soil body (ICOLD, 2015). Before 1980, there was a lack of in-depth studies into intergranular studies except for Terzaghi filter criteria which were designed keeping in mind the ability of larger granular particles to limit the flow of sediments through them (USACE, 2013). In the mid-1980s period, Sherard (Sherard et al., 1984) developed new standards through continuous laboratory testing and back calculating the data gathered from previously failed dams. These studies were further analyzed by Foster (Foster et al., 1998) to create new filter criteria for assessing dam susceptibility to internal erosion.

According to USBR, internal erosion poses higher risks to dam safety as it can occur during normal operations, and this process also affects the safety of levees. Internal erosion can develop in dams in response to these following types of loading mechanisms (USBR, 2014):

- Static/Normal Operation – at normal reservoir level or a threshold level that initiates internal erosion.
- Hydrologic Loading – during floods or at elevated levels of water head than operating level.
- Seismic Loading – deformation or cracking caused by seismic energy can initiate internal erosion along the cracks.

Contact erosion is an internal erosion mechanism which develops along the embankment foundation boundary zone when seepage flow is parallel to this boundary Figure 1. Although there is no record of any structural failures due to contact erosion, this mode of erosion can lead to the development of sinkholes and pipes if left unchecked (ICOLD, 2015).

![Figure 1. Potential failure mode due to contact erosion (ICOLD, 2015)](image)

Potential hazards like this make the main reason for conducting laboratory experiments to study contact erosion phenomenon more closely. According to Beguin (Beguin, 2011) broadly graded cohesionless soils are more susceptible to contact erosion. Glacial till is indigenous to Swedish geology, and it is used to create the core for embankment dams. Unfortunately, numerical methods cannot successfully analyze the potential failure modes developed due to internal erosion due to the complexity of...
processes associated with them. Hence, laboratory experiments have been conducted to replicate the scenarios inside an embankment dam.

This thesis aims to study the initiation and effects of contact erosion on the structural integrity of dams in the foreseeable future.

1.2 Motivation
According to a report from University of New South Wales (Foster et al., 1998), analysis of dam failures from historical accidents in embankments of large dams constructed from 1800 to 1986 showed the results represented in Figure 2

![Figure 2. Dam Failure Statistics (Foster et al., 1998)](image)

Embankment dams in Sweden are made up of broadly graded cohesionless glacial till having $d_{\text{max}}$ ranging from 30 to 50 mm and typically laid over a foundation of solid rock with the voids filled with grout to avoid development of seepage paths. With the passage of time, the injected grout in the bedrock or foundation may start to erode making contact zone between the embankment dam and its foundation may become more pervious. Therefore, the region has a potential for contact erosion to initiate. Contact erosion can also originate inside the dam where core and filter layers are in direct contact with each other. At this stage, knowledge about contact erosion in glacial till core dams is minimal, hence the necessity arises of performing tests on the glacial till to assess the long-term effects of contact erosion.

As field monitoring methods like core drilling are expensive and time-consuming, laboratory testing of base soil using contact erosion tests can save time and resources. Previously tests conducted by Schmitz (Schmitz, 2007) and Beguin (Beguin, 2011) have shown values of critical velocity at which contact erosion develops. These tests have been useful in predicting the long-term effects of continued erosion of the core. Hence, assessment of the core soil performance against undergoing contact erosion can be done by testing methods established by Beguin (Beguin, 2011).
1.3 Thesis Aim
Compilation of this thesis report is done with the primary goal of studying the behavior of the contact zone between the core and filter layer of an embankment dam made of glacial till core. The objectives of doing experimental work on contact erosion were to determine:

- $D_{15}/d_{85}$ ratio which leads to contact erosion.
- Critical hydraulic gradient and inflow velocity which initiates contact erosion.
- Effect of compaction on the development of contact erosion.
- Effect of pore pressure on the contact erosion process and base soil structural stability.
- Effect of erosion on the grain size distribution of contact zone and core.
- Observing the ability of the core to self-heal during ongoing erosion.

All these data are compiled to investigate the long-term effects of elevated hydraulic loading on the performance of core soil.

1.4 Overall Methodology
Two glacial till soils native to Swedish geology with different fine-grained particles content (20 % and 30 %) were chosen as base soil layer. The laboratory method of creating conditions for investigating contact erosion process involved compacting multiple layers of glacial till soil until a height of 15 cm on top of a filter layer of 5 cm height in a plexiglass apparatus with measurements of (30*20*50) cm³. An overhead tank was used to maintain a hydraulic gradient and water flowed through the filter layer, tangential to the boundary between the two soil layers.

Water entered through a hose with a diameter of 10 mm into the bottom part of the lateral walls of the apparatus. Piezometric tubes located along the longitudinal section recorded the pore pressure changes throughout the tests. The flow rate was measured from varying time intervals at the downstream side to determine the velocity of water going through the filter soil layer.

Turbidity measurement of the outflowing water on the downstream side gave the approximate rate of contact erosion at any given instant of time. Testing duration varied depending upon the base soil layer’s response to contact erosion, a steady range of turbidity values implied point of equilibrium had been reached for any gradient.

On the downstream side, the outlet drained into a set of three sedimentation ponds containing sieves of 125 µm. Collected sediments were then dried and sieved to check for the particle size distribution to record losses in the base soil layer.
2. Literature Review

2.1 Introduction

Internal erosion is the process of dissolving of soil particles due to the passage of water through its body (ICOLD, 2015). Although most of the dams are constructed keeping internal erosion in mind, there have been cases where improper monitoring and inaction led to failure in the main embankment. The methods to measure and quantify internal erosion exist but their results are highly debatable as they are generally based on the probabilistic approach leading to a risk matrix (ICOLD, 2013).

Internal erosion develops and progresses due to inherent defects in the core soil body while construction or compaction of the layers. It’s a gradual process, and sometimes it may take years to see any visible change in the surface of the dam. Potential failure modes can develop due to loading conditions at normal reservoir operating conditions or at a threshold level or even due to seismic loading.

According to (Garner & Fannin, 2010) initiation of internal erosion is dependent on the factors as shown in Figure 3.

Internal erosion encapsulates a chain of events from initiation till breach, USBR and FEMA have developed a generic tree for describing the chain of events from background conditions till a potential failure mode as shown in Table 1.

![Figure 3. Parameters leading to internal erosion (Garner & Fannin, 2010)](image-url)
Table 1. Post erosion phase events (USACE, 2013)

<table>
<thead>
<tr>
<th>Reservoir Loading</th>
<th>Threshold level to initiate erosion process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existence of flaws</td>
<td>Presence of cracks, high permeability zone and zones subject to hydraulic fracture.</td>
</tr>
<tr>
<td>Initiation</td>
<td>Commencement of erosion</td>
</tr>
<tr>
<td>Continuation</td>
<td>Existence of unfiltered or inadequately filtered exit leading to uncontrolled seepage flow.</td>
</tr>
<tr>
<td>Progression</td>
<td>• continuous stable roof or side walls</td>
</tr>
<tr>
<td></td>
<td>• failure of the upstream zone to limit flows and</td>
</tr>
<tr>
<td></td>
<td>• No self-healing by upstream zone</td>
</tr>
<tr>
<td>Detection</td>
<td>Unsuccessful detection and intervention.</td>
</tr>
<tr>
<td>Breach</td>
<td>Uncontrolled release of stored water.</td>
</tr>
</tbody>
</table>

According to USBR, internal erosion mechanisms are:

- **Backward Erosion Piping** - Commences at the exit zone of seepage flow on the downstream side and erodes backward towards upstream side supporting pipe along the pathway as shown in Figure 4. It is the most dangerous mechanism as it involves the progression of a subsurface pipe towards the reservoir.

*Figure 4. Phases in Backward Erosion Piping (van Beek et al., 2010)*
In some cases, piping leads to the formation of sinkholes when soil particles migrate downwards but involve aggravated conditions exacerbated by the presence of precipitation or seepage flow. A temporary void grows near the seepage path until the pipe cannot be supported giving rise to sinkholes.

- Concentrated leak erosion – Occurs when tractive seepage forces along a crack within the soil, adjacent to wall or conduit are enough to detach and transport soil particles into an unprotected area as shown in Figure 5. Once initiated, it can lead to backward erosion piping or sinkholes (ICOLD, 2016). They may also occur through cracks formed by differential settlements, tension cracks or hydraulic fracture of a cohesive clay core (ICOLD, 2013).

![Figure 5. Concentrated Leak Erosion (ICOLD, 2016)](image)

According to (Fell et al., 2014), highly erodible soils like silts, silty sands, and dispersive clays may start eroding at a crack width of 7 to 13 mm under a low hydraulic gradient of 0.1 and widths as small as 1 or 2 mm under a hydraulic gradient of 0.5.

- Contact Erosion – Defined as “scour” by USBR, is the selective erosion of fine-grained particles from the contact zone between embankment and foundation or core and filter during a tangential flow regime parallel to the contact zone (ICOLD, 2015). The flow of detached particles occurs through the filter layer as shown in Figure 6. Backward erosion piping can develop if this process goes undetected for a more extended period.
Figure 6. Potential locations for contact erosion (Beguin, 2011)

- Internal Instability – it involves two processes called suffusion and suffosion and soils with a glacial origin like tills are susceptible to this kind of internal erosion.

Suffusion is the erosion of fine-grained particles from the coarser particle’s matrix having a point to point contact in a manner that finer particles are transported through the voids between coarser particles through seepage flow and a soil skeleton composed of coarser particles left behind as shown in Figure 7. The volumetric change is negligible in this case.

Figure 7. Suffusion process (USACE, 2013)

Suffosion is the selective erosion of fine-grained particles from the coarse particles which are not in point to point contact resulting in volume changes often leading to the development of sinkholes as shown in Figure 8. It has a lower probability to develop under conditions found in typical embankment dams (ICOLD, 2015).
2.2 Contact Erosion
Contact erosion originates along the boundary along embankment and foundation, or along the core and filter under the condition of tangential flow inside the filter layer. The range of eroded materials depends upon the filter performance or its ability to trap the detached soil particles from the base soil layer. Progression of contact erosion can lead to sinkholes formation. A schematic sketch of contact erosion mechanism is shown in Figure 9.

Contact erosion is the selective erosion of fine-grained particles in contact with the filter layer on the condition of horizontal flow regime through the filter layer. As the erosion initiates and progresses from the contact zone between the different soil layers, this process is called as contact erosion (Beguin, 2011). Upon commencement, a process like the development of an upstream piping pathway or internal migration may mitigate. It can also lead to enlargement of an existing defect along the seepage pathway (Beguin et al., 2010). It only relates to the condition that the flow in the filter layer is parallel to the interface between the filter and parallel layers. Contact erosion can also happen between any granular layer (filter, rip rap or drain) and base soil layer in contact. Contact erosion can lead to the formation of
a pipe at the interface, sinkhole development, the creation of a weaker zone leading to slope destabilization, clogging of the filters and increase in pore water pressure (ICOLD, 2015).

Undetected measures or unsuccessful intervention in case of contact erosion can lead to a variety of failure modes on the dam superstructure as shown in Figure 10.

Figure 10. Consequences of contact erosion (Beguin, 2011)

Black arrows in Figure 10 indicate a groundwater flow through a more permeable layer (light grey) under a less permeable dam (dark grey). (a) Sinkhole daylights (b) beginning of backward erosion piping (c) creation of weaker zone initiating instability (d) clogging the permeable layer and increase in pore water pressure.

It is necessary to ensure complete adherence to guidelines governing the configuration of filter particles to provide structural stability. In case of non-compliance of geometric criterion, the hydraulic gradient must be kept low to prevent the initiation of contact erosion.

2.2.1 Parameters Leading to Contact Erosion

Contact erosion can develop in a wide variety of soil ranging from non-dispersive clays to broadly graded glacial tills. Generally, broad graded soils are more susceptible to contact erosion not only due to the absence of interparticle cohesion but also due to the presence of numerous interfaces between the soil itself due to the varying grain sizes (Beguin, 2011). The initiation and subsequent chain of events depend upon particle size distribution of base soil, the degree of compaction, interparticle cohesion, saturation level, hydraulic gradient, and geometric condition (Beguin, 2011).

Figure 11 shows the summary of the geometric and hydraulic conditions to be fulfilled for the initiation of contact erosion.

<table>
<thead>
<tr>
<th>Description</th>
<th>Grading ratio $D_{90} / D_{50}$</th>
<th>Geometrical condition</th>
<th>Geometrical and Hydraulic condition</th>
<th>Hydraulic condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brunau (1985) soil with $n=0.4$</td>
<td>7.5</td>
<td>Geometrical condition</td>
<td>25</td>
<td>Geometrical condition</td>
</tr>
<tr>
<td>Werman (1992) soil with $D_{90}=0.88D_{80}$</td>
<td>8.1</td>
<td>Geometrical and Hydraulic condition</td>
<td>14.6</td>
<td>Hydraulic condition</td>
</tr>
<tr>
<td>Den Adel (1994) soil with $D_{50}=D_{90}/0.9$</td>
<td>11.7</td>
<td>Grading ratio</td>
<td>11.7</td>
<td>Geometrical and Hydraulic condition</td>
</tr>
</tbody>
</table>

Figure 11. Domain of particle size influence on non-plastic soils (Beguin et al., 2010)
According to Brauns (Brauns, 1985), Wörman (Wörman & Olafsdottir, 1992) and Den Adel (Den Adel et al., 1994), the critical conditions to initiate contact erosion have been divided into three boundaries, which are tested for a configuration when the coarse layer is above the compacted fine soil layer. The $D_{15F}/d_{85B}$ ratio between "geometrical condition" boundary and "geometrical and hydraulic condition" boundary is the critical geometric criterion required for contact erosion to initiate. Brauns (Brauns, 1985) postulated that based on his experimental results, at $D_{15F}/d_{85B}$ ratio between 25 and 57, the critical darcy velocity can be calculated without taking into account the coarse layer grading.

For domains ranging between the "geometrical condition" and "geometrical and hydraulic condition", the critical velocity depends upon the particle size distribution of the coarse layer which makes calculation of erosion laws difficult. Evolution of erosion between these two boundaries depends on both geometrical and hydraulic conditions (Bonelli, 2013). Due to this, the erosion laws proposed by Brauns (Brauns, 1985) and Wörman (Wörman & Olafsdottir, 1992) are valid only in the hydraulic condition boundary where the coarse or filter layer has minimal influence (Bonelli, 2013).

The hydraulic gradient at which contact erosion initiates is called as a critical gradient (Beguin, 2011), and it varies for different soil types, and it depends mainly upon the permeability of the filter layer. Darcy velocity for erosion initiation is directly related to the base layer’s resistance to erosion.

2.3 Contact Erosion Tests
Contact erosion tests were first conducted by Brauns (Brauns, 1985), followed by Anders Wörman (Wörman & Olafsdottir, 1992), Schmitz (Schmitz, 2007) and more recently by Beguin (Beguin, 2011). As proven in previous research, contact erosion conditions inside a dam can be successfully replicated by laboratory testing (Beguin & Pinettes, 2016). In this paper, the focus laid upon the tests conducted in the University of Grenoble (Beguin, 2011). Two configurations are possible for studying contact erosion on a laboratory scale.

![Soil layers layout for Contact Erosion tests](image)

**Figure 12. Soil layers layout for Contact Erosion tests (Beguin et al., 2010)**

2.3.1 Coarse over fines configuration
This layout involved placing base soil in a bottom of the testing apparatus compacted until a height of 15 cm and the filter layer was placed on top of the base soil layer. This testing method was first used by Brauns (Brauns, 1985) and Schmitz (Schmitz, 2007). Water flowed through the filter layer, and flow was parallel to the contact zone between the soils as shown in Figure 13.
Testing apparatus was a steel box of volume 300*700*265 mm$^3$ and fed by water from an overhead tank. The control valve on the inlet side regulated the flow inside the apparatus. The base soil (fine layer) was compacted to a density equivalent to 90% of Proctor Maximum density at Proctor Optimun Moisture Content. An inflatable rubber bladder applied a static load of 0-100 kPa on the sample. The hydraulic head was applied to the apparatus through the opening of 5 mm height along the width of the device. Openings were designed to coincide with the height of the filter layer to ensure a tangential flow regime along the boundary between the soil layers. Geotextile prevented erosion at both ends by reducing the influence of boundary conditions on the flow. A differential pressure sensor measured the head loss in the sample.

Tested base soils were uniformly graded sand ($d_{50}$ - 250µm, $C_u$ – 1.7), broadly graded silt ($d_{50}$ - 250µm, $C_u$ – 1.7), illite clay ($d_{50}$ - 4µm, $C_u$ – 5.3) and gap-graded mixtures of 10% and 20% illite with sand. Four types of uniformly graded gravels with ($d_{50}$ – 3, 5.2, 9 and 17 mm) constituted the filter layer. Gravity was the main stabilizing force in this type of set up.
2.3.2 Fines over coarse configuration

This setup features the inverse of the design shown in Figure 13 where gravity acts as a destabilizing force. Schmitz used the experimental design (Schmitz, 2007) followed by (Beguin, 2011) and involved compacting a fines soil layer of 15 cm height on top of a filter layer of 5cm. The principles and the soils used for testing were the same as used in section 2.3.1 Coarse over fines configuration.

The main apparatus was constructed from Plexiglass with a volume (30*20*20) cm$^3$ with removable top and bottom plates which were secured to the main chamber by bolts. The transparent box allowed visual monitoring of any contact erosion happening at the boundaries between the fine and filter soil. The constant flow rate was maintained in the filter layer by using a flow meter, and head losses were measured using a differential pressure transducer. A rubber bladder was placed on top of the fine layer to induce a load within the 10-200 kPa range. The rubber bladder which was filled with water through a graduate column to measure the settlements on the fines layer. The schematic flow process is shown in Figure 15.

![Diagram of Contact Erosion Test](image)

*Figure 15. Contact Erosion Test (Configuration 2), (Beguin & Pinettes, 2016)*

These methods evaluated the quantity of eroded soil:

- Turbidity measurement to quantify fine-grained particles in suspension
- Collector at the exit to store the coarse particles transported by bed load.

Collected soil particles were then dried, and wet sieving tests were performed on them to determine the mass loss in various grain sizes and then compared with the original base soil sample. This test was used to determine the critical Darcy velocity for initiation of contact erosion as shown in Figure 16.
Figure 16. Critical velocities from previous tests (Beguin et al., 2010)
3. Laboratory Work
3.1 Material Description
Contact erosion tests in this thesis were performed on two different types of glacial till which are indigenous to Swedish geology. Generally, broad graded soils are more susceptible to contact erosion not only due to the absence of interparticle cohesion but also due to the presence of numerous interfaces between the soil itself due to the varying grain sizes (Beguin, 2011). In this thesis, the base soil represented the core material typically used in Swedish embankment dams, glacial till with $d_{\text{max}}$ 16 mm; while the filter was represented by layers of different gravels having a $D_{\text{max}}$ ranging from 19 mm to 50 mm described in 3.1.2 Filter Properties.

3.1.1 Base Soil Properties
Two types of glacial till core soils codenamed “JS” and “IS” were used for experiments having grain size distribution ranging from 0.002 mm to 16 mm and a particle size distribution as seen in Figure 17.

![Figure 17. Particle size distribution for tested base soils](image)

JS had a fine-grained particles content of 19% and 3.5% of total mass was below the size 0.002 mm, while IS had a fine-grained particles content of 31% and 1.4% of total mass was below 0.002 mm. The granular properties are summarized in Table 2.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>$d_{10}$</th>
<th>$d_{30}$</th>
<th>$d_{50}$</th>
<th>$d_{60}$</th>
<th>$d_{85}$</th>
<th>$C_c$</th>
<th>$C_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS</td>
<td>0.012</td>
<td>0.17</td>
<td>0.65</td>
<td>1.23</td>
<td>6.83</td>
<td>1.96</td>
<td>102.5</td>
</tr>
<tr>
<td>IS</td>
<td>0.014</td>
<td>0.06</td>
<td>0.18</td>
<td>0.32</td>
<td>2.5</td>
<td>0.80</td>
<td>22.86</td>
</tr>
</tbody>
</table>

Higher $C_u$ values for both soils indicated a widely graded granular distribution. As the mass of particles below size 0.002 mm was very low, therefore Atterberg limit tests were not performed.

Compaction curve was obtained by performing the modified Proctor compaction method on both the soil types. Compaction data for JS was taken from (Lagerlund, 2018), while the compaction test was
conducted for IS at LTU and the comparison is shown in Figure 18. $I_{\text{sat}}$ and $J_{\text{sat}}$ represent the zero air void curve for IS and JS respectively.

![Compaction curve for tested base soils](image)

**Figure 18. Compaction curve for tested base soils**

Table 3 shows the summary of mechanical properties of both the base soil types.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>$\theta$ (%)</th>
<th>$k_{\text{sat}}$ (m/s)</th>
<th>$\gamma_{u}$ (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS</td>
<td>3</td>
<td>$10^{-7}$</td>
<td>21</td>
</tr>
<tr>
<td>IS</td>
<td>1</td>
<td>NA</td>
<td>20</td>
</tr>
</tbody>
</table>

Mechanical and granular properties for JS were taken from previous tests conducted (Lagerlund, 2018) and mechanical properties of IS soil were determined from laboratory testing at LTU.

### 3.1.2 Filter Properties

Filter size selected for the final testing phase was done based on Terzaghi’s filter criteria. The density of material was 2600 kg/m$^3$ and has a unit weight of 21 kN/m$^3$ (Lagerlund, 2018). The porosity of 0.35 was experimentally determined for a particle size range of 22.4 mm to 31 mm. Seven different types of filter combinations were tested with $D_{\text{min}}$ ranging from 2 mm to 31 mm and $D_{\text{max}}$ ranging from 19 mm to 50 mm respectively as shown in Figure 19. The particle size distribution for the filter was chosen as $d_{\text{min}}$ of 22.4 mm and $d_{\text{max}}$ of 31 mm for terminal tests.
All the seven filter combinations were used for the preliminary tests, while the combination named “CET” was used for the final testing program.

3.2 Apparatus Design

The apparatus design was based on previous contact erosion tests conducted at the University of Grenoble, France (Beguin et al., 2010) and Stefan Schmitz in Munich (Schmitz, 2007). Schematic diagram of the testing apparatus and all the supporting components are shown in Figure 20.

The device was constructed from plexiglass and had dimensions of (30*20*50) cm³ having 20 mm diameter holes drilled into the lateral walls until a height of 5 cm for water passage. The apparatus walls had a thickness of 5 cm. Top and bottom components were removable and attached by bolts to the main frame. The water reservoir was an overhead tank with a 50 liters capacity. The constant head was
maintained using an outflow hosepipe of 1 cm diameter and water was fed to the apparatus inlet through a 1 cm diameter hosepipe. A control valve was placed along the inlet pipe to regulate the flow. The maximum achievable height of the water head for the overhead tank was 265 cm, and the minimum height to which the experimental box could be lowered was 50 cm. Maximum achievable water head was thus 215 cm.

Two holes of 1 mm diameter along the longitudinal section measured pore water pressure by attaching piezometric tubes. Styrofoam layers were placed at the top of the core soil to prevent any uplift movement during testing, and the top was secured by a 5cm thick plate attached by bolts.

The outlet drained into a set of three sedimentation ponds which were placed to capture the eroded soil particles. Each sedimentation pond contained a mesh of 125 microns size.

3.3 Testing Program

3.3.1 Preliminary tests

Preliminary tests were conducted to check the geometrical criterion which gives rise to contact erosion, and the tested geometrical conditions are documented in Table 4. Tested filter configurations

<table>
<thead>
<tr>
<th>Filter Series</th>
<th>D\text{min} (mm)</th>
<th>D\text{max} (mm)</th>
<th>D_{15F} (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>2</td>
<td>22.4</td>
<td>4.16</td>
</tr>
<tr>
<td>F2</td>
<td>5.6</td>
<td>22.4</td>
<td>8</td>
</tr>
<tr>
<td>F3</td>
<td>8</td>
<td>22.4</td>
<td>14</td>
</tr>
<tr>
<td>F4</td>
<td>16</td>
<td>22.4</td>
<td>19</td>
</tr>
<tr>
<td>F5</td>
<td>16</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>CET</td>
<td>22.4</td>
<td>31</td>
<td>28</td>
</tr>
<tr>
<td>F6</td>
<td>31</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

These tests were conducted to check the following conditions

- Geometrical configuration of the filter which leads to the initiation of contact erosion.
- The behavior of core soil after contact erosion is initiated.
- Inflow water velocity which initiates contact erosion.
- Checking the influence of boundary conditions like hydraulic gradient, types of compaction, the height of filter and inflow rate.
- Granular distribution of soil particles collected from sedimentation ponds.

3.3.2 Terminal Tests

The testing program consisted of two contact erosion tests on JS and IS soil, thus giving a total of four tests. Variable parameters were fine-grained particles content and degree of compaction for the tests as shown in Figure 21. Hydraulic gradient was varied throughout the test procedure depending upon the soil response to contact erosion. The idea behind changing the filter height was to check the influence of boundary conditions on the initiation of contact erosion process.
3.4 Experimental Procedure

The experimental procedure was based on the work done by (Beguin et al., 2010). The experimental setup for contact erosion testing was based on the concept of particle detachment in the core soil along the contact zone due to the tangential flow of water in the filter layer. The base soil was compacted into three layers of 5 cm each until a total height of 15 cm on top of the filter layer. The primary objective behind placing the filter layer until 5 cm height was to ensure that water always flowed through the filter layer.

Gravel of varying sizes as described in Table 4 was placed on the base until a height of 3-5 cm as shown in Figure 22.

The preparation for each test was done with the following steps:

- Placement of the filter particles layer at the bottom of the apparatus to a height of 5 cm.
- Freezing the filter layer to avoid segregation of base soil particles during compaction.
• The first layer of core soil was placed on top of the filter layer and compacted 15 or 30 times with a weight of 11.8 kg dropped from a height of 30 cm. Compaction was done at optimal water content for both base soils.

• Two more layers were compacted in the apparatus as described in step 2 and shown in Figure 23.

![Figure 23. Compacted Base Soil Layout a. Bottom Layer(5cm) b. Middle Layer(10cm) c. Top Layer(15cm)](image)

• The structure was bolted shut from the top, and a layer of Styrofoam was placed on a top layer of base soil forming a seal thus prevented any upward movement of base soil.

• The inlet and outlet components were secured to the apparatus by bolts with silicone and petroleum jelly to prevent any water leakage through the joints and had circular openings of 5 cm.

• Water was fed through a 10 mm diameter hose from the water reservoir and entered the chamber through side walls contain circular holes of approximately 10 mm diameter at the bottom of side walls, while the outlet drained directly into the sedimentation ponds as shown in Figure 24.

![Figure 24. Water drainage into sedimentation ponds.](image)
• Testing started with a cleaning phase at lowest hydraulic gradients (i=1.5 or 2) to remove the soil that had settled into the filter voids as shown in Figure 25.

![Figure 25. Cleaning operation in progress](image)

• After the cleaning phase, the hydraulic gradient was successively increased between 3 and 12.2 in timed increments depending on soil behavior to contact erosion. This aiming to study the chain of events before and after erosion. The velocity of water entering the apparatus from the upstream side was termed as inflow velocity, and Velocity of water exiting from the downstream side was named as outflow velocity. Depending on the gradient the inflow velocity ranged from 4cm/s (i=3.9) to 11.85 cm/s (i=12.2) (APPENDIX 1).

• Turbidity was measured, and the range of turbidimeter is 0 to 1000 FNU (Formazin Nephelometric Units) at an interval of 30 seconds to assess the condition of base soil layer stability and progression of erosion. Turbidity was expected to change rapidly for ongoing erosion. Otherwise, it should stay in a range of 10 to 50 FNU. Inlet water from mains supply had turbidity reading of 4.7 FNU.

• Pore pressure readings were taken from piezometric tubes at fixed intervals of 10-15 minutes to check the water level inside the apparatus, and the flow rate was measured on the outlet side using a container of 550 mL volume and a stopwatch. The two piezometric tubes were named as PP1 (upstream side) and PP2 (downstream side) as shown in Figure 26.

![Figure 26. Location of piezometric tubes](image)
• The collected sediments in the sedimentation ponds were oven dried at 105°C for 24 hours. The dried soil particles were then weighed and wet sieved.

• For the terminal tests, the filter was frozen in a climate-controlled room for 24 hours as shown in Figure 27, and the base soil was compacted on top of it, and the same procedure was followed in the steps above. The idea of frozen the filter layer and subsequently compact the core soil on top of ice aimed to reduce the mass losses into the voids of the filter layer during compaction. Cleaning operation was still performed on these tests.

*Figure 27. Frozen filter Layer*
4. Results:
The preliminary tests answered the most critical questions of testing purpose, i.e., the hydraulic gradient, and inflow velocity and what combinations of the base soil and filter lead to contact erosion initiation. Earlier it has been documented that laboratory tests were also in sync with a large-scale test conducted in University of Grenoble or increase in the size of interface did not have a significant impact on the outcome of test results (Beguin & Pinettes, 2016).

4.1 Preliminary Test Results:
Preliminary tests paved the way for the development of a non-ambiguous roadmap to identifying parameters that lead to contact erosion in dams. These tests were performed using JS as the base soil and they also showed the limitations of laboratory testing and the range of approximations for experimental evaluation of results. The chronological order of preliminary tests and parameters involved in them are shown in Table 5.

Table 5. Chronology of preliminary tests

<table>
<thead>
<tr>
<th>Test code</th>
<th>Duration (mins)</th>
<th>$i_{\text{min}}$</th>
<th>$i_{\text{max}}$</th>
<th>Base soil layers Compaction (blows)</th>
<th>$D_{\text{min}}$ (mm)</th>
<th>$D_{\text{max}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>75</td>
<td>3</td>
<td>12.2</td>
<td>30</td>
<td>2</td>
<td>22.4</td>
</tr>
<tr>
<td>T2</td>
<td>75</td>
<td>3</td>
<td>12.2</td>
<td>30</td>
<td>5.6</td>
<td>22.4</td>
</tr>
<tr>
<td>T3</td>
<td>75</td>
<td>4</td>
<td>12.2</td>
<td>30</td>
<td>8</td>
<td>22.4</td>
</tr>
<tr>
<td>T4</td>
<td>140</td>
<td>4</td>
<td>13.7</td>
<td>30</td>
<td>16</td>
<td>22.4</td>
</tr>
<tr>
<td>T5</td>
<td>140</td>
<td>4</td>
<td>12.2</td>
<td>30</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>T6</td>
<td>140</td>
<td>4</td>
<td>10.7</td>
<td>30</td>
<td>22.4</td>
<td>31</td>
</tr>
<tr>
<td>T7</td>
<td>105</td>
<td>4</td>
<td>10.9</td>
<td>30</td>
<td>31</td>
<td>50</td>
</tr>
</tbody>
</table>

4.1.1 Tests T1, T2, & T3
Tests T1, T2 and T3 were only used for observations about flow regime inside the soil body and simultaneously check for signs of erosion. All the tests were held for a duration of 75 minutes and no erosion was observed at any time. Turbidity was not measured in these tests. No soil particles were found in the sedimentation ponds after the tests as illustrated in Figure 28.

*Figure 28. No erosion for T2, a. i=5, b. i=12.2*
Pore pressure readings and outflow velocity variation for these three tests were not documented.

4.1.2 Tests T4 & T5
Tests T4 and T5 were conducted with larger sized particles having $D_{\text{min}}$ 16 mm and $D_{\text{max}}$ of 19 mm and 22.4 mm respectively showed no erosion as earlier tests in 4.1.1 Tests T1, T2, & T3. Test T4 had the highest recorded inflow velocities of all the tests combined as shown in Figure 29, and had high pore pressure readings on the upstream side, the height of water in the piezometers was about 11 cm at a gradient of 13.7 and inflow velocity of 13 cm/s. After these two tests, it was concluded that bigger sized filter particles were required for contact erosion to initiate.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure29.png}
\caption{T4 Pore pressure}
\end{figure}

High outflow velocity in response to high inflow velocity as shown in Figure 30 led to the conclusion that no contact erosion had developed.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure30.png}
\caption{T4 outflow velocity variation}
\end{figure}
Figure 31. Sedimentation ponds T4 test at i=13.7 (duration – 110 mins)

The absence of fine-grained particles in the outflowing water as shown in Figure 31 proved that no erosion was undergoing on the contact zone.

4.1.3 Test T6
Test T6 was the first time where contact erosion was observed. The filter dimensions of $D_{\text{min}}$ 22.4 mm and $D_{\text{max}}$ of 31 mm gave an optimum filter height of 5 cm. The base soil was saturated for 24 hours, and testing commenced with cleaning operation for 30 minutes. Erosion initiated at a hydraulic gradient of 5.4 or inflow velocity of 7.2 cm/s associated by the formation of cavities along the interface as shown in Figure 32.

Figure 32. Cavities formation at the interface

The piezometric height of 9 cm indicated clogging of the filter due to contact erosion, while low pore pressure on the downstream side meant the filters offered no resistance to the passage of soil particles. High pore pressures on the upstream side also prove that sedimentation rate was higher than bed load transport rate of fine-grained particles while there was no contact erosion undergoing on the downstream side.

Differential pore pressures also lead to the hypothesis that settlement of particles into the filter layer was happening at differential rates which caused the diversion of water into areas of larger voids and areas of low settlements.
Figure 33. T6 pore pressure

Erosion continued for 15 minutes and gradually ceased, the test continued at this inflow velocity for 25 minutes as seen by constant pore pressure from 30 to 45-minute period in Figure 33. After increasing the inflow velocity to 7.89 cm/s, contact erosion reinitiated. The occurrence of turbidity was imminent on the outflowing water, and the same change of sequence was observed as in the earlier gradient, the pore pressure reading remained constant throughout this inflow velocity and increased after 20 minutes.

Pore pressure had a small variation for the final inflow velocity of 10.3 cm/s, where erosion continued for 13 minutes. The test was conducted for 140 minutes and was stopped when the outflowing water showed no signs of turbidity for a continuous duration of 15 minutes.

The contact erosion phenomenon in this test showed two stages of erosion, i.e., initiation and progression. The base soil layer was able to heal from the undergoing contact erosion process as shown in Figure 34.
Most of the losses were in the fine-grained particles and this loss gave rise to turbidity in the downstream side outflowing water. Fine-grained particles content on the contact zone decreased from 29% to 24%. For this soil type, the lower mass of fine-grained particles helped in the process of self-healing of the base soil layer.

The interface before and after erosion had a particle size distribution as shown in Figure 35.

![Figure 35. T6 interface comparison](image)

The total amount of eroded soil in this test was 237 g and had a particle size distribution as shown in Figure 36. Largest particle size or \( d_{\text{max}} \) was 4mm, \( d_{50} \) was 0.25 mm, and the fine-grained content was 19%. The fine-grained particles content was not accurate due to continuous flow which prevented the complete capture of smaller and lighter particles before they could be sedimented.
4.1.4 Test T7

Test T7 was conducted with the filter particle size distribution (31 mm to 50 mm) to check the impact of contact erosion on base soil layer stability. This test ran for 105 minutes, and the chain of events was quite like test T6 in section 4.1.3 Test T6. The test procedure remained in entirety the same as in the previous tests, with the particle size of the filter being the only exception. Saturation of the base soil layer was done for 24 hours, and testing began with the cleaning phase. Trial commenced at gradients ranging from 4 to 10.9 with inflow velocities varying from 6.35 cm/s to 10.5 cm/s.

Contact erosion initiated at a lower gradient this time at inflow velocity of 6.35 cm/s as shown in Figure 37. The core destabilization was much higher in this test as compared to T6 and had elevated pore pressure readings as shown in Figure 38.
Outflow velocity was mostly constant for all gradients, and it depended on the pore pressure at the time of the reading. Faster rates of cavities formation and their progression vertically lead to detachment of more fine soil layers thus clogging the filter layer as a result. Elevated pore water pressure on both piezometric tubes was due to a higher settlement rate and clogging of the filter layer. This stagnating flow due to clogging of filter gave rise to lower outflow velocities as seen in Figure 39.

Post erosion the fine-grained particles content of the contact zone decreased to 23% from an initial base of 29% as shown in Figure 40.
Mass of eroded soil collected in sedimentation ponds was 123 g and had a particle size distribution as shown in Figure 40. Largest particle size $d_{\text{max}}$ was 5.6 mm, and $d_{50}$ was 0.3 mm. Mass of settled base soil particles in the filter layer and base of apparatus was not considered.

4.2 Terminal Tests Results

The lessons learned from the preliminary tests were put into use in the final testing phase in which the following were documented:

- Turbidity
- Pore Pressure
- Outflow velocity
- Granular distribution of interface or contact zone after experimentation
- Mass and granular distribution of soil collected in sedimentation ponds.
The duration for these tests was based on the study of base soil response to contact erosion which was either self-healing or structural failure of the base soil layer in the worst-case scenario. Each test had its own set of parameters which were documented in a chronological order shown below in Table 6.

Table 6. Terminal Tests Description

<table>
<thead>
<tr>
<th>Test code</th>
<th>Base Soil</th>
<th>Fines (%) (Interface)</th>
<th>Duration (mins)</th>
<th>D_{min} (mm)</th>
<th>D_{max} (mm)</th>
<th>i_{min}</th>
<th>i_{max}</th>
<th>\rho_{t} (t/m^3)</th>
<th>\rho_{b} (t/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J30</td>
<td>JS</td>
<td>29</td>
<td>55</td>
<td>22.4</td>
<td>31</td>
<td>5.1</td>
<td>12.2</td>
<td>1.95</td>
<td>1.85</td>
</tr>
<tr>
<td>J15</td>
<td>JS</td>
<td>29</td>
<td>100</td>
<td>22.4</td>
<td>31</td>
<td>3.1</td>
<td>3.1</td>
<td>1.79</td>
<td>1.70</td>
</tr>
<tr>
<td>I30</td>
<td>IS</td>
<td>36</td>
<td>69</td>
<td>22.4</td>
<td>31</td>
<td>3.1</td>
<td>4.3</td>
<td>1.88</td>
<td>1.79</td>
</tr>
<tr>
<td>I15</td>
<td>IS</td>
<td>36</td>
<td>94</td>
<td>22.4</td>
<td>31</td>
<td>2.8</td>
<td>12.2</td>
<td>1.72</td>
<td>1.63</td>
</tr>
</tbody>
</table>

4.2.1 J30 Test

J30 test was conducted to check the behavior of highly compacted base soil layer and had a compaction level of 30 blows per layer on top of the frozen filter layer and lasted for 55 minutes. Cleaning phase was not considered as part of the primary test duration. Testing began at an inflow velocity of 7.4 cm/s and then was increased to 7.89 cm/s after 15 minutes. No erosion was seen for these inflow velocities; hence documentation was not considered to be necessary for them. The gradient was then increased to 12.2 giving an inflow velocity of 11.85 cm/s after 25 minutes from the start which led to a spike in turbidity as shown in Figure 42.

![Figure 42. J30 evolution of turbidity](image)

The exponential rise in turbidity at 29 minutes was a probable sign of initiation of contact erosion, which then slowed down gradually until the next spike at 35 minutes interval. While erosion progressed, not all the eroded particles were transported downstream. Some particles from the base soil layer settled down within, but the majority were washed downstream.
Pore water pressure measurements were taken in intervals from 38 minutes until the end of the test. An increase in pore pressures from 38 minutes indicated clogging of the filter with a resulting elevation of the phreatic level in the filter. The pore water pressure variation due to change in inflow velocity is shown in Figure 43.

![Figure 43. J30 Pore Pressure](image)

The final phase of accelerated erosion was seen at 50 minutes explaining turbidity of 635 FNU and spike in pore pressure simultaneously. At this phase, the filter had trapped most of the eroded soil particles as seen from the exponential drop in turbidity in Figure 42. As the range of turbidity variation had significantly decreased compared to earlier measurements between the time interval of 52 to 55 minutes, the test was stopped after 55 minutes.

Outflow velocity depended on the rate of erosion at any given instant of time, as the gradient was kept constant. High outflow velocity as seen in Figure 44 concerning inflow velocity indicates either contact erosion progression rate was slow or filter layer was free from clogging.

![Figure 44. J30 Outflow velocity variation](image)
The interface was divided into two parts of 10 cm along the longitudinal section at both ends and labeled as inlet and outlet. Of interest was to check the particle size distribution on both ends and the post erosion gradation chart is shown in Figure 45.

![Figure 45. J30 post erosion interface particle size distribution](image)

Post erosion sieving results showed that the inlet had a fine-grained particles content of 20 % and the outlet had 24% against original fine-grained particles content of 30% indicating erosion was higher on the upstream side. The total mass of collected sediments was 167 g with a fine-grained particles content of 22% and had a particle size distribution as shown in Figure 46. Largest particle size $d_{\text{max}}$ was 4 mm, and $d_{50}$ was 0.3 mm.

![Figure 46. J30 eroded soil particle size distribution](image)

4.2.2 J15 Test
The J15 test was performed with a lowered filter layer height of 3 cm. Base soil layers had a compaction level of 15 blows per layer. This test was conducted only at a single hydraulic gradient of 3.1 and inflow
velocity of 4.5 cm/s and was stopped after 100 minutes due to development of a backward pipe and significant losses in the base soil mass along the upstream side.

High turbidity readings as shown in Figure 47 were the result of the rapid progression of cavities formed at the interface. Also due to low inflow velocity, settlement occurred at higher rates than particle transport. The high turbidity values are a testimony that most of the interface was eroded and settled down in the filter layer and clogging the filters.

![Figure 47. J15 Evolution of Turbidity](image)

Pore pressures varied as shown in Figure 48 and were high for this low gradient and inflow velocity indicating large-scale erosion of the contact zone and subsequent clogging of the filter layer. Pore pressure readings might be a result of continuously rising phreatic level attributing to continuous contact erosion.

![Figure 48. J15 Pore pressure regime](image)

This clogging of filter layer resulted in low exit velocity numbers as shown in Figure 49.
For this test, a nearly constant outflow velocity, pore pressure, and hydraulic gradient were measured while high turbidity numbers lead to the hypothesis of structural failure if continued for long enough and flow is unchecked. Development of a backward pipe after 49 minutes indicated hydraulic fracturing of the core soil layer as shown in Figure 50.

The substantial mass loss at the upstream side was the reason for a stoppage of test and caving of the roof can be observed in Figure 50. Approximately 8 cm of core soil was eroded in the upstream side from the original height of 15 cm, and the entire process of erosion was cyclic with varying rates on different intervals.

Large cavities in the core sample made interface separation as inlet and outlet difficult. Thus, the eroded interface was taken as a single sample, and the particle size distribution for this material is shown in Figure 51. Fine-grained particles content dropped to 16% as opposed to the original content of 30%.
4.2.3 I30 Test

I30 test was performed with a filter height of 3 cm as used in tests J15. IS soil was used for creating the base soil layers. Testing continued for 69 minutes until complete core structural failure was observed. This test was conducted at two hydraulic gradients: 3.1 and 4.3. Erosion initiated at the inflow velocity of 4.52 cm/s (i=3.1) and continued until structural failure at an inflow velocity of 6.3 cm/s (i=4.3).

Turbidity was high from the start as shown in Figure 53 and it became out of measurable range after 45 minutes. This test had the highest rates of erosion of all the tests as displayed in the high turbidity values and the exponential drop in exit velocity.
Figure 53. Evolution of turbidity

Pore pressure was high at the upstream side while remaining zero at the downstream side as shown in Figure 53 until the stage in which backward erosion initiated and a pipe subsequently developed. Pore pressure at pp1 recorded higher values as like the same in J15 test mainly due to a constant elevation of the phreatic level. The instant at 45 minutes marked the initiation of hydraulic fracturing of the base soil layer with a sudden spike in pore pressures in both piezometers. Accelerated rate of structural damage was observed after 62 minutes.

Figure 54. Pore pressure regime

Outflow velocity stayed mostly constant until the inflow velocity was increased as shown in Figure 53 followed by a sharp drop when inflow velocity was increased from 4.48 cm/s to 1.25 cm/s at a fixed gradient of 4.3 leading to the conclusion that the filter layer had been getting clogged due to an accelerated rate of erosion.
All the charts presented for I30 tests led to the hypothesis that pipe development started as soon as the gradient was increased, and structural collapse started at 45 minutes after testing began.

Figure 55. I30 outflow velocity variation

Figure 56. I30 stages of structural failure. a. Pipe development (40 min) b. Pipe progression (45 min) c. Initiation of roof caving (60 min) d. sinkhole development (69 min)
Figure 56 illustrates the stages of structural failures observed in the test which started with the development of a backward pipe at 40 minutes from the start initiating backward erosion of the interface towards upstream. Roof caving began at 60 minutes, and between the time interval of 62 minutes to 69 minutes, a sinkhole developed leading to caving of the base soil layers at the upstream side as shown in Figure 56.

The interface or contact zone was non-existent due to roof collapse due to which it was carefully excavated into two parts as done in Test J 30 and had the particle size distribution as shown in Figure 57.

![Figure 57. I30 post erosion interface](image)

The inlet and outlet had an almost similar size distribution, and the number of fine-grained particles in them was 25% against an original fine-grained particles content of 36%. This drop was mainly attributed to the structural collapse, which made the interface uniform while erosion progressed. The constant particle size distribution at the interface after erosion also led to the hypothesis that the entire interface was homogeneously eroded and washed away downstream.

The core failure generated the total eroded soil mass of 4048.85 g which clogged the mesh inside the sedimentation ponds. The largest particle size was 11.2 mm, and \(d_{50}\) was 0.125 mm, while the fine-grained particles content was 30%. The eroded soil particles had a particle distribution curve as shown in Figure 58.
4.2.4 I15 Test

I15 was the final test in the plan, had a low base soil compaction of 15 blows on a filter height of 5 cm at four different hydraulic gradients for 94 minutes. The test was stopped when the turbidity became gradually constant, and the same method followed for changing gradients. Although the fine-grained particles content was high in this test, the core structure remained stable throughout.

Turbidity followed a regime as shown in Figure 59. Turbidity had the lowest figures in this test as compared to the previous ones.

Pore pressures showed a steady rise at both tubes, until 65 minutes into the test. At this point, the pore pressure dropped at the downstream side, while it increased in the upstream side as shown in Figure 53.
This test did not show signs of accelerated erosion rate at any instant instead contact erosion here initiated at the inflow velocity of 8.42 cm/s. After the initial spike, turbidity did not reach high levels again throughout the test. It was perceived that although erosion was going, most of the particles were trapped by the filter.

Outflow velocity was high in the higher gradients due to the reduced erosion rate as shown in Figure 61.

After a lapse of 75 minutes, the rise in turbidity and pore pressure led to decrease in outflow velocity. As turbidity variation was used to assess the rate of erosion, because of the small range of change in turbidity between 80 and 90 minutes led to the stoppage of the test.

Core structure remained stable throughout the test as opposed to the previous tests as shown in Figure 62 taken at an inflow velocity of 11.85 cm/s and duration of 85 minutes.
Contact erosion followed the trend of differential rates, as the upstream side was more eroded than the downstream side. Visual observations as shown in Figure 62 and the particle size distribution chart in Figure 63 indicate a fully developed seepage flow path. Inlet and outlet sides had a post-erosion fine-grained particles of 26% and 31% respectively against an original content of 36%. Higher pore water pressures at the inflow side were attributed to the higher loss of particles as in all the previous tests. Ideally, after erosion was initiated this trend of differential erosion rates at the upstream and downstream remains the same for all the tests conducted.

![Figure 62. I15 test progress (85 min) a. Rear view b. Front view](image)

Mass of eroded soil was 541 g which had $d_{\text{max}}$ as 16 mm and $d_{50}$ as 0.5 mm, with a fine-grained particles content of 22% and a particle size distribution as shown in Figure 64.

![Figure 63. I15 post erosion interface particle size distribution](image)
Figure 64. 115 eroded soil particle size distribution
5. Discussion

5.1 Base Soil Stability Comparison

Base soil layers stability analysis based on the empirical charts developed by Sherard (1979) and US Bureau of Reclamation (USBR, 2014) shows that historically dams made up of cores having a particle size distribution similar to JS and IS have shown signs of internal erosion. This analogy further strengthens the argument of a continued erosion or dam breach scenario can develop in dams constructed from both these soils as Sherard Unstable band consists of the particle size distribution of base soils which have experienced internal erosion and, in some cases, have led to dam failures. According to the chart presented in Figure 65 and experimental results from section 4. Results: both the tested soil types are highly susceptible to contact erosion as they coincide with the Sherard Unstable band.

![Figure 65. Base Soil Stability Analysis (Sherard et al., 1984) 
Soils with a higher amount of silt and clay particles are highly susceptible to contact erosion, and this hypothesis is derived from results of tests I30 and I15 which had a high amount of eroded soil particles. Soil with 19% of fine-grained particles and high compaction showed only two out of four stages of erosion, i.e., initiation and progression, while the core was able to heal itself from contact erosion at any given head. Soil with 19% fine-grained particles and loosely compacted showed all the phases of erosion, i.e., initiation, progression, continued erosion and breach leading to structural damage. Combination of high fine-grained particles content soil and low filter height should be avoided at all costs while designing dams in the future.

5.2 Soil Compaction Process

Preliminary tests were done to check for core soil mass loss into the filter layer voids for filter size range of 8 mm to 22.4 mm. A byproduct of these tests was the necessary soil layer thickness required to bring the height of each base soil layer to 5 cm. Mass loss into the filter voids was around 20%, and the compaction height was 2 cm i.e., 7 cm of soil was needed to bring down the thickness of the compacted layer to 5cm. Mass loss was concentrated in the lowermost soil layer which is in immediate contact with
the filter. Due to this mass loss into voids of the filter, the interface was loosely compacted and might have influenced the results of preliminary tests.

Due to this mass loss during compaction, the idea of freezing of filter was adopted. The frozen filter layer led to minimal mass losses into voids, although some of the loose soil particles on the interface during compaction fell into the voids after melting of ice. Therefore, taking mass losses into account the mass of each soil layer for creating the base soil layers was 5.6 kg. Cleaning operation in each test eliminated these settled soil particles, and they were not considered as eroded soil particles. Although cleaning operation flushed out some of the settled soil particles from the filter voids, it was still possible that some of the interface particles were not detached immediately after compaction. These particles are the first to get separated from the interface during the erosion process.

Therefore, an accurate assessment of the mass balance of the system after test completion could not be done. Sedimentation ponds were drained before the start of testing procedure after completion of cleaning phase.

5.3 Particle Rearrangement at Interface due to compaction
While comparing the results of preliminary tests T6 and T7, it was observed that fine-grained particles content of the interface was higher than the fine-grained particles content of base which led to the idea of particle rearrangement due to compaction. As particle rearrangement was imminent after soil compaction, therefore the interface did not have the same gradation curve as the original soil before compaction.

To further strengthen this argument both core soil types were subjected to compaction by modified Proctor method and then the interfaces at the bottom, 5 cm, and 10 cm were cut out using a field knife and then subjected to wet sieving test. The thickness of interface for sieving tests was 1 cm with 0.5 cm on either side of markings in the samples as shown in Figure 66. The base of the sample represented the actual interface in contact with the filter layer in the apparatus and was the part of the base soil layer where contact erosion was initiated, and for sieving the bottom part of the sample 1 cm of core soil was measured from the bottom and up.

Figure 66. Interface division for the base soil layers
The post-compaction particle size distribution for JS soil sample is shown in Figure 67.

![Graph showing particle size distribution for JS soil](image)

*Figure 67. Post compaction granular distribution of JS soil*

The post-compaction interface had 30% of particles below the 0.063 mm size as compared to original fine-grained particles content which was 19%.

Similarly, for IS the post-compaction curve is shown in Figure 68.

![Graph showing particle size distribution for IS soil](image)

*Figure 68. Post compaction granular distribution of IS soil*

Contact zone had an increased fine-grained particles content of 36% as opposed to 31% in the original sample. The increment in this particle size range is lower in IS than JS because of the presence of more silt in the base soil. This sieving curve served as the interface particle size distribution and used to assess the post erosion characteristics of soil particles.

5.4 Effect of Filter Design
The height of the filter influenced the phreatic level inside the apparatus and the boundary conditions. Tests conducted with filter height of 5 cm showed the filter’s ability to arrest contact erosion in the
continuation phase thus preventing any further structural damage to the base soil layer. Due to this, preliminary tests, J30 and I15 tests showed no signs of continued erosion phase.

While it has been proved in section 5.1 Base Soil Stability Comparison that both soils have similar granular distribution as some previously damaged dams, a new comparison was done for both JS and IS with some dams in Scandinavia which have shown signs of suffusion in the past. Although, laboratory tests have been conducted for suffusion in LTU by Silva (Rönnqvist & Viklander, 2014) have shown that base soils satisfying the Terzaghi criteria are internally stable.

Table 7. Summary of Code Names for Tested Dams and Soil Types (Rönnqvist & Viklander, 2014)

<table>
<thead>
<tr>
<th>Code Name</th>
<th>Dam</th>
<th>Country</th>
<th>Installation Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hytteljuvet</td>
<td>Norway</td>
<td>1965</td>
</tr>
<tr>
<td>L</td>
<td>Lövön</td>
<td>Sweden</td>
<td>1973</td>
</tr>
<tr>
<td>N</td>
<td>Viddalsvattn</td>
<td>Norway</td>
<td>1971</td>
</tr>
<tr>
<td>P</td>
<td>Porjus</td>
<td>Sweden</td>
<td>1975</td>
</tr>
<tr>
<td>S</td>
<td>Songa</td>
<td>Norway</td>
<td>1962</td>
</tr>
<tr>
<td>JS</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IS</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Base soils JS and IS were added to the above Table 7 to compare their performance against dams having internal erosion history and represented in Figure 69.

Figure 69. Tested Soils Susceptibility to Internal Erosion (Rönnqvist & Viklander, 2014) an adaptation

The green solid represents IS soil, and the solid purple line represents JS soil. The numbers represent $C_u$ for the base soil used for constructing the core. Although no dams have been built using the soils used
for contact erosion tests in this report, a problem may arise in the future construction projects, due to which a risk matrix was developed for both the soil types based on contact erosion tests.

Table 8. Risk Matrix for Glacial Till Core Dams

<table>
<thead>
<tr>
<th>Fines (%)</th>
<th>$D_{\min}$ (mm)</th>
<th>$D_{\max}$ (mm)</th>
<th>$D_{15F}$</th>
<th>$d_{85b}$</th>
<th>$D_{15F}/d_{85b}$</th>
<th>Compaction type</th>
<th>Initiation gradient</th>
<th>Contact Erosion risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>5.6</td>
<td>22.4</td>
<td>8</td>
<td>5.6</td>
<td>1.4</td>
<td>HIGH</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>4</td>
<td>22.4</td>
<td>6.3</td>
<td>5.6</td>
<td>1.1</td>
<td>HIGH</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>22.4</td>
<td>4.2</td>
<td>5.6</td>
<td>0.7</td>
<td>HIGH</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>8</td>
<td>22.4</td>
<td>14</td>
<td>5.6</td>
<td>2.5</td>
<td>HIGH</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>16</td>
<td>19</td>
<td>17</td>
<td>5.6</td>
<td>3.1</td>
<td>HIGH</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>16</td>
<td>22.4</td>
<td>19</td>
<td>5.6</td>
<td>3.1</td>
<td>HIGH</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>22.4</td>
<td>31</td>
<td>24</td>
<td>5.6</td>
<td>4.3</td>
<td>HIGH</td>
<td>5.4</td>
<td>Medium</td>
</tr>
<tr>
<td>19</td>
<td>31</td>
<td>50</td>
<td>40</td>
<td>5.6</td>
<td>7.1</td>
<td>HIGH</td>
<td>5</td>
<td>High</td>
</tr>
<tr>
<td>19</td>
<td>22.4</td>
<td>31</td>
<td>28</td>
<td>5.6</td>
<td>5</td>
<td>HIGH</td>
<td>12.2</td>
<td>Medium</td>
</tr>
<tr>
<td>19</td>
<td>22.4</td>
<td>31</td>
<td>28</td>
<td>5.6</td>
<td>5</td>
<td>LOW</td>
<td>3.1</td>
<td>High</td>
</tr>
<tr>
<td>31</td>
<td>22.4</td>
<td>31</td>
<td>28</td>
<td>2.43</td>
<td>11.5</td>
<td>HIGH</td>
<td>4.3</td>
<td>High</td>
</tr>
<tr>
<td>31</td>
<td>22.4</td>
<td>31</td>
<td>28</td>
<td>2.43</td>
<td>11.5</td>
<td>LOW</td>
<td>7.7</td>
<td>High</td>
</tr>
</tbody>
</table>

The results presented in Table 8 lead to the conclusion that Terzaghi Filter Criteria ($D_{15F}/d_{85b} > 4$) based on permeability tests with the vertical flow and typically applied to evaluation suffusion can also be applied to tests with horizontal flow aiming to assess the potential of contact erosion.

Figure 70 represents the suggested boundary to define the region where filter gradation fulfils the Terzaghi’s criterion in broadly-graded base soils with $d_{\max}$ around 22.4 mm. Considering that Terzaghi’s filter criterion is applicable to both suffusion and contact erosion, the suggested boundary is consequently extended to include suffusion tests.

![Figure 70. Dam Safety Criteria based on filter size for IS and JS as base soils](image-url)

```
5.5 Effect of pore pressures

Level of pore pressure should be ideally equal to the thickness of the filter layer which indicates phreatic level lies at or below the interface. Therefore, for all the preliminary tests and J30 and I15 test contact erosion was not initiated at piezometric heights below 5 cm. Similarly, for J15 and I30 test, any piezometric height below 5 cm was an indication of no contact erosion at the boundary.

However, a result of contact erosion is a spike in pore water pressures. Therefore, tests J15 and I30 can be stated to be experiencing contact erosion initiation from the start as pore pressures were high right from the point when water was allowed to pass through the filter layer. Pore water pressures should be as low as possible throughout any dam’s operating life. High pore water pressures are the result of a clogged filter, which might occur due to partial or complete clogging of filters or a clogged filter drain.

On an aborted trial test, the filter soil layer and drainage holes along the width were entirely clogged which led to the piezometric height of 68 cm which was the same as the inlet water head. This induced capillarity in the base soil layer and subsequently led to hydraulic fracturing as shown in Figure 71.

![Figure 71. Dam Blowout Scenario](image)

This aborted test was the reason behind the plan to expand the outlet holes of the apparatus to 20 mm while ensuring filter layer did not get washed away with the outflow water.
6. Conclusion

All the base soil and filter soil configurations fulfilling the Terzaghi’s Filter Criteria $\frac{D_{15f}}{d_{85b}} < 4$ (ICOLD, 2013) can prevent the initiation of contact erosion. Hence, the filter criteria are the most critical factor to look for while investigating the risk for contact erosion initiation. The thickness of the filter with respect to the height of inlet voids dictates the mechanism of contact erosion, and the potential failure mode in the core.

Soils with a higher number of fine-grained particles are highly susceptible to contact erosion, and this finding is synchronous with previous tests conducted on silty and clayey soils due to their high erodibility and proved by higher mass of collected sediments in I30 and I15 tests.

Compaction plays a significant role in the development of contact erosion, as experiments with base soils having a low degree of compaction have a higher mass of eroded soil particles in the sedimentation ponds. In loosely compacted base soils, erosion initiates at lower inflow velocities.

Erosion rate and its progression directly influence the pore pressure levels inside the base soil layers. Elevated pore water pressure readings are the result of clogging of filter layers due to the settlement of eroded base soil particles in the voids causing segregation. Pore water pressures on the downstream side lead to a very high rate of particle transport, although it is also a testimony that no erosion is taking place in that side.

Turbidity was a good way of assessing the erosion, but it is not a precise factor in a dam with proper filter geometry, as most of the eroded particles are trapped. Hence turbidity follows a lower range of values. Although the spikes are an indicator of erosion progressing, it gradually falls to a range of less than 40 FNU if no further erosion takes place.

The ability of the core to self-heal from effects on contact erosion depends primarily on the thickness of filter layer, as only tests with 5 cm thick filter layer showed this result.
7. Future Research

Although this thesis project was able to answer some of the preliminary questions about the evolution of contact erosion in glacial till core dams, many questions still need to be addressed. This experimental setup albeit simple in design and construction allowed visual monitoring of contact erosion process; the unanswered parts of the project are:

Flow regime inside the filter layer
Use of fluid mechanics to: (i) study the flow regime changes throughout the experimental duration and (ii) developing the mathematical relation between the rate of erosion and water velocity in the filter layer.

Comparison of erosion mechanism with inverse configuration
This report has laid the groundwork for geometrical configuration for contact erosion initiation between core and filter layer on the downstream side and the embankment and foundation, so it is necessary to evaluate the results and compare with the reverse configuration when the filter layer lies on top of the core. The filter criteria for a situation when gravity acts as a stabilizing agent might be different from the one which was developed based on the report.

Evaluation of mass loss due to the compaction process
Mass loss due to compaction is different for each type of soil test which makes the assessment of eroded soil very complicated. This phenomenon happens mainly due to loosening of soil particles at the interface, a study of this mass loss in the voids will be required to assess the actual quantity of core mass loss due to erosion process.

Evaluation of particle transport due to seepage water
Sedimentation ponds were useful in assessing the particle sizes of eroded soil particles, yet the total scale of granular distribution of soil particles was not measured fully. This can be done by immaculate excavation of the filter layer along with the settled particles by dividing it into three zones along the longitudinal section. These zones then should be studied for eroded particles from the base soil and be sieved again for obtaining a particle size distribution of the particles transported by the outflowing water. This method can be used to assess the quality of filter and to check for signs of clogging at each cross sectional area of the filter voids.

Risk matrix for dams in operation
Although a risk matrix could be generated based on tested soils for contact erosion development, it is essential to assess the same for dams in the present. Future work in this sector must be done on core soil samples used in dams throughout Sweden and check for their long-term structural integrity. This risk study should be used to generate a generic probability index for risk of contact erosion initiation.
8. References


APPENDIX 1
Calculation of Inflow Water Velocity

Inflow and outflow water velocities were measured on the circular cross-sectional areas as indicated in the Figure 72:

![Figure 72. Velocities measurement points](image)

As shown in the figure above, velocities are measured in the circular cross-sectional segments on the upstream and downstream sides. Both the cross sections have an inner diameter of 5.08 cm. for measuring the inflow water velocities, container of 550 cm³ and 12000 cm³ were used based on hydraulic gradient and amount of flow. For measuring outflow water velocity, only 550 cm³ container was used.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Flow Rate</td>
<td>cm³/s</td>
</tr>
<tr>
<td>V</td>
<td>Volume of Container</td>
<td>cm³</td>
</tr>
<tr>
<td>A</td>
<td>Cross Section Area</td>
<td>cm²</td>
</tr>
<tr>
<td>(v_i)</td>
<td>Inflow Water Velocity</td>
<td>cm/s</td>
</tr>
<tr>
<td>(v_o)</td>
<td>Outflow Water Velocity</td>
<td>cm/s</td>
</tr>
<tr>
<td>i</td>
<td>Hydraulic Gradient</td>
<td>-</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>s</td>
</tr>
</tbody>
</table>

Time taken to fill the volume of containers were noted for both velocities types and these following formulas were used to generate the number for flow velocities as shown in Table 9
Area of cross section \[ A = 0.25 \times \pi \times 25 = 20.26 \, \text{cm}^2 \]

Flow Rate \[ Q = \frac{V}{t} \, \text{cm}^3 / s \]

Flow velocity through a cross-section \[ v = \frac{Q}{A} \, \text{cm/s} \]

Table 10. Inflow Velocity Table

<table>
<thead>
<tr>
<th>i</th>
<th>V (cm³)</th>
<th>t (s)</th>
<th>Q (cm³/s)</th>
<th>A (cm²)</th>
<th>( v_i = Q/A ) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>550</td>
<td>7</td>
<td>78.57</td>
<td>20.26</td>
<td>3.88</td>
</tr>
<tr>
<td>3.1</td>
<td>550</td>
<td>6</td>
<td>91.67</td>
<td>20.26</td>
<td>4.52</td>
</tr>
<tr>
<td>3.5</td>
<td>550</td>
<td>5</td>
<td>110.00</td>
<td>20.26</td>
<td>5.43</td>
</tr>
<tr>
<td>4.2</td>
<td>550</td>
<td>4</td>
<td>137.50</td>
<td>20.26</td>
<td>6.79</td>
</tr>
<tr>
<td>5.1</td>
<td>550</td>
<td>3.7</td>
<td>148.65</td>
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<td>3.44</td>
<td>159.88</td>
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<td>12000</td>
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</tr>
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<td>8.71</td>
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<td>13.22</td>
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