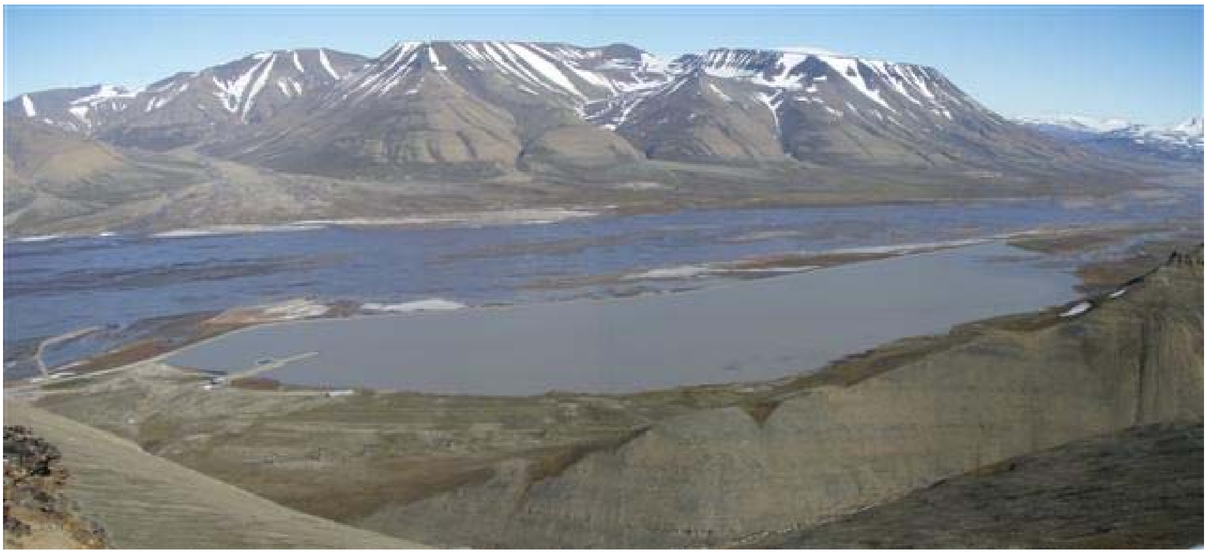
UNIS

Isdammen report 2009



AT- 205

Frozen Ground Engineering for Arctic Infrastructure

Abstract

Longyearbyens waterreservoir, Isdammen, is leaking and the Lokalstyre in Longyearbyen has asked NGI to perform some surveys evaluate the situation. As a part of the UNIS course AT205 the students have done some drilling and analyzed the samples, and put one termistor string in the embankment of the dam. The students task is to use their results combined with other information to come up with a possible solution for Isdammen.

Isdammen was originally three small dams that were combined. There seem to be very little documentation concerning work on Isdammen. The results from the students and NGIs drilling indicate that there have been used local masses to build the dam, and that the masses are just piled up, without any proper dam construction plan. Modeling in PLAXIS shows that water flow will occur through the embankment.

Data from the termistor strings show that the temperature is higher than expected for this permafrost area, a fact that can explain why there is unfrozen water in the ground. The samples used for laboratory testing are both from the embankment of Isdammen, and from Nordlysstasjonen, upstream Isdammen. The samples from Nordlysstasjonen are taken at a greater depth than the ones from Isdammen, and they have a high content of organic material. It is most likely that this organic layer can be found also under Isdammen, and since organic material is highly permeable this might be one of, or the leaking layer.

To decide on a good solution for Isdammen, more geotechnical surveys and a proper water balance calculation needs to be carried out and the results must be evaluated in comparison to the risk analysis.

The main solution presented in this report is based on the risk analyzes and a technical point of view. The risks discussed in this report are sudden dam failure, drainage of the dam and decreasing water depth due to sedimentary fill up, and the suggested solution is a three-step-plan to lower these risks, and to lower the maintenance costs of the road on top of Isdammen. The first priority is to stop the leakage by improving the dam with an impermeable core. This will prevent washout of material in the dam which can lead to failure, and also the risk of drainage of the dam. Second, a better drainage control can give less sedimentation in the dam, and also lover the erosion on the embankment. And finally, by increasing the freeboard the erosion on the road embankment is decreased.

There are also some other, more expensive solutions to the problem, like artificial freezing of the ground, the use of grouting and impermeable fiber fabric. These are just briefly discussed in the report.

When more surveys are carried out, it might be possible to keep Isdammen the way it is today. If a better overview is gained, it is possible to monitor the important things, and initiate measures if that is needed.

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Introduction

Isdammen consisted originally of three smaller lakes but due to lack of fresh water resources, these dams where built together. The dam has a length of 2,5 km, and it is shallow, approximately 4,5 meters deep and an it is covering an area of approximately 1,2 km^2.

The dam is located in Adventdalen, east of Longyearbyen, next to the road to mine 7 and provides the inhabitants with drinking water. During wintertime Isdammen is the only fresh water resource for Longyearbyen. In cold regions there is a challenge with fresh water resources because the ground water is located underneath the permafrost, which can be several hundred meters down. The dam is leaking at several points, and it is considered likely that Isdammen has had this leakage over a long time period. Now Lokalstyre in Longyearbyen wants to map the extent of the leakage, and NGI was asked to perform some investigations.

This report is the result of the main student project in AT205 at UNIS during spring 2009. The main purpose of the task was to discuss the risk of this leakage considering Isdammen being the only water reservoir in Longyearbyen. In addition we were asked to suggest improvements and to find solutions to the problem. This problem fits well with the objective of the course which is giving an introduction to frozen ground engineering. The course also contains the challenge in planning infrastructure in cold regions and knowledge about the affect permafrost has on constructions. The students participating in this course all have different backgrounds within subjects as geology, construction and technology. This results in a broad and useful amount of knowledge and creates possibilities for good discussions about the leakage problem in Isdammen.

The students participated in the core sampling next to Isdammen arranged by UNIS in February 2009 and have later performed laboratory work on these samples. The results of this work were used as a base for the geological part of the discussion in this final report. The report will contain several different aspects with Isdammen like the history behind the construction, its hydrology and the geology in the area where it is located. It will also contain some geotechnical aspects and a suggested solution which makes sense with respect to both economy and the size of the leakage problem.

1. The history of Isdammen

Water supply in Longyearbyen has always been a challenge. Svalbard has almost no natural lakes, and is in a relative dry climate. In the winter time melting of snow was an opportunity, but because of the low density of snow, ice was preferred.

Isdammen in Adventdalen was originally three natural lakes, but with some work they became one dam. In the beginning of the 1950`s, the work with Mine 5 in Endalen started. The road is placed at the shoreline of Isdammen, and it is supposed that the three dams were made into one under the roadwork. When constructing on Svalbard, it is usual to take the material you have, and therefore it is believed that material for the road filling, is material from Adventdalen, near today's dam.

When it is full, the amount of water is around 4 million m^3. If the dam should break, still it will be 2-3 millions m^3 of water. It won't be of the same quality, and harder to reach, but it will be possible without too much work. In older times, the water was taken out as ice blocks, and bottom freezing would not have been a problem as it is today, when they take out free water.

The name Isdammen comes from the way they got water out of it in the beginning. Blocks of ice were cut out, and transported to Longyearbyen with horses, and later belt wagons.
In 1960, it was built a cable from Isdammen to Funken, and water was transported into the mine network.

It is assumed that Isdammen get supplies from free water under the surface in the wintertime. The fact that the dam is leaking into Adventdalen makes that statement even stronger. In the summertime the supply comes mainly from the river Endalselva that runs in Endalen, but Isdammen is not used as a water reservoir for the city in the summertime. Then water is taken from Gruvedalen. Therefore, the leaking in the summertime can be even higher than in the winter, without noticing. Isdammen drains melt water from the mountains around, but also glacial melt water from the glacier Bogerbreen.

The daily use of water in Longyearbyen is around 800-900 m^3. Water is pumped up from Isdammen into a pressure pool with a capacity of 1600 m^3, which is enough to secure the water supply for two days.

2. Geology of Adventdalen

Svalbard has a long geological history, which goes back to the Permian period. To better understand the background for the quaternary sediments in Adventdalen and the forming of Isdammen it is necessary to know some of it.

2.1. Rock history

During the Permian period, more than 245 million years ago, Svalbard was under the sea level, and was a part of an enormous sea bed. Calcareous deposits on the sea floor became carbonate rocks. Around 245 million years ago the land started to rise, and Svalbard became dry land. For millions of years the rocks were exposed to wind and water which eroded and weathered the sedimentary rocks. Then the water started to rise again, and Svalbard once again became a part of the sea bed. The basins were filled by deposits from huge river deltas. When Svalbard rose above the sea for the second time, these sediments became sandstones, siltstones and shales. Then, in the beginning of the cretaceous period about 140 million years ago, the spreading of the Atlantic Ocean continental plates began, and this caused some tectonic activity on Svalbard as well, which resulted in shallow magma intrusions. These intrusions are mostly sills, which mean that they are parallel to the sedimentary layers. Since there are no sediments from the late cretaceous period, it is assumed that Svalbard at that time again was above the sea. In the early tertiary period, 65 years ago, the western part of Svalbard, Vest-Spitsbergen was folded and rose to a mountain range due to the fact that the Barents- and the Greenland shelf were moving apart. It was also during this period that the coal on Svalbard was formed. [4]

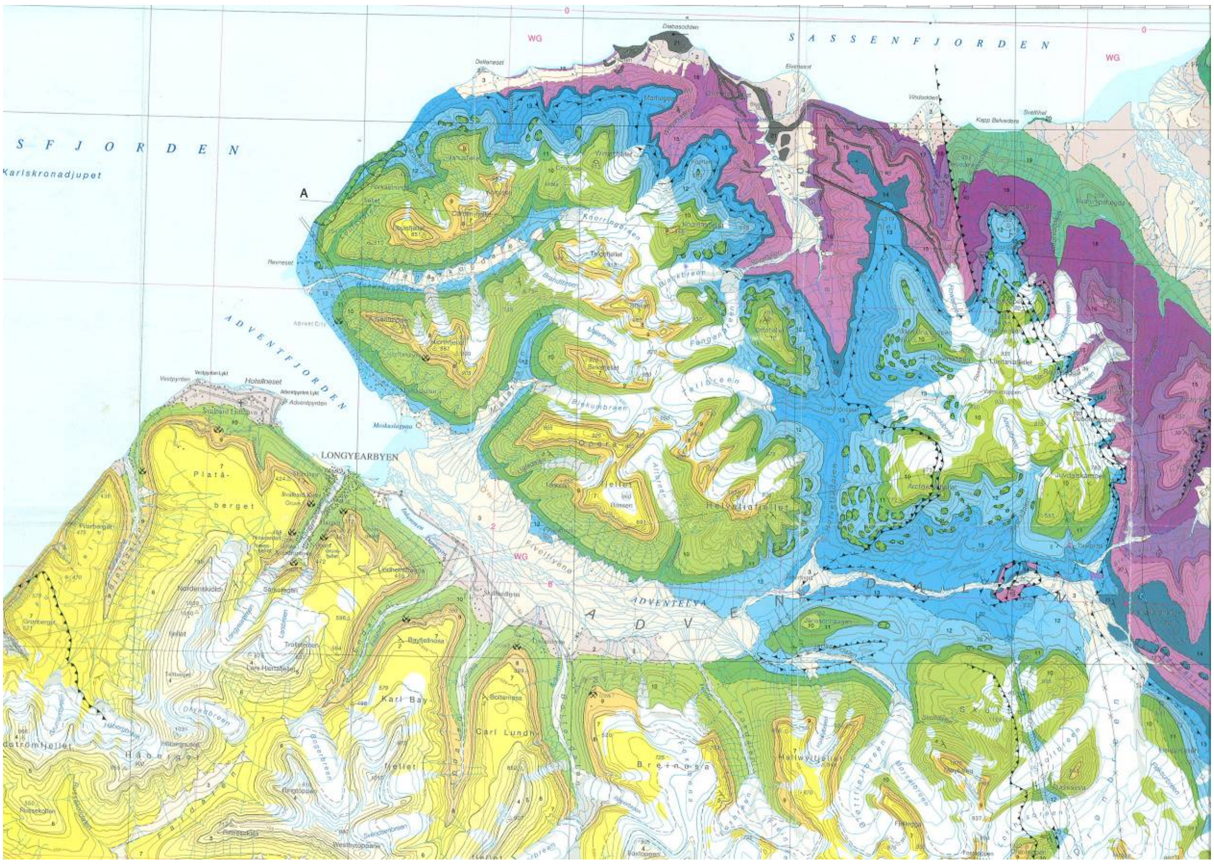

Figure 1: Geological map from Adventdalen [4]

In and around Adventdalen there are only sedimentary rocks, and the area is dominated by sandstones, siltstones and shales, with some coal seams. In the eastern end of the valley there are some locations with conglomerate with phosphoric nodules. The lower sequence, visible in the east end of the valley, is several hundred metres of organic rich, clayey and silty rocks, while the upper sequence has shales with less organic material and sandstones. [4]

2.2. Quaternary history

In the area in and around Adventdalen, 62% of the area, which is not covered by ice, is covered with weathered material. Only 5% is covered with till from inland ice sheets. This differs a lot from the mainland of Norway, where most of the deposits are till. The weathered material is mostly decided by the local rocks. On the surface it is not unusual to se signs of the layering and composition of the rocks underneath. Since this is the case also in quite steep terrain, it can be assumed that the weathered material has not been transported, at least not very far. [4]

The landforms in the same area are mostly made by local glaciers, weathering, frost processes and rivers. Some of the big landforms are more or less decided by the structure and the composition of the sedimentary rocks. Quite a few mountains are flat on the top, where the top layers are rocks with certain hardness, which can resist weathering. [4]

The big valleys, Adventdalen included, are wide, flat valleys formed in the sedimentary layers with only a relatively thin layer of deposits on top. The smaller valleys, ending in the bigger ones, are more V-shaped, which indicates that they are formed by water, freezing and weathering. There are not too many landforms made by the ice sheets. This is because the sheets for long periods had a temperature close to zero near the bottom, and therefore didn't erode, but conserved the surface. [4]

On ice free areas on Svalbard there can be continuous permafrost down to several hundred metres. This affects the transport of sediments, since the water can not go down in the ground, but is located in the active layer, the upper part of that melts during the summer. This results in a higher water content in the upper layer than it is on the mainland. The ground water is under the permafrost. The permafrost gives a few typical landforms as pingos, ice-polygons and rock glaciers. [4]

During the last years there have been measured creep and solifluction in Adventdalen, and the largest movement is found to be 4 cm per year. In some locations there are not found any movement at all, even if the terrain is steep. This may be because the climate is so dry. [4]

The landforms formed by deposits are many. Since the deposit consists of the rocks in the area, the type and composition of the deposits depends on the type of rock. A fine grained rock, as siltstone and shales, becomes fine grained soils, while sandstones and conglomerates give more coarse deposits. The grading of the deposits depends on the transportation and sedimentation. [4]

Weathered material, in-situ and transported: Weathered material can, as already mentioned, be in-situ materials or transported. The transportation can be by wind, water or snow and ice. The grain size of weathered material can vary a lot, from big boulders to fine grained sand.

Till: The composition of till will vary with the type of moraine. Terminal and medial moraines will have a more dense deposit with bigger grain size than bed moraines. Common for all till is that it is not sorted, and contains a lot of fine grained material as silt and clay.

Dead ice terrain with mounds and depressions: Big blocks of ice that has loosened from the glacier and covered by deposits, can give dead ice depressions when they melt.

Fluvial deposits: This can be both recent and pre-recent deposits. The recent fluvial material is deposited on active fluvial fans or plains, while the pre-recent deposits no longer are affected by fluvial erosion and therefore there may be some vegetation on top. If the river floods, or change its way, this vegetation will be covered, and can explain th e organic material below the deposits visible today. Common for the two types are that the material is sorted and rounded, with a low content of fine grained material.

Glacifluvial deposits: This is a deposit formed by melt water from the glaciers. It is characterised by sorted sand and gravel, and can look a lot like fluvial deposits, but the grains are not as rounded as in fluvial deposits.

Pingos: This landform is formed by water coming up from the ground. When the ice freezes it expands upwards, and this results in a mound with an ice-core covered by the local deposits. If the water comes from the bedrock, parts of this rock can be loosened and brought up. The pingos have a lifecycle, and they may grow for several years before they melt.

Marine deposits: Is mostly silt and clay, with a certain salt content. The lower parts of Svalbard were under seawater a long time ago, and therefore it can be salty deposits on shore.

Figure 2: Quaternary map from Adventdalen [4]

In Adventdalen all this deposits can be found, but the lower part is mostly fluvial deposits, both recent and pre-recent. In the eastern end there are some locations with till as well. Since the Advent River and other rivers in the smaller valleys are constantly eroding and depositing masses, the material in Adventdalen have different origins. It can be hard to decide exactly what kind of deposit it is. It can also vary with the depth, if old deposits are covered by younger ones. When deposits are mapped it is the upper 50cm that decides what deposit that should be marked. So even if most of Adventdalen is mapped as fluvial deposits, there can be other deposits under it. Most likely there are moraine or marine deposits. [4]

No one seems to know how Isdammen was formed. But we know that it originally were three individual dams, that later was formed into one big dam. The origin of the three dams is hard to decide, but there are some possible explanations. First of all they can have been dead ice depressions from the time that Adventdalen was covered by ice, or old river courses which have been isolated when the river changed its course. They can also have been old, melted pingos. The growing ice-core may have pushed old deposits aside, creating a small dam. Since the dam is close to the slope, it can also be caused by creep or solifluction. The deposits may have slide down the slope and formed a natural dam, but it is impossible to tell for sure. [4]

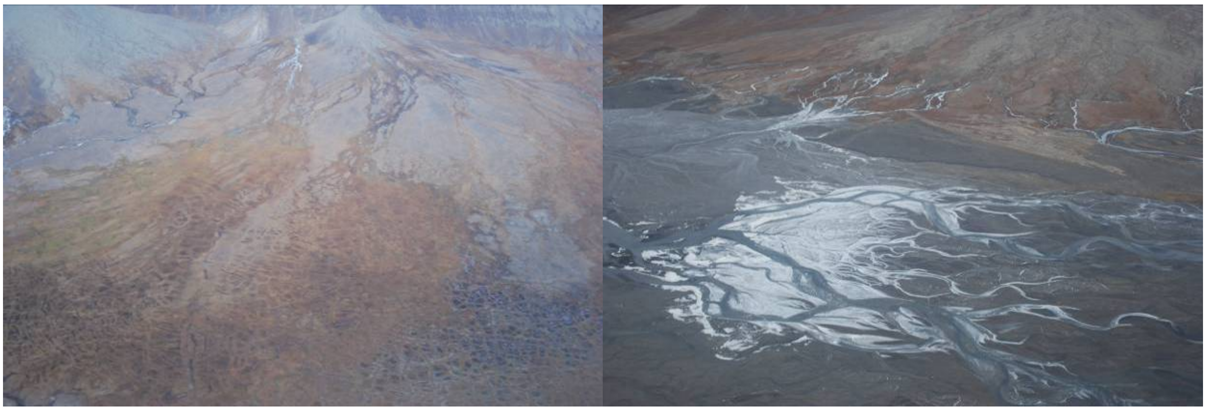

Figure 3: The Advent River plain and delta

3. Hydrology

When potential reservoirs sites are investigated, there are two types of essential data needed, topographical maps and hydrological records. Since Isdammen, as mentioned wasn't originally built as a reservoir, this investigations probably haven't been carried out. Despite this, Isdammen seem to work just fine. The run-off season is short, but it seems that Isdammen also get free water from below and that this keeps the water level stable.

3.1. The Isdammen Catchment

This catchment is located at Nordenskiøld Land close to Longyearbyen, as seen on Figure 4. Isdammen, a small man-made lake close to the river outlet, is the water supply reservoir for Longyearbyen. The catchment area is 34.4 km^2, with glaciers covering approximately 5.1 km^2 (15%) and lake area 1.3 km^2 (3.7%). The catchment extends from Isdammen close to the sea level up to 1015 m a.s.l. Medium elevation is 425 m a.s.l.

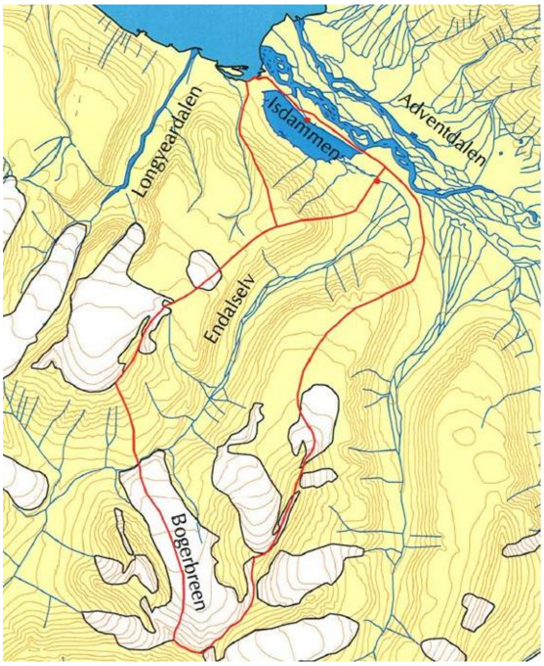

Figure 4: River Endalselv catchment area and location of the monitoring stations at the inlet and outlet of the Isdammen water reservoir

3.2. Svalbard Hydrology

The runoff season is short in Svalbard, with no runoff during winter-time. This season lasts for approximately four months in Spitsbergen, usually it starts in late May, early June when the temperature rises above 0 degree Celsius and ends in late September, early October. Precipitation falls as snow for the most part of the year, except during the summer. It is when the highest floods occur, caused by heavy rainstorms and glacier melting. The snowmelt in the Arctic is very intense, and a major part of the runoff is from snowmelt early in the season.

3.3. Permafrost Conditions

With a mean annual air temperature of about -6^{o}C, most of the land area in Svalbard has permafrost. Permafrost depth is dependent on many features of the landscape and the climate, such as snow cover, glaciers, type of ground, vegetations, presence of lake, and the orientation of surfaces slope. Permafrost depths of between 100m near the sea and up to 500m in the mountains have been measured.

3.4. Water balance studies

The leakage of the dam could be a problem for the future if new different points of leakage will be created. It will increase the leakage discharge and may cause a negative water balance. In the water balance studies you have to take into account the spring snow storage, the areal summer precipitation, the actual evaporation and finally the areal storage change. In this case the leakage discharge will be subtracted to the water balance equation. In the future temperature and rain precipitation will increase and will cause a bigger runoff during the summer due to a bigger melting of glacier. But it could be a problem for this catchment particularly; Isdammen catchment is just covered by 5% of glaciers. Moreover certain years the areal storage change a lot, it could cause a drying out of Isdammen during the winter when most of the water is ice in the water reservoirs. So it will be interesting to know really the average leakage discharge and study if it could be a danger for these next years.

Figure 5: One point of leakage of Isdammen water reservoirs [NGI report]

3.5. Sediment Transport and Erosion Process

Sediment transport in rivers is an important aspect of physical water quality. Large concentrations of particles are regarded as pollution, even if the sources are natural. Water charged with a high content of particles in suspension is unsuitable for drinking water without further treatment. Pollutants may be associated with particles.

Sediment transport may also affect the sedimentation in Isdammen water reservoirs. If the sediment transport is high, reservoirs may be filled up. This is not a problem in mainland Norway where lakes are abundant. It is, however, a major problem in the Arctic. In Svalbard, lakes are rare and the sediment transport rate is considerably higher than in the water bodies used for drinking water in mainland in Norway. In the dynamic landscape of Svalbard, erosion rates may change rapidly and a situation that seems stable may soon become unstable.

Most of the sediment transports in Endalselv occur during four months, from June to September as we can in Figure 6.

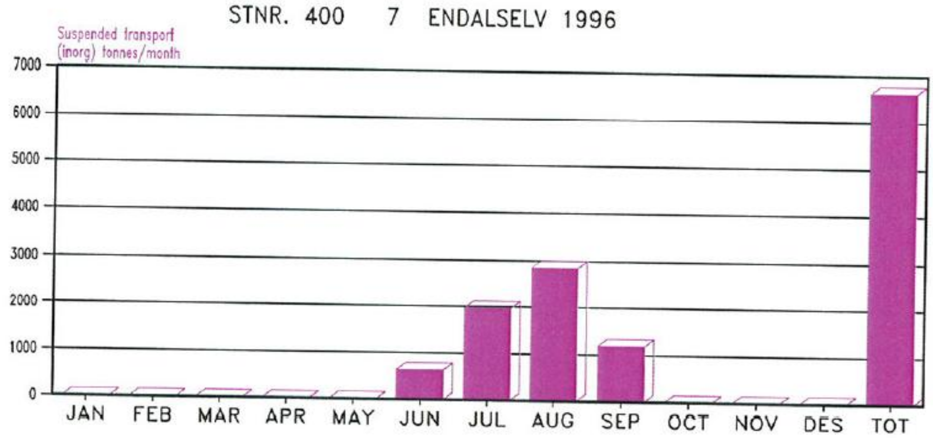

Figure 6: Monthly Inorganic suspended sediment transport in river Endalselv in 1996, and annual total

Different erosion processes are present on Isdammen, the main processes are erosion by the snowmelt runoff, rainflood during the summer and wind that cause waves.

Figure 7: Erosion process, erosion caused by waves coming from frequents winds [1]

4. Field investigation

Field investigations are carried out to find the properties of the materials we are dealing with. There have been two investigations carried out by NGI, one in 1979 and one in 2008. As a part of these course UNIS students drilled one hole with intend to take core samples, and installed one thermistor string. Samples from other UNIS courses have also been analyzed. It might be difficult to compare data from different institutions, and the arctic climate adds another challenge due to seasonal changes in frost conditions.

4.1. Comparison of lab results from students and NGI

When we compare NGI's map over their sampling area with the sampling from 2009, we assume that the 2009 sampling was taken in between the third and fourth hole from 2008. This makes it natural to compare the 2009 results with NGI's results from these holes. Because NGI has not presented their results from the fourth hole in the report this chapter compares the 2009 results with the 2008 results from the third hole.

4.1.1. Comparison of visual inspection

Tabel 1: Visual inspection

Test	Visual inspection	
Material	Isdammen 2009	Isdammen 2008, hole 3
Sample depth		
1,0 – 1,5	Fine grained material with gravel. Some fine sand, dry, not washed. Little quarts, no organic material. Big variation in grain size	Top layer is described as gravel. The next layer is described as sand with gravel, while the bottom layer is fine sand and silt with a possibility of clay. The layers are not specified with depth, the report states that at three meters depth there is silt, gravel with sand and some organic material. At 5-6 meters depth there is gravel and silt sand.
1,5 – 2,0	More course material, some of the gravel is crushed, some is not, some big particles. more moisture than the first sample	
2,0 – 2,5		
2,5 – 3,0	Some gravel, wet, a lot of silt, fine sand and silt with gravel. maybe gravel from the upper layer, and that the sample is disturbed?	
3,0 – 3,5	Silt and clay with some fine sand, a lot of water	

The visual inspection from 2008 classifies the layers after Norwegian standard, while the one from 2009 is after American standard. This may cause a difference in the description of the visual inspection.

The two visual inspections describe a top layer containing gravel followed by a layer of sand with gravel. NGI discovered some branches, while we could not see any organic material in the shallow layer. Because of a lot of water in the ground the drilling in 2009 ended at approximately four meters depth, while the one from 2008 went down to at least five-six meters depth.

4.1.2. Comparison of grain size distribution

Comparison of grain size data with respect to depth gives an impression of a remarkable difference in grain size from September 2008 to February 2009. It seems like the grain size at one depth in 2009 fits well with the grain size at a couple of meters deeper in 2008. In a geological perspective, such a short time period rejects this impression. In Figure 8 the black lines illustrates the grain size curves from 2008 while the blue ones illustrate the distribution curves from 2009. The solid drawn curves show the top layer distribution, while the blue dotted curve should correspond to the two different black dotted curves which illustrate deeper layers. Because the drilling in 2008 went deeper than in 2009 it is suspected that curve F should correspond best to the blue dotted line. As the Figure illustrates, the solid drawn curves corresponds well. The 2009 curve is moved a little to the right for the 2008 curve, as expected due to the difference in the grain size data. The similar shape of the curves indicates constant variances in grain size, which implies that the difference came during the drilling process. This dissimilarity was predicted in the lab report from AT205 spring 2009 at page 16, because of an observation of crushed material.

The dotted curves also have an acceptable similarity. Due to lack of knowledge about depth it is difficult to compare, but it is assumed that the first part of the blue curve should fit with curve F, while the last part should fit with curve G. As the Figure shows this comparison gives a similarity which fits well to the assumption. As for the solid drawn curves, the curve from 2009 is moved a little to the left and, as mentioned, this may be due to sampling.

This comparison gives the impression that the grain size is smaller in 2009 than it was in 2008. As mentioned, this difference may have occurred because of crushing of material during drilling. It may also partly be caused by the sharing of lab work among several inexperienced students.

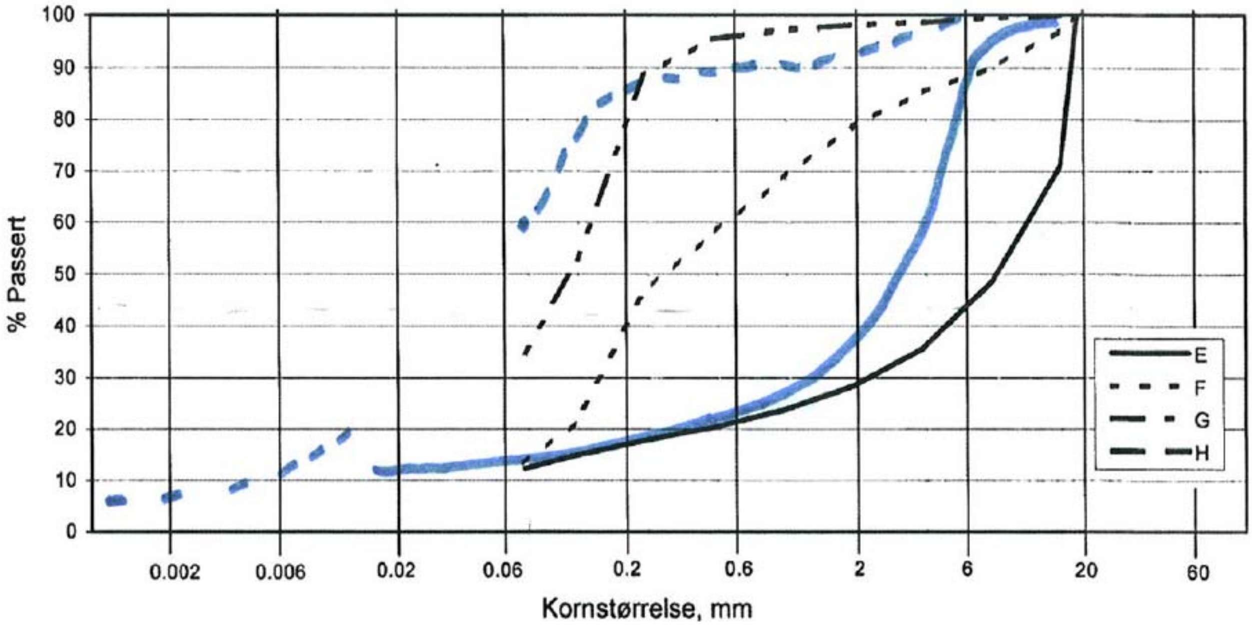

Figure 8: Grain size distribution, [1]

4.1.3. Comparison of NGI's result in 1979 and 2008

In 1979 there were not taken any tests near by the third hole from 2008. All tests in 1979 were taken close to the end of Isdammen, direction Longyearbyen. We have chosen to compare results from point P1 with the eighth hole and P2 with the seventh hole. The visual inspection of the eighth hole results in sand gravel at six meters depth, while silt sand clay occurs at nine meters depth. The seventh hole is described as sand gravel at six meters depth, while wet conditions further down. This fits well with the inspection from 1979, even though we should comment that the report from 1979 does not give us any indications of depth.

4.1.4. Comparison of salinity

NGI measured the salinity in the fourth hole to be 71 g/l pore water at five meters depth. Regarding the third hole, it is commented that the salinity is remarkable high at this point. This may be explained by the fact that the ground contains pockets filled with water with high salinity and that the sampling may have hit one of these pockets. Our salinity measurements give 4-5 g/l pore water at 3-3, 5 meters depth. Like NGI's measurements, this indicates marine deposits. We do not expect the salinity to change over such a short time period, and this is not considered likely to have any impact on the leakage in Isdammen.

4.1.5. Correlation between field investigations

Due to lack of depth specification in NGIs report it is difficult to compare these results with the results from 2009 and we can not expect the result to be precise. At the same time, the amount of samples is so small that it is difficult to use the results to conclude. The differences we found are most likely caused by accidental crushing of material during sampling. The ground is not homogenous and it is assumed that there are differences in the ground even within short distances. The samplings in 2009 took place close to the third hole from 2008, but not close enough to ignore this.

Differences in water content at same depth in different years may be caused by variations in temperature. The tests from 2008 are taken in September, while the sampling in 2009 took place in February. This may also be a problem considering our comparisons. It would have been interesting to see if there has been any change in flow rate, but this kind of measurements have not been done.

4.2. Permeability and presences of organic material

In 2008 NGI found the permeability to be 1, 3 m/year. According to NGI, this has not changed since 1979. There has not been done any tests on this in 2009, but due to the stabile past it is not suspected that the permeability has changed dramatically from September 2008 to February 2009.

As mentioned in our labreport it was found a layer in the samples from Nordlysstasjonen containing considerable amounts of organic material. This layer was present from 2.48 to 2.70 meters. Due to topography and geological history it can be assumed a presence of a similar layer under Isdammen. The layer is assumed to be deeper then the depth we reached during drilling. We can assume that this potential layer is at least four meters under the top of Isdammen. Organic layers have a high

Figure 9: Orangic material found at Nordlysstasjonen

permeability, are frost susceptible and are a very soft material. If this layer exists it can be one of the explanations of the leaking and frost related damages to the dam.

4.3. Possible future geotechnical investigations at Isdammen

The problem of leakages at Isdammen is still not completely studied, and therefore further investigations are highly recommended before trying to implement any solution for the existing problems. Water in the embankment combined with low temperatures caused problems during the sampling in 2009, and this very well may happen again. Optimal sampling can therefore be difficult, or even impossible.

We can call three main types of investigations to be carried out to understand the layout of the leakage problem in a better way.

4.3.1. Hydrological and meteorological investigations

These investigations can help us understand the climatic and hydrological setting at the site. Most important of these would be an attempt to assume the water and temperature balance of Isdammen. At the present time we do not have any data concerning water income at Isdammen, and even the output is not completely known, thus we cannot assume the exact amount of leakage and its temporal distribution, from whish seasonal is the most important. The following methods of hydrological investigations can be applied.

Water level measuring at the reservoir

The simplest method, yet giving a sufficient contribution to understanding the water balance. There is a row of water level meters available, with some capable of automatic non-maintained measurements. Setting such a water meter would also help to predict and prevent floods, especially if to build an automatic system in connection with the levee sluice. If we know the exact volume of the reservoir (see Topographical investigations), we can estimate the volume of water in it, and knowing the exact amount of water consumption, we can estimate the amount of leakage and its distribution in time.

Water income studies

This is important to estimate the degree of threat to Longyearbyen water supply caused by the leakage. The water income must be studied timewise, because this can help us understand is there any critical period of time when leakages appear to be a serious hazard to the water supply. This includes the following parts:

- Estimating the snowmelt income. For this, we should know average amounts of snow accumulating in the Isdammen basin. Environmental modeling can be very helpful at this task, although it is a rather complicated and not absolutely reliable method. Some models used by Ole Humlum at UNIS may be relevant for this. Furthermore, some calibration with use of field investigations may be needed for the model (for example, survey of snow depth and density at some key points in the Isdammen basin).

- Estimating the discharge of Endalselva river (which is the main tributary of Isdammen) may need establishing a hydrological station at a place where the river has one single channel. This would be an expensive and complicated method, yet not giving all the income since there is a number of non-perennial springs flowing from the slope of

Lindholmhedga, which discharge is relatively hard to estimate correctly. A fitting site for establishing a hydrological station is near the Endalen solifluction measuring site.

- An attempt to find out any ground water income directly to the bottom of Isdammen. This may need a thermal survey of Isdammen water body and maybe a chemical investigation of is water in the bottom and side parts. We suppose this income not to be critical in forming the Isdammen water balance, although it may affect the characteristics and behavior of the water body in winter time. Therefore, this investigation is only complementary.

Water outcome studies
These studies must be carried out timewise as well. They include:

- Water consumption monitoring. This is the most essential part since Isdammen is used as a drinking water reservoir of the town.

- Loss of water due to evaporation is calculated depending on weather parameters (temperature, humidity, wind speed) and lake surface area. But this loss may turn out to be negligible.

- Direct observations of the leakages if possible, with attempts to estimate their discharge. This requires frequent field observation of the outer side of Isdammen, and if we find any obvious springs there, approximate amount of released water (calculated from area of section and flow speed), its temperature and maybe salinity must be recorded.

Meteorological investigations
These are maybe the cheapest part since we have the running weather station in Adventdalen at the former Aurora station. Although, the amount of rainfall must be taken into consideration, as long as this automatic weather station cannot measure it directly. The climatic data are useful for environmental and thermal modeling.

4.3.2. Thermal investigations

The cryological investigations are important to understand the seasonal distribution of leakage volumes. If the body of the dam freezes over completely in the winter, we may expect sufficiently lesser amounts of leakage, especially in the most critical spring time when the income of water into the reservoir is nearly absent, and consumption is still at a high level. Furthermore, if we assume the artificial freezing of the dam to be a solution for preventing the leakage, then the cryological survey becomes essential before we start to design a cooling system. Thus, the main goal of cryological investigations is to find out the distribution of temperatures and permafrost within and nearby the dam.

Termal sensors
Setting thermal sensors (mini-loggers) on the ground surface along the outer side of the dam – this may give us the distribution of temperatures at the leakage site. Particularly interesting is whether the leakage channels stay unfrozen during the whole winter, or what the time when they do not freeze over is. This investigation also can give us a picture of leakage channel distribution, which is important for designing the solution of the leakage problem. But setting a sufficient amount of loggers may be time consuming (both in setup and dealing with their data) and not cheap.

Thermister strings
If termistorsrtings are placed in boreholes they can give us a picture of temperature distribution inside the dam. This is critically needed information if we want to set up freezing equipment (thermosyphons or active freezing) into the dam to prevent the leaks. Also this would be very useful data for thermal modeling of the dam. Of course, this requires a sufficient number of boreholes to be drilled (preferably close and far to the points of leakage below the dam, to understand thermal influence of leakages in a better way).

BTS survey
Studying the bottom temperatures of snow pack with special thermister-based probes and loggers can be useful identifying distribution of ground surface temperatures (GST) and presence of permafrost. This method is relatively fast, cheap and comprehensive in means of creating sufficient measurement network density. But it requires big (not less than 50cm) thickness of snow pack for BTS values to coincide with GST and probability of permafrost in better way; since there is a scooter track right outside Isdammen, this might be a problem.

Water temperature monitoring:
This can provide data for further thermal modeling and possibly indicate the presence of ground water inflow to the reservoir, if there is one.

Infrared thermal monitoring
This is an expensive method but a very comprehensive and scalable one. If there is a thermal camera already available, it may be used to observe temperature distribution on the outer side of the dam, especially in late autumn and early winter when the snow cover is thin and doesn't insulate the temperature distribution. The assumption is that we would have thermal anomalies (warm spots) at the points of leakage.

TEMPW modeling
This is the final stage of cryological investigations before we start to design a solution to the leakage problem. Before the modeling we must obtain as much temperature-related data as possible. The use of modeling can help us understand the life of leakage channels and therefore the danger of leakages to Longyearbyen water supply.

4.3.3. Geotechnical investigations

There is a row of investigations that must be carried out before the start designing any solution to the leakage problem. Among them there is topographic survey, geological investigations (primarily drilling) and possibly an additional GPR survey.

Topographic investigations
These investigations should provide the data to deal with the following tasks:

- Evaluate the exact volume of the Isdammen reservoir as a form of relief
- Recognize the exact dimensions of the dam
- Possibly, recognize the volume of ice formed due to leakages in winter time (this can be done by a repeated topographic survey under the foot of Isdammen in autumn (before the start of formation of the icing) and spring (before the snowmelt) time)

Topographical investigations may be carried out using DGPS technique or traditional triangulation-based instrumental methods. Large-scale airborne LIDAR survey is also applicable, but must be used with respect to accuracy. To study the bathymetry of Isdammen, echo sounding may be used, in line with instrumental depth measurements.

GPR survey

This is highly recommended since it can point out presence of unfrozen water inside the dam. It may also be useful in identifying the geological structure of the dam, for this it must be used together with coring which serves as reference during interpretation. Preferably medium frequencies (50 – 250MHz) should be used. It is reasonable to make 2 profiles along the dam on both sides of the road and several cross-sections, which should go both through points of maximum leakage and in between them. The profiles should preferably go through the boreholes and sites of monitoring, to provide better accuracy when interpreting the acquired data. The aim of GPR survey is to identify the geological structure and cryotic conditions inside the dam. It may also be reasonable to make a repeated survey in winter (before the start of melting) and summer (before the start of freezing).

Coring

More coring should be undertaken to study the material of the dam, since in our investigations in spring semester 2009 we were not able to get an undisturbed or at least disturbed sample of the dam material. These samples then must be used for laboratory tests to determine their properties and therefore engineering conditions of the dam. The boreholes should be used to place thermistorstrings and therefore acquire data on the thermal conditions inside the dam.

Drilling

Drilling can be used for cone penetration tests and to get more remolded samples of dam material for further testing and studies of geological structure. Its advantage is that it does not require that much effort and funding as drilling does, and thus can be used to widen the network of boreholes. Cone penetration tests give us reliable information on presence or absence of frost at a given site and thus they can be used for cryological mapping in addition to geological. The boreholes can be used to place thermistorstrings as well.

5. Geotechnical calculations of existing dam

For geotechnical problems in the arctic area, it is essential to know something about the temperature regime. Freezing of water in the soil can changes the properties of the soil radically. Freezing and thawing of soil leads to a seasonal unbalance in the pore pressure. Effects like volume changes and excessive pore pressure can lead to problems like reduced stability and differential settlements.

We have done some modeling of the existing dam, and we have chosen to make two models, one for summer and one for winter. These exclude the freezing and thawing problems during spring and fall. The models are kept simple because of limited data. The result from the investigation in this course was mainly used to identify different layers and frost conditions. Most of the parameters for the layers are taken as standard values. Some are tried estimated from the field investigation data.

5.1. Previous field investigations concerning temperature

NGI (Norwegian Geotechnical Institute) has done field investigations along the 2.5 km road embankment enclosing Isdammen in 1979 and 2008 (Figure 10).

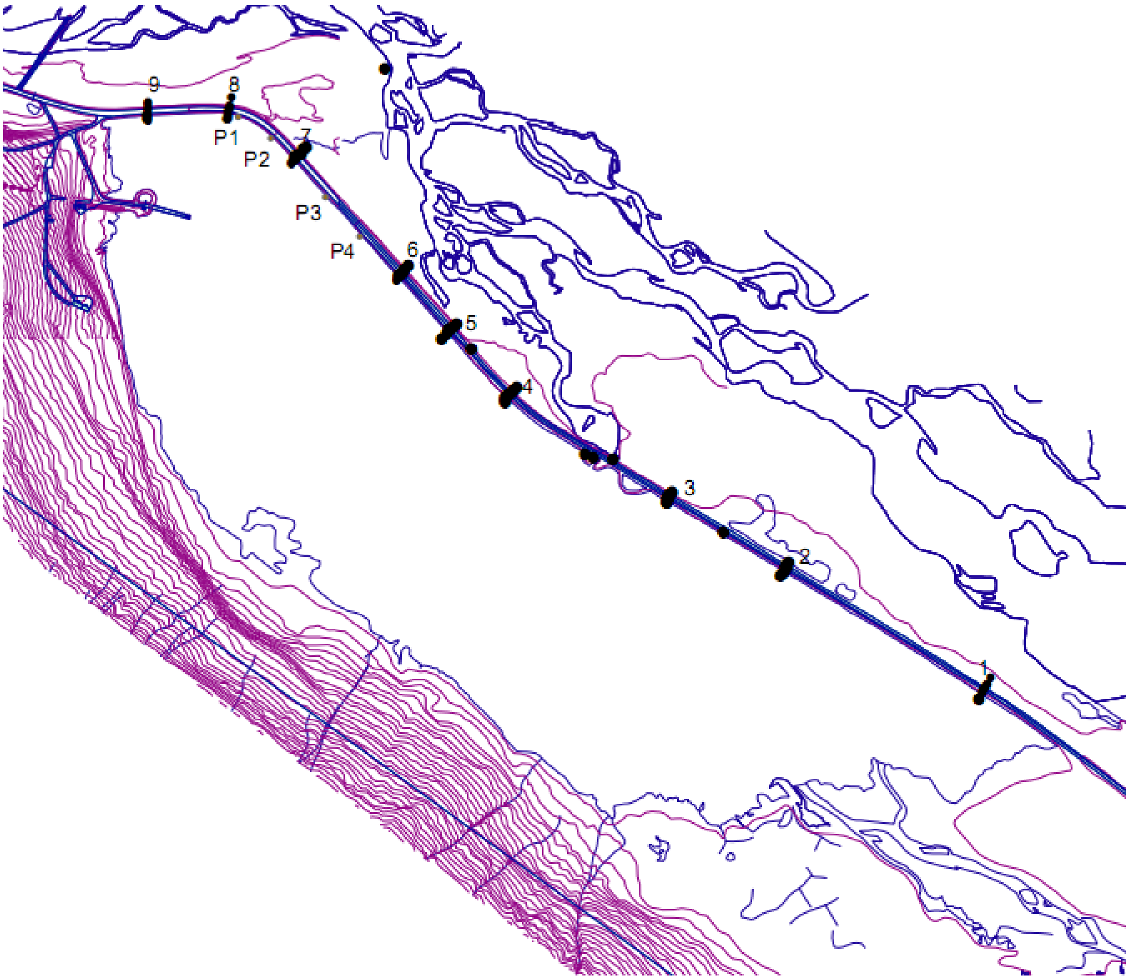

Figure 10: Road embankment enclosing Isdammen water supply for Longyearbyen. Cross sections P1-P4, May 1979, and 1-9, September 2008 [1]

The survey in 1979 was based on soil samples from bore holes along profile P1-P4 on the upstream (waterside) shoulder of the dam, including grain size distribution (GSD) analysis, description of soil type, water content, permeability, salinity and depth of permafrost table.

The survey in 2008 was somewhat more comprehensive than the previous one, based on additional profiles covering the entire length of the dam construction. The survey included geotechnical investigations i.e. GSD analysis from bore holes (all profiles except no. 4 and 6), soil samples (classification), permeability, salinity (not all profiles). In addition also description of hydrology, thermal regime and risk assessment was addressed.

Other previous investigations include Norwegian Water Resources and Energy Directorate (NVE), *report no. 7 (1996)* and *document 11/1999*, mainly concerning hydrology but also GSD analysis conducted in 1994-1997.

5.2. Thermal regime

In areas with permafrost, an understanding of the temperatures in the ground and how they change during the year is important. Materials change their properties with the temperature, especially around the freezing point, and it is of great interest to find the zero degree isobar. There is available software to use for ground modeling, and it can be really helpful to visualize the effect of measures.

5.2.1. Air temperatures

Svalbard is situated at latitudes where continuous permafrost is dominant. During spring the uppermost layer of the ground thaws, and this is called the active layer. In and around Longyearbyen the active layer extends 1-1.5m below the ground surface.

Historical records from Norwegian Meteorological Institute (DNMI) 1961-1990 of mean monthly air temperatures show sinusoidal fluctuations throughout the year (Figure 11).

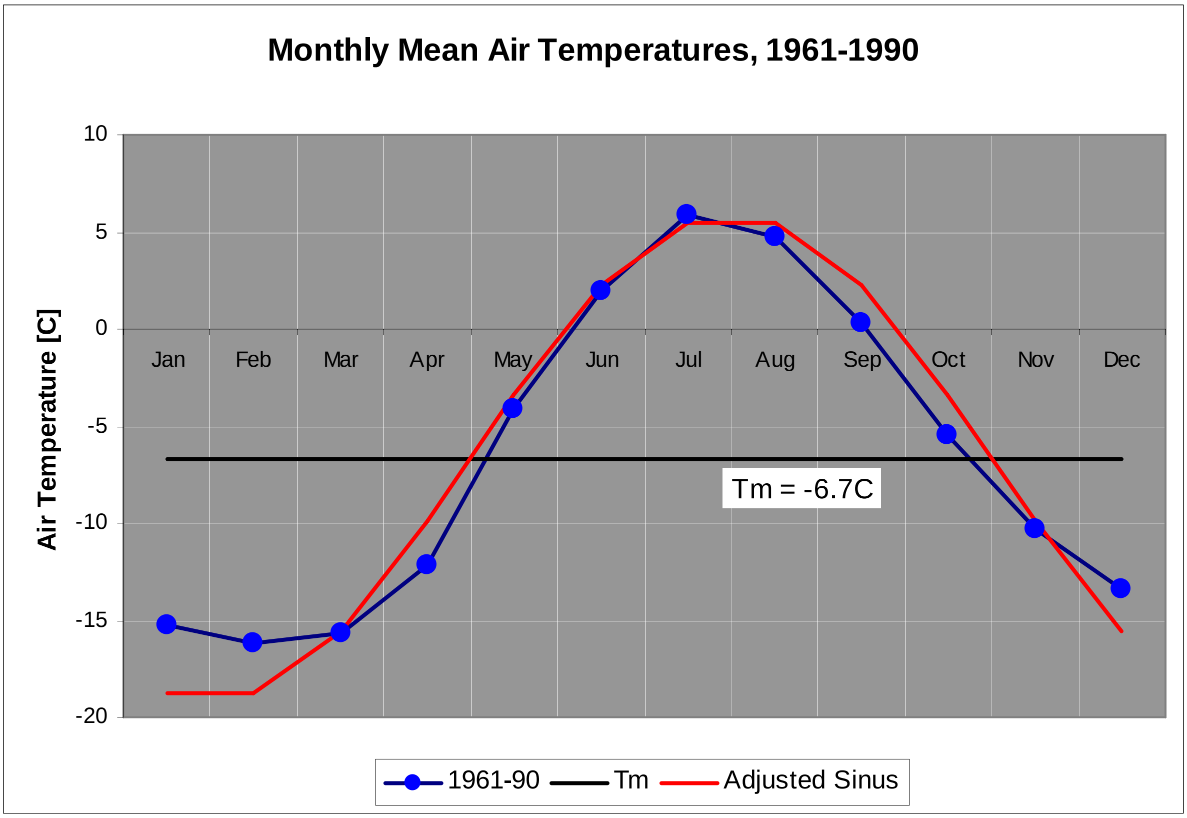

Figure 11: Historical records of monthly mean air temperatures for Longyear Airport, mean annual temperature (Tm) and a sinusoidal approximation

The lowest air temperatures are to be expected during February and Mars. Only 4 months of the year have average temperatures above 0°C, which means a relatively short period of thawing compared to e.g. mainland Norway where it is seasonal frost.

Ground temperatures are determined by air temperatures, heat flow from the earth's core and soil thermal properties and will have both a time lag and smaller amplitudes compared to air temperatures. The time lag increases while the amplitude decreases by depth.

5.2.2. Ground temperatures

Temperature attenuations with depth can be approximated as a response to varying air temperatures shown in Figure 12, resulting in a so called whiplash curve. Such calculations have been done for Longyearbyen, shown in Figure 12. The results indicate an active layer down to approximately 1,3m.

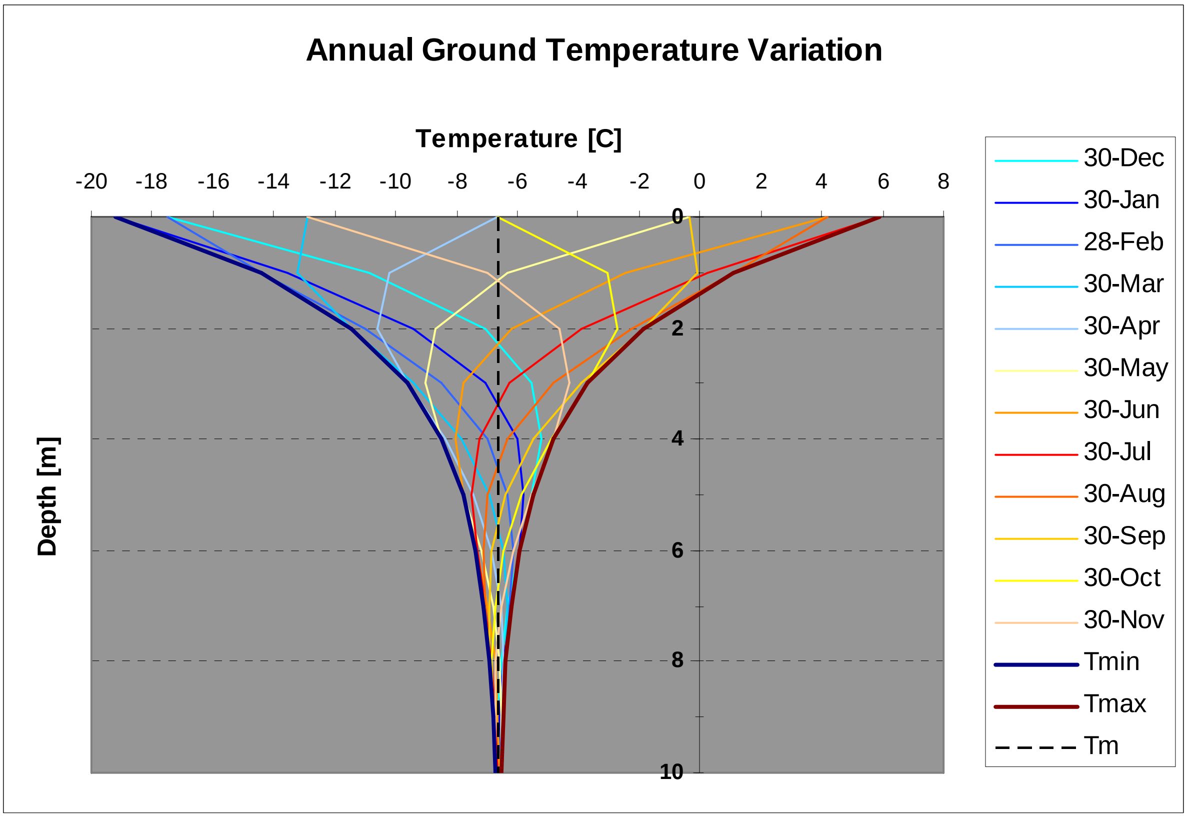

Figure 12: Approximate annual ground temperature attenuations for Longyearbyen region, based on annual mean air temperature for Longyear Airport 1961-1990

In the case of Isdammen, the depth of the active layer may be altered by the road embankment itself as it acts as an insulating layer on top. Coarse materials would allow for heat loss due to convection, but as mentioned in previous reports the construction contains considerable amounts of fine grained soils e.g. clay, silt and sandy silt. Also high salinity content could give extended thawing depths and thus a deeper active layer than expected.

The effect Isdammen water body may have on the top of permafrost table (TTOP) is another consideration. Normally one would expect a depression of TTOP under lakes – possibly with lateral effects into the upstream shoulders of the dam.

5.2.3. Thermistor string

Temperature readings from a thermistor string in a 4.8m deep bore hole between profile 3 and 4 (Figure 10), containing 10 thermistors, where obtained for the time period February 25th to May 24th. The bore hole is placed on the downstream shoulder (outwards side) of the road embankment. Results are plotted in Figure 13.

Channel 10 represents the ground temperature 4.8m below ground surface. The mean ground temperature at this depth is -0.9^{o}C for the entire measurement interval of nearly 2 months. According to Figure 12 one normally should expect much lower temperatures at such a depth at this time of the year, i.e. close to -7^{o}C.

Plausible reasons for this can be that the road embankment acts as an insulating layer, influence of high salinity, TTOP depression under parts of the upstream shoulder (discussed in 5.2.2) or a combination of all above. Further implications are temperatures above the 0-isotherm at this depth in late autumn when the thawing has reached its maximum.

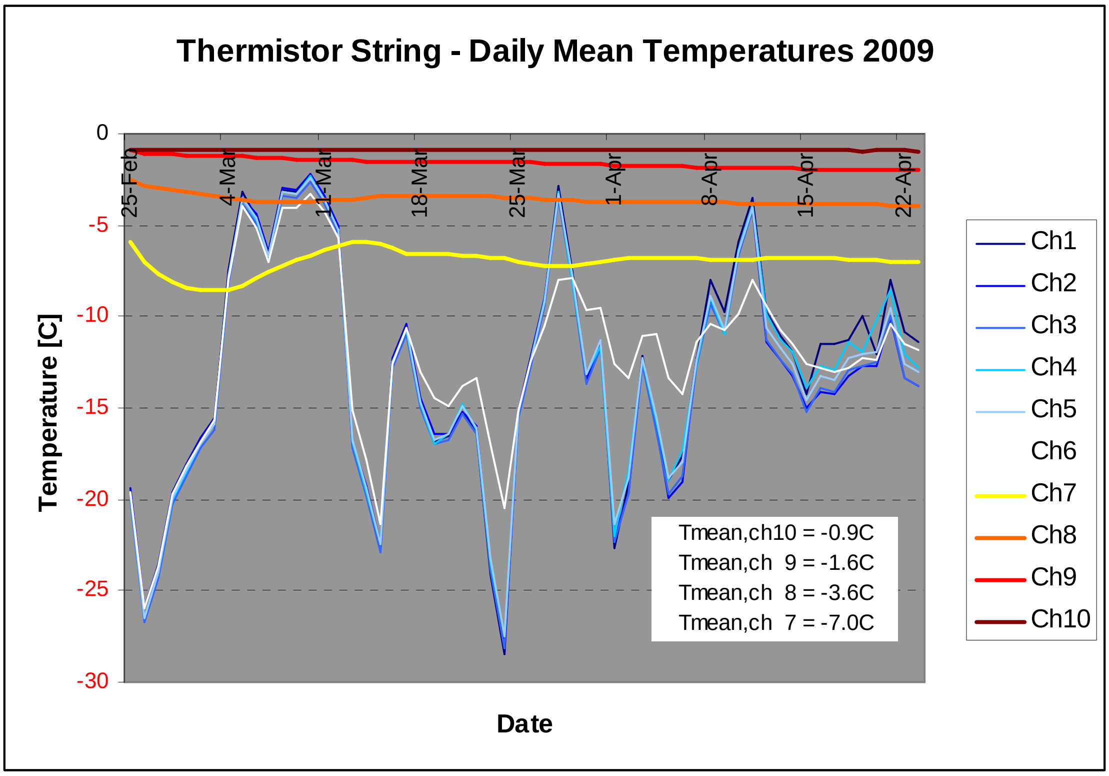

Figure 13: Daily mean values of air and ground temperatures in bore hole at road embankment of Isdammen. Thermistor channels 1-5 is located approximately 0,5m above ground surface, channel 6 approximately at ground surface and channels 7-10 gradually downwards to bottom of the bore hole at 4.8m

Channels 1-5 represents air temperatures as those thermistors are coiled up in the top of the access tube 0.5m above ground level, and responds closely to solar radiation after about mid Mars. This effect is not that obvious in Figure 13 because the curves are averaged daily values. Channel 6 is not responding in the same way to solar radiation and is therefore assumed to be at or slightly above ground surface level.

5.2.4. TEMP/W modeling (GeoSlope software)

The *NGI report 2008* present results from 2D heat flow simulations at a given cross section of the dam construction. One simulation represents autumn (Figure 14) and a second the conditions during spring (Figure 15).

The model must be considered an approximation as it simplifies the geometry and especially the layering, and does not take into account that running water influence on the heat balance of the system.

As shown in Figure 14 the top layering of the road embankment has thawed in the autumn, but there is still a considerable frost wedge in the lower part of the downstream shoulder. This presumably stops any major leaks during this time of year.

Figure 15 shows the same profile during spring where the embankment is more or less frozen, forcing the 0-isotherm far out on the upstream shoulder.

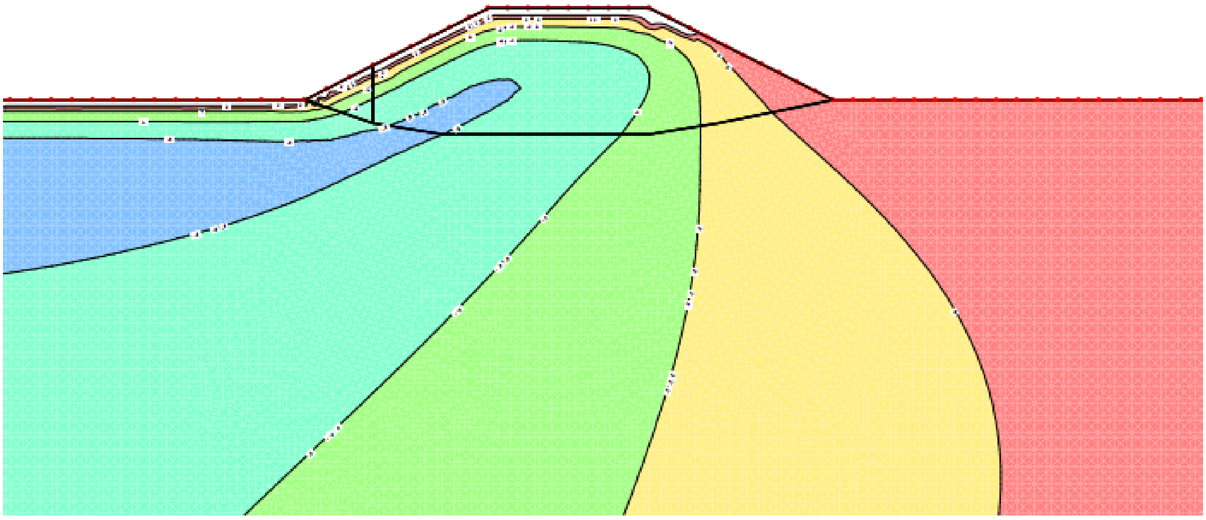

Figure 14: Early autumn. 0-isotherm is between red and yellow. Temperature intervals are 2°C [1]

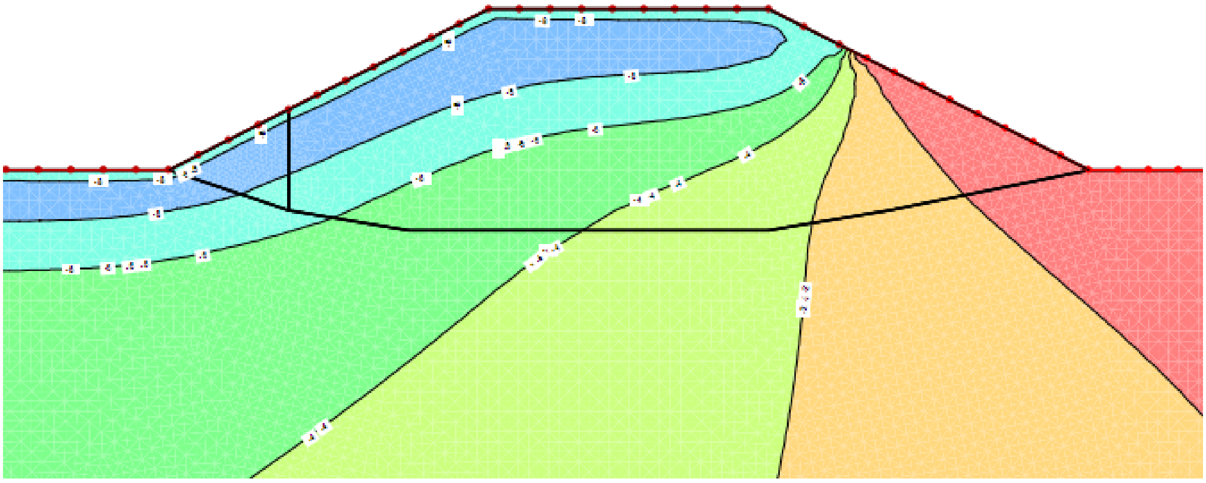

Figure 15: Spring. 0-isotherm is between red and yellow. Temperature intervals are 2°C. (Annual mean air temperature increased by +2°C from -6.7 to -4.7°C) [1]

5.3. *PLAXIS modeling of current dam*

In Plaxis 8.2 it was made an approximate model of the Isdammen Dam. The model simplifies the geometry, layering and soil properties. Nevertheless it makes possible to understand quality side of the problem, its hydrology and forces that affects on the dam.

5.3.1. Model of dam

Properties of the soils were considered standard, except permeability. The value for permeability was taken from the NGI report, 1.3 m/year for sand material. Gravel material is considered to be more transparent for water and has the permeability coefficient equals to 2 m/year.

As mentioned in chapter 4.2 there might be a layer of organic material under Isdammen. But since we do not know the depth or the temperature regime in the layer, it is difficult to model it. We mean that modelling this layer would be too complex model based on too spares data. Instead we have chosen to model with a layer of sand that is given permeability from the NGI report.

Organic material will influence the results of stability and settlement analyses. But this is more important if the layer thaws or freezes, and we have not done any calculations on this and nor do we know anything about the temperature regime in a possible layer.

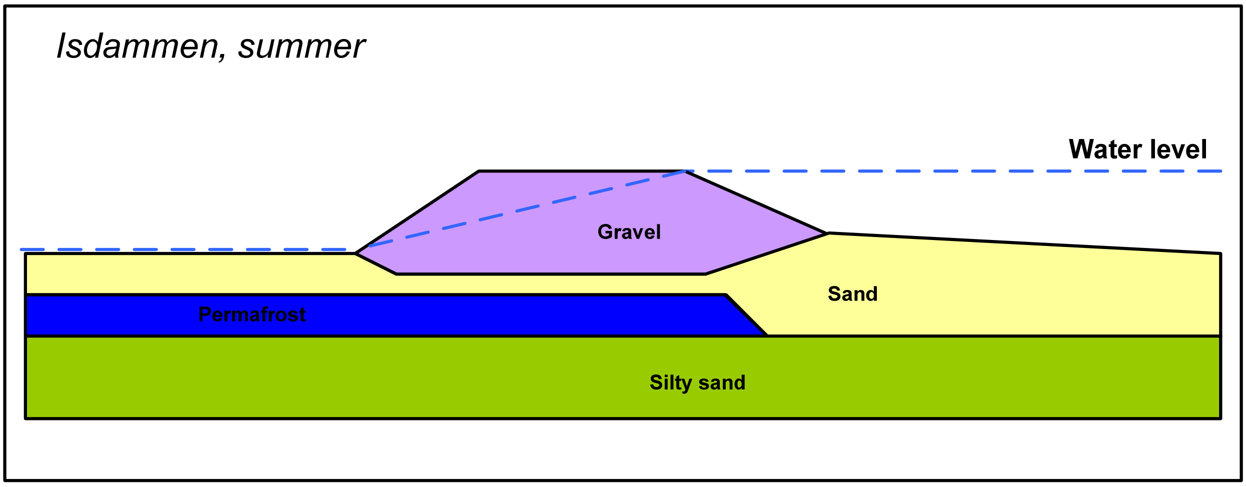

Figure 16: Model of Isdammen dam during summer

Also winter and summer states were taken into account. The water level and condition of the soils are different depend on the season. During winter most of the soils are frozen. There is a small area under the road which is unfrozen due to heat fluxes from the lake. In the field investigations we've found this area with unfrozen water. Also the water level in Isdammen is decreasing because of freezing.

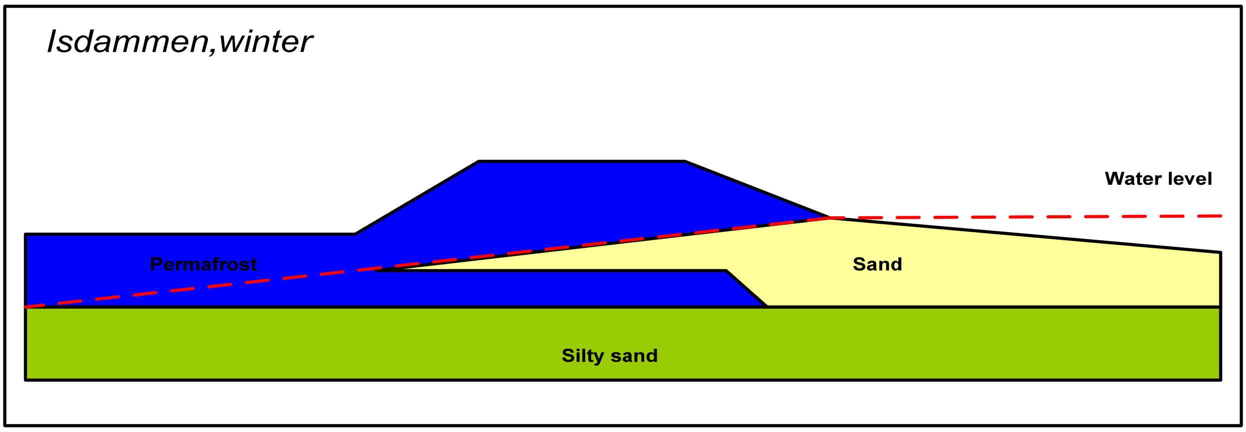

Figure 17: Model of Isdammen dam during winter time

5.3.2. Results

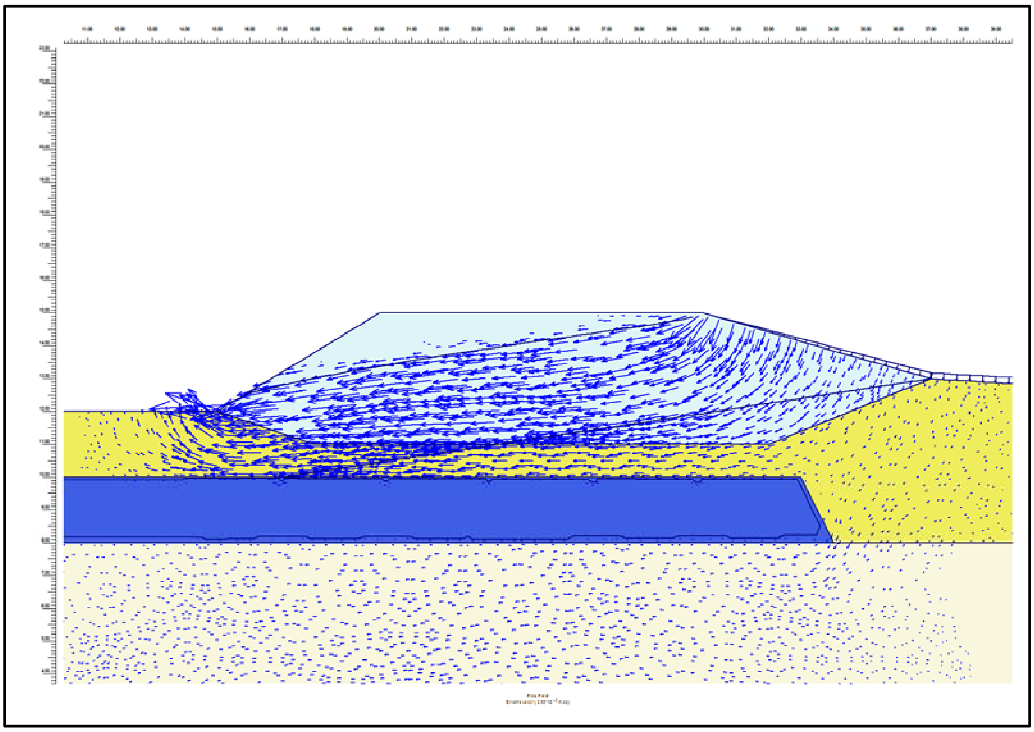

Figure 18: Flow field, extreme velocity 2,55e-3.

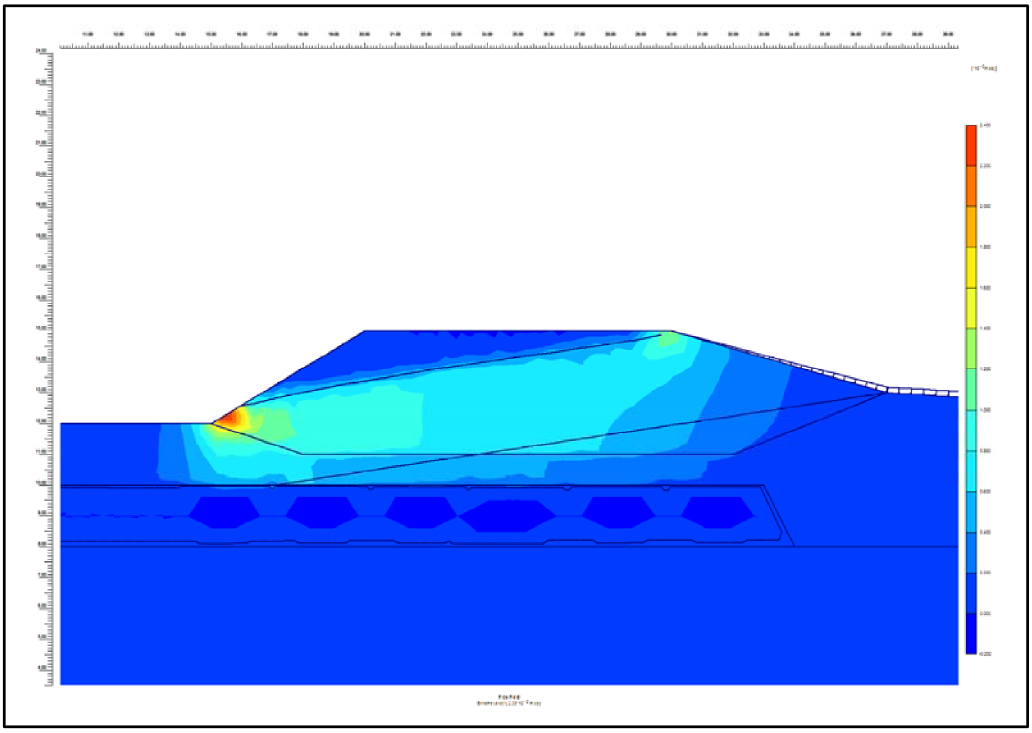

Figure 19: Flow field in shadings

These figures represent water flow during summer period. The flow starts from the lake's bed. It goes under the road at the depth of 2-4 m and comes from the bottom part of the dam. Where the flow has the maximum velocity, 2,5e-03 m/day. This process causes corrosion of the soils. On the next Figure we can see deformations.

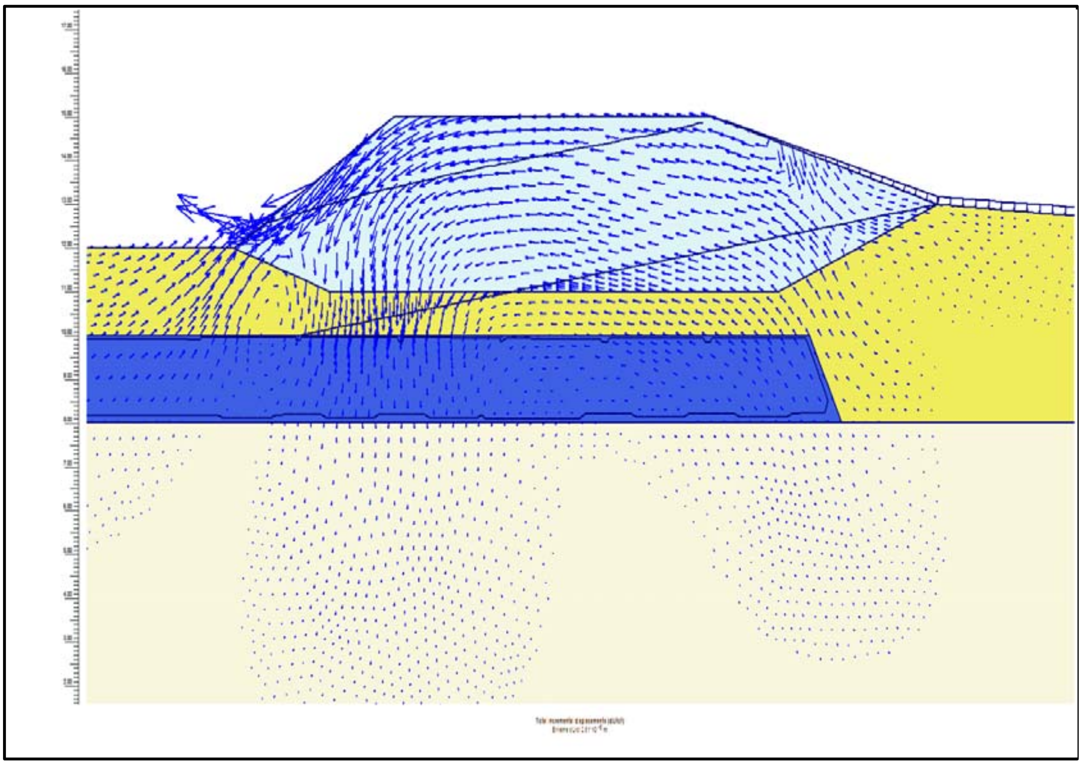

Figure 20: Total increments of deformations

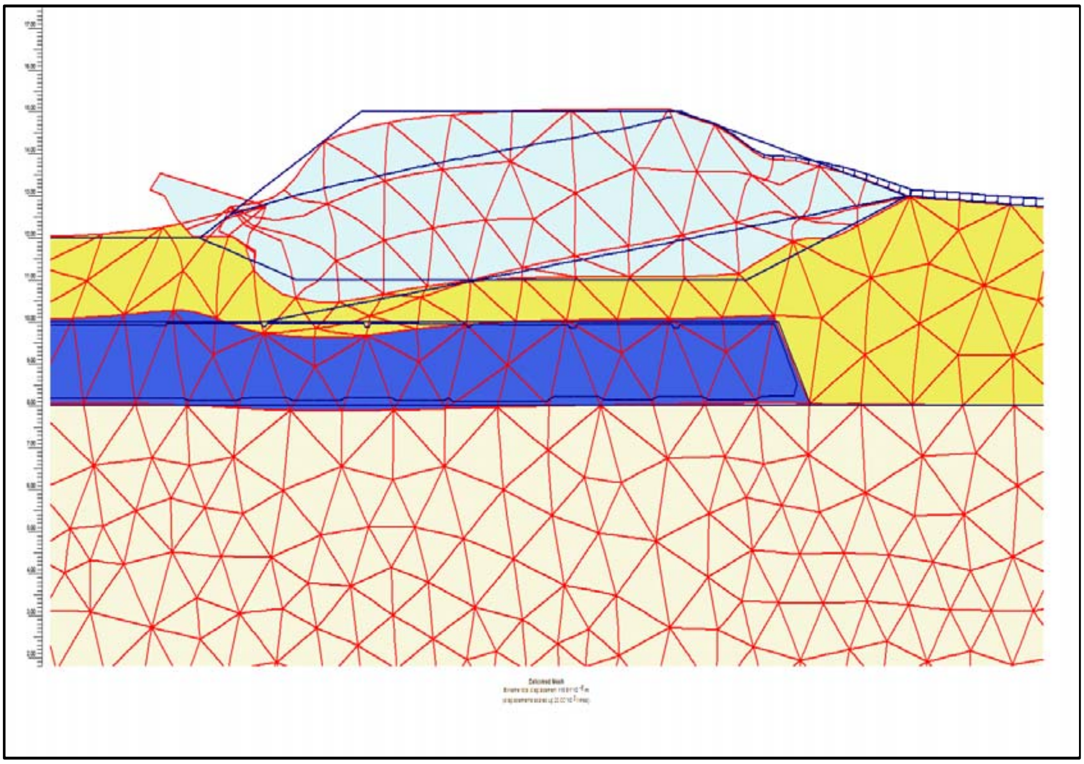

Figure 21: Deformed mesh (Scaled up 20e+03).

The top part of the dam starts to slide down. Also there is deformation process of the lake bed, erosion of the soils. This process isn't very large (maximum deformation is 2,5e-06). Anyway it has effects on the road pavement.

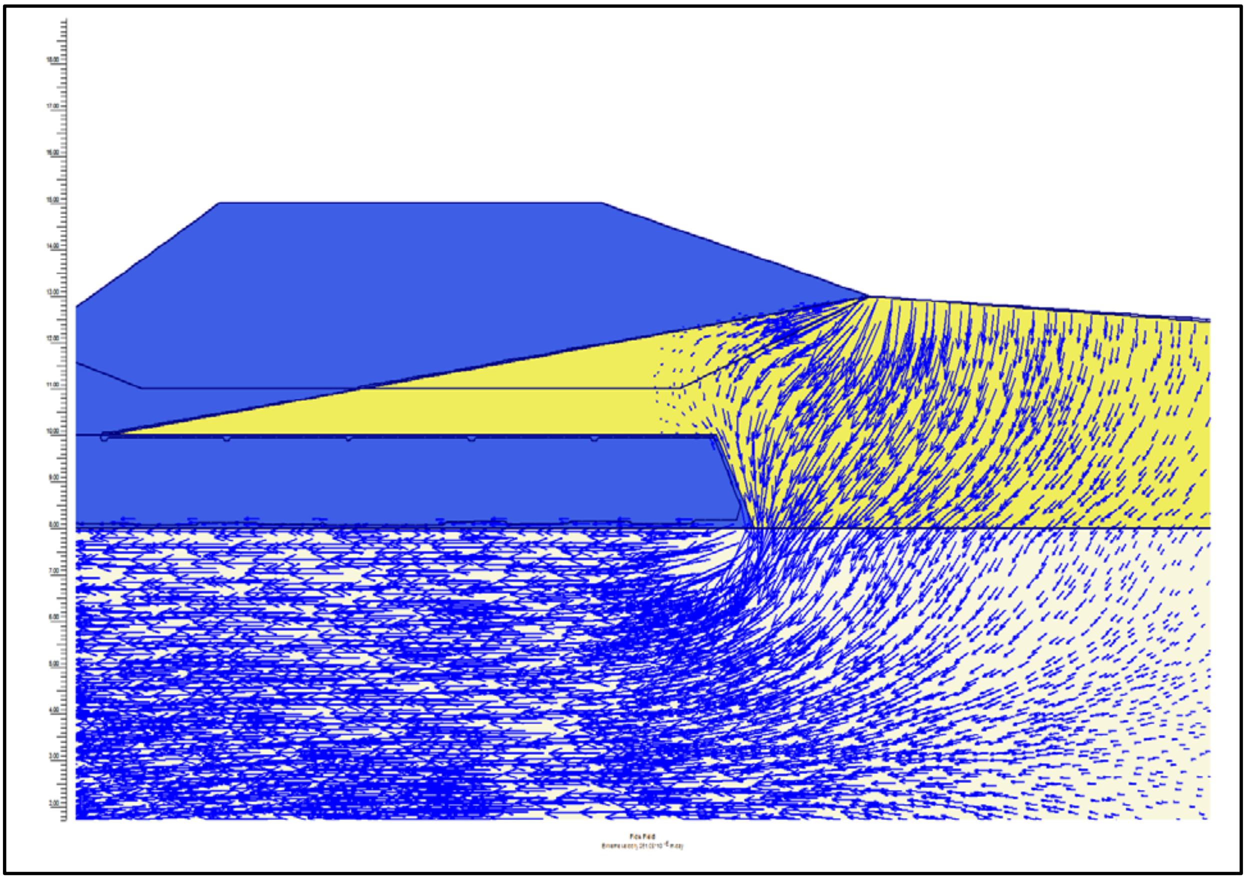

Figure 22: Flow field during winter

During winter water level undergoes deeper, also large portion of soils is frozen. So water flows downwards or underneath the lake. The velocities are quite small (the maximum is 250e-06 m/day). During this period there's no big damage to the dam due to the properties of permafrost.

6. Dam construction

Dams have been built for decades, and the knowledge of interaction between water and different material has increased a lot. Good investigations, proper planning and precise execution are key factors for a good result. By combining and using the properties of the materials, dams can be made out of local material. This will reduce the cost and the need for transport and reduce the negative impact on the environment.

6.1. Theory of dam construction

Dams may have more than one purpose, for example water supply, flood control and hydro-power plants. The type, size and shape of the dam will vary a lot from site to site, but there is one thing that they all have in common. They shall stabilize and control the flow of water. In order to do that, both the dam itself, and the site must have the leakage lowered to a minimum. This requires good investigations of the reservoir sites before the dam is build, suitable material and a correct decision concerning the type, shape and size of the dam. On the mainland of Norway there are built a lot of dams for hydro-power purposes, and there are a lot of experienced people with a lot of know-how. In 1991 there were 250 dams exceeding 15metres in height in Norway [2]. Finding the right dam construction and site should therefore not be a problem.

6.1.1. Different dam construction

There are two main types of dam constructions, concrete dams, and embankment dams. The concrete dams can be divided into three subgroups, gravity dams, arch dams and buttress dams. The embankment dams can be divided into two subgroups, rock fill dams and eart fill dams.

Gravity dams are rigid structures with a trapezoidal cross section and most often straight in plane. They can resist the hydrostatic pressure from the reservoir water only due to their own weight, and they can only take the smallest differential movements. They are most common when the site is a quite narrow valley, and the bedrock is of good quality, both in the floor and the abutments.

Arch dams are built by high strength concrete and have a curved shape in plane, with the convex pointing upstream. The arch shape transmits most of the thrust to the abutments, and this makes them capable of resisting high water pressures even though they have a much thinner cross-section than gravity dams. They can take large deflections in the foundation as long as the deflections are uniformly distributed. Due to the fact that they are so thin, they impose high stresses on narrow zones, both at the base and the embankments. This means that the bedrock must be of a really good quality.

Buttress dams are an alternative if the valley is a bit wider. These dams are built with a slab of reinforced concrete, with slopes upstream. The dam is supported with by buttresses with certain spacing. These buttresses have their axes perpendicular to the dam. The load is transmitted to the ground by the buttresses.

Rock fill dams and earth fill dams have the same structure, but differ from each by the material used in the construction. In rock filled dams more than 50% of the material is natural stones or boulders, or rocks from quarries and excavations. An earth filled dam is built with more than 50% clay, silt, sand or gravel. These dams can be homogenous or zoned, depending on the access to proper materials. Common for both types of dams are that they have a core of impermeable material. This can be clayey material, or membranes made of concrete or asphaltic concrete.

The embankments dams can be built in vide valleys, and they have been built on a lot of different foundations, ranging from weak, unconsolidated fluvial or glacial deposits to high strength ingenious rocks. Since these dams have such a broad base, compared to the concrete dams, they impose a much smaller stress to the ground than the concrete dams. They can also take some deformations, due to settlements or tectonic activity. Flexible asphalt membranes overcome the problem of cracks where seepage can occur.

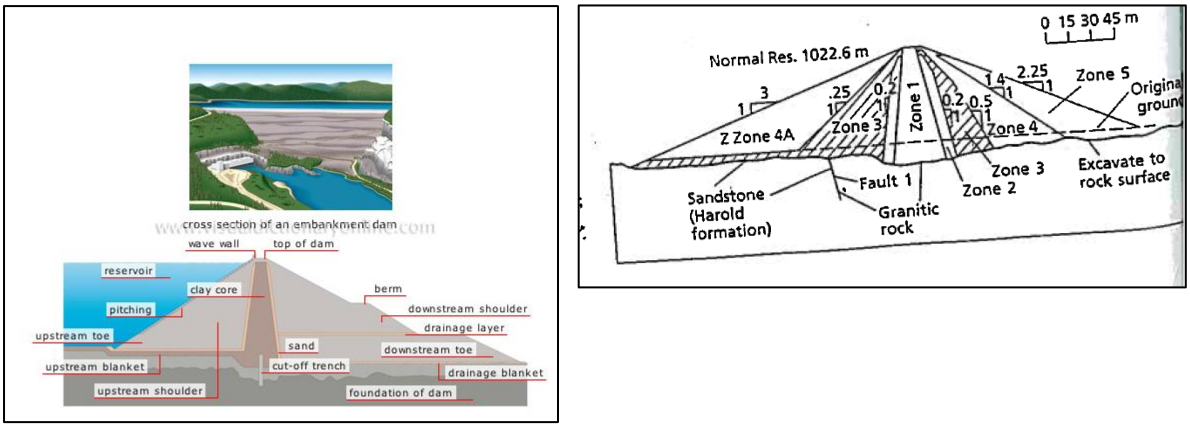

Figure 23: General dam construction [3]

Rock fill dams usually consist of three basic elements. A loose rock fill dump that should resist the thrust from the reservoir, an impermeable core and rubble masonry between the two first ones that acts as a cushion for the membrane. The number of vertical zones in the dam are decided by the availability and type of borrow material. The important thing is that the permeability is increased from the core towards the outer slope. Water trapped in the dam construction will decrease the effective stresses and give a lower stability.

The core can be replaced by an upstream none permeable face, but this is not common. The core of the dam is often extended below the ground level and then even further with a grout curtain. This is done to control the seepage under the dam.

6.1.2. Dam materials

When it comes to constructing dams, it is a question of utilizing the available material. A big variety of materials can be used, as long as the materials in the different zones don`t have too big varieties in their grain size distribution. As a consequence of this, it is not possible to set some absolute rules, but Norwegian constructers do have some rules of thumbs.

The core should have a high content of low permeability material. To prevent the segregation of stones in the core, the content of stones must be limited. In Norway it is usually moraine material used for this purpose. Bottom and front moraines are better than ablation moraines due to higher content of clay. It is important that the grains in the material doesn't weather or crumble, so grains from strong rocks are better than grains from weaker rocks.

When it comes to the filter zones and the transition zones, the main grain size should increase as the distance to the core increases, so that the permeability as increases down stream, and decreases upstream. Therefore it's not possible to give an exact description of this material. But the ideal filter material in Norway would be broadly graded gravelly sand with a low content of stones.

The supporting fill should be constructed with coarser material that can protect filter and transition materials, and support the rip-rap. The protective cover of the dam should be built with a certain compressive strength. As a rule of thumb, they should have a compressive strength of 30 MPa or more, and they should withstand wave action and be resistant to frost and weathering forces. This excludes most shales, shists and phylittes. Quite a few igneous rocks and some sandstone should be strong enough.

6.1.3. Erosion on dams

The dam construction is exposed to erosion by change in the water level, waves, ice and flood. The upstream face should be covered with an erosion resistant material. Asphalt, concrete or big blocks and boulders are used for this purpose. The outlet is very exposed to erosion, and should be built in concrete or steel.

6.2. Isdammen, the dam construction

We don't know too much about the construction or original design of Isdammen. But we can assume that it wasn't constructed as a proper dam. And we do know that there is a road on top of it, and that the road embankment is a part of the dam construction. Since road embankments have horizontal layers, and dams should have vertical layers, this may cause some leakage. Most likely the road has been repaired when needed and new material is probably just put on top of the old one. As we drilled in the embankment we did observe different horizontal layers, opposed to vertical layers or homogeneous material, and this confirms our suspicion that the dam isn't built with proper dam design.

Figure 24: Leaking point [1]

6.2.1. Leakage

Isdammen have probably always had leakage [1]. Indications from test done by NGI show that the permeability in the dam material has been stabile for the last 30 years. But we do not know anything about changes in total leakages through the dam. Currently there is no problem with supplying Longyearbyen with enough water in winter time, and the leaking situation doesn't seem to be critical. However it is very hard to determine the stability of a leaking dam. Water can wash out material and reduce or weaken the dam. It is impossible to tell if or when the leakage is going to reach a critical level, or if the dam can break down. If it drains or breaks down, it will cost a lot of money to fix it again, and if it happens during winter time Longyearbyen will be without water. A sealed dam with a supporting fill that is not filled in its own angle of repose is a much more stabile situation, which easier can be kept control of.

6.2.2. Drainage

The current drainage system is a stop log and three drainage pipes with an approximate diameter of 1.2 meter. This system probably has some free capacity [1]. But if the natural drainage trough the dam is sealed, a bigger drainage system is probably required.

6.2.3. Freeboard

Another problem with Isdammen is that the freeboard, the height between water surface and top of the road, is too low. When the dam is filled waves washes over the road, and damage the road. This can be prevented by lowering the water level, or increasing the dam height.

Figure 25: Water washing over the road [1]

6.2.4. Dam geometry and material

The NGIs report points out the fact that some of the slope angles are so steep that fine grained is in the angle of repose. The material will creep when the dam thaws during the summer. Combined with wash out of material this might result in that the dam settles over time. A lower dam will increase the problem with water wash over the road, and can in the long term decrease the volume and depth of the water inside the dam.

The material in the dam, as mention before, has high silt content. Silt is a frost acceptable material, and the dam can be affected by frost heave in the active layer under it. This may result in a reorganization of the grains, which can increase the leakage.

6.2.5. Erosion control

The dam is being eroded on the upstream side due to lack of erosion control and steep angle on the dam (steep for fine grained material). The drainage gate and pipes under the road is secured against erosion with concrete.

7. Risk analysis

Risk analysis is often required by law for constructions and infrastructure where potential hazards might have great consequence. Risk is defined as a hazard, which is the probability for a certain event, times the consequence.

Isdammen is Longyearbyens only water supply resource during the winter. There is different failure modes association to the dam structure. There are also failure possibilities on the supply and pipes into the town, but in this report we only discuss hazards that can happen to the dam structure. So other obvious hazards like contamination are neither discussed in this report.

Risk can be very difficult to assess properly, and often relay on deep knowledge and understanding of the problem, experience and subjective reasoning. Risk analysis can also require a lot of research and collection of data. In many cases there are not enough resources to do much investigation, so the analysis relies on the subjective reasoning of the analyzer. We do not have enough data, experience or knowledge to make a sufficient risk analysis of Isdammen. But we can try to identify the most obvious failure modes, and try to asses some level of probability and consequence. There very well might be failure modes connected to the dam that we left out of the report.

There has been done a risk analysis of the dam, probably by NGI. But Lokalstyre did not want to give us a copy of this report.

7.1. Sudden dam failure

Sudden dam failure will lead to a set of critical problems.

7.1.1. Hazard

Sudden and complete failures to the dam structure due to weakening by erosion from waves, slippages on the dam walls or flooding.

The probability for this scenario to occur is probably very small. Isdammen is a very shallow reservoir and only 4.5 meters at its maximum depth. This means that the pressure gained from the water on the inside of the dam will be small and the erosion on the dam will have to be severely high before the water pressure becomes a hazardous factor. Huge erosion on the dam would likely to be discovered long time before dam failures occur.

7.1.2. Consequence

The preliminary classification of the dam by NGI is class 1 in NVEs classification system. This means that there is 1 house were people might stay temporary that is threaten by a dam failure [1].

If a sudden dam failure during the winter half year where to happen, the consequence for the town's water supply could be critical. If the failed area on the dam is rather large and increasing due to washout, we could have a severe loss of water from the reservoir. The whole town including the power plant requires around 34-36 m^3 of water per hour to operate/function under normal conditions during the winter. If the water level would to decrease in such a rapid pace that the reservoir does not managed to supply the town, some backup systems would kick in. There is built a pressure pool between Isdammen and

Longyearbyen that contain 1600 m^3 of water and is enough for 2 days of water supply, while the emergency power plant would deliver electricity to the houses. The backup system is a short term solution and if the dam is not repaired, and the main power plant that's depending on fresh water cannot restart in 48 hours, Longyearbyen has to be evacuated.

Damage to the road will also be an issue in such a scenario. The consequence that will appear due to wash out of the road could be both large or just a minor problem. The power plant is dependent on fresh delivery of coal from mine 7 to operate under optimal conditions. If the damage to the dam is so severe that the water level has dropped to a critical level, the power plant doesn't depend on the coal delivery since the plant won't work without water from Isdammen.

7.1.3. Risk evaluation

The consequence of this scenario is major in economical sense, and to some degree political sense. An evacuation of a major part of the population in the only large Norwegian settlement on Svalbard is bad thing from a political view point .But the chance of this scenario to happen is rather small, and probably on an acceptable risk level. There are probably other failure modes which are not connected to the dam constructed that could lead to water supply failure which have higher probability then this scenario.

7.2. Slow drainage of dam

A situation that has been going on since the dam was constructed. If the leakages reach a critical level or the inflow is reduced over a longer period, a slow drainage of the dam can be a problem.

7.2.1. Hazard

Large amounts of water running through the dam construction results bought in loss of water and weakening the dam. The high content of salt in the soil influences the waters freezing point. Also the presence of organic matter in the soil makes the permeability of the dam to be higher than preferable.

Dam construction
The core samples taken from the ground at Isdammen reveals that large parts of the dam consists of fine grained sediments as silt and clay. Slow drainage trough the dam can result in a weakening of the construction due to scouring of sediments. The continuous scouring will also lead to increased drainage and may cause a sudden dam failure if too much of the dam material is washed-out.

Water supply
There hasn't been any thorough survey on how much inflow of water there are to Isdammen or on how much it is leaking. The assumption today is that the inflow is larger than the outflow. Due to just assumptions on the inflow, a scenario could be that the drainage and consumption will exceed the inflow. In near future there will be a survey on Isdammens groundwater source. This is a demand from Bydrift that wants to reveal the amount of inflow in the relation of upgrading Isdammen to also being the reserve drinking water of Longyearbyen. [6]

There is a probability of these scenarios, but due to lack of proper knowledge about the amount of leaking and the inflow from underneath the dam it is difficult to estimate the probability. There are no fatal signs of collapses or damages to the construction due to the continuous drainage. The drainage has been going on for many years without causing bigger problems and a suddenly drop in water level is unlikely.

7.2.2. Consequence

The demand of water exceeds the water supply. The situation will probably be known about long before it is critical. And if measures for water conservation are put in place, the short time consequences are not server. On long term Isdammen will have to be improved or a new water source has to be established.

7.2.3. Risk evaluation

This is by our estimation the biggest risk for Isdammen. The scenario of insufficient water supply from Isdammen due to leaking and unknown water inflow might happen. But this scenario has a fairly small consequence on short term.

7.3. Decreasing Water depth due to sediment fill up

The situation occurs during the late spring and summer months when large amounts of melting get transported to Isdammen.

7.3.1. Hazard

The main contributor Endalselva, transports a severe amount of sediments into the reservoir. A survey made by NGI from 1994-1998 estimates the amount of sediment transportation to be around 8102 tons and around 5649 out of the dam.

It is mainly the coarse sediments that deposits in Isdammen. Some of the fine grain sediments deposits as well, but most of it gets transported out trough the outlets. Causes that sediment transport can lead to if we see this over a longer period of time, is decreased volume of the reservoir and disturbance to the inlet of water.

The probability of this scenario is rather small. The scale of Isdammen is huge compared to the amount of sediment accumulation. The survey made by NGI estimates the accumulation to be 2 ‰ of the yearly volume, of the volume shallower than 3 m, and 4 ‰ of the volume shallower than 2m. These numbers form a small threat, and it will take many decades or centuries to decrease the volume to a critical level. Within that time-frame it's likely to think that other solutions to secure Longyearbyens water supply is done.

7.3.2. Consequence

If the volume of Isdammen is decreased because of sediment fill up the reservoir will be smaller. The consequences are the same as discussed in part 7.2, that Isdammen can not supply enough water.

7.3.3. Risk evaluation

Failure of Isdammen as a water supply caused by fill up by sediments, as the only factor, will not happen in an interesting time frame. But sediment fill up of Isdammen might be a factor in combination with increasing drainage of the dam. But this will only be a minor factor to the probability that Isdammen becomes an insufficient water supply.

7.4. Conclusion

The probability of critical failures on the dam construction in the future can be seen as rather small. The dam construction has been standing for decades without any major damages or critical situations, and it’s likely to think it will stay like this for many years to come. Longyearbyen Lokalstyre told us that a risk analysis of the dam construction is done, and that there are no definite plans at the moment to improve the construction. There is more than enough water in Isdammen to supply Longyearbyen during the winter. The current state of the dam is that the inflow is larger than the outflow. This low risk of a reduction in volume makes it likely to believe that upgrading the dam or repairing the leakages is not necessary at the moment.

Factors that might affect the current situation in the future can be everything from increased population, infrastructure or climate changes. A higher population and increased activity in Longyearbyen demands better water supply and backups. As a result of improving Longyearbyens water supply, Longyearbyen Lokalstyre has experimented with melting glaciers and desalination of sea water to find methods that can be used in emergency situations or as a source for reserve drinking water.

8. Suggested improvements to Isdammen

The leakage from Isdammen is a complex problem, with several possible solutions. The main purpose of these solutions is to increase the functionality of the dam and minimize the risk of failure as Longyearbyens water supply. As pointed out in chapter 7 this includes avoiding failure, negative water balance and filling of Isdammen by sedimentation.

As engineers it is our task to find a good solution for Isdammen. The challenge is to find the solution that gives the highest positive value when the advantages and disadvantages are compared. To be able to do this, we need to get an overview of the situation, so that the whole problem can be analysed. This is done through field investigations and labtests, and combining this with the results NGI got in 1979 and 2008. There are many opinions, wishes and considerations that should be considered. In this report we have focused on finding a technical solution, and briefly discussed factors as economy and the environment.

Economy can be considered in both a long and a short perspective. The length of a structures lifetime need to be considered, and what may be cheapest right now, can turn out to be the most expensive in a long-term, due to maintaining work. Since the “Svalbardmeldingen” is positive to coal-mining on Svalbard even after 2012, Longyearbyen will need water supply for many years, and this may justify larger investments than if the coal-mining where to be closed down. Another question is weather to use local entrepreneurs, even if others are better or cheaper, or not. But this is more an issue for the local government. If only a small amount of money is granted, these money need to be spent wisely, and some priorities have to be done.

The nature on Svalbard is very vulnerable, and all impacts must stay as small as possible. If one of the solutions for Isdammen includes the use of local masses both the sand pit and potentially new roads need to be planned really good to avoid too big damages. Revegetation will go really slow, and all impacts will be visible for many years. Adventdalen is the point of departure for many locals and tourists when they are going out on trips, and Isdammen should therefore be as a natural part of the surroundings as possible. It is also important to keep the consequences for the animals living in Adventdalen during the constructing period as low as possible.

8.1. Dam improvement suggestion

As pointed out under 5.2 Isdammen, the dam construction” there are more than one problem with Isdammen. Our suggestion for the dam is therefore a list with four sets of measures in prioritized order; stop leaking control and increase the drainage, increase the freeboard and carry out some erosion protection.

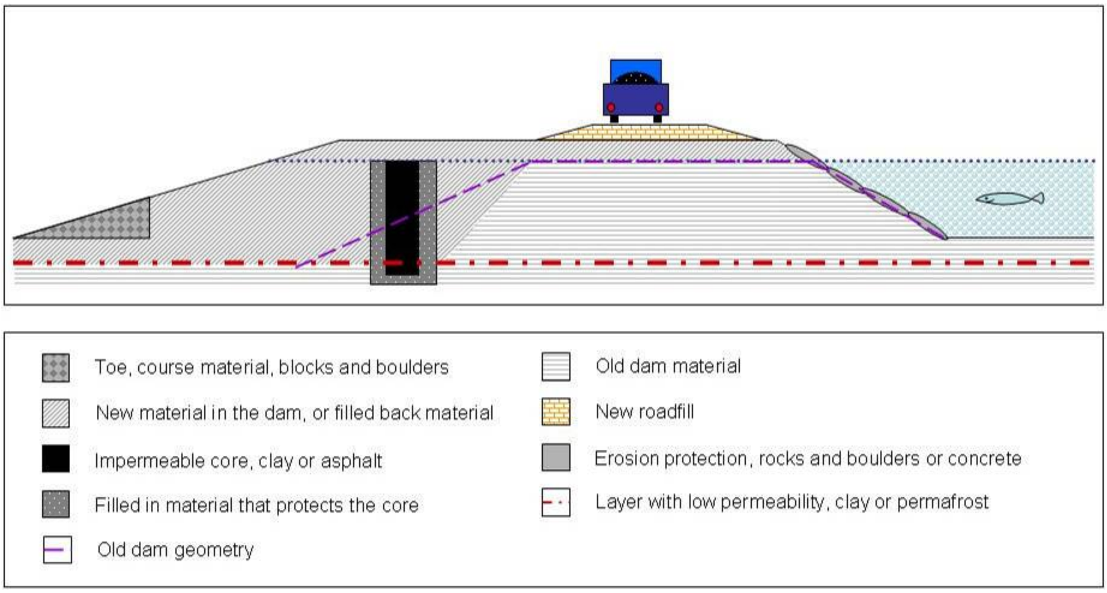

Figure 26: Suggested improvements

8.1.1. Stop leaking

First of all the leakage should be stopped. Our suggestion is to use the old embankment as a part of a new dam. The new dam needs to be wider than the old one, and it needs to have an impermeable core. This core can be made out of local masses, if they fulfil the required grain size, the masses have an acceptable salt content, and there are enough masses. If not, the core must be constructed with asphalt or concrete. A flexible asphalt membrane can tolerate some movements due to frost activity in the dam. The important thing is that the core reaches all the way down to a more or less impermeable layer of clay or permafrost. New investigations can be carried out, and if they show that the thickness of sediments is not too high, the core can be constructed down to the solid rock. From there it can be extended with a grout curtain. On both sides of the core there have to be a fine grained layer, that protects the core. This layer also needs to fulfil the required grain size. Then a supporting fill must be constructed outside, to keep the whole dam in place. The filling should have an increasing permeability from the core and out, to avoid trapped water and low effective stresses. Since silt is frost susceptible the amount of silt should be lowered to a minimum. Maybe some of the local material can be uses for this purpose, either directly or with small adjustments. The inclination of this filling must be low enough to ensure the stability of the dam. Small grained material have a lower angel of repose, and may slide when they thaw.

It may be a problem that the embankment upstream the core has horizontal layers. But since the only alternative is to rebuild the whole dam this chance has to be taken.

Before the dam can be built there must be carried out some geotechnical calculations to ensure that the foundations can take the load of the dam. Since alluvial deposits are poorly consolidated the dam may cause some problems. If lack of shear strength seems to be a problem, the slope of the embankment can be flattened.

Calculations in PLAXIS using the same model as the first calculations, but with an impermeable core, shows that the water flow will go in the ground and not through the embankment. The biggest flow gradient is much lower with the core than without. But this requires, as mentioned, a presence of a low permeability layer.

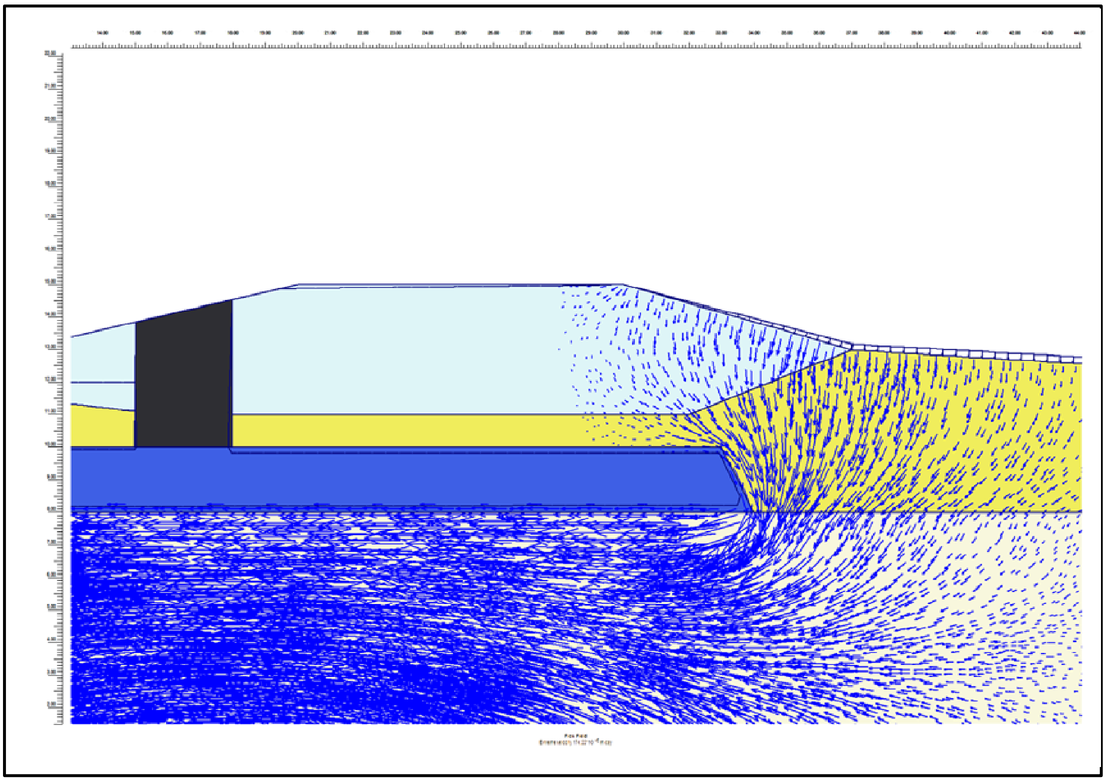

Figure 27: Flow field in case of impermeable core.

The core solves the problem of water flow. The water goes downwards. The maximum velocity is 170e-06, it is in thousand times less than without. But there is a problem of core stability.

8.1.2. Drainage

If the leakage is stopped, the drainage of the dam will be even smaller than it is today. The more water that's in the dam, the more damage it does to the road embankment, and to the dam. Since Longyearbyen gets its water from Gruvedalen during the summertime, there is no need for a high water level in the dam, and a lot of the water can be let out in Adventelva. This requires an outlet that's dimensioned for high water flows. The present outlet has a high enough capacity to stand the present water flow, but if more water should be let out it may be necessary to enlarge it, or to build another one. To avoid damaging of the dam by erosion, the outlet should be built in concrete or steel.

During the melting season huge amounts of water passes through Isdammen, and this water carries a lot of sediments. If the water could just pass by Isdammen in this period, the amount of sediments in Isdammen would be reduced increase the lifetime of the dam, due to sediment filling.

8.1.3. Increase the freeboard

To day there is a lot of water in the road embankment, which reduces the bearing capacity of the road. Low bearing capacity requires more maintenance work, and that costs a lot of money. To lower the frequency of maintenance work, we suggest that the road should be lifted from the present height/level. This will also contribute to less erosion from waves, and reduce the scouring of the road embankment.

The amount of money and the effort put into the new road must be related to the lifetime of Mine 7 and future planed activity in Bolterdalen.

8.1.4. Erosion control

To protect the dam from wave erosion, and lower the maintenance costs, the upstream face of the dam should be protected. It can be protected by big blocks and boulders or concrete. As mentioned in the dam material description, these rocks should have a compressive strength of 30 MPa or more, and this may cause some problem here, since most shales and shists are excluded. But most likely one or more of the sandstones have an acceptable strength.

8.2. More adventures suggestions

All these measures are quite expensive, and they don’t reflect the importance of the dam.

8.2.1. Impermeable fiber fabric

To seal the dam from the inside using a type of fibre fabric that is impermeable. Since the dam is quite shallow, and the area of leaking is wide, this will be a lot of sealing per amount of water gained.

8.2.2. Cooling liquid

To freeze the soil under the road using the same principle used on the Trans-Alaskan pipeline. Here they use cooling liquid placed in pipes drilled down in the soil. The cooling liquid absorb heat from the ground, evaporates, and gets cooled by the wind until it condensates. This keeps the ground cooled and as a self-propelled system that doesn’t need any power supply.

8.2.3. Mortar/sealing mass

Another possibility could be to inject a kind of mortar/sealing mass into the soil and gravel of the dam. The mortar will fill the gaps and bind the soil together, preventing the water to escape.

Conclusion

A leaking water reservoir is far from an ideal situation. And it is natural to try to assess if the situation is unacceptable and what improvements that can, or has to be done.

From our brief risk assessment of the dam, the current situation might be within an acceptable risk level. Our biggest concern is that a leaking dam is an unstable situation which might be difficult to monitor properly. It is hard to asses a water balance when there is poor data for inflow and leakage. Future investigations and more thorough analyses have to be done.

With better data for the dam, it might be concluded that the current dam is sufficient. And minor repairs, like road maintenance is enough for keeping the dam in an acceptable state in regard to how much water that can be used, quality of water and the stability of the dam.

If an improvement to the dam has to be preformed, we believe that the suggested solution given in chapter 8 is a viable one. It is mostly based on materials that can be found in the Adventdalen and it makes the dam structure much more impermeable and stable. It might also lower the maintenance cost of the dam to some degree. The decision on what to do with Isdammen must depend on a complete evaluation between risk, economy and environment.

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APPENDIX