CHALMERS

# Preventing Icicle Formation on a Rock Cut
## Feasibility study; Kongsberg, Norway

*Master of Science Thesis in the Master's Degree Program,*
*Infrastructure and Environmental Engineering*

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Cover:
The icicles hanging on the existing rock cut in Kongsberg as it looked 26.02.2013.

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# Abstract

In road construction in hilly terrain, where there are strict requirements to vertical and horizontal curvature, it is not uncommon to make rock cuts to make space for road beds. Icicles growing on these rock cuts pose a threat to bypassing traffic below. This is the case in Kongsberg, where a new road with higher traffic volumes will be constructed in an icicle prone area. There are many ways of dealing with this problem.

In order to find best practise solution in the chosen, high risk, study area, finding the source of water, which causes the icicle growth, was considered highest priority. After finding out where the water came from it was possible to evaluate the solutions which have been used in the past. Efficiency of icicle removal, overall safety and stability of the rock cut were among factors which determined what solution was chosen.

After thorough investigation on site it was concluded that icicles were growing throughout the winter, which hinted that groundwater was the governing problem. The groundwater was, however, both flowing out of fractures in the rock wall and on top of the terrain above it. To solve this problem a shallow canal, filled with gravel, along the top of the cut was suggested to capture the surface water, and holes drilled from the bottom of the cut to penetrate water bearing fractures.

Capturing the water before it becomes ice on the face of the rock is concluded to be best practice.

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# 1. Introduction

In road construction, it is not uncommon to make way for new road beds by blasting away bedrock with so called cuts. This is done for example in hilly terrain so that requirement for vertical and horizontal gradients can be met. In other cases bumpy terrain is evened out with filling of lose material. In order to make the construction of the road as economical as possible, road designers try to balance out as possible the ratio between cuts and fills and that is one of the factors which decides the road alignment. The terrain itself, however, is the governing factor.

Early 2014 work will begin on a new road project in Kongsberg municipality, Norway. The terrain will call for some eye-catching, up to 15m high rock cuts when the new highway E134 bypass will be constructed. It includes a tunnel, leading the traffic away from the town centre, to a new four lane road along a large river, which flows through the middle of the town, the Numedalslågen River. In accordance to flood risk the road must be somewhat more elevated than the present road. In addition it has two more lanes so it takes up two times the space. In order to make this possible designers have decided that a rock cut will have to be made in the terrain on the hill-side of the road.

In the terrain, above which the highest rock cuts are to be made, some amount of uncontrolled water flows down the hill-side or resides in local depressions. This does, under normal circumstances, not cause significant problems. But uncontrolled water always has the risk of being detrimental to road constructions with e.g. changing weather conditions and is therefore undesirable. In winter time this water is transformed into big blocks of ice, which hang on the face of the present bedrock cuts.

The bare bedrock in rock cuts makes very favourable conditions for ice to form. The surface of the rock is cooled down easier than any soil or vegetation nearby due to its thermal transferring properties. Early winter, the bedrock will therefore reach sub-zero temperatures while still being fed with water from uphill soil cover. Water will freeze progressively faster as the outside air temperature (and the bedrock) gets colder (Freitag & McFadden, 1997). It is therefore important to try and limit the water flow towards the bare bedrock as much as possible.

Although common, there has not been a lot of focus put on researching this problem. When it comes to ice and rock structures, more weight has been put on researching frost in roads, frost cracking of bedrock and upheave due to frost segregate. In Norway around 300 cases of ice falling down on road are registered each year, despite the fact that ice is commonly physically removed from road cuts before it falls down and causes damage. The quantities associated with each event vary somewhat and range from less than one cubic metre, which is most common, to over 100 m$^3$ (Bjordal & Helle, 2011). Falling ice can cause a lot of damage to bypassing vehicles, and with this amount of registered cases each year a lot can be benefitted from finding a practical solution to the ice block accumulation by roads.

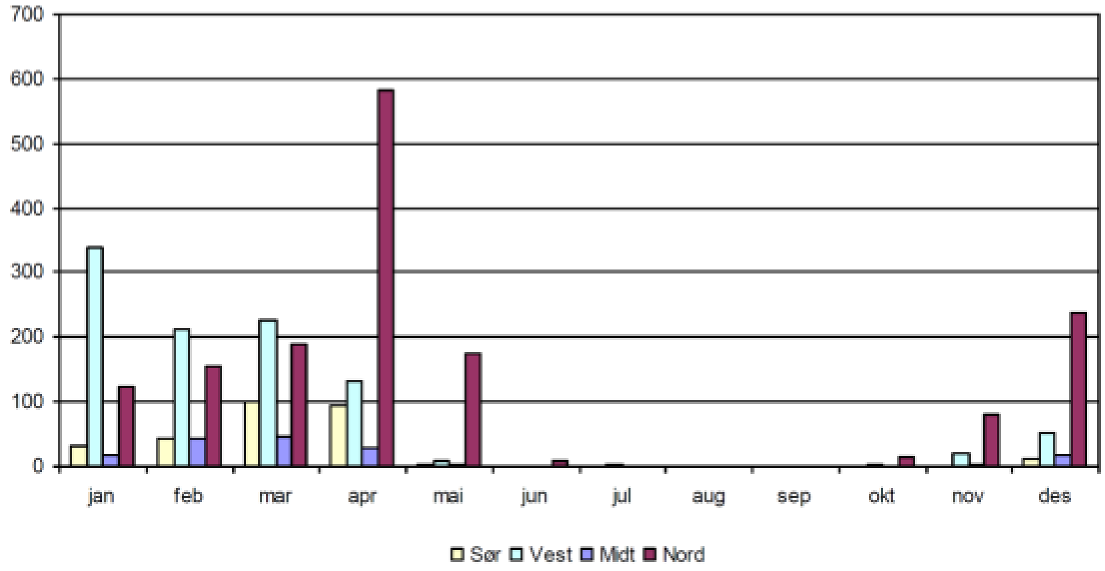

**Figure 1: Statistics for registered cases of ice falling down on roads, divided by month, in the four geographical regions the NPRA is separated to, from 2000-2009 (Bjordal & Helle, 2011).**

## 1.1. Aim

The aim of this report is to find the most important parameters associated with ice accumulation on rock cut, so that the risk of falling ice can be reduced and the safety of bypassing traffic increased. In addition the attention is on finding a suitable solution that could be carried out in the case study area, as well as other sites, in the future.

## 1.2. Problem

This report aims to answer the following questions:

1. *Is the ice in the case study area formed by surface water, groundwater or both?*
2. *What effect does the ice have on the face of the rock cut?*
3. *What problems has ice on rock cuts presented in the past?*
4. *What solutions are currently being practiced to prevent icicles on rock cuts?*
5. *Is it practical to drain the rock cut with bore holes?*

When these questions have been answered the following question, which forms the basis of report, will be tackled:

6. *What solutions are most feasible for preventing ice formation on the planned rock cut in Kongsberg?*

## 1.3. Delimitation

Lack of on-site sample data will have biggest impact on the thesis results. This holds especially true for transmissivity of the bedrock and the height of the groundwater table, which affect the speculations of ice forming from groundwater and the efficiency of drainage boreholes. More research will be done in the study area before the construction work starts, which will give stakeholders the opportunity to gather any information needed to complete or update necessary calculations.

## 1.4. Method

A conceptual model will be made based on assumption and gathered data in order to evaluate the feasibility of draining bedrock with boreholes. In addition the posed questions in section 1.2. will be answered with desk studies, internet and library searches, field trips and questioners to professionals in rock and road engineering. Furthermore expert support will be provided from the Norwegian Public Road Administration (NPRA), which funds the research and provides facilities and equipment.

## 1.5. Outline of the report

Chapter 1 – A short introduction of the project, aim, the problem dealt with, the limitations and the methods used for solving the problem.

Chapter 2 – The theoretical background used for design and calculations needed for solving the ice problem in the study area.

Chapter 3 – The conceptual model used for presenting the assumptions drawn from site visits. The model is in three parts; one for explaining current situations, one for what is expected to happen with unchanged design and finally what is assumed to happen with the improvements proposed.

Chapter 4 – A description of site visits and a thorough description of the study area, accounting for any parameter that is thought to be likely to influence the outcome of the project. In addition problems generated by icicles are highlighted and solutions practiced against this problem by the NPRA in the past are explained.

Chapter 5 – An analysis of the design proposed for solving the ice formation problem in the study area.

The report ends with chapter 6 – discussion and concludes with chapter 7 – conclusions.

# 2. Theoretical Background

For adjusting the design parameters for solving the ice formation problem, one must establish understanding of the properties of ice and how it is being formed on the rock cut today, the difference between how water behaves when flowing under atmospheric pressure and underground, and what happens when a borehole penetrates the bedrock when attempting to drain it.

## 2.1. Groundwater properties

Groundwater is defined as the part of the hydrological circle which takes place below the surface. As long as a medium below ground has some hydraulic conductivity, it can store water or let it flow through it. This mostly includes faults in crystalline rock and pores in porous media. The common term for a media which lets through water is *aquifer*. The *water table* is a term used for the boundary between the pores and fractures media which is saturated with water, and the media above. The upper limit of the water table can be defined as the location where the water pressure head is equal to the atmospheric pressure. In sands and fractured rock, the water table forms a somewhat horizontal line (Freeze & Cherry, 1979).

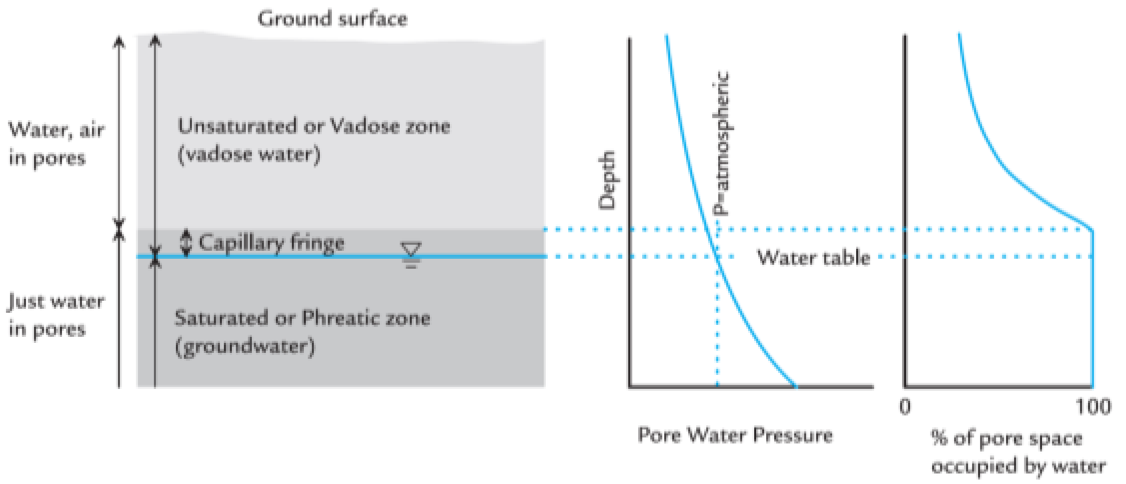

**Figure 2: A conception sketch of how the table if defined (Fitts, 2002).**

The groundwater always recharges from the surface. It usually flows downhill under the influence of gravity until it reaches the surface again. The residence time can vary greatly, depending on the hydraulic conductivity. The residence time can range from a few days in shallow aquifers to tens of thousands of years in deep aquifers (PhysicalGeography.net, n.d.). Water in porous media usually flows considerably slower than water in crystalline rock, but the flow velocity always depends on the hydrological conductivity, K [cm/s] (United States Environmental Protection Agency, n.d.) (Bear, 1972).

Although groundwater is relatively well protected from conditions at the surface, there are seasonal variations in the water table. Measurements carried out around Gardermoen airport, just outside Oslo, showed that the water table fluctuates within a range of one meter throughout the year. The water table was lowest during the summer time, when vegetation is blooming, evaporation is high, and there is relatively little precipitation, but highest in November after the autumn rain season. (Colleuille, et al., 2001). Where the water table is considerably high, the delay between precipitation and alteration water table height can be as short as few hours. The more the moisture content of the top soil is when the precipitation event starts the faster the rainfall reaches the groundwater (Colleuille, et al., 2001).

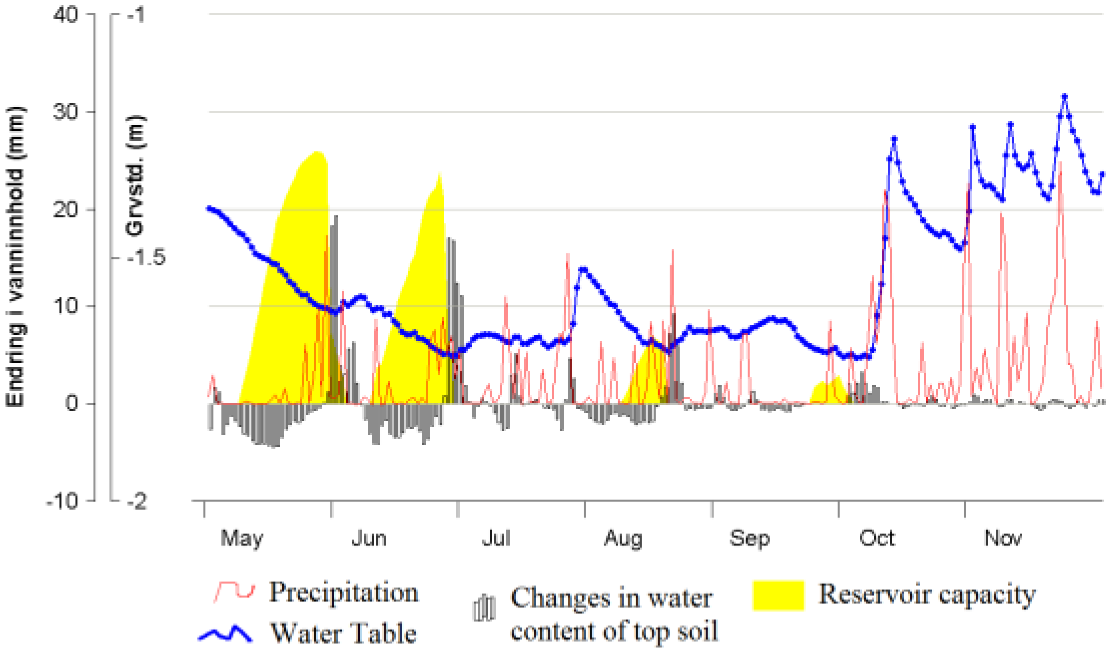

**Figure 3: Seasonal fluctuations of the water table shown with precipitation (Colleuille, et al., 2001).**

Although there are also seasonal changes of the temperature of groundwater, it can be used as a rule of thumb that the temperature is close to the annual mean temperature of the air. At the depth of 10m the temperature changes of the groundwater become minimal and the annual mean temperature of the air rule becomes better applicable than at shallow depths. (Norges Geologiske Undersøkelse, 2008). The temperature of shallow groundwater is mostly affected by the recharging surface water. During spring time, when snow is melting and the runoff is cold, the groundwater can become colder, but during warm summer days it can be recharged with warm water. If groundwater is pumped up by for consumption, it increases the ratio of newly recharged surface water in the aquifer and enhances temperature fluctuations (Dagestad & Hans de Beer, 2008).

The water table usually follows the topographical gradient of a landscape. However, the table and the surface sometimes cross. When rock cuts are made in steep terrain, it often creates conditions where suddenly the water table is no longer subsurface. This creates risk of water flowing out through faults and fracture networks that have been intersected by the new rock face. When this happens a natural spring of flowing water emerges from the ground (U.S. Geological Survey, n.d.). Natural springs can be in the form of water coming directly from fractures in the bedrock, water appearing from porous media aquifers or moisture from capillary driven leakage (Fitts, 2002). The difference in water table height and seasonal variations in the hydraulic cycle cause difference in flow from natural springs (LaMoreaux & Tanner, 2001).

## 2.2. Water flow in fractures

In many geological formations, water flows predominantly within fractures (Bodvarsson & Zimmerman, 1996). Flow rate within a fracture is determined by its hydraulic aperture. If laminar flow is assumed the following equation can be used for calculating flow Q through a fracture (Larsson, 1997) (Snow, 1968):

$$Q = \frac{\rho * g * W * b^3}{12 * \mu} * i \qquad (1)$$

ρ is the density of the fluid, g is the gravity acceleration, W is the height of the sample for a vertical fracture and width if the fracture is horizontal, μ is the viscosity of the fluid, i is the hydraulic gradient and b is the aperture. The problem with using this setup is that it is only applicable to one fracture, so the study area must be very small. It also fails to take into account the roughness of the fracture. The governing factor of this formula is the aperture. When the water pressure within the fracture decreases, the aperture tends to be reduces as well and vice versa (Fitts, 2002). The affective stress of the rock works the opposite way; when the affective stress of a rock mass increases the aperture is decreased (Burton, 2012). This means that fractures are more open closer to the surface; hence transfer more amount of water.

In tunnelling jobs, groundwater flow through fractures in the tunnel wall has been reduced by the use of *grout*. Holes are drilled into the rock and grout injected in order to fill up the fractures and stop the water flow. For this to be successful, the boreholes must hit a fissure connected to the fracture leaking water into the tunnel. The large fractures are affected the most by the grout (Burton, 2012). The pre-grouting boreholes are drilled into the face of the tunnel. The closer the fracture sets are to being perpendicular to the tunnel direction, the more likely it is that the boreholes hit a water transporting fracture. One might therefore argue that if the same logic applies to rock cuts, then the dip and orientation of the main fracture sets determine whether it's more favourable to drill draining holes from the top of the cut and downwards, or from the face of the rock cut and inwards.

If the fractures leaking water out on the face of the rock cut freeze tight during winter, water pressure builds up behind rock wall. This affects the stability of the rock wall, especially if the water is leaking inside a slip surface fracture. Maximum water force, U, applied to a we surface $L_w$ can be calculated with the following formula (Rocscience, 2001):

$$U = P * L_w = \frac{1}{2}\left(\frac{1}{2} * Z_w * \gamma_w\right)\left(\frac{Z_w}{sin\alpha}\right) = \frac{Z_w^2 * \gamma_w}{4 * sin\alpha} \qquad (X)$$

Where P is water pressure, $Z_w$ is hydraulic head; $\gamma_w$ is density of water and α is the angle of the surface the force is applied to. This formula is applied if the maximum water pressure is applied on the middle of the cut. If, however, the maximum pressure is applied at the toe of the rock cut, the formula is multiplied with 2. In other words; if the maximum pressure is applied at the toe of the wall, the force of the water is two times higher than if it's in the middle and is considered worst case scenario.

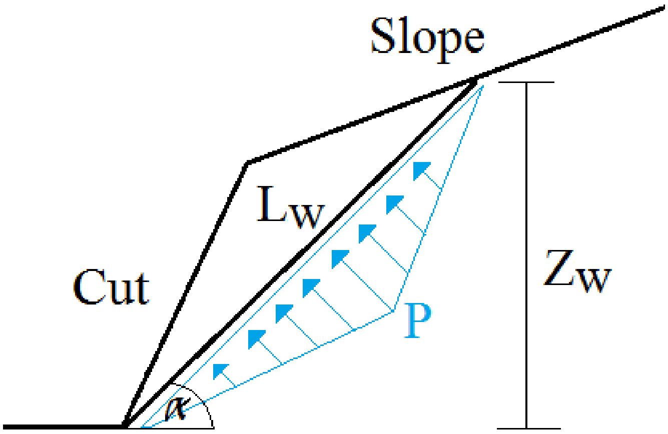

**Figure 4: A demonstration of the sizes needed to calculate maximum water force applied to a wet surface in a rock cut.**

## 2.3. Water flow in soil

Soil layers which transport water are called aquifers (Fitts, 2002). As precipitation flows through the soil mass its flow speed is greatly reduced. This effect helps lowering runoff flood tops. When draining soil, it is important to consider its permeability as it is one of the governing factors which controls how fast the water flows through it. According to

Darcy’s law, the flow velocity is proportional to the hydraulic gradient in the aquifer (Fitts, 2002). The formula is presented as following:

$$\upsilon = K * i \qquad (2)$$

Here $\upsilon$ is flow velocity in cm/s, K is the hydraulic conductivity value in cm$^2$/s and  is the unit less hydraulic gradient slope. The velocity which can easily be substituted with Q/A for solving metric flow, where Q could be in cm$^3$/s (l/s) and A in cm$^2$.

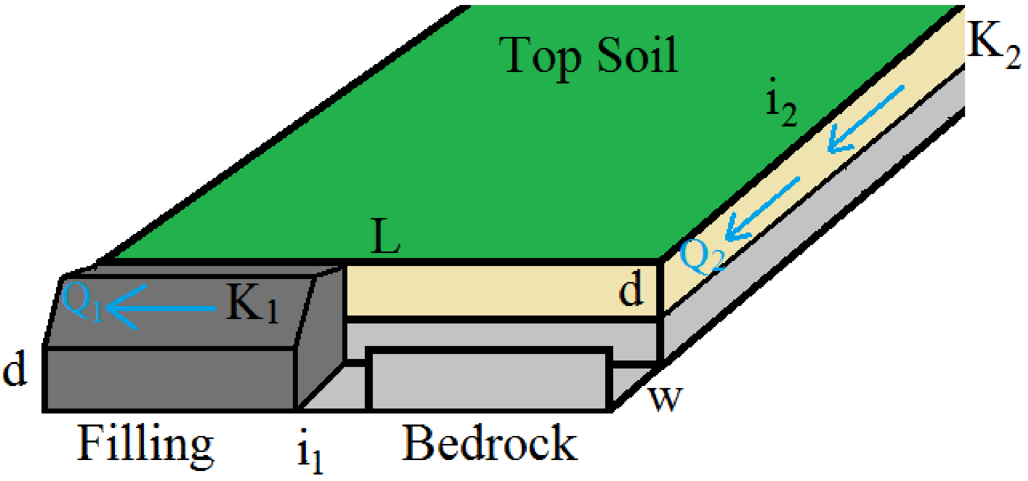

**Figure 5: Schematic picture with the parameters needed to calculate metric flow with Darcy’s law both in top soil and in filling material used in closed drainage canals..**

## 2.4. Surface runoff

Surface runoff is driven by precipitation or re-emerging groundwater. Water, which flows laterally through unsaturated soil, is called interflow (Fitts, 2002). The interflow is protected from cold air immediately after the air reaches sub-zero temperatures by the insulation of soil. The time lag before the soil is cooled to 0ºC is up to 70 hours at 60cm depth (Fowells, 1948). Early winter this will increase probability of ice formation from interflow which emerges from the soil cover. Large parts of the winter the temperatures only fall below zero during the night. Due to the isolation properties of the soil and the temperature time lag, the interflow will not freeze during night but continue to feed the icicle forming areas with water.

As for rock cuts, Handbook 018 from the NPRA also has detailed guidance for draining system design. For watersheds under 5 km$^2$ the Rational Formula method can be used (Mays, 2010) (United States Department of Agriculture, 2004) (Statens Vegvesen, 2011):

$$Q = C * i * A * K_f \qquad (3)$$

Where:
Q = Max runoff [l/s ]
C = Ground coefficient.
i = The runoff intensity [mm/time]
A = The total watershed area. [$m^2$]
$K_f$ = The climate coefficient for the area.

This formula will give different results between different researchers, mostly based on the chosen ground coefficient (Hiemstra, 1968). When a surface consists of more than one type of ground, weighted ratios are used. The following table is to be used for determining the coefficient (Statens Vegvesen, 2011):

**Table 1: Coefficient ranges for different surface types for the Rational Formula (3) (Statens Vegvesen, 2011).**

| Surface type | Runoff coefficient, C |
|---|---|
| Concrete, asphalt, bedrock | 0,6-0,9 |
| Gravel roads | 0,3-0,7 |
| Farmland and public parks | 0,2-0,4 |
| Forrest | 0,2-0,5 |

For road design in Norway, one must collect data for rainfall intensity from the Norwegian Meteorological Institute. The rainfall intensity is established on probability of return based on observations. For a design which is supposed to have 100 year life span, and therefore withstand a precipitation event with 100 year return period, it is advised that the observation time series is at least 25 years. The shorter the time series are, the more uncertainty in the design (Statens Vegvesen, 2011). For determining the length of the precipitation event the construction must withstand one must use the following equation (Berg, et al., 1992):

$$t_c = 0.6 * L * H^{-0.5} + 3000 * A_{se} \qquad (4)$$

This equation is used for estimating detention time in forest terrain in minutes. L is maximum length that a raindrop in the watershed must travel to the destination drain and H is the height difference. If there are lakes in the watershed, then $A_{se}$ accounts for the proportion of the watershed covered by lakes and is explained in formula 5. This is to account for the increased detention time caused by lakes. The time is very important for choosing the intensity, just as important as the chosen design return period. With proper equipment and data, the result value should be fairly independent on the researcher.

$$A_{se} = \frac{1}{A^2}\sum(A_i + a_i) \qquad (5)$$

$A_i$ = Watershed for lake *i*
$a_i$ = Total area of lake *i*
A = Total area of the original watershed.

The climate coefficient is supposed to account for climate change in the future and is reliant on the return period used for the design. The longer the return period is, the higher the climate coefficient. In Table 2 the climate factors for different design periods can be seen (Arnbjerg-Nilsen, 2008):

**Table 2: This table the future climate adjustment factor can be approached (Arnbjerg-Nilsen, 2008).**

| | 2 years | 10 years | 100 years |
|---|---|---|---|
| Climate factor | 1.2 | 1.3 | 1.4 |

## 2.5. Gravity driven water flow

Capacity of free surface water transporting canals and can be calculated with the use of Manning’s equation (Camp, 1946) (Chaudhry, 2008):

$$Q = M * A * R^{\frac{2}{3}} * I^{\frac{1}{2}} \qquad (6)$$

Here Q is given in $m^3/s$. M is the Manning coefficient, in $m^{1/3}/s$, given for the chosen base material, A is the cross-section area of the canal in $m^2$, R is the hydraulic radius inside the canal in meters and I is the gradient of the canal in m/m.

Hydraulic radius is calculated with:

$$R = A/P \qquad (7)$$

Where A is the cross section of the canal or pipe and P is the length of the wet surface.

The same formula can be used for calculating the capacity of pipes, both partly filled and full. For a design project such as this one, Q would be calculated from rational formula 3 and Manning's equations solved for A. The shape of the canal is found in design manuals and can be seen in chapter 4.4.4. and the depth would be solved as a function of A. Similarly the diameter of a pipe would be solved from the calculated A.

One of the most important design parameters for open canals is the velocity of which the water in the canal travels at. This is because of the risk of erosion. Velocity is a simple function of flow and cross-section area, as seen in formula (8), where A is the cross-section of the canal and Q is the original flow.

$$v = Q/A \tag{8}$$

In Table 3 below is presented by NPRA (2011) for the Manning's coefficient for different types of materials used for the bottom of a terrain canal and the maximum water flow speeds allowed for that material before erosion preventing measures are required.

**Table 3: Here the different Manning's coefficients for common canal linings are presented as well as the maximum water flow allowed before erosion of the lining material starts to occur.**

| Type of Material | Manning's coefficient, M [$m^{1/3}/s$] | Maximum water flow speed before erosion [m/s] |
|---|---|---|
| Concrete | 50-80 | 2.5-5.0 |
| Large stones (evened out) | 30-60 | 2.0-5.0 |
| Gravel | 30-50 | 1.0-1.5 |
| Soil without vegetation | 25-30 | 0.5-0.8 |
| Soil with some vegetation | 20-30 | 0.5-1.2 |
| Smooth plastic pipe | 66-111 | x |

## 2.6. Trajectory of a waterfall

When water runs over the edge of a rock cut, it's important to consider how close to the nearest lane the water will land. With a known height, H, of the rock cut, the downward angle of the slope above the cut, α, and the velocity at which the water is traveling, v, the offset, L, at which the water lands can be calculated with the following formula (Norem, 1998):

$$H = L * \tan(\alpha) + \frac{0.5 * g}{(v * \cos(\alpha))^2} * L^2 \tag{9}$$

All the sizes are put into the formula as positive values in this form. As the formula is a quadratic equation, it will return both a positive and negative value. In this case the negative value is ignored.

## 2.7. Frost penetration

The boundary at which frozen ground and unfrozen meet is called frost line. Frost penetration is mostly affected by the local freezing day index, although moisture content, heat capacity, latent heat and thermal conductivity all play a part (U.S. Army Corps of Engineers, 1984). A lot of studies have been published where frost penetration depth in roads in calculated. The purpose of these studies is usually to prevent frost upheave in the road sub-base during the winter season. The models which fit the measures penetrations depths vary between places and studies. Using these results for estimating the frost penetration into a drainage canal will not work since these studies are all conducted on roads which have no snow or soil cover. Organic soil is about 6 times better insulator than sand or gravel and snow about 10 times better insulator than organic soil (Colleuille, et al., 2001). Using studies which does not take the presence of organic soil and snow into account is therefore thought to give a skewed representation of the real frost depth.

As the temperature of the groundwater is relatively steady through the year it will not stop flowing when outdoor temperatures fall below zero. Where groundwater emerges from the ground, it can keep the soil unfrozen throughout the winter season. Rock has relatively high thermal conductivity, opposed to soil, or around 2.83 W $m^{-1}K^{-1}$ (Kukkonen, et al., 2011) versus 0.8 W $m^{-1}K^{-1}$ (Colleuille, et al., 2001), respectively. This means that during sub-zero temperatures, frost will penetrate deeper into bare bedrock than it can when there is soil cover. In addition, snow, which will not accumulate on the near vertical new rock cut surface, is an excellent thermal isolator, with a range of 0.06-0.71 W $m^{-1}K^{-1}$ depending on how compacted the fallen snow is (Colleuille, et al., 2001), adding to the thermal insulation effects of the soil cover. The insulation effects of soil and snow, combined with the steady temperature of groundwater will help to keep spots where groundwater surfaces from freezing.

Soliman, Kass & Fleury (2008) presented a model based on measurements in Manitoba, Canada. The model is a very simplified version of the Stefan equation but still had an 89% agreement with the test records:

$$D_f = 4.8 * \sqrt{F} \qquad (13)$$

Here $D_f$ is the frost penetration in centimetres and F is accumulated freezing day index in days. This equation does not take into account the properties of the soil, or in this case the bedrock, but puts more focus on correct freezing day index data. Weather data is usually easily accessible datasets. This formula should therefore be very beneficial when ground conditions are uncertain to get some idea of frost penetration depth.

## 2.8. Water table down draw

When draining an aquifer, a cone of depression is formed around the source of action, similarly as when water is pumped out of a well. The area within which the change in water table can be measured is the radius of effect. Applying Thiem's solution to a steady-state system allows interpolating between measurement points with the following equation (Väisäsvaara, 2009):

$$h - h_0 = \frac{Q}{2 * \pi * T} * \ln(\frac{r}{R}) \tag{14}$$

Here $h$-$h_0$ is the calculated lowering of the water table at distance r from the borehole, within the area of effect – R, with a given aquifer transmissivity T. Q is the amount of water leaking out through centre of the system.

## 2.9. Ice properties and icicle formation

Most of the ice theory studied to date involves ice formed on rivers, on lakes and reservoirs and on hydrological structures such as hydro dams. The physical properties of ice change from how it is formed, most notably the density. The density of ice depends on how pure it is. The most common pollutants in freshwater ice are air bubbles, soil and unfrozen water trapped within the ice. The air bubbles decrease the density and the water increases it. It is difficult to estimate the extent of these pollutants and therefore get the exact density of the ice. (U.S. Army Corps of Engineers, 2006). Density of freshwater ice at 0ºC is 916.8kg/m$^3$.

Specific heat of water is the amount of energy required to change the temperature of water by 1°C, and is temperature dependant (U.S. Army Corps of Engineers, 2006). It can be calculated with the following equation (Heggen, 1983):

$$C_p = 4174.9 + 1.6659 * (e^{\frac{r}{10.6}} - e^{-\frac{r}{10.6}}) \tag{4}$$

Where $C_p$ is the specific heat, and $r = 34.5 - \theta$ for $\theta < 35°C$. This means that at a temperature of 6°C, which is common for ground water, the specific heat is around 4199.3 J/kg °C. This is somewhat higher than the specific heat of ice, which can be calculated with the following equation (Andreas, 2005):

$$C_{pi} = 2114 + 7.789 * \theta \tag{5}$$

Here θ is in Celsius degrees. This means that the specific heat capacity of ice decreases as it gets colder. In other words, it takes more energy to heat the ice as it approaches melting point.

The process of icicle formation is a bit different from the one when ice forms on lakes and river in a way that the icicles are generally formed on a much smaller scale, and that they are always vertical. Due to the fact that ice has very high surface energy, water can spread more easily over its surface and make a film of water as thin as 40 – 100µm (Makkonen, 1988). This water film flows down the icicle due to gravity. The water freezes due to heat loss into the cold air around it. The icicles are formed by the process of dripping. The slower the water drips, the faster the icicles gain length, but if the supply is too little the water freezes before reaching the tip. For an icicle to gain length, a water drop must therefore reach its tip and stop for enough time for its surface to freeze (Makkonen, 1988). The growth rate is therefore a function of heat loss and water supply (Szilder & Lozowski, 1994). The water drop does not freeze solid right away but makes a tunnel of trapped unfrozen water up through the icicle. Given enough time and frost this water will freeze. If there is not a drop on the end of the icicles it is not gaining length vertically, but it can still be growing horizontally. The vertical growth rate is usually 20-60 times faster than the horizontal growth rate (Makkonen, 1988).

Ice lenses or ice segregate is formed when water freezes inside porous media. This happens when there is water in the medium above the frost line. Ice lenses form both in rock and soils. For the process to start there has to be ready supply of frost and water within pores and small fractures. Walder & Joseph (1985) presented a numerical model which shows that fractures in rock grow fasters in temperature from -15°C to -4°C. If the temperature is lower the water transport is limited by the cold and if the temperature is higher the ice does not produce enough pressure to break the ice. The fracture length over a winter season can grow up to 3 meters annually. Maximum pressure produced by ice frozen in a fracture is 207MPa at -22°C (Matsuoka & Murton, 2008). This is enough pressure to fracture any rock. This much pressure only develops where there is no air for the ice to expand to, which is rare in natural conditions. According to Matsuoka & Murton (2008) frost fracturing has the fastest weathering effect on rock.

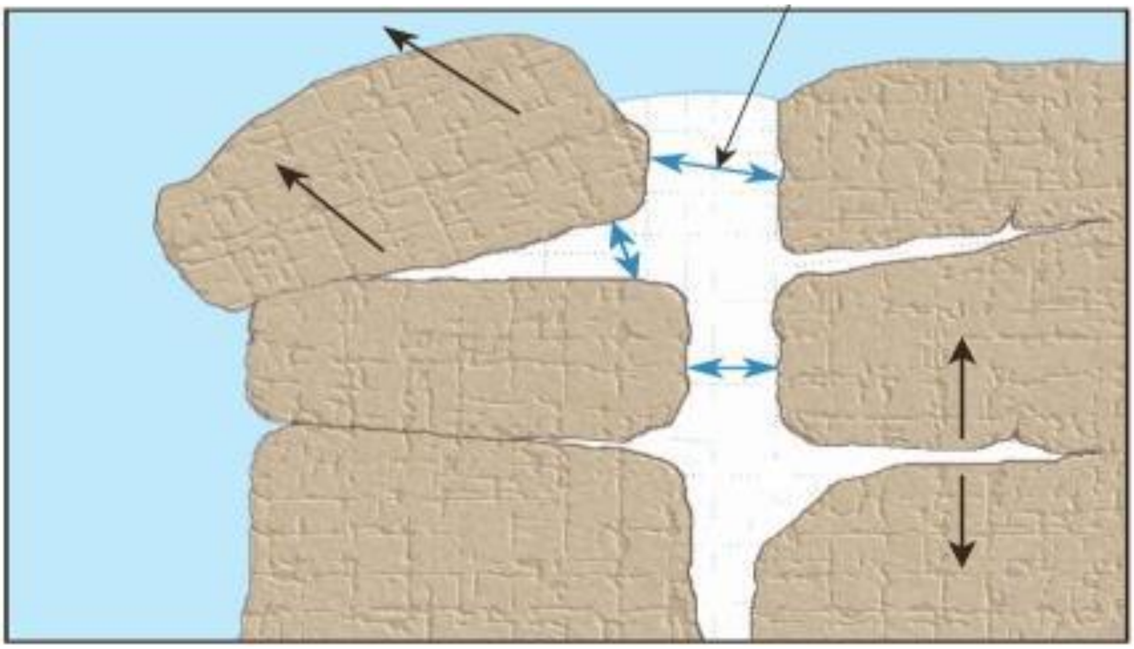

**Figure 6: Here pressure applied by ice lenses in fractures is demonstrated.**

# 3. Conceptual Model

The conceptual model presented is used for simplification of the processes which affect the icicle formation on the rock cut. It was developed both before and after site visits, based on literature, experience and interviews. The model is split in three parts; one for analysing what's happening in the study area today, one for predicting what would happen on the new road construction area without changing the design, and one for presenting and analysing possible countermeasures to the icicle problem.

## 3.1. Modell before construction

What's happening in the slope today can be seen in Figure 7. This conception model is based mostly on observations on site. The fracture orientations are based on observations and on geological reports. A more detailed account of on-site observations and properties can be found in chapter 4.

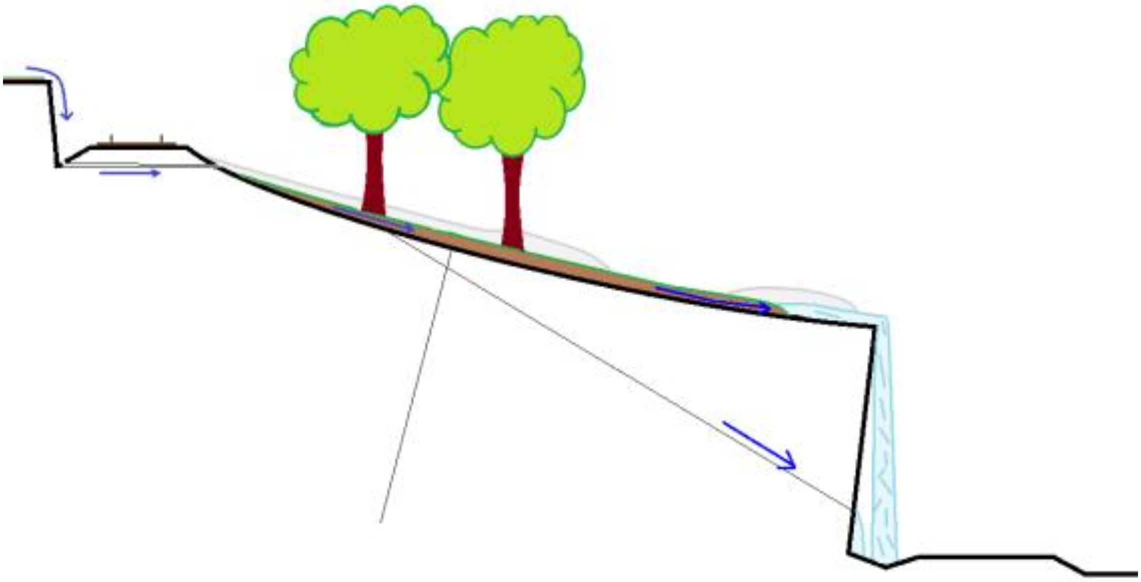

**Figure 7: What's happening in the slope today; Ice is red, flowing water are blue arrows. Soil is green. Snow is "white".**

Today the biggest icicles that are formed on current rock cut evolve from top of the cute and down to the ground. The existing rock cut is overhanging so the icicles are hanging down vertically. Surface runoff, caused by precipitation in late autumn, is not considered a source for icicle formation during this period in winter. The reason for this is that the soil cover is very thin so the water stored in the soil is limited. Instead the icicles are believed to be mainly caused by groundwater, with temperature around 6°C, which flows up through the thin soil cover and freezes when it comes in contact with the cold rock. Spots with no snow cover and wet soil were observed just above the edge of the cut where the biggest icicles are. This observation was made during prolonged sub-zero temperatures when the ground around was deeply frozen. In addition to flow up through these wet spots, groundwater is believed to emerge in the terrain above the nearby railway, and leak down into the study area throughout the winter period.

Ice from fractures in the rock wall was also observed, indicating strongly that fractures in the bedrock are filled with water. These fractures, however, produce significantly smaller icicles. This is believed to be because, at some point during winter, frost penetrates long enough into the rock wall to freeze the water before it reaches daylight, or the fractures are simply closed by at the surface. The lack of height from the ground is also a big factor. Whether this causes the water table just inside the wall to rise, because of increased water pressure in the frozen fractures, is unknown but considered a possibility at this point. This could be confirmed with piezometric measurements.

## 3.2 Modell after construction without countermeasures

Should the new rock cut be constructed is it believed that the icicles problem will stay the same, only the icicles will become larger and due to increased traffic, the risk of causing harm to trafficants will become bigger. This scenario can be seen in Figure 8.

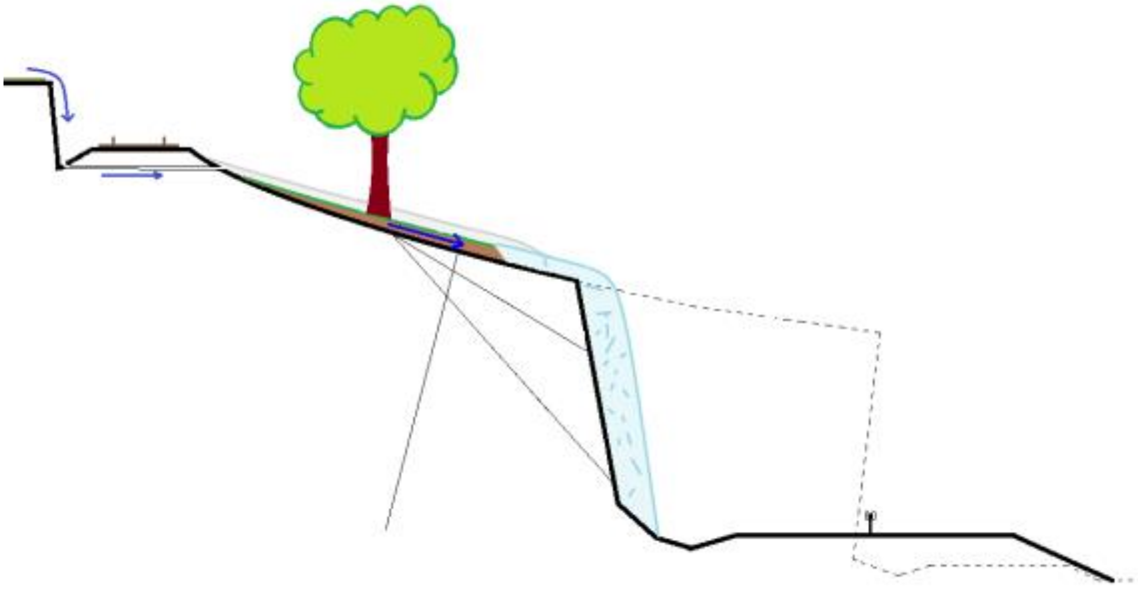

**Figure 8: A demonstration of the new construction without any countermeasures. The scenario is similar to current situation; only the icicles have become longer and, due to the reduced gradient of the slope, now cover the whole surface of the rock cut.**

What is likely to happen is that the water leaking from fractures with a low angle now flows out higher up in the rock wall, causing longer and more dangerous icicles. It's also a possibility that due to the decreased gradient of the new cut, the icicles will be lying on the surface of the rock. This may change the behaviour of the ice as it breaks, causing it to slide rather than fall, see chapter 4.5.2. Now the fractures, which lie close to the ground on the old rock cut, are higher up on the rock wall. This will cause longer icicles to be formed from fractures. Due to the fact that the wet patches, which were found in the terrain just above the cut, are also present during warm periods, it's considered unlikely that they are being fed with groundwater which can't escape through the face of the rock cut.

## 3.3 Modell after construction with countermeasures.

The aim of the countermeasures is to cut off water reaching the new rock cut for limiting the icicles formation. A simple sketch of the proposal can be seen in Figure 9.

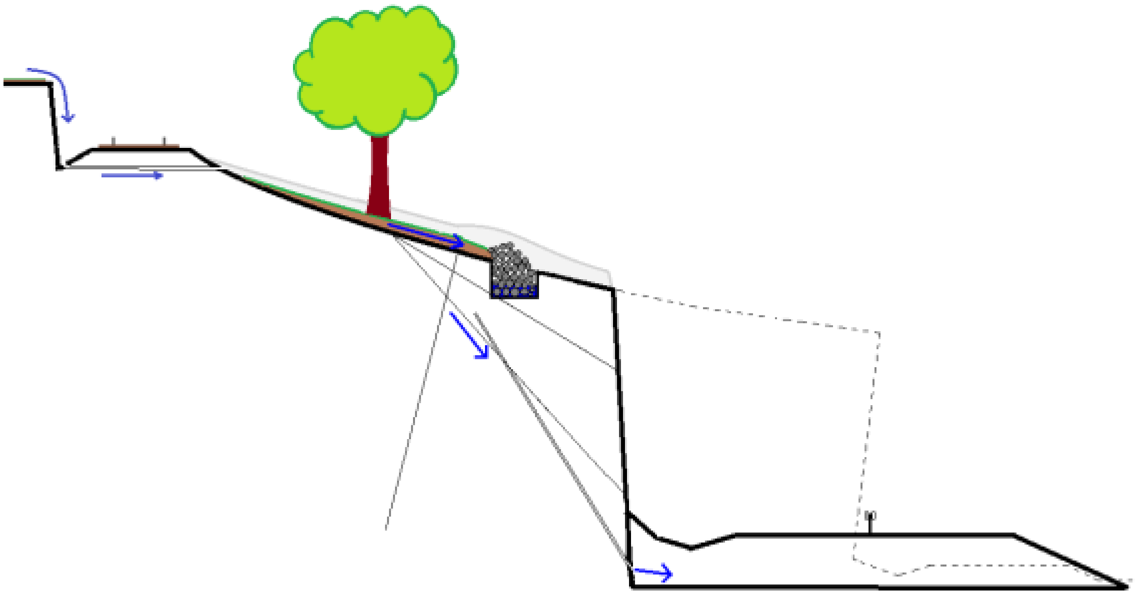

**Figure 9: The rock cut with proposed countermeasures. A second option would be to skip the vertical drain hole and make a horizontal one instead. This would require a new waterway for the drained surface water.**

The solution proposed is in two parts:

A) A ditch that would be constructed parallel to the edge of the rock cut to screen off any flow of surface water. The ditch would have to be filled with frost free material so that it would be functional throughout the year. Having a snow melting cable in the top of the ditch is considered a possibility to secure that water flows into it all year round, but unfeasible due to maintenance and operation costs. The canal will have to be blasted into the bedrock so that the any water flowing on the boundary between soil and bedrock will be caught in the canal. Due to large difference in flow on the surface of the soil and through it, a twofold system is proposed. The bottom part of the canal is well graded gravel for maximum leakage, which is meant to take up any water leaking through the top soil. On top of the gavel would be a thin layer of soil, which would be secured from erosion with solid material on top. The upper part of the canal would take care of high intensity surface runoff, for example induced by snow melting or precipitation events with long return periods. The water would then be transferred down the rock cut with either pockets, blasted into the rock wall, or pipes drilled vertically into the bedrock from the bottom of the canal.

B) Boreholes drilled from the footing of the rock wall at an upward angle, which would intercept water flowing into fractures which lie high up in the rock wall. This way icicles formed from water leaking through fracture would be reduced. In addition, water content of the fracture penetrated would be decreased, which would increase the stability of the rock cut.

# 4. Local Description and Design Parameters

In order to improve the current design of the project it is important to outline what the current proposal looks like, what local forces are at play and design guidelines the NPRA uses in its design process. In the following chapter these parameters are highlighted and explained: Local geology and hydrogeology, climate conductions and the road structure. But first is a detailed account of observations made on in the study area.

## 4.1. Site Visits

During the period from January to May 2013 the study area was visited several times. The purpose of these visits was to gather necessary information regarding the ice forming process on the existing rock cut and in the terrain around it. This information would help deciding whether any action against the ice formation would be needed for the new road project. If the answer would lean towards some sort of action then the info gathered would help choosing which solution would be best fitted for solving the problem. At first the conclusions about the ice formation process was mostly based on assumptions, as the ice was already covering the whole existing rock cut during first site visit. In the beginning of March the ice was removed, which made it possible to monitor the process of new ice forming on the cut. In April, as the snow on top of the ice started to melt, it was possible to map locations of ice formations in the terrain above and around the existing rock cut, which are thought to be likely to affect the new road construction. The most important question which needed to be answered is where the water feeding the ice formations process throughout the winter season is coming from.

**Figure 10: The existing rock cut during a site visit on the 25th of January 2013. This picture was taken 13:29 so it's clear that the sun does not shine in the study area some part of the winter.**

During the first site visit the whole existing rock cut was already covered with icicles to the point which is was almost not visible, see Figure 10. From this sight, the conclusion that the water was flowing on the surface of the terrain and over the top of the rock cut was made. The problem was that at this point in the season, the outdoor temperature had been sub-zero more or less for over two months. In addition the soil cover in the area is very limited, too little for the water in the soil to be able to flow frost free over the whole winter. As the ice was already there during the first visit, it was impossible reject to the possibility that the ice had been formed early winter, before the frost was able to penetrate the soil and stop the water flow towards the rock cut. No attempt was made to measure the thickness of the ice or to evaluate if it was still growing. Where it was possible to go behind the hanging icicles, there was visible running water but it was impossible to see where it was coming from.

Three weeks later the site was visited again, in another attempt to find a water source. This time a small creek, seen in Figure 11, which had been mapped the previous summer (see red circle on Figure 23), was investigated. At the time which it had been studied previously, it had looked like and ordinary creek fed with rainwater from the terrain. Much to a surprise, the creek was still flowing at similar intensity as before, despite the cold and dry winter season. This gave a reason to believe that the creek was being fed with by a spring form groundwater. After following the waterway higher in the terrain, a hole in a road filling of Ove Gjeddesvei, out of which water was flowing, was discovered, see Figure 11. There were more small patches soil around the opening which were wet and not covered with snow. The temperature of the water flowing out of the hole was measured and it turned out to be between 5 ºC - 6ºC. In addition the temperature of the water in the wet soil was measured and it turned out to be just over 4ºC. Given the temperature profile of groundwater in Kongsberg the measured temperature supports the theory that the creek is groundwater fed and that groundwater is seeping up through the soil around the opening in the road filling. At this time in the road project, it is still considered a possibility that this water is coming from a leaking drinking water pipe inside the road filling. Measurements done in the spring revealed that the water flow out of the hole was about 1 l/s.

The creek is too small to flow in a concentrated waterway in the steep terrain just above the existing rock cut so it spreads over a wide area before flowing over the edge, lowering the flow velocity and increasing the risk of the water freezing on the rock cut. The area is nevertheless nowhere wide enough to explain the ice formation of the whole rock cut. The creek is still considered a big part of the ice formation problem and needs to be considered during the process of choosing solution to the ice problem.

**Figure 11: The source of the creek marked with a red circle on Figure 23 is to the left and the creek itself is on the right hand side. The picture on the right is taken up towards the railway.**

Soon after the discovery of the warm water in the creek the general experience of the winter season and weather forecasts indicated that the daily high temperatures would soon cross the 0ºC mark so the physical removal of the ice was scheduled. On Tuesday the 7th of March the ice was removed by the contractor NCC. The process took around 5 hours, from 9:00 to 14:00, during which the two direction traffic through the study area was controlled by the contractor through one lane. The traffic volume is low during this time of the day so there was no extensive queuing. There was though at least one small collision between passenger vehicles in the queue during the ice removal process. At one time, during the removal of the icicles, water started to flow at considerable intensity from under the ice on the rock shelf above the rock cut. The water had clearly been under some pressure under the ice and started to flow out when the ice was broken. This only lasted for a few minutes and it’s difficult to estimate how much water it was.

After the ice had been removed the outdoor temperatures fell again, providing an unexpected chance to monitor the ice accumulation process on the existing rock cut. Needless to say the ice growing rate was staggering, as can be seen in Figure 12. At that time there had still not rained in the area since the beginning of the study, which further strengthened the believe that the ice forming process was constantly being fed with groundwater throughout the winter season. After the ice removal it was easier to see what was going on top of the rock cut. It was still very slippery so it was too risky to go to close to the edge. After it became clear that the ice was still growing from water flowing over the top of the rock cut, this area became the focus point as it could lead to finding the source of the water.

**Figure 12: On the left is the existing rock cut the day after the ice was removed. The picture on the right is the same location 5 days later. The rock was notably wet under the removed ice.**

In the terrain above the rock cut, there was a familiar sight. In the snow covered landscape, there were patches of wet ground which were not covered with snow, just like the ones near the source of the creek. With no visible flowing water around or above these patches, they could not have emerged any other way than by groundwater, or interflow, flowing up through the soil. These patches are very clearly visible inside the red circles on Figure 12 and are shown in more detail in Figure 13. The reason for the lack of snow cover could not have been trees, since the whole area had the same vegetation coverage. There was no sign of running water on the patches themselves, but it became visible on the bedrock shelf above the rock cut. The water was running on top of the already formed ice and was dripping over the edge of the rock cut. One of these patches turned out to be directly above where water had sprayed out from under the broken ice.

The water which flows up through these patches is thought to be the main source of ice formation on the existing rock cut. This water is believed to flow up through the bedrock and then on the boundary between soil and bedrock before flowing over the edge of the rock cut. The fact that its temperature, when flowing from the bedrock, is not effected by the outdoor air temperature, and gets insulation from the soil cover, makes it possible for even slow flowing water to find its way to the rock cut before freezing. What will make it more complicated to deal with this water is the fact that some of these wet patches will be blasted away during construction of the new road, which might mean that the water transporting fractures which make these patches might end up in the middle of the fresh rock wall.

**Figure 13: One of the patches above the rock cut which was not covered with snow. There was no sign of running water but the ground was wet and unfrozen. This area will be blasted away during construction of the new road.**

An end-April site visit revealed that there was some ice to be found in the terrain above the existing road. It was, however, not as thick or spread-out as expected, and nowhere near as spectacular as the ice on the existing rock cut, despite the fact that it was allowed to grow out of control throughout the winter season. It was therefore concluded that this ice had not been supplied with water during the coldest months but had been formed earlier in the season when the top soil was still leaking water. That indicates that despite the extent of the icicle problem on the existing rock cut, the problem will not necessarily expand throughout the soon-to-be much longer cut. This will be a valuable observation when it comes to defining the extent of necessary countermeasures against the icicle formation.

## 4.1. Local geology

Norway belongs to the geographical region called Ferro-Scandinavia. At the time of its beginning, around 3500 million years ago, it was part of a supercontinent called Rodinia. The oldest bedrock is found in Norway is found in the north and is expected to have formed around 2900 million years ago, during the early Palaeoproterozoic orogeny. The northern parts of Norway are considerably older than the south regions, which are dated to a period ranging from 1750 – 900 million years ago. The bedrock in Southern Norway makes up the youngest part of the Fennoscandian Shield (Ramberg, et al., 2008).

The bedrock in the area where the rock cut is going to be made is, according to a geological map, expected to mainly consist of massive gabbro, believed be around 1200 m.y.o.. It is both folded and banded and consists of medium to coarse-grained amphibolite (Nilsen & Siedlecka, 2003). This correlates well with on-site observations and more detailed geological reports made by both Multiconsult and Rambøll for the NPRA (Rambøll, 2011) (Moen & Roe, 2012). Around 500m north of the cut is an end of a fracture zone which extends to the north-east. The strike of the fractures registered by Nilsen & Siedlecka (2003) is mostly parallel to the existing rock cut but the dip ranges from 50º-80°.

In April 72 fractures and planes were registered in the study area, most of the on the existing rock cut and in the slope above. The results were not very surprising; vast majority of the planes registered were similar to the existing rock cut. Further details and results from analysis of the strike and dip registration can be found in chapter 4.2. This, again, is supported by other reports and by fracture registration made in field trips, see Figure 14 and Figure 15.

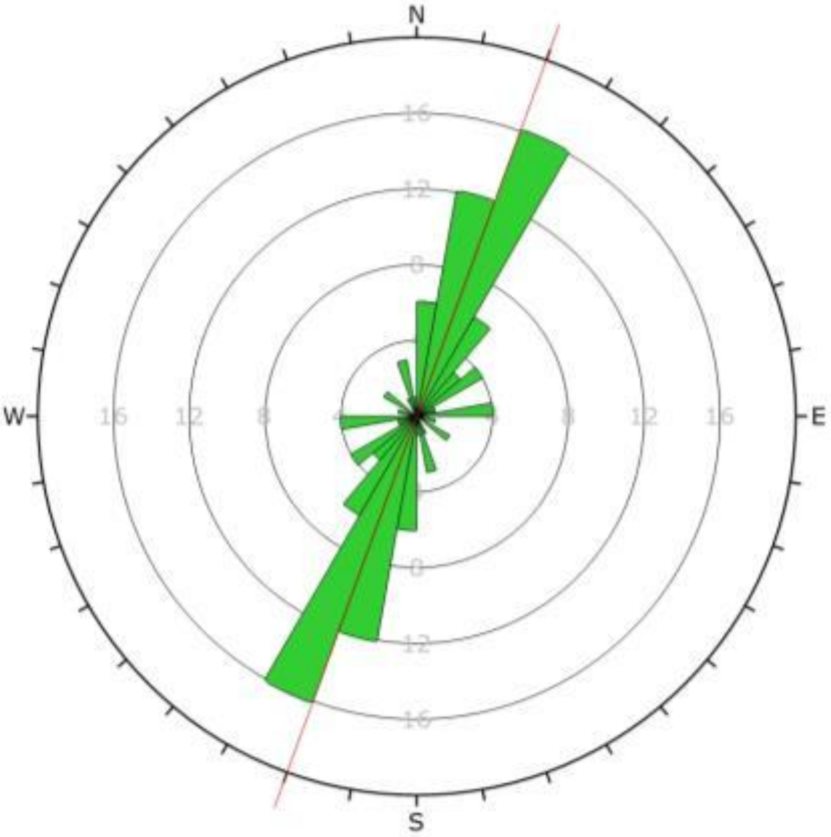

**Figure 14: A fracture rose of the registered strikes and dips in the study area.**

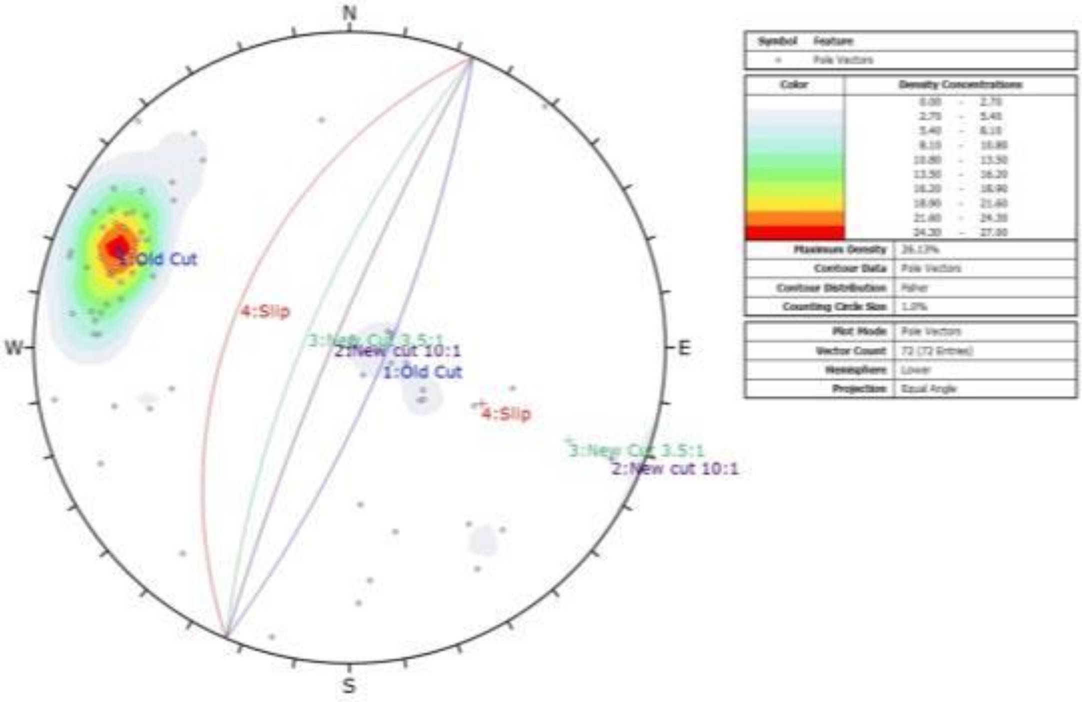

**Figure 15: A stereonet plotted from the strikes and dips registered in the study area.**

**Figure 16: A map from the NGU. The scale of the original map is 1:50000, but still it correlates well with more detailed reports from the site (Nilsen & Siedlecka, 2003). Massive-Gabbro is in pinkish colour, dioritic gneiss in light-brown and light-grey is a thick moraine.**

## 4.2. Local hydrogeology

The bedrock in the area is crystalline rock with low permeability. This means that the groundwater flow is assumed to be mainly restricted to fractures and fissures in the bedrock (Banks & Robins, 2002). The rock is affected by weathering to considerable depth. These weathering effects are assumed enhance the leakage of water through the bedrock into a tunnel that is planed nearby (Rambøll, 2011). Considering how much deeper in the bedrock the tunnel lies than the planned rock cut, one can expected that the weathering will not have less effect on water flow through the new rock cut.

There have not been conducted any known measurements of the water table height in the study area. However, verbal accounts confirm that water has been known to flow out of shallow openings in the terrain nearby (Berge, 2013). The groundwater table in the area can therefore be assumed to lie relatively close to the surface. If that is the case, then simple borehole measurements would confirm that (Fitts, 2002). The temperature in shallow aquifers is more likely to fluctuate throughout the year than deep aquifers (Dagestad & Hans de Beer, 2008). The temperature of the groundwater in the study area is believed fluctuate between 5°C to 7°C throughout the year (Dagestad & Hans de Beer, 2008) (Norges Geologiske Undersøkelse, 2008) (Båsum, 2013).

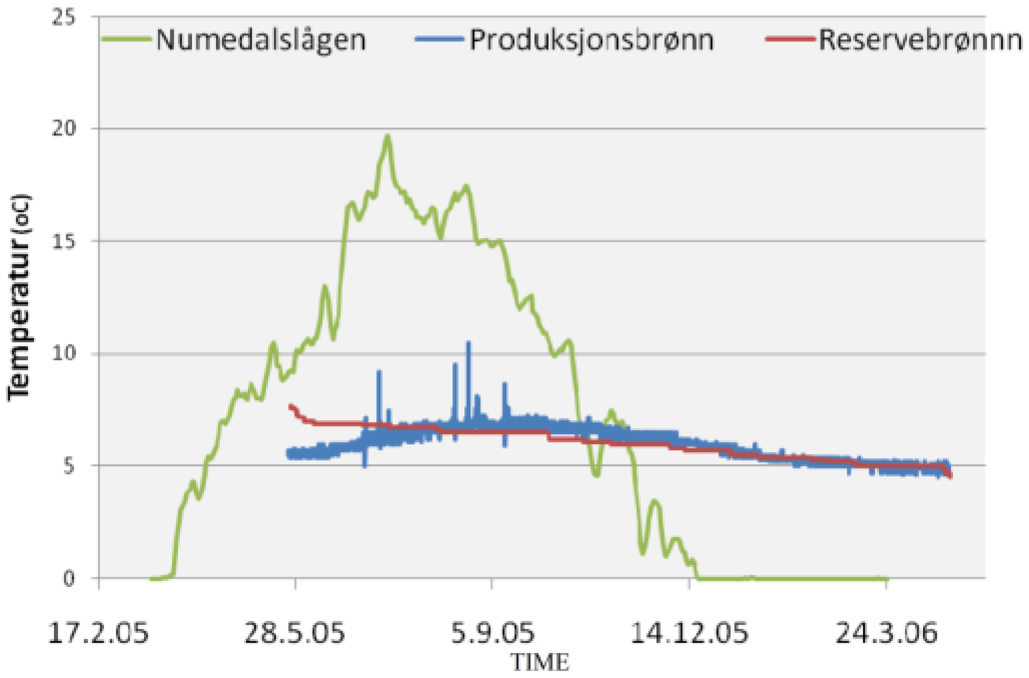

**Figure 17: Comparison of annual temperature fluctuation in a nearby borehole and the river Numedalslågen, which flows adjacent to the road (Dagestad & Hans de Beer, 2008).**

The soil cover is relatively thin in the area. It does not contain clay and constructions in the locality are not likely to be affected by lowering of groundwater table (Rambøll, 2011). Due to little soil cover, saturation overland flow is likely to occur and runoff peaks can be expected to become relatively high after precipitation events. This is something that must be taken into consideration during design of any solutions related to diverting surface water away from the top of the rock cut. High permeability of the bedrock should help lowering the runoff peaks (Fitts, 2002).

There has been drilled number of drinking water boreholes in the municipality, most of which are in bedrock. Three of three of these boreholes are scattered around 1km away from where the rock cut is planned and might give some indication about the amount of water that one might find on the construction site. In direct line of sight from the rock cut to the highest peak in the area is a 90m deep borehole drilled from around 225 m.a.s.l., or to the approximate height to the rock cut. The registered flow of water at the bottom of the hole is 500-1000 litres per hour. Another borehole, reaching similar depth in terms of sea level, is only registered to have 50 litres per hour (Norges Geologiske Undersøkelse, n.d.).

## 4.3. Weather

Weather is one of the key factors when it comes to ice formation, both the temperature and precipitation. The climate in Kongsberg is considered in-land climate. This means that the summers are warm but the winters are considerably cold. It also means that most part of the annual precipitation falls during late summer with high intensities (Berg, et al., 1992).

The average precipitation in the Kongsberg area is recorded to be 836 mm/year, based on monthly rainfall data from 1979 to 2002 (Norwegian Meteorological Institute, n.d.). The average evaporation in Norway is 386mm/year but is estimated to be around 500mm/year in the southern parts of the country (Hanssen-Bauer, et al., 2009). This means that the maximum annual runoff in the study area is estimated to be 336 mm/year, which accumulates to 10.7 l/s per km$^2$ over a year. This is the maximum groundwater recharge. The more likely groundwater recharge should be less or close to 50% (Colleuille, et al., 2001).

The annual mean temperature in Kongsberg is 4.5°C. The mean temperature is the made from the daily average from a 30 year period; 1961 – 1990 (Norwegian Meteorological Institude, n.d.). When considering the amount of ice that can emerge on the face of the rock cut, one must take into consideration the days with temperature degree below zero. Freezing degree days (FDD) are a measurement of the time and the amount of which the daily mean temperature is below zero. The accumulated freezing degree days (AFFD) sum up the degree days over a month, subtracting the degree days which have positive daily average from the FDD. The AFFD is used in the Stefan equation for estimating thickness of ice on lake and rivers. (U.S. Amry Corps of Engineers, 2004). The total AFFD for the winter months (dec, jan., & feb.), which give a positive index, is around 391 days or 9379 hours. Another approach is presented be Steuer (1996) where the negative mean temperature of a month is multiplied by the number of days or hours. This method gives an air-freezing index of 13,454 hours, using local temperature series from 1982-2012. This is considerably closer to the freezing index presented in NPRA’s Handbook 018 which is 16,000 hours for 2 year return period. The freezing indexes for 10 and 100 year frost hours are 28,000 and 31,000 respectively (Statens Vegvesen, 2011).

There are no frost penetration measurements available for Kongsberg. The closest measurement point was found at Gardermoen airport. The measurements there showed that maximum frost penetration, in similar soil and vegetation as found in Kongsberg, is 102cm (Colleuille, et al., 2001). When taking into account that the snow depth in Kongsberg is usually two times more than around Gardermoen and that the freezing day index is similar for both places (Norwegian Meteorological Institute, n.d.), this is considered to be maximum frost penetration depth in the study area.

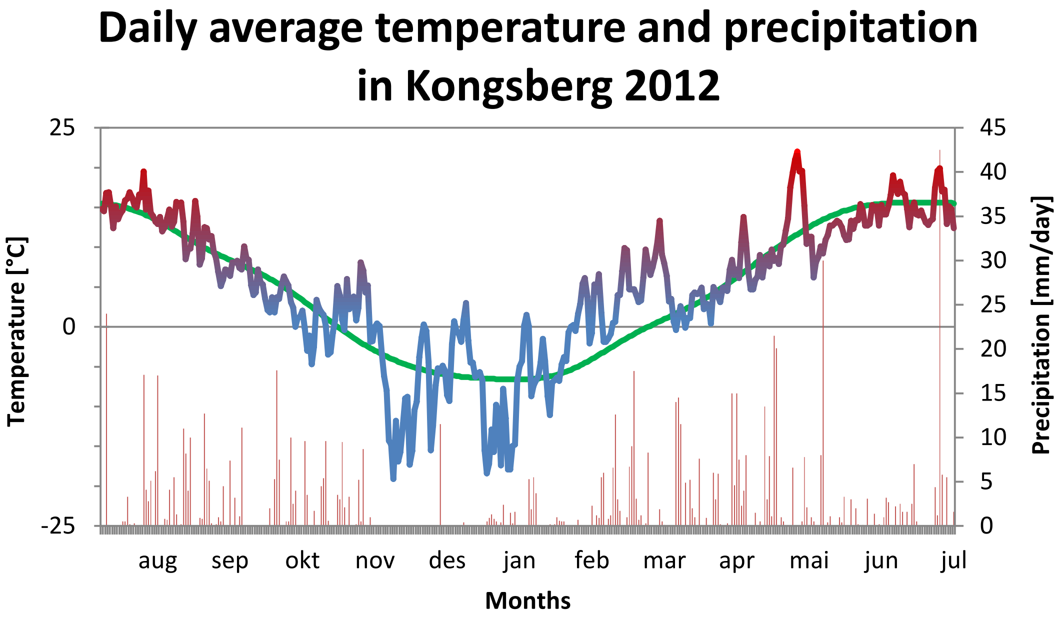

**Figure 18: This graph shows the daily median temperature in Kongsberg in 2012 with the blue and red curve. The green curve represents the mean temperature from 1961-1990. The bars show the daily precipitation (Norwegian Meteorological Institude, n.d.).**

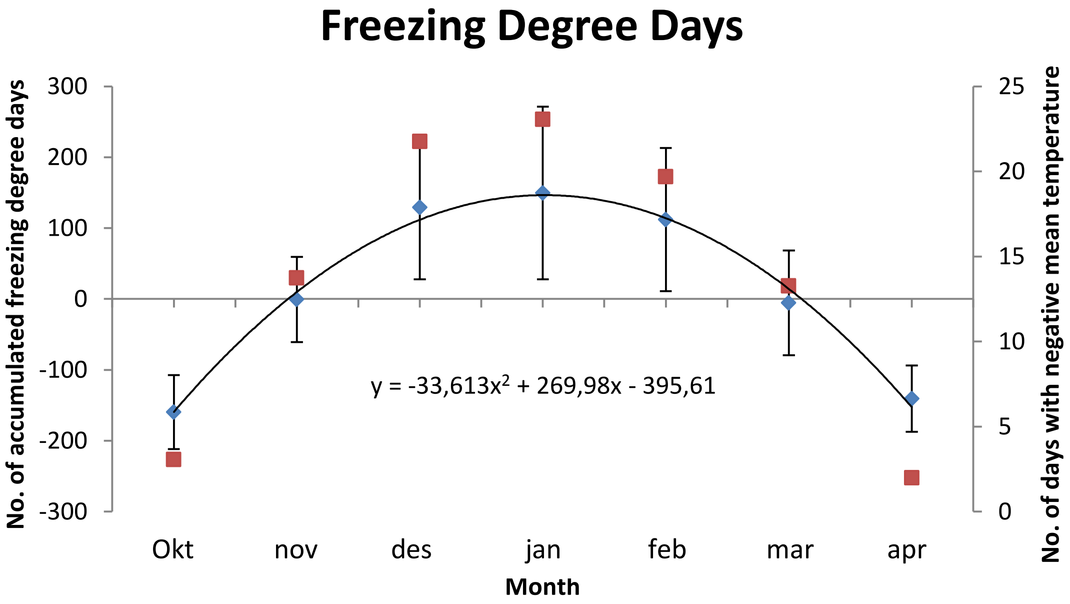

**Figure 19: This graph shows with blue diamonds the average number of accumulated freezing degree days per month from 1982-2002, with standard deviation error bars, read from left axis. The red squares show the average number of days per month with mean temperature below zero over same period, read from right axis.**

As can be seen in Figure 19, one can anticipate ice accumulation from mid-November to mid mars. This correlates well with both the statistics presented in Figure 1 and experience from the NPRA local road maintenance representatives (Berge, 2013).

## 4.4. The construction

The parts of the road construction which are of most concern for the ice formation problem are the road bed, the rock cut above the road and the draining system. Each part will be covered under separate heading. The discussion takes note of how the design of the road is today.

### 4.4.1. The road

As stated in the introduction, the road through the case study area is a four lane road. It is a S6 type of road from NPRA Handbook number 17. This means that the speed limit will be 60 km/hour; somewhat lower than a regular highway. This is because this section of the road goes through an urban area. The width of a S6 road is 16 meters from shoulder to shoulder, but each lane is 3.25m wide. It is made for 12,000 – 20,000 average annual daily traffic (AADT) (Statens Vegvesen, 2008).

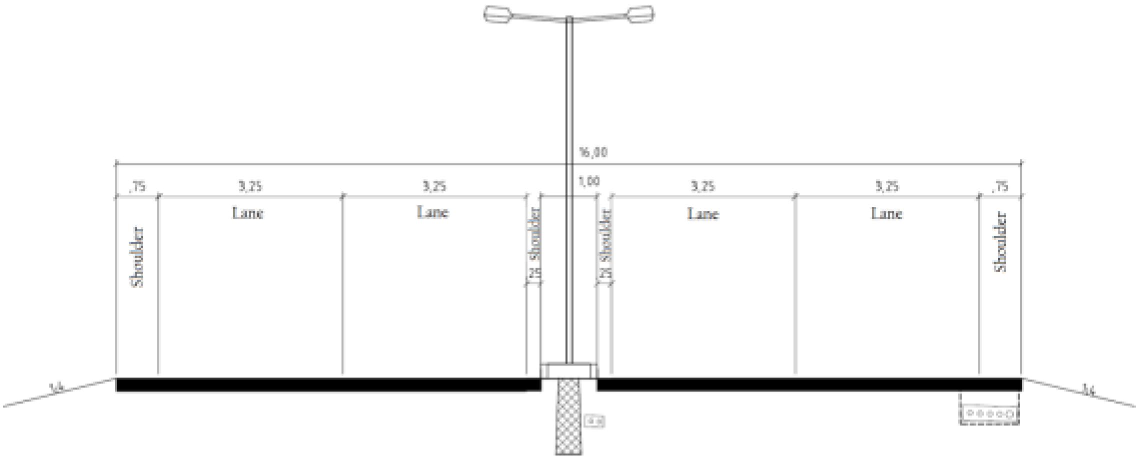

**Figure 20: This is a typical S6 cross section. Each lane is 3.25m wide and the total width of the cross section is 16m (Statens Vegvesen, 2008).**

The width of the road is important with respect to the landscape it will be constructed in. Due to the steep terrain above the current road bed there will be need for considerate removal of bedrock.

### 4.4.2. The rock cut

Design regulations for the steepness and the side of the roads area presented in Handbook 018 from the NPRA. The design categories for rock cuts are two; one for cuts below 10 meters height and one for cut that are higher. A rock cut lower than 10 meters is not considered very challenging as opposed to ones that are higher. According to Handbook 018 all rock cut that are higher than 10 meters fall into the highest geotechnical complexity lever, number 3. This means that the following research needs to be carried out before construction can be carried out:

Desk study:

- Identification from maps of: Outcrops and soil and potential fracture zones.

Field investigation should identify the following:

- Soil thickness and types of soil.
- Rock types and boundaries.
- Rock layering and foliations.
- Fracture patterns, fracture offset, strike and dip.
- Hydrogeological properties and risk of ice formation.
- Rock quality.
- Risk of landslides from terrain above the cut.
- Assessment of need for geophysical investigations.
- Assessment of need for core drilling or other types of test holes.

According to Handbook 18 it is normal to make a rock cut with a slope of 1:3.5 and current design takes note of that, see Figure 21 (Statens Vegvesen, 2011). However, due to proximity to an adjacent railway line to the new road construction, this slope might have to be increased. Increasing the slope to 1:10 will reduce the space needed by a 10m high rock cut by 1.85m and a 20m high rock cut by 3,71m. There is therefore considerate amount of space to be gained. These changes will have some effect on the factor of safety for the rock cut so the stability calculations will have to be updated.

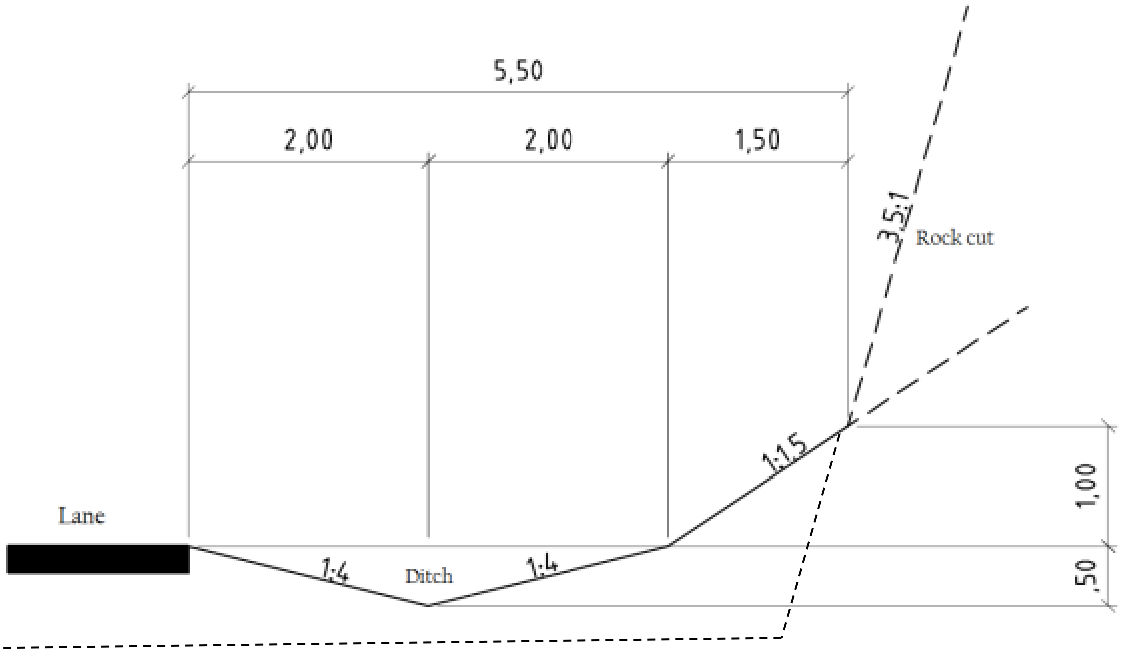

**Figure 21: This is how the side of the road is supposed to be constructed. The rock cut is designed with 1:3.5 slope. This might possibly be changed to a steeper slope due to lack of space from the top of the cut to adjacent railway.**

Make a profile of the aspect between the top of the cut and the road.

Maybe also make a profile of the horizontal distance from the cut to the railway.

### 4.4.3 Draining system

There is not much unusual about the proposed draining system for the area. It aims to collect water from the hill side of the road and release it into the river which flows by. Overview of the draining system can be seen on Figure 23 and the typical cross section of the layout for manholes and drains on Figure 22. It's interesting that despite reports of severe ice formation in the area, there do not seem to be any attempts made to collect or control water above the rock cut. There is one exception to this through, to the top right corner of Figure 23 is a small ditch to control existing creek. This creek is not in an ice problem area today so it is unlikely that ice played a big role in the design.

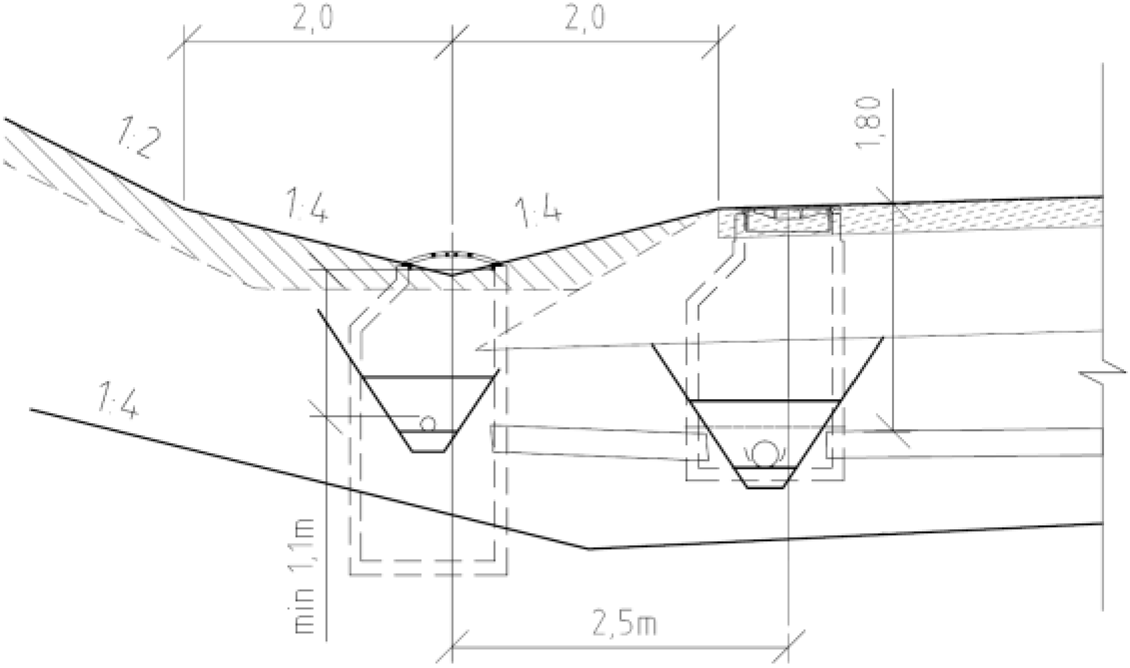

**Figure 22: A typical cross section of a draining system for the project.**

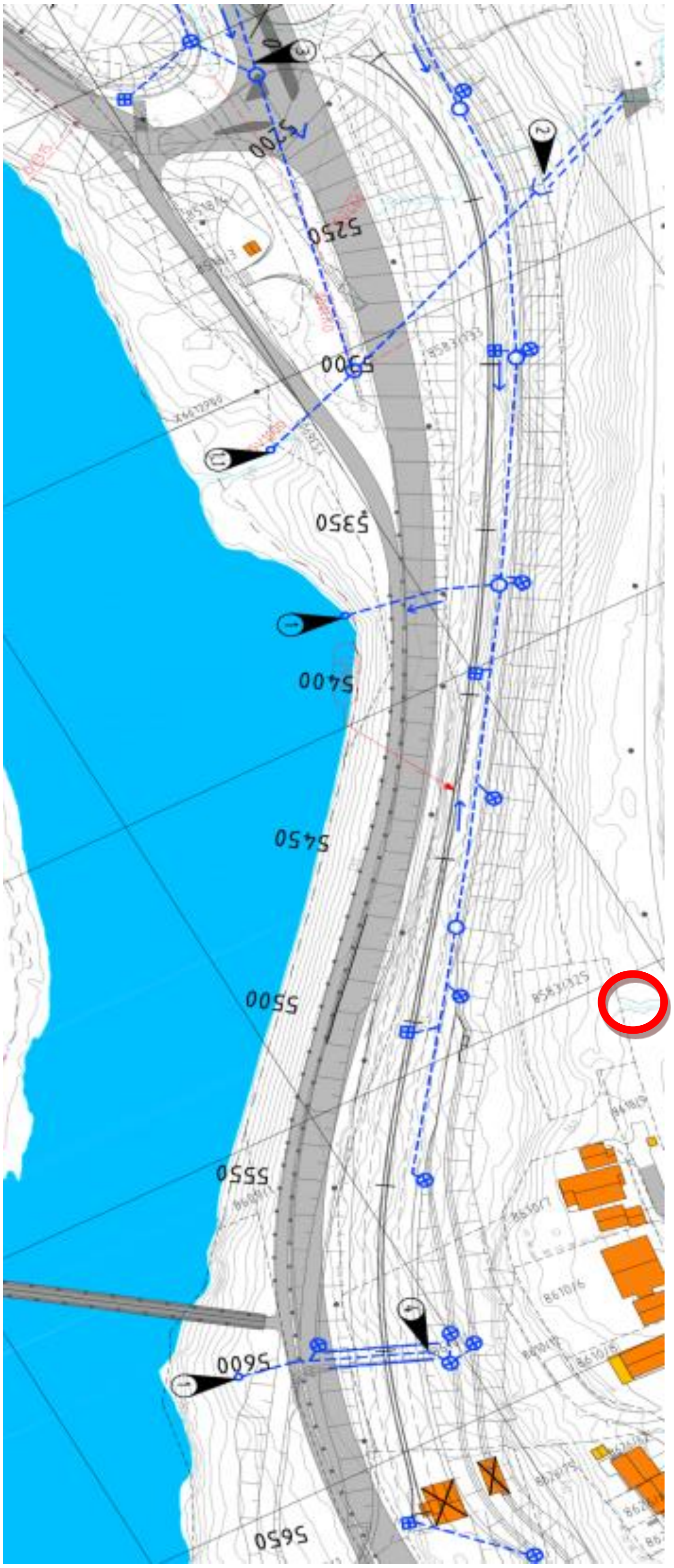

**Figure 23: Overview of the proposed draining system in the case study area. Take not that the existing road is grey in the map, not the proposed road. Draining pipes are blue dashed lines, manholes are circles with a cross and drains are squares with a cross. There is a small creek under the red circle.**

### 4.4.4 Canal dimensions

Open canals are one of the countermeasures NPRA proposes against surface runoff. The purpose of the canals is to capture surface runoff, and in some cases lower the water table, to protect the road bed from erosion or frost heave. A well-known formula for estimating the needed size of a canal with respect to maximum flow is the Manning's equations. This method is advised in handbook 018.

As principal, water transporting canals are made with the minimum of 0.5m for canals that are dug along roads, and the same requirement applies when it is done on the top of a rock cut. The slope of the sides should be 1:2 and the material chosen should be able to withstand erosion from the water flow. When cuts are constructed above rock cuts, it should be placed at least 2m from the edge of the cut. It is suggested that draining canals on a top of a rock cut is in two parts; the deeper part is filled with frost free material and is separated from the upper part of the canal with erosion securing filter material. This help preventing freezing in the canal during winter months.

The advantage of closed canals is that they pose less threat for people to fall into them and, when place by the side of a road, decrease the risk of vehicles tipping over during an accident. They also leave a much smaller scar in the landscape than open canals.

### 4.4.5. Pipe dimensions

When it comes to draining, the NPRA splits pipes into two categories; one for the pipes which capture water from the surface, and one for the pipes used to transport water from one side of the road to the other. These pipes vary somewhat in size, the latter usually being considerably bigger. The purpose of the pipes is similar to the one of canals; to drain the terrain and offer protection from erosion and frost heave.

When concrete drain pipes are laid out to capture surface water, the minimum diameter should be 150mm and the gradient 1:200. If plastic pipes are used the diameter can be 100mm, due to less friction. If, however, the pipes are part of a combined system for surface and ground water, the pipes should always be at least 200mm in diameter. The diameter of the pipes should be chosen so that there will be minimum sedimentation inside the pipe, but also so that there isn't risk of erosion due to turbulence. If needed, the gradient of the pipe can be increased to increase flow speed.

## 4.5. Problems generally associated with ice on rock cuts

There are a lot of things that can go wrong when ice is allowed to form uncontrolled on rock cuts. The stability of the structure is decreased, there is a risk of ice falling down on the road and then there is risk of decreased sight line in curves.

### 4.5.1. Rock stability

When water in fractures freezes, it causes increased pressure on the rock around. The pressure can be enough to extend the fracture or make new fracture perpendicular to the existing one. The length of a freeze/thaw induced fracture can be up to 3m in a season (Walder & Hallet, 1985). Over prolonged time, this process will loosen up a bigger and bigger part of the rock face, causing rock to start falling down, as illustrated in Figure 6.

It is highly unlikely that a rock cut can be made completely dry. This is both because of the nature of water flow in crystalline rock and water trapped in pores. With respect to the ice segregate forming process, one can anticipate that decreased water flow will slow down the frost weathering process. Water draining procedures would therefore reduce maintenance and increased lifespan of the construction.

**Figure 24: This stone block was stuck in the ice removed from the rock cut in the study area. It is around 65cm across.**

### 4.5.2. Falling ice

During spring, the risk or ice fall increases significantly. This happens because the ice smelts free from the rock face. Around 75% of registered cases of ice falling down on a road in southern Norway happened in March and April during the period 2000-2009 (Bjordal & Helle, 2011). Although most registered falling ice masses are less than $1m^3$ in size, falling ice can cause roads to become impassable, forcing road administrators to close it until the problem has been solved. A more serious problem is the risk of vehicles hitting ice blocks on roads at high speeds. In addition to the almost certain property damage, the health of the driver and passengers is also put at risk. Moreover, vehicles getting hit by falling ice could have severe consequences.

There are three main categories in which ice fall can be divided in, see Figure 25; tipping over, falling and sliding. When icicles tip over, they are most likely to fall on the road. This is can to happen in moderately high rock cuts where the icicles freeze from the top and all the way to the bottom of the cut. Visits to the study area showed that this type of fall is likely to occur if the ice is not removed.

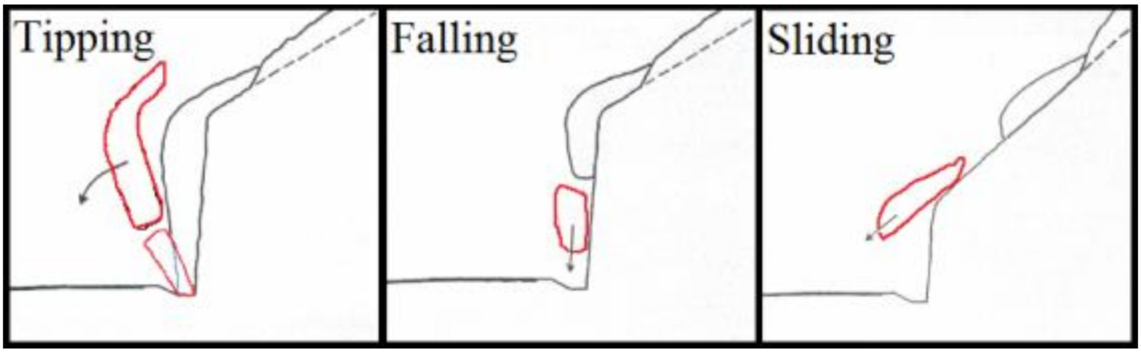

Figure 25: Different types of ice fall (Norem, 1998).

### 4.5.3. Visual distraction

Where there road bends, it is important to design the curve in a way that the length of line of sight allows safe stopping distance (SSD) at all times. Where icicles have grown from the top of the rock cut to the ground, and have gained significantly in horizontal size, see Figure 26, the line sight can be reduced enough for affecting the safety of the road. The higher the speed limit on the road, the bigger the effect of the reduced line of sight.

**Figure 26: Picture taken in the study area. Here the ice reaches the side of the road, reducing line of sight for bypassing traffic.**

## 4.6. Known Solutions practiced by NPRA

In NPRA's handbook 018, there are three solutions highlighted, without any precise technological details. These solutions are draining holes, ditch to capture falling ice and so called ice net or rock net. In other literature, more solutions are introduced. In the report *Securing roads against ice fall* by Harald Norem (1998), published by the NPRA, the following methods are added: support fences, both rigid and net structures, ice bolts and water diverting walls. These methods have all been practiced at different places around Norway. All these technological solutions have their pros and cons.

When choosing an icicle reducing technique which fits best to a given area, there are several key factors that need to be considered. The construction cost has to be kept at minimum, but one must take into consideration that it often does not take long for maintenance expenses to bypass the starting capital. It is therefore important to choose a solution which has a long lifespan. Most icicle prevention techniques do not have any direct operational costs, although the boundary between operation and maintenance is sometimes vague. It is therefore suitable consider these two factors as one when evaluating a best practice solution. Aesthetics play a bigger role inside urban area as opposed to rural road constructions. Some support structures have a bigger visual impact than others so it’s important to take that factor into consideration. In addition to varying visual effects, direct impact on the environment and sensitive nearby structures around the construction also have to be taken into consideration.

### 4.6.1. Preventing ice formation

When possible, the safest way of dealing with ice formation is stopping the problem at its source; that is cutting of water supply to the ice forming areas. This can be done by either cutting of surface water with water transporting canals, or drilling holes into the rock for controlling water transport in fractures. As these solutions aim at preventing icicle formation, they are bound to provide better safety than those who don’t. This approach can involve diverting surface water to existing streams so the effects of this newly introduced surface runoff on the existing creek has to be evaluated. In addition, the lowering of groundwater could affect nearby structures founded on water sensitive soils, so that has to be take into consideration.

#### *4.6.1.1. Canals*

Water transporting canals are considered by the NPRA to be the best practice solution for preventing icicle formation (Norem, 1998). Where possible, the surface water should be diverted from the top of the rock cut. As the purpose of these canals is to transport water throughout the winter season, it’s important to make them frost resistant. The water should be diverted to either a natural creek and away from the cut or to specially made pockets in the rock cut for transporting the water to lower ground. These pockets should be at least 2m deep. Where the fall of the water is too much some sort of energy reducing countermeasure should be taken, for example a stone formation inside the pocket. These pockets allow the water to freeze at controlled places and further away from the road than otherwise. In addition the concentrated flow will reduce the icicle formation.

In order to make the canals frost resistant, it’s important to fill them with coarse stone material. As the main purpose of these trenches would be to capture water flowing on the boundary between bedrock and soil, the icicle prevention capabilities of the canal will not be restricted by coarse filling materials party covered with soil. This will also reduce the waterway’s visual impact. Digging a water canal on top of a rock cut is not likely to affect the way motorists experience the construction. Canals can, however, become visual scars in the landscape for those who see the rock cut further away from the road, for example in high constructions in urban areas. Due to the proximity of the canal to the rock cut, it is very unlikely it will have any negative effect on nearby structures but there is some possibility of affecting the ecosystem in receiving streams.

The construction cost of a canal like this depends on the thickness of the soil cover. Where there is too little cover, costs will be raised with blasting of bedrock and where the soil is thick the trenches will have to be made deep to reach the contact surface between soil and bedrock. As most of the water the canal is meant to transport seeps through the soil and/or is groundwater flowing from fractures in the terrain above, there will not be any considerably high flow peaks. This will limit the geometry of the waterway considerably as the uncertainty of the expected flows will be smaller than usual runoff calculations usually involve.

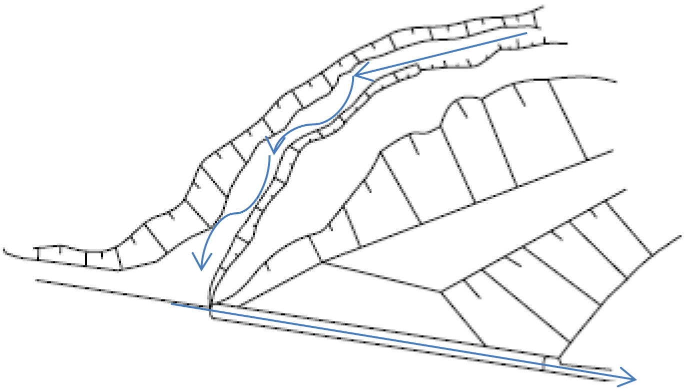

**Figure 27: Illustration of a water transporting canal above a rock cut (Jernbaneverket, 2010)**

### *4.6.1.2 Draining holes*

When water is flowing through a fault in the middle of the rock wall it is not possible to divert and control it with same methods as surface water. When this happens, boreholes, drilled from the face of the rock cut, are made for capturing the water and leading it out of the bedrock at controlled places. This procedure is required by handbook 018 where shotcrete is used as reinforcement to reduce the risk of ice segregate forming between the rock and the shotcrete. For this method to work the dip of the main water transporting fractures has to be favourable. The draining boreholes are drilled either systematically along the rock cut, or aimed specifically at areas where the rock cut is never dry (Ødegaard, 2013).

What this method offers is reduced risk of icicle formation in the middle of the rock cut. These icicle formations are very difficult to control by any other means. There is the possibility of grouting the rock cut, but that involves the risk of water pressure building up behind the rock cut, decreasing its stability and/or groundwater flowing up to the surface and over the top of the rock cut. That procedure will therefore not be recommended or discussed further. In areas where there are soils sensitive to sedimentations, it is not advised to drain the rock cut with this method as it lowers the groundwater table in area above the rock cut.

The drainage holes need to be protected from frost penetration. It is therefore advised that they are drilled low enough on the rock cut wall to be frost protected by water bearing back filling. This filling is required by Handbook 018 for reducing the risk of vehicles hitting the rock wall when going off the road. As the boreholes would be drilled behind this filling they will not have any effect of the appearance of the rock wall. The cost per meter of drilled drainage hole depends on the diameter. The most common diameter is 75mm. The depth of the boreholes is in proportion to the height of the rock cut. As the water flowing through the rock is very clean, it is considered highly unlikely that any maintenance will be required throughout the lifetime of the rock cut. The effect of the ice removal is dependent on the orientation of the main water bearing fractures.

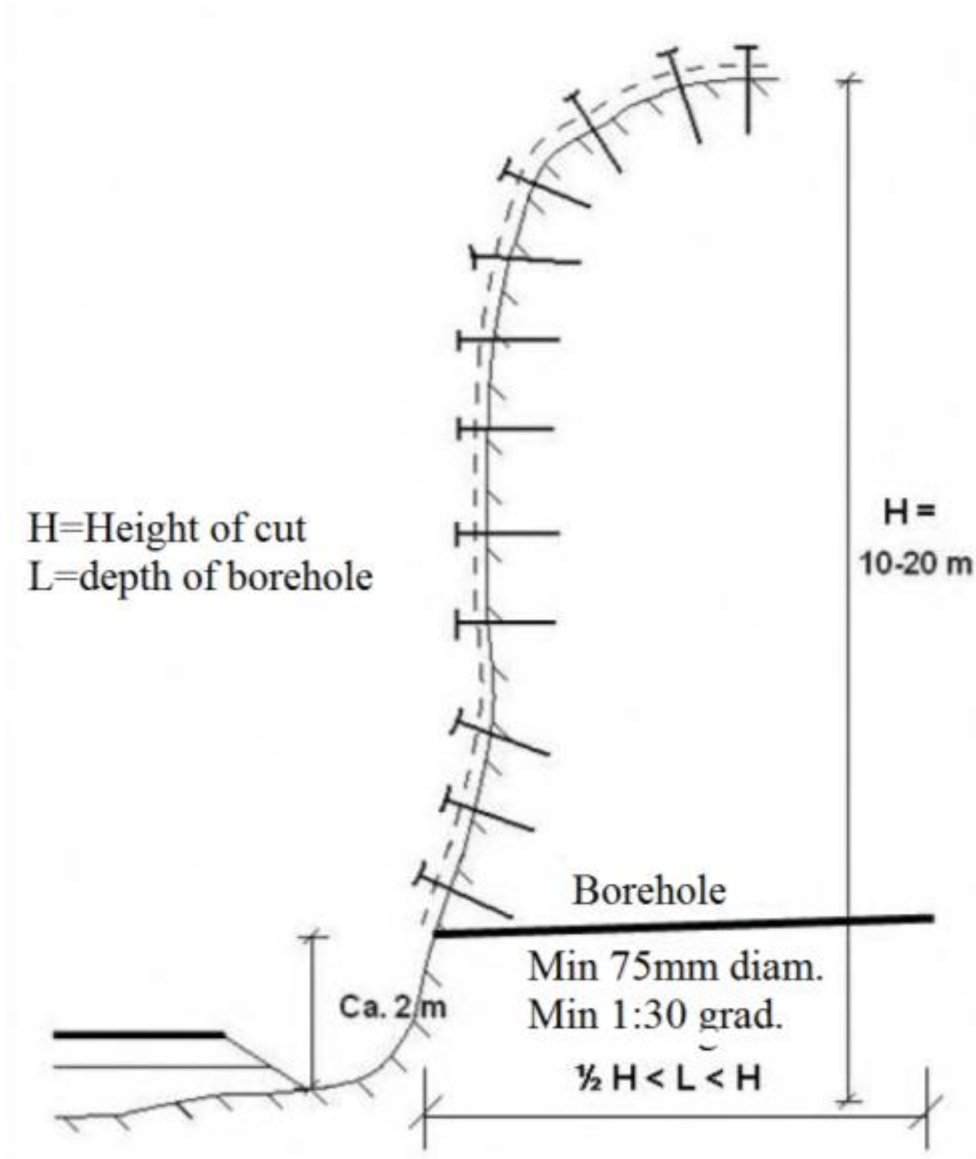

**Figure 28: Principle drawing of drainage holes for a rock cut that is over 10m high. In this drawing an ice net is also bolted to the rock face. This drawing does not take note of a typical cross section of a rock cut footing (Statens Vegvesen, 2011).**

### 4.6.2. Reducing risk of falling ice

Where preventing water to flow over the top of the rock cut proves for some reason to be either impossible or unfavourable, measures for preventing the fall of icicles onto nearby roads have been used. This includes ice nets, ice pins and wide trenches at the bottom of the rock cut. These procedures aim at making water freeze at controlled places. Iron is about 20 times better heat conductor than granite (Engineering Toolbox, n.d.) so it has proven to be very useful for this. In addition it is strong enough to withstand the heavy loads of accumulating ice.

#### *4.6.2.1 Ice net*

The risk of ice falling down is largest during thawing periods. When outdoor temperatures start to raise the heat from the rock causes the ice to lose its attachment to the rock face. To reduce this threat, ice nets are sometimes mounted on the outside of a rock wall. The nets have some offset from the wall itself so the ice does not accumulate on the surface of the rock, but on the net itself. This way water is able to flow behind the ice during thawing periods and the effects of frost weathering are reduced. In addition the risk of stone and ice falling down on the road is reduced.

This method has proven to have good results against ice fall. It does, however, not reduce the amount of ice which is formed over the winter period. Therefore the risk of ice fall is reduced but not eliminated. Furthermore the net has big effect on the aesthetics of the rock cut as the net is visible to all who pass it. In high rock cuts with big risk of ice formation, the weight of the ice load accelerates the need for maintenance. Any maintenance is likely to cause the road to be closed for traffic in one direction. The runoff from the ice net will include zinc from the galvanized iron in the ice net. If the galvanization is covered with PVC the zinc content will be minimized. It is important that all lose rock on the face of the rock cut is removed before the net is put up as falling rock will cause damage to the net and increase maintenance (Norem, 1998).

The cost of mounting an ice net is directly related to the surface area of the rock cut and the number of bolts needed to hold the net. The number of bolts advised is 0.4 per meter square. It’s normal to have the net ending 2 meters above the road, but where the side ditch is wider than 3 meters this height can be more. The net should be at a 20-30cm offset from the rock wall, and not more than 80-100cm.

**Figure 29: Mounting of rock safety net along Grimsrud road in Hurums municipality, Norway. The net is identical to the one used for securing ice (Royken og Hurums Avis. 2010).**

### *4.6.2.2. Ice bolts*

Bolts have been used for reducing risk of ice fall. They are drilled into the face of the rock cut in a pattern where ice is likely to accumulate. As the ice starts to form, it freezes stuck to the ice bolts. During thawing periods the ice bolts help maintaining the structure of the ice. As a result the ice stays up longer and smelts more before it can fall down at controlled places.

The ice bolt method has been used in an experiment project in Hordaland, northern Norway. The experience is that the method works well, but has few advantages over the ice net and more disadvantages. Furthermore, due to the amount of drilling needed, the cost of this securing approach is similar to mounting an ice net (Norem, 1998).

### *4.6.2.3. Side trenches*

According to the latest design manuals published by the NPRA, trenches by the foot of rock cuts are supposed to capture falling rock, ice and water (Statens Vegvesen, 2011). Where there is a risk of falling ice, these trenches can be made wider. In urban spaces, such as the study area of this report, the proximity to existing structures limits the possibility of extending these dig outs. When this approach is used, the scar made by the road construction in the landscape becomes bigger, so the local environmental impact of the rock cut increases. At the same time, the driving experience is improved, as the rock wall is moved further away from the road.

When rock cuts are made in steep terrain, every meter of road width has a big influence on the height of the cut. At the same time the cost of construction is increased considerably with a wider road bed. Moving the rock cut further away from the road may reduce expenses on extra safety measures, but the increased construction cost could easily out weight the solutions that are available. As water is allowed to flow uncontrolled over the edge of the cut, the weathering process of the rock cut will not be reduced and the risk of ice and rock fall is not reduced. In the event of lose rock or ice falling down the rock cut, the width of the side trench should be enough for preventing the rock reaching the road. For the side trenches to function when needed, it’s important that they are not filled with snow and ice during winter time or the thawing period.

#### *4.6.2.4. Physical ice removal*

Where ice has been allowed to accumulate without any attempts to decrease the ice mass, physical removal of the icicles has been used, see Figure 30. One might call this the zero-solution; that is, taking no action in the design process against the ice formation itself. This has been thought to be a practical solution where the rock cuts are not high and the traffic volumes are low. Closed lanes affect the traffic at the time of removal. The removal process usually takes place as late in the winter as possible, but before the ice starts to fall spontaneously. This is done so that the process does not need to be repeated due to new icicles (Berge, 2013).

The down sides of this method have already been highlighted in chapter *4.5. Problems Generally Associated with Ice on Rock Cuts,* as it involves allowing the ice to grow out of control but removing it at a time which is thought to be practical. Although the ice usually does not start to fall until the spring thawing, there is always the chance of temporary warm periods over the winter, which increased the risk of ice fall (Bjordal & Helle, 2011). Those responsible for the ice removal must therefore pay close attention to the ice formation throughout the winter period.

**Figure 30: Physical removal of ice in Kongsberg on the 8th of March 2013.**

# 5. Analysis of Design Proposal

An overview of the approaches currently practiced by the NPRA to keep control on ice fall shows that there are many options available and a lot of different solutions have been tried out. This gives hope for the possibility that NPRA's administrators are open for trying out new things when it comes to solving ice formation problems. Any new solution will have to have presented well for standing a chance against methods which have been used for many years with good results.

The designs for the study area are based on site visits, overview of literature and interviews with experts with experience of road construction. The results will be backed up with calculations from known theory, where possible, with assumptions drawn from site visits and recognized material properties. For achieving maximum safety for the bypassing trafficants, the proposed design proposal will aim at limiting the icicle formation as much as possible. As the water causing the icicle problem is believed to flow both in fractures in the bedrock and on top of the bedrock, the solution will be split in two separate features; a water transporting canal and drainage boreholes.

## 5.1. Ice growing from surface water

The icicles on the existing rock cut in the study area grow mostly from the top of the cut and down to the side ditch. This gives strong indication that the water which feeds the ice forming process flows on top of the surface. Even so, the water causing the ice problem is still believed to be mostly groundwater. One of the characteristics of groundwater flow is that the flow is steady throughout the year so there are no flow peaks. However, according to Handbook 018, the rock cut should be protected from the erosion of surface water, so surface runoff in the area should also be considered. There are two known creeks flowing from the terrain above the creek so these will have to be somehow led down the rock cut.

### 5.1.1. Terrain waterway

To screen off the water flowing on the boundary between the bedrock and the soil a water transporting canal along the top of the rock cut is proposed. According to NPRA's design manuals, it would have to start at the end of the 2m rock shelf above the cut. The most important feature of the canal is frost protection. In order for it to function throughout the winter season, the canal will have to be able to transport water down to lower ground before it freezes. The design manuals, the depth of drain trenches along roads should be 1.8m in the study area. Considering the proximity of the canal to the edge of the bedrock, and the thickness of the soil cover, this depth it thought to be unrealistic to achieve. That leaves the options of either insulating the canal or keeping it unfrozen with heating cables. As one of the goals of the design is to keep the operational and maintenance costs to minimum, the latter is not considered desirable. This leaves only insulation as a choice.

The depth of the soil cover varies along the rock cut. In some places it is through to be around 1m but in other the bedrock is visible. This makes the design of a homogenous cross section along the whole rock cut difficult. A more feasible solution would be to have one cross section for thin soil cover and another for places where there is little or none. The dimension of drainage canals along roads is somewhat governed by Handbook 018, but there are no clear instruction on what a canal on top of a road cut should look like, bar the fact that the bottom should be at least 0.5m wide and have a minimum slope of 10‰. The size of the canal will therefore be decided by the amount of surface runoff from a 25 year precipitation event.

#### 5.1.1.1. Open canal for surface runoff

The results of the rational formula returned a flood event of 200 l//s for the area which is believed to be causing the biggest icicle problem. The calculations are available in Appendix A. According to weather data, see chapter 4.3, the average annual rainfall amounts to about 10.7 $l/s/km^2$ or about 1.1 l/s/ha so this will be ignored in the 25 year flood dimension calculations. Due to topography of the terrain above the rock cut, the watershed can be split into 3 parts, which are just about equal in size. The waterways, which transport the water down the rock cut, would be placed fairly centrally within the watersheds to minimize total length of each canal.

After solving the rational formula and using the design parameters from Handbook 018, all the parameters for finding the area of the cross section of an open water canal, using the Manning’s formula, are available. The calculations are available in Appendix B. Assuming a rectangle shaped, half full canal with slope of 10‰ and bottom width of 0.5m the depth needs to be about 53cm to have a capacity of 200l/s. Given the same design parameters but a full canal, the depth would have to be about 45cm. As one of the main objective of the canal is to function throughout the winter, it will prove to be very difficult to make it frost prove an open with this deep, given the frost penetration lengths presented in chapter *2.7. Frost penetration.* Making the waterway deeper by blasting further down into the bedrock is unfeasible given the proximity of the drainage canal to the edge of the rock cut.

#### 5.1.1.2. Closed drainage canal

Is order to decrease the likelihood of the canal freezing during winter, it is advised that it should be filled up again with material which lets water through easily. The material of choice would be well sorted gravel or blasted rock. The capacity of the filling material in the canal is determined by Darcy’s law (Colorado Department of Transport, 2004), see chapter 2.3. As the main purpose of the canal is to capture water leaking through the soil, the conductivity of the filling material would have to be higher than it is in the soil the water comes from. The minimum difference of the conductivity of the filling material and the soil is dependent on the length of the canal. According to the maximum length of a filled canal within each of the three separated watersheds, about 160m, the conductivity of the filling material therefore needs to be about 7200 times higher than that of the soils. By comparing known hydraulic conductivity values of well sorted gravel (10 cm/s) to the conductivity of semi pervious, poor aquifer, which consists of silt, fine sand and peat (0.001 cm/s), this can be achieved (Fitts, 2002). The filling material would have capacity between 250-2500 l/s through the given cross section of the drainage canal. Again, the calculations can be seen in Appendix B.

Assuming that half the depth of the 50cm deep canal is in bedrock and the rest in soil, a fully soaked soil cover would leak about 0,75l/s/m into the canal. This accumulates to 120l/s in the 160m long canal. Supposing that a 25 year precipitation event occurs during these circumstances, adding 200l/s to the system, the canal would be overflown. This could possibly flush drainage material from the canal down the slope and over the edge of the rock cut. As the main purpose of the filling material is to prevent the water in the canal, which flows from the slow leaking soil, from freezing during the winter months, it is suggested that the canal is covered with a membrane which does not leak more than 0.5 l/s/m of canal, or 1 l/s/m$^2$, vertically. That way the surface runoff and the soil interflow would be separated, which would protect the filling material from being washed out during high intensity precipitation events. This could be achieved by adding a thin layer of soil on top of the drainage material in the canal, which would be protected with erosion secure material, such as laid out stones. With the infiltration capabilities of this layer, the surface water part of the canal would need to be about 30 cm deep, given that the infiltration layer is 50cm wide.

The filling material in the canal would have to be covered with geotextiles for prevent it from becoming filled with finer materials which reduce its capacity (Norem, 2012). In addition, the bottom of the canal would have to be made waterproof, for preventing the water from leaking into the bedrock and out to the rock cut. It can be expected that the bedrock will become somewhat fractured from blasting the canal.

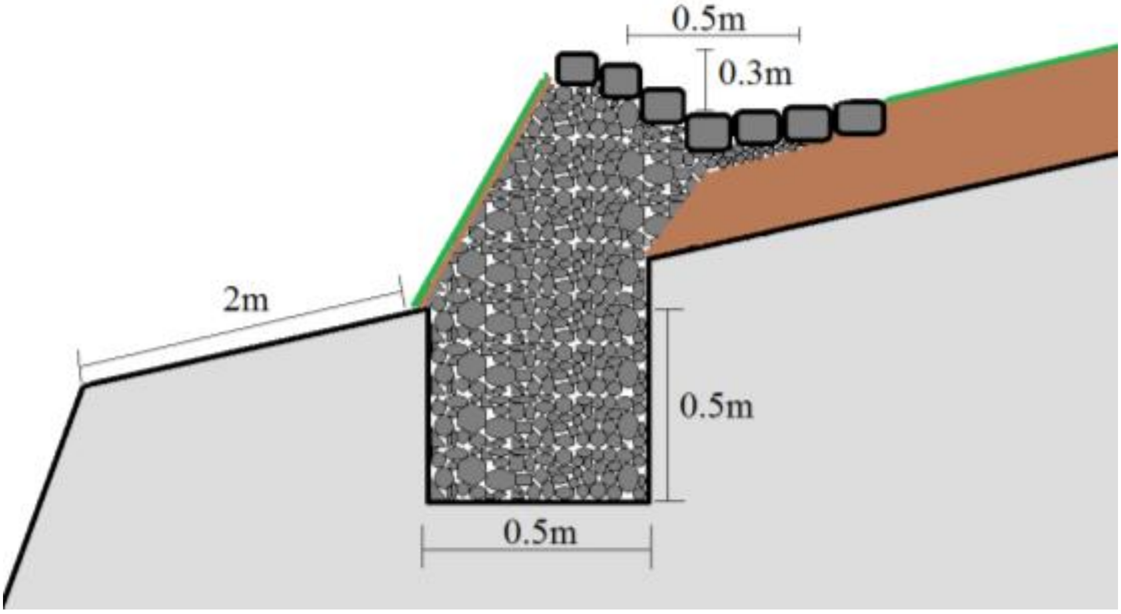

Figure 31: Proposed cross section of a closed drainage canal in the area where

### 5.1.2. Frost penetration

When evaluating whether the drainage canal will be functional during the winter period or not, one will have to calculate the frost penetration in the area. Handbook 018 does not present the frost penetration length, but does supply the thickness of material with different thermal properties needed to prevent frost heave in roads, including sand and gravel. According to Handbook 018, the thickness of the gravel layer would have to be 165cm to prevent frost heave in a road in Kongsberg. According to equation 13 this depth would be 94cm. Measurements conducted not that far away from the study area show a frost penetration depth of 102cm. Given the fact that the figures in Handbook 018 apply to a road with no soil or snow cover, and the insulation effect these layers have, the height of the filling material to the bottom of the canal is advised to have the minimum depth of 102cm.

### 5.1.3. Increased gradient of rock cut

In order to make up more space for the terrain canal between the railway and the top of the rock cut, it might be lucrative to increase the gradient of the wall from 3.5:1 to 10:1. Increasing the gradient will decrease the factor of safety of the rock wall. In order to assess the change, strike and dip in the area was registered and the stereonets plotted with the help appropriate software, *Dips*, see chapter 4.1. This software was used to find a slip fracture, which was used for worst case scenario stability calculations. This data was taken to software, called *Rockplane,* where a model of the rock cut was sketched up, using known geometry of the site. The factor of safety turned out to be 2.18 for the originally planned slope of the rock cut, but was decreased to 1.80 for the proposed 10:1 slope. That a decrease of around 17%. The FS is still acceptably high. The model used for calculation in Rockplane can be seen in Figure 32 and the results of a sensitivity analysis of the proposed rock cut slope in Figure 33.

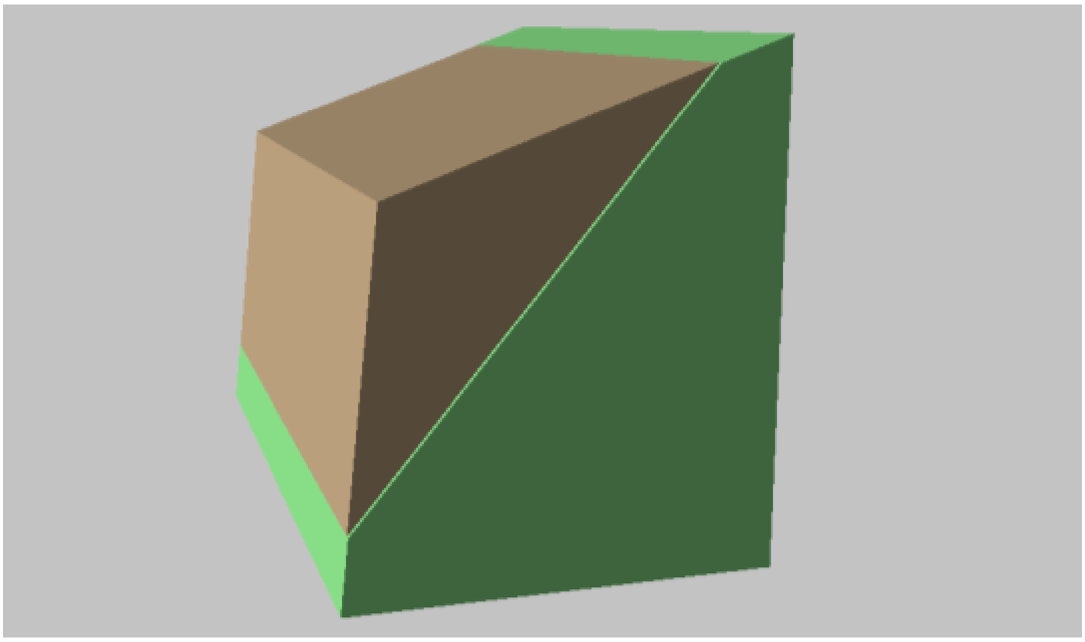

**Figure 32: A demonstration of the model used for stability calculations in *Rockplane*.**

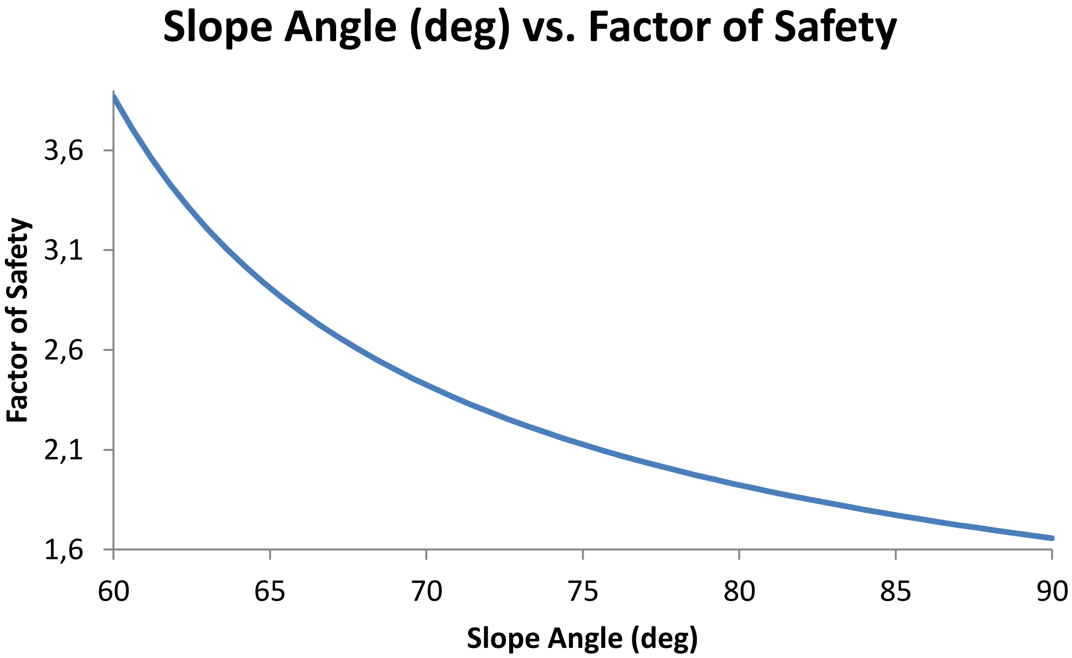

**Figure 33: Sensitivity analysis of the proposed slope angle of the rock cut. The FS for the 3.5:1 slope and 10:1 slope turned out to be 2.18 and 1.80, respectively.**

### 5.1.4. Transporting surface water down the rock cut

Since the planned rock cut is so long, it is impossible to lead the water running on in the terrain above it away from the top of the rock cut. It can, however, be moved down at controlled places. These places would be somewhat decided by the topography of the terrain between the railway and top of the rock cut, as well as the main water bearing areas. One should avoid transporting the water too far in a drainage canal as it increases the risk of water freezing in it; which would render it useless. The most common way for transporting water down a high rock cut is blasting a pocket into the rock wall, which dimensions take note of the trajectory of the waterfall as well as the risk of ice filling up the pockets during winter.

#### *5.1.4.1 Blasted pockets*

Blasting extra space into the rock for transporting water down rock cuts is a common method used in Norway (Norem, 1998). For this method to work, one must first collect the water above the rock cut and divert it to these pockets, see Figure 34. The depth of the pocket is a function of velocity of the water running over its top, the angle of the top edge and the height of the rock cut, see formula X. All these parameters are fairly stable for a given location of the pocket, bar the velocity of the water. One can manipulate the trajectory a bit by changing the top slope of the pocket before the water runs over the edge; the steeper the angle the shorter the offset at which the water lands at. When calculating the depth of a pocket, one must remember to take into account for the slope of the rock wall itself and subtract it from the resulting L.

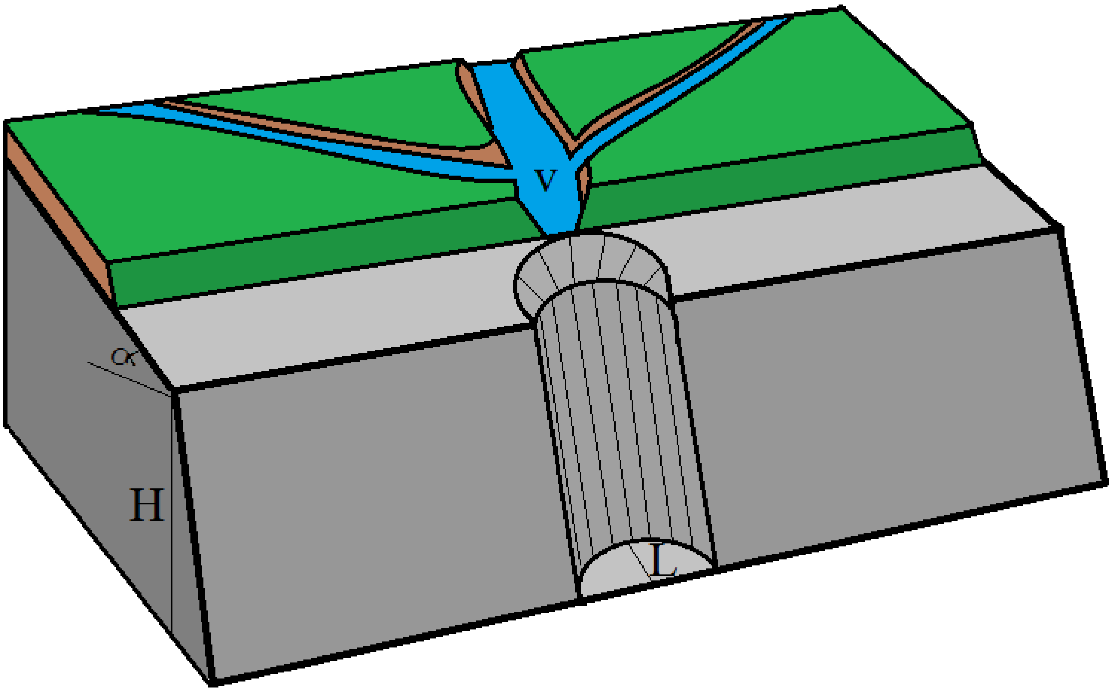

**Figure 34: An illustration of what a blasted pocket would look like. Its purpose is to transfer water down the rock wall there so that there is control on erosion and ice caused by the water flow.**

As the velocity is a bit unknown a sensitivity study of the distance the water travels in the air at different initial velocity was conducted. In addition different trajectory angles were taken into account and different slopes of the rock wall. A common height of the rock cut, 10m, was used. It might seem more likely that the pockets would be made where the height is less. The results can be found in Figure 35. It can be seen how the distance from the rock wall can be decreased with a steeper trajectory angle. The slope of the rock cut does not affect the trajectory of the water, but affects how far the water travels in air before hitting the ground, if the speeds are low enough. In other words; a flow of 1 m/s would flow on the rock face of a 3.5:1 slope about half the height of the slope, but if the slope was 10:1 it would hit the surface about 1m away from the footing of the slope, missing the rock wall all together.

The steeper the slope the more kinetic energy the water has when it hits the ground. This will result in erosion and might cause problems in the lifetime of the road if not dealt with right away. With a gentler slope the rock surface that the water is in contact with is bigger, resulting in more risk of the water freezing. The will cause other kind of erosion which over time also causes problems.

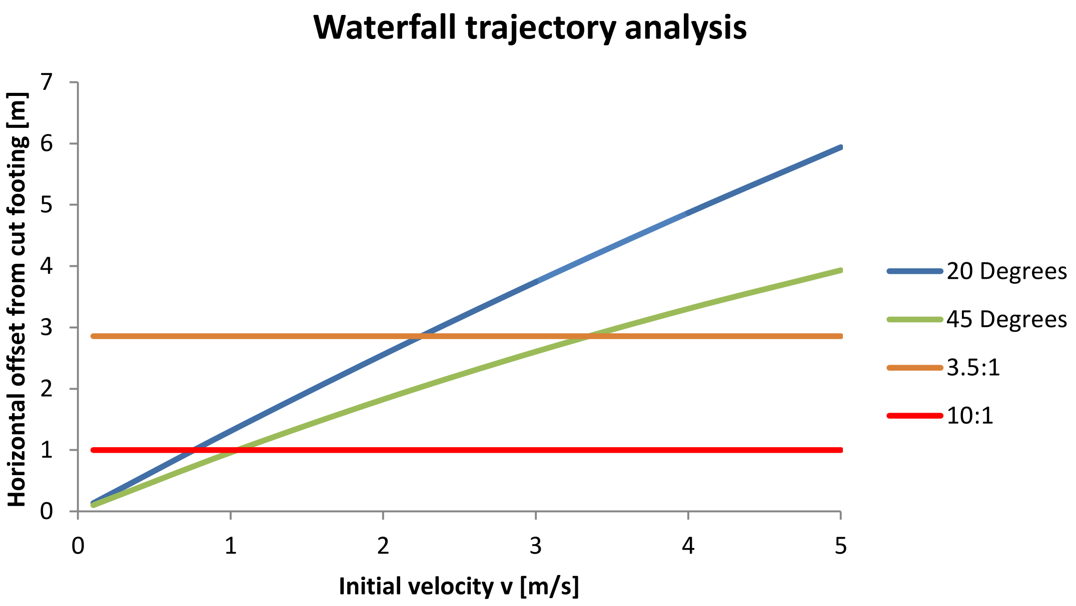

**Figure 35: Analysis of how far from the rock cut's footing a waterfall lands different initial velocities and downward angles. The analysis was done with a 10m high rock cut (blue) and a one 10m high (green).**

Using the flow in the suggested near rectangular drainage canal during a 25 year precipitation event, flow velocity up to 1 m/s. can be anticipated in the canal leading to the blasted pocket. If the angle on the edge of the pocket is somewhat steeper than the canal, then this number could be increased somewhat. Assuming that the velocity of the water would stay the same, due to spreading out over a larger area, the offset would be

1m for a 45º downward angle and 1.3m for a 20º initial angle. This means that for a 10:1 slope wall, some sort of energy dampening measures should be taken. The pocket should therefore be at least 1m deep, but given the fact that the ice on the existing rock cut around 1m thick, it is suggested that an extra meter is added to the depth to account for the ice.

#### *5.1.4.2. Drilled vertical pipe*

Drilling tunnels in rock for transporting water to hydropower plants is a well-known method for transporting water in elevated landscape to lower ground. This method has, however, not been known to be used in road construction for the same purpose. This is, however, well possible for transporting small creeks or leakage water down rock cuts in frost free environment. It might be difficult to maintain such a pipe, especially if it was to transport surface water. If it was, however, only meant to transport leakage water during winter time, it would be highly unlikely that it would get clogged by debris. Such a pipe would have to be drilled from the bottom of the drainage canal and at a near vertical angle downward. The hole could be drilled straight down and out of the rock wall, but that would increase the risk of the water in the pipe freezing during winter. Instead, another hole could be drilled upwards from the bottom of the rock cut, which would connect to the near vertical one. The latter hole could be drilled under the level of the back filling material to increase frost protection.

The downside of such a solution is that it’s difficult to maintain, or provide, enough capacity to deal with surface runoff with a single hole. Rough calculation, which can be seen in Appendix B, shows that capacity of a 168mm hole would be around 126 l/s. It is therefore able to handle a fully soaked top soil situation. The hole is, however, nowhere near capable of handling the expected 25 year precipitation event within the watershed. This solution would therefore require either multiple drilled pipes or some sort of overflow. Given the fact that the profile of the terrain above the rock cut is relatively uneven, and that it’s not feasible to make deep blasted canals close to the edge of the cut to create desired minimum slope of a drainage canal, it might be lucrative to drill numerous smaller dimension pipes in local depressions.

## 5.2. Ice growing from groundwater

Water transporting terrain canals, such as the ones described in chapter 7.1. are meant to capture water in and on top of soil and will not affect water flowing in fractures in the bedrock. It’s difficult to map where water can be expected to flow in fractures in the bedrock before the rock cut is blasted. One can still get some indications from the wet spots in the terrain, which were mentioned earlier. For prevention ice from growing from groundwater emerging from fractures, it is however suggested that such measures are taken after the cut is ready. Water in the bedrock does not only present risk of frost damages on the rock or falling ice, but reduces the overall stability of the rock cut due to water pressure and decreased friction in between fracture surfaces.

### 5.2.1. Drainage holes

Theim's solution for calculation the groundwater table draw down.

To transport the water running in fracture inside the bedrock making up the rock cut out at controlled places, it is suggested that drainage holes are drilled from the bottom of the rock cut at an upward angle. This is a known method for draining rock cuts that have been stabilized with shotcrete, see chapter 6.1.1.2. The purpose of these holes is to capture the water running in fractures and lead the water out of the bedrock in a way that it does not freeze. For this to be possible, the drainage holes will have to be drilled under the back filling at the bottom of the rock cut. The diameter of the drainage hole plays a big role in its effect.

### 5.2.2. Effects of groundwater on stability

When water is flowing in fractures in rock, there is always the possibility that the water bearing fissures become tight. This can for example happen during winter when the rock freezes so that no water is able to flow out. When this happens force is applied to the back of the rock cut by the accumulating water, decreasing the stability of the face of the cut. A sensitivity analysis was conducted to see the effects of water in fractures on the stability a 10:1 cut and 3.5:1 cut, with the maximum pressure applied at the toe and in the middle of the slope. The same model as was presented in chapter 5.1.2. was used. The results can be seen in Figure 36.

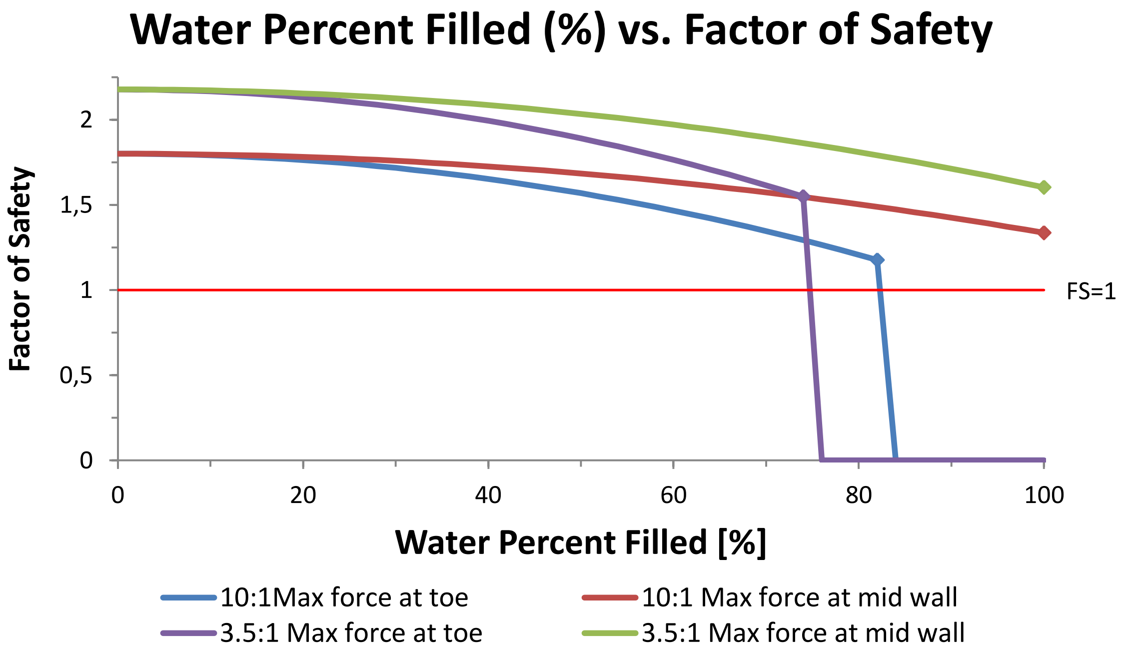

**Figure 36: Results from a sensitivity analysis for effect of water content in fractures on the stability of the rock cut.**

As was to be expected, the lowest factor of safety was achieved during when the water pressure was applied at the toe. What was a bit surprising what that it takes more water content to cause failure at in the 10:1 cut than in the 3.5:1 when the water pressure is applied at the toe, even though the FS is higher for the 3.5 slope until it fails. The 3.5 slope fails with 74% water content but the 10:1 with 82%. Neither slope fails when the water force is applied at the middle of the cut. These results show how important it is to keep the bottom surface of the rock cut drained throughout the winter season.

## 5.3. Weathering

Maintenance costs and overall stability of a rock cut is highly dependent on the erosion forces of weathering. Erosion by running water has a big impact, but frost damages play the biggest role. The expansion force of ice growing in confined spaces can easily fracture sound rock or tip over lose blocks. By limiting the water which has access to fractures or the surface of the rock wall, these effects are limited and the lifetime operation costs of the construction are limited.

## 5.4. Aesthetics

Since the rock cut is construction in the middle of urbanized area, there is some concern about how it will fit into its environment and the overall impression not only for those who drive by but also those who see it from their homes. The suggested solution to the icicle problem is not likely to have a big impact on the aesthetics of the rock cut. The largest effect will be the increased gradient of the face of the wall, which has to be considered somewhat negative. The canal on top of the slope is not likely to be very visual from afar, especially if the filling material is covered with soil. The drainage holes drilled from the bottom of the cut would never be seen after the construction is finished.

# 6. Discussion

Analysis of the proposed solutions shows that there is a lot to consider when choosing a solution to the icicles problem. The proposed techniques do not have any considerably big disadvantages from a theoretical point of view. It is difficult to account for the effects on frost on the drainage canal during winter. It does appear that the water will be flowing above frost line, but concentrating the water flow in the terrain to a single canal might produce enough flow velocity to counter the effects of the frost.

There are a lot of ways to deal with the icicle problem. Chapter 4.6 highlights methods which have been used in the past by NPRA to solve problems related to icicles on rock cuts. For comparing these solutions, one has to decide what is expected of the support structure. The most important factors were chosen to be, in this order: Security for bypassing traffic, operation and maintenance costs, negative effects on surrounding constructions, erection cost, environmental impact and negative aesthetics. The weight of these factors can vary from project to project. Aesthetics play, for example, bigger role in urban environment than they do in rural area. Each factor was given a grade from 0 – 3.

Each of the solutions mentioned earlier was given a grade based on impression from literature and experience. No direct research was done, such as statistical analysis of safety or direct cost. If statistics would be collected for these factors, then a matrix guide such as this one would become a powerful tool in finding the solution which fits each individual project. The results for this project can be seen in Table 4.

**Table 4: Here is an evaluation of the possible solutions to the icicle problem in Kongsberg. Each category was given a grade from 0-3. The lower the value in the Result column the better the solution is.**

| | Start cost | Operation and maintenance | Lack of Security | Negative Aesthetics | Emvironm. Impact | Effects on surrounding structures | Result |
|---|---|---|---|---|---|---|---|
| Factor | 0.75 | 1.5 | 2 | 0.5 | 0.6 | 1 | |
| Zero-solution | 0 | 3 | 3 | 2 | 0 | 0 | 11.5 |
| Ice net | 2 | 2 | 1 | 3 | 1 | 0 | 8.6 |
| Drain Holes | 2 | 0 | 1 | 0 | 2 | 1 | 5.7 |
| Ice fence | 1 | 2 | 3 | 2 | 1 | 0 | 11.35 |
| Wall | 3 | 2 | 0 | 2 | 0 | 0 | 6.25 |
| Canal | 3 | 1 | 0 | 1 | 1 | 0 | 4.85 |
| Wider trench | 3 | 1 | 1 | 0 | 1 | 0 | 6.35 |
| Ice bolts | 1 | 1 | 2 | 1 | 1 | 0 | 7.35 |
| Warm cables | 2 | 2 | 0 | 1 | 2 | 0 | 6.2 |

The grades and weight of the factors were chosen from as unbiased perspective as possible. The results still show that the solutions which fit best to this project are a canal on top of the cut and the drainage holes. Other solutions which score a good grade are the wider side trenches and warm cables.

# 7. Conclusions

Icicles hanging over or around roads pose a lot of threat to passing traffic. In Tislegård, Kongsberg, this has been a problem for a long time. Physical removal of the icicles is used to counter the problem. The ice was removed on the 7th of March during the winter 2012-2013 and the process took around 5 hours. During the removal the traffic was controlled by the contractor, which did the removal, as one lane of two was completely closed. When the existing road will be expanded to a four lane road, the space the new construction requires forces the rock cuts along the road to become significantly higher and longer. In addition to significantly increased traffic, the height of the rock cuts and change in the layout of the road will make physical removal a very unfeasible option in the future.

For replacing the current method used to counter the ice problem, preventative actions are proposed, which aim at stopping the icicles from forming on the rock wall all together. Based on observations made in the study area, it has been concluded that the ice is formed both from re-emerging groundwater, which flows on the surface and over the edge of the cut, and water which flows out through fractures in the rock wall. The countermeasures are therefore based on screening off the surface water from the rock wall with a shallow canal, which would have to be blasted into the bedrock. For preventing the water transported in the canal from freezing, it would have to be filled with well graded gravel. For preventing water from flowing out through fractures in the rock wall, one would have to drill drainage holes from the bottom of the cut which penetrate the water bearing fissures.

Increasing the gradient of the slope to 1:10, to gain increase the distance between the top of the cut and the nearby railway reduces the stability of the cut by 17%, from a FS of 2.18 to 1.80. This is considered acceptable. In addition to decreasing the risk which falling ice poses to bypassing traffic, the proposed design also increases the critical stability of the structure by reducing the amount of water in fractures. Furthermore, since less water will be dripping down the wall, frost weathering and water erosion will be reduced as well.

For solving icicle issues on rock cuts, attacking the source of the problem is considered the best option. Limiting taking control of the water flowing in the terrain above the cuts and transporting it to lower ground at safe places is advised as best practice for limiting maintenance costs and maximizing security for bypassing traffic.

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# Appendix A: Calculations of Surface Runoff

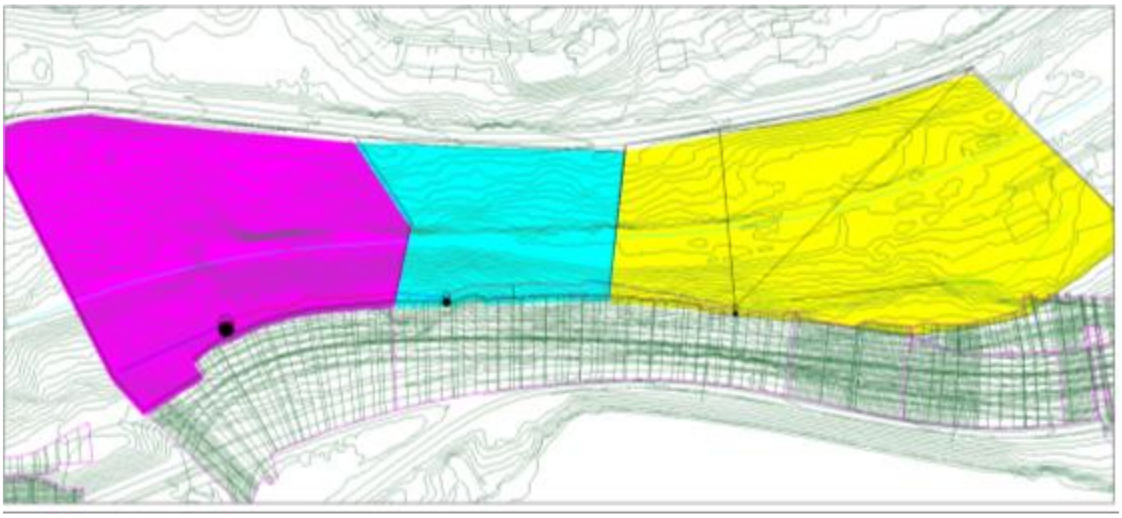


**Figure 37: The watershed which is most critical is here shown in yellow colour. The black circles are low points in the watersheds, suggested for transferring the water down the rock cut.**

The yellow area in Figure 37 is used to solve formula 4:

$$t_c = 0.6 * L * H^{-0.5} + 3000 * A_{se}$$
$$t_c = 0.6 * 146 * \frac{1}{\sqrt{22}} + 0$$
$$t_c = 18.67min$$

This time is then used for finding the intensity in the table for an event with 25 year return period.

**Table 5: Return periods and precipitation intensities from a weather station nearby. Data is in l/s/ha.**

| year | 1 min. | 2 min. | 3 min. | 5 min. | 10 min. | 15 min. | 20 min. |
|---|---|---|---|---|---|---|---|
| 2 | 240.8 | 203.6 | 181.6 | 155.1 | 116.4 | 92.2 | 76.5 |
| 5 | 297.7 | 256.9 | 232.3 | 199.9 | 158.9 | 126.4 | 103.4 |
| 10 | 335.3 | 292.2 | 265.9 | 229.6 | 187 | 149 | 121.2 |
| 20 | 371.4 | 326.1 | 298.2 | 258.1 | 214 | 170.7 | 138.3 |
| 25 | 382.9 | 336.8 | 308.4 | 267.1 | 222.6 | 177.6 | 143.7 |
| 50 | 418.2 | 369.9 | 339.9 | 294.9 | 249 | 198.8 | 160.4 |
| 100 | 453.2 | 402.8 | 371.2 | 322.5 | 275.2 | 219.9 | 177 |
| 200 | 498 | 440.5 | 407 | 353.1 | 302.5 | 240.6 | 192.7 |

Interpolation shows that the precipitation intensity is 168.6 l/s/ha. This result is used to solve equation (3), the rational formula:

$$Q = C * i * A * K_f$$
$$Q = 0.5 * 168.6 * 1.7 * 1.4$$
$$Q = 200.6 l/s$$

# Appendix B: Calculations for Canal Dimensions

## Manning's equation

For calculating the dimension of the open canal, manning's equation was used for calculating the minimum cross section area for a full canal with capacity of 200l/s. The design guide says that the bottom of the canal should be at least 0.5m wide, and that the minimum slope is 10‰:

$$Q = M * A * R^{\frac{2}{3}} * I^{\frac{1}{2}}$$

$$200 = 30 * 0.5 * x * \left(\frac{0.5 * x}{0.5 + 2 * x}\right)^{\frac{2}{3}} * 0.1 * 1000$$

$$x = 0.45$$

So the minimum depth of the canal is 45cm.

Similar calculations were done for a pipe, but then A becomes $\pi * r^2$ and the surface diameter $2 * r * \pi$ and r is the unknown.

## Darcy's law

Darcy's law was used to calculate the maximum water which would leak through the soil into the drainage canal. The capacity of the filling material was calculated with K=10 cm/s and 100cm/s and for the soil 0.001cm/s.

$$Q = A * K * i$$

$$Q = (50 * 50) * 10 * 0.1$$

$$Q = 250 \frac{cm^3}{s} = 250 l/s$$

K=100 returns 2500l/s. It is therefore obvious that the capacity of the canal is not limited by the filling material but by its dimensions.

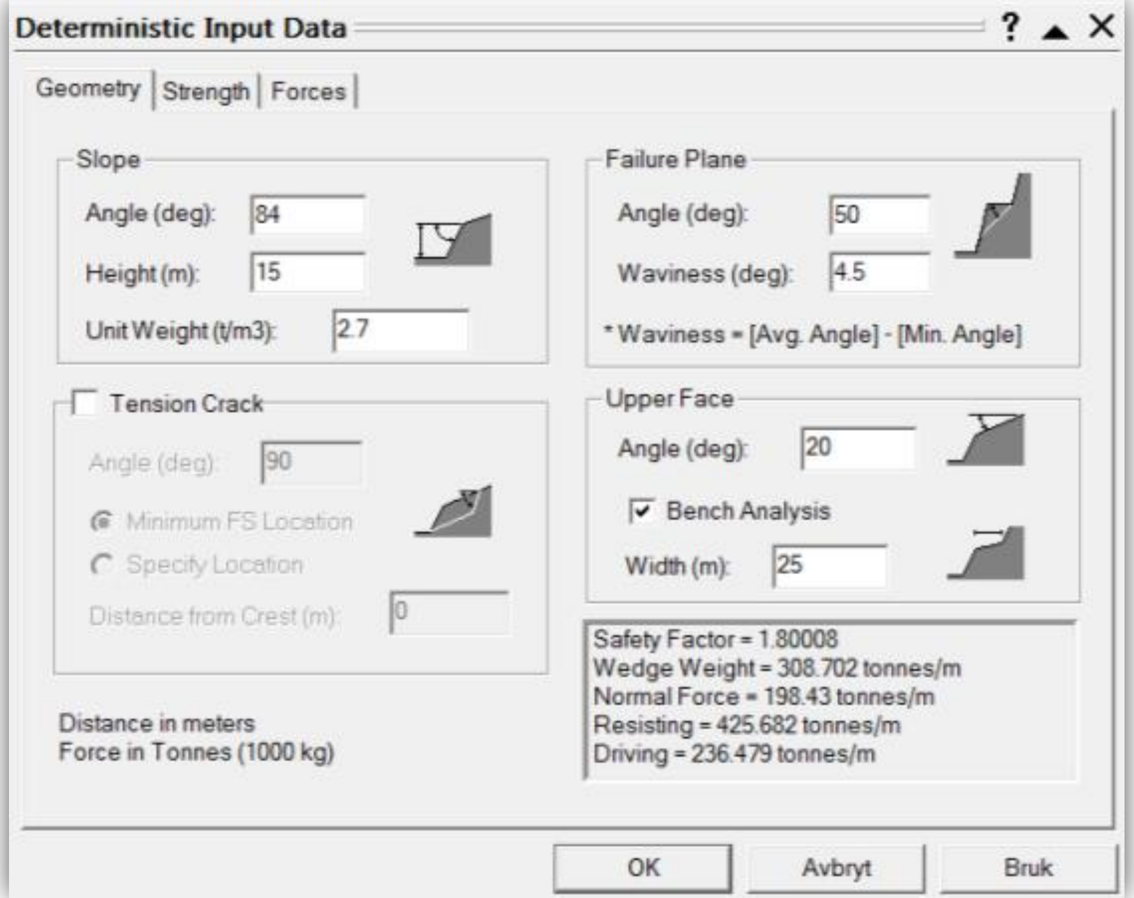
Same calculations were conducted for the soil, but this the cross section is the total length of the canal and depth of the soil and with slope of the terrain:

$$Q = (25 * 16000) * 0.001 * 0.3$$

$$Q = 120 \frac{cm^3}{s} = 120 l/s$$

# Appendix C: Input data for stability calculations.

Rocscience was used to calculate the stability of the rock cut. The input for the program can be seen in Figure 38.



Slope
Angle (deg): 84
Height (m): 15
Unit Weight (t/m3): 2.7

☐ Tension Crack
Angle (deg): 90
● Minimum FS Location
○ Specify Location
Distance from Crest (m): 0

Failure Plane
Angle (deg): 50
Waviness (deg): 4.5
* Waviness = [Avg. Angle] - [Min. Angle]

Upper Face
Angle (deg): 20
☑ Bench Analysis
Width (m): 25

Safety Factor = 1.80008
Wedge Weight = 308.702 tonnes/m
Normal Force = 198.43 tonnes/m
Resisting = 425.682 tonnes/m
Driving = 236.479 tonnes/m

Distance in meters
Force in Tonnes (1000 kg)

**Figure 38: Input data in Rockslope for a 10:1 rock cut. For a 3.5:1 rock cut the input data was the same, but the slope angle was decreased to 74º. That change resulted in a factor of safety of 2.18.**