# Modelling life time costs of maintenance in hard rock tunnels

## Using spreadsheet as a modelling tool

*Master of Science Thesis in the Master's programme Geo and Water Engineering*

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Master's Thesis 2012:134

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Cover:
Borehole in shotcrete covered rock with groundwater flowing. Photo: Johan Thörn

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## ABSTRACT

Calculation of the total life time cost for different technical alternatives, maintenance options and way of uses is required for all kinds of products. Rock tunnels are one of them, and if the life time cost can be estimated different technical solutions can be compared, and the best alternative can be selected. However, very little work regarding LCC analyses and rock tunnels in infrastructure projects has been performed - a fact that initiated this project.

This thesis is a first attempt to build a model in which the total life cost of tunnel maintenance can be estimated, focused on the tunnel structure. It includes the most common reinforcement types and water controlling methods in Scandinavia, together with suggestions of maintenance frequencies and costs. Section 3 in this report give a general review of the basic reinforcement and water control methods used in the construction of tunnels in Scandinavia, followed by an introduction to the life cycle cost and the interpretation of it in the model.

The model is constructed with Microsoft Excel as a basis, which is broadly used and widely available software. To get a copy of the model contact the author via email at sebastian.almfeldt@gmail.com.

Key words: LCC, LCC of tunnel maintenance, tunnel maintenance

En modell för beräkning av livscykelkostnaden för underhåll av tunnlar i hårt berg
Med kalkylprogram som modelleringsverktyg
*Examensarbete inom Mastersprogrammet Geo and Water Engineering*
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## SAMMANFATTNING

Det här examensarbetet som är utfört på avdelningen för Geologi och Geoteknik på Chalmers tekniska högskola i Göteborg under 2010 och 2011 presenterar en livscykelanalysmodell för bergförstärkningar med avseende på kostnad och livstid.

Syftet med en livscykelanalysmodell för bergförstärkningar är att bergbyggare skall kunna välja det ekonomiskt mest lönsamma alternativet med avseende på underhåll och livslängd hos den använda förstärkningsmetoden. Genom att ange vilken typ och vilken omfattning av förstärkning som har använts eller kommer att användas i det aktuella studieobjektet (exempelvis en tunnel) kan de totala livstidskostnaderna för olika förstärkningsalternativ utvärderas och utifrån detta kan det lämpligaste alternativet och/eller underhållsintervall väljas.

För att utföra de exempelberäkningar som återfinns i rapporten har erfarenheter från bland annat rapportserien ”Underhåll av berganläggningar” (Lindblom, 2009) använts som ingångsdata. Livscykelkostnadsanalysen är konstruerad i linje med hur ordinarie livscykelanalyser byggs upp, där kostnader för olika delar i systemet och deras återkomster summeras. Hänsyn tas även till inflation (behöver uppskattas) och ränta (även detta måste uppskattas).

Resultatet av studien är en modell baserad på Microsofts Excel, ett kalkylprogram som finns på de flesta datorer idag. Modellen kan användas för att, ur ett LCC-perspektiv, utvärdera konsekvensen av olika alternativa förstärkningsförslag, där en del standardmetoder för bergförstärkning, så som dräner, sprutbetong och bergbult är angivna, men modellen bjuder på stora möjligheter till förändring och tillägg av egna metoder.

Modellen som presenteras i den här rapporten är en grund för vidare utveckling där de värden som används noga behöver övervägas för att ge realistiska resultat, men modellen kan svara på huruvida ett alternativ är mer lönsamt än ett annat, och när det blir lönsamt.

Nyckelord: LCC, LCC av tunnelunderhåll, tunnelunderhåll

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# Preface

Supervisor for this thesis has been Lars-Olof Dahlström at NCC Teknik (adj. Prof. CTH) and Ulf Lidblom, professor emeritus, former professor at Chalmers University of Technology. The examiner was Gunnar Gustafson, professor at Chalmers University of Technology who sadly passed away during the thesis work. Assistant professor Lars O Ericsson became the new examiner for this thesis.

This master thesis project was initiated of and suggested to me by Ulf Lindblom, with intended use for further research.

Göteborg 2012

Sebastian Almfeldt

# Notations

## Roman letters

| | | |
|---|---|---|
| C-C | (m) | Distance between two points |
| $I$ | (SEK) | Cost of investment for all components at construction |
| $I_x$ | (SEK) | Cost of investment for component x at time t=0 |
| $K_x$ | (SEK) | Net present value of future maintenance of component x from time t=0 to t=n |
| $k_{xt}$ | (SEK) | Cost of maintenance of component x at time=t |
| $r$ | (%) | Discount rate |
| $R_t$ | | Cash net flow at current time |
| $S_t$ | (SEK) | Net present value of future stoppage due to inspection, maintenance and incidents |
| $s_t$ | (SEK) | Cost of stoppage t years after start of usage |
| $t$ | (years) | Time of cash flow |

## Greek letters

| | | |
|---|---|---|
| $\beta_x$ | | Capitalisation factor. Depends on interest and inflation |

## Abbreviations

| | |
|---|---|
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Cost |
| LCP | Life Cycle Profit |
| NPV | Net Present Value |
| SEK | Swedish krona |
| W/C | Water-cement ratio |

# 1 Introduction

## 1.1 Background

Construction of rock tunnels generates a long-term maintenance responsibility and the capitalized value of the future maintenance may even be larger than the construction cost itself. Therefore the maintenance cost in a lifetime perspective should be acknowledged in an early stage in the development of a tunnel project. Lack of resources for maintenance can at worst lead to reduced service life and reduced safety for a tunnel. The maintenance must be planned so that the proper function of the tunnel is ensured throughout the operating time at minimum cost.

By estimating the technical lifetime of maintenance intensive parts in a tunnel, the maintenance frequency may be predicted and therefore also the cost of maintaining the tunnels operation over time. The technical lifetime can be obtained by analysing the processes that break down shotcrete, concrete constructions, bolts, drains and grouting in a tunnel.

## 1.2 Objective and scope of the study

The aim of this study is to:

- Develop a generic LCC (Life Cycle Cost)-model to be suitable for tunnel maintenance
- Determine what kind of data should be used as input and what quality is needed
- Describe how data from surveys should be interpreted and transformed into usable LCC input data
- To present the result from the LCC in a proper and lucid manner

## 1.3 Limitations

This thesis will deal with LCC analysis of maintenance including the following structural rock tunnel reinforcements and measures for water control: the rock itself, scaling (removal of loose rock or sprayed concrete), bolts, drains, sprayed concrete and grouting with respect to material and labour cost, but will also take into account interest costs and net present value. If the tunnel is used for transportation with any kind of vehicle the cost for temporary stoppage during maintenance is a large part of the life time cost. It will be exemplified, but is not included in the model (mainly due to the complexity to calculate these costs correctly). Other important parts to sustain a tunnels function, such as infiltration to sustain groundwater pressure will not be included nor will installations in the tunnel such as pipes, pumps, cables or roads. Neither will the environmental impact (which is often an objective in combination with LCC analysis) be touched upon.

# 2 Previous works regarding LCC and tunnel maintenance

There is a lot written about Life Cycle Costing, but at a first glimpse not much seems to be related to tunnelling. However, one contributor in this area is Statens Vegvesen (the Norwegian road administration) which has made research in this area. A summary can be found in *Publikasjon nr. 97* (Statens Vegvesen, 2001). In this publication Statens Vegvesen has developed a LCC model for the purpose of optimizing tunnelling management and maintenance. They have also made a LCP (Life Cycle Profit) model. However, the focus in their study has been on installations and not the reinforcements used in the tunnel.

According to *Internrapport 2158* and *Internrapport 2178* (Statens Vegvesen, 2000) the LCC model actually is up and running. The model is using Microsoft Excel as a base. In *Internrapport 2178* an image of what the model in Excel looks like can be found. This is further developed in *Internrapport 2224* (Statens Vegvesen, 2001), in which the final model is reported. But still, this model calculates a LCC for the management and maintenance of installations in the tunnel rather than the actual support structures and measures for water control.

So far analyses for management and maintenance of installations inside the tunnel seems to be well covered, and Statens Vegvesen actually has a model that calculates the LCC and gives advice on which decision should be made to get the most quality for the least money.

In *Drift, underhåll och reparation av trafiktunnlar*, (Ansell *et al., 2006)* suggests that more work should be done regarding data fitting into a LCC model. The report identifies the problem as lack of quality data; a suitable method for LCC calculations is available, i.e. the same models as used when calculating other LCC costs. Ansell *et al.* (2006) also made an extensive literature review. And the most relevant section, in respect to this study, is to be found in chapter 10.3.1 in the publication.

In Silwferbrand (1999) the difference between passive and active maintenance is defined, and from this definition it is clear that active maintenance should be used in combination with a LCC analysis. Active maintenance can be explained as “doing the maintenance when there is a need for it” rather than “doing maintenance with a certain frequency without knowing the actual need”, which is more like passive maintenance.

In Lindqvist *et al.* (1999) the reader is introduced to Life Cycle Costing and railway tunnelling. The work is a compilation of how LCC could and should be used to determine the most favourable alternative when building and maintaining a railway tunnel. The (pre)study is more of a guideline of how to think rather than a practical manual. The study also points out the need for correct and plentiful data.

# 3 Tunnel support, sealing and their need for maintenance

A reinforcement system in a tunnel contains several parts and the purpose of it is to install different structural elements to ashore the structural integrity of the rock around the tunnel. The main structural element is the rock itself, but bolts and sprayed concrete is installed to assist the rock acting as the load bearing element. These reinforcements also prevents block from falling in the tunnel, and to prevent degradation and possible collapse. Pre or post grouting is used to seal the tunnel from inflowing groundwater as far as possible. In extreme poor condition or in soft ground condition grouting may also be used for temporary stabilization. The pre grouting aims to seal fractures before blasting and post grouting is used to seal fractures after blasting (this is often fractures that didn't get sealed during the pre-grouting phase). If groundwater still flows into the tunnel drains can be used to divert the groundwater into a sewer system where pumps evacuate the water out of the tunnel. The collected groundwater might be used for infiltration to recover a lowered groundwater level in the ground surrounding the tunnel (Lindblom, 2010).

The most common structural support elements in Scandinavia except the rock itself are rock bolts and sprayed concrete (unreinforced or reinforced with steel fibre). At occasion, at extremely difficult ground conditions, concrete or steel structures (pillars and arches) are used. The purpose of the rock bolt is to anchor rock wedges in the firm rock and prevent them from falling out from the tunnel wall or roof in the firm rock behind. Alternatively in poor rock condition, the bolts are installed in a pattern in order to, together with the rock, form a structural element. The needed distance between the bolts can be calculated when the spacing and directions of fractures when the fracture system are known (Lindblom, 2010).

Shotcrete is a layer of concrete that is sprayed or shot at the bare rock surface with high pressure. Often reinforcements are added to the concrete in form of steel fibres or as ordinary concrete steel bars or net that is formed in advance and coated with the shotcrete. The concrete shell that is formed shall be resistant to take the load (from punching) for a rock block of defined size. Important parameters are material strength, thickness and adhesion (Lindblom, 2010).

## 3.1 Prevent groundwater flow into the tunnel

There is reason to believe that a tunnel completely free from water is the tunnel with the least need for tunnel maintenance. Experienced tunnel owners and maintainers agree that this is the case – inflowing groundwater is always a problem and it leads to more problems, according to Blixt[1]. Such problems are for example dealing with the water volumes, corrosion of support elements and installations, and formation of icicles, which is a great risk in traffic tunnels.

To seal the tunnel from inflowing groundwater, grouting is usually used. To take care of remaining water that has not been successfully blocked by the grouting, drains can be used. A drain is a hollow space where water can flow and drain into the tunnel drain system preventing water to pour or drip into the tunnel and on tunnel installations. The drains are often insulated to prevent formation of ice flows and icicles that can ruin installations, damage vehicles and obstruct traffic. The drain can typically consist of a permeable material; see Figure 1 for a photo of an installed drain before shotcrete is applied.

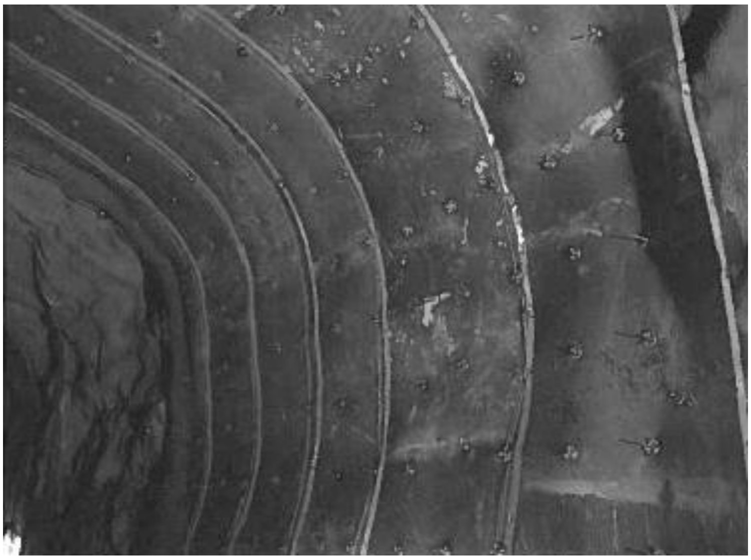

*Figure 1: Drain in tunnel before the application of shotcrete (Lindblom, 2010). Photo: T. Ellisson.*

### 3.1.1 Grouting

Grouting is made to seal fractures in the rock, to prevent groundwater to enter into the tunnel. In extreme poor rock conditions, grouting is sometimes used to temporary stabilize the ground, to increase “the stand up time” to allow for erection of temporary and final support. The grouting process works as follows; holes are drilled in the rock in a certain pattern, see Figure 2. The pattern is designed with respect to the fracture network, fracture aperture and groundwater pressure. A packer is installed in the borehole close to the rock surface and a grouting agent is pumped through the packer

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[1] Bo Blixt, Göteborg Energi, interview 25th of February, 2010

with high pressure. The ambient groundwater pressure and properties of the rock mass determines what grouting pressure, the length of the boreholes, what type of grouting agent and its flow properties that should be used, (Lindblom, 2010). To get a more detailed review of the grouting design methods, deeper studies of technical grouting literature is recommended to the reader. For instance, “Cementinjektering i hårt berg” by Magnus Eriksson and Håkan Stille (SveBoFo, 2005) should cover the process thoroughly.

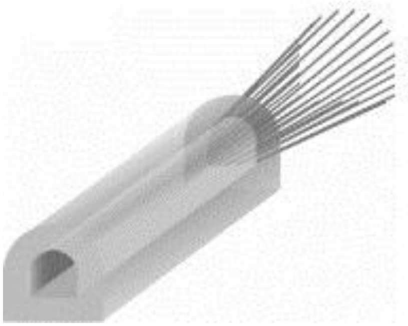

*Figure 2: Grouting fan. (Fransson et al., 2010)*

Recent research has shown that cement grout stays in good condition if the pH of its pore water is higher than 12. The study further shows that the main mechanism for degradation is diffusion of OH-ions from the cement to the surrounding groundwater. This is however a process that takes long time if the grout quality is good (Gustafson et al., 2008), i.e. if grouting is performed in a good manner, maintenance on the grouting is not needed. However, due to other reasons, such as stress redistribution and weathering processes, new fractures in the fracture network may be activated and water find new paths to enter the tunnel.

#### 3.1.1.1 Grouting materials

There are a lot of different grouting materials available. The most common is cement grout. Often the cement in cement grout is milled finer than ordinary cement used in casted constructions in order to penetrate finer fractures, i.e. fractures with smaller apertures. The thickness of the fluid is related to water/cement-ratio (W/C), which also control the viscosity and yield strength, and there by the penetration ability.

Chemical grouting agents are a wide range of different substances used for special cases where the use of cement grout is not enough, e.g. heavy inflow, need for fast hardening or sealing of very small fractures.

Silica sol is a grouting agent which is being used in small scale and subject for on-going research. The advantage of silica sol is that it can seal smaller fractures then ordinary cement grout (which cannot seal fractures smaller then ~100µm). Silica sol is a colloid solution of silica particles and the solution is gelling in contact with sodium chloride. The gel time can be adjusted by changing the ratio between the salt and silica.

#### 3.1.1.2 Pre grouting

Pre grouting is performed before the blasting and hence much higher pressure can be used with deeper penetration as result. Pre grouting requires that the subsequent blasting is carefully performed; otherwise the grouting and its sealing effect can be destroyed. (Lindblom, 2010).

#### 3.1.1.3 Post excavation grouting

Post excavation grouting is used to seal leakage that occur after the tunnel has been built or maybe if the rock is naturally free from fractures and just has to be sealed sporadic. The pressure when post grouting cannot be as high as the pre excavation grouting pressures since risk of block fall out is present when pressurising fractures close to the rock surface. (Lindblom, 2010).

### 3.1.2 Drains

Drains are used to get rid of dripping water, that was not successfully handled in the grouting process, in tunnels and diverts the incoming water either to a sewer system or to be used in infiltration purposes. There are several things that can lead to clogging in drains: chemical and biological precipitation of metal ions in groundwater, material suspended in groundwater, material falling out behind drains, shotcrete ending up behind drainages when applied and ice forming between drains and the tunnel surface. The greatest risk of those above is chemical and biological precipitation (Ekliden, 2008).

Drains should be used to divert inflowing water which appears during the tunnel usage period and not systematically in designs of new tunnels, i.e. drains should be thought of as temporary constructions.

Often there is a demand for a certain maximum inflow of water to a tunnel. If the tunnel is not sealed enough, the groundwater that is diverted out from the tunnel must be pumped into the ground again to sustain the groundwater table.

Drains are constructed with carpets of expanded cell plastic, usually polythene, which is positioned over the water bearing fracture and bolted to the tunnel side. For fire protecting purpose the drains are coated with sprayed concrete; see Figure 1 which shows a drain before the shotcrete is applied. As understood by this, it is costly to change the drains; the shotcrete and old drain needs to be taken away, and the new drain needs to be reinstalled and coated with new shotcrete. (Lindblom, 2010).

Drains demand lots of maintenance due to clogging. The most common maintenance action is flushing (2-4 times per year), however for most installed drains flushing is not possible, and if the chemical and biological quality is too harsh eventually the drains needs to be exchanged. For chemically active groundwater about 10% of the drains needs to be exchanged every $10^{th}$ year. For biologically active groundwater about 25% of the drains needs to be changed every $10^{th}$ year. (Lindblom, 2009).

## 3.2 Hard rock support

When building constructions in hard rock the properties of the building material can vary a lot. There can be fractured zones where the rock is crushed and therefore has no structural strength, or it can be solid rock with little or no fractures at all.

Different rock types have different properties regarding density, compressive strength, deformability and brittleness. All those properties need to be accounted for when designing the hard rock support for the underground construction (Lindblom, 2010). In this chapter bolting and shotcrete as reinforcement methods are described.

### 3.2.1 Rock bolting

Rock bolts are supposed to transfer the load from the unstable rock (rock wedges/blocks) to the more stable firm rock behind it and prevent the wedge or block from falling into the tunnel, see Figure 3 which describes how rock bolts keeps blocks from falling in.

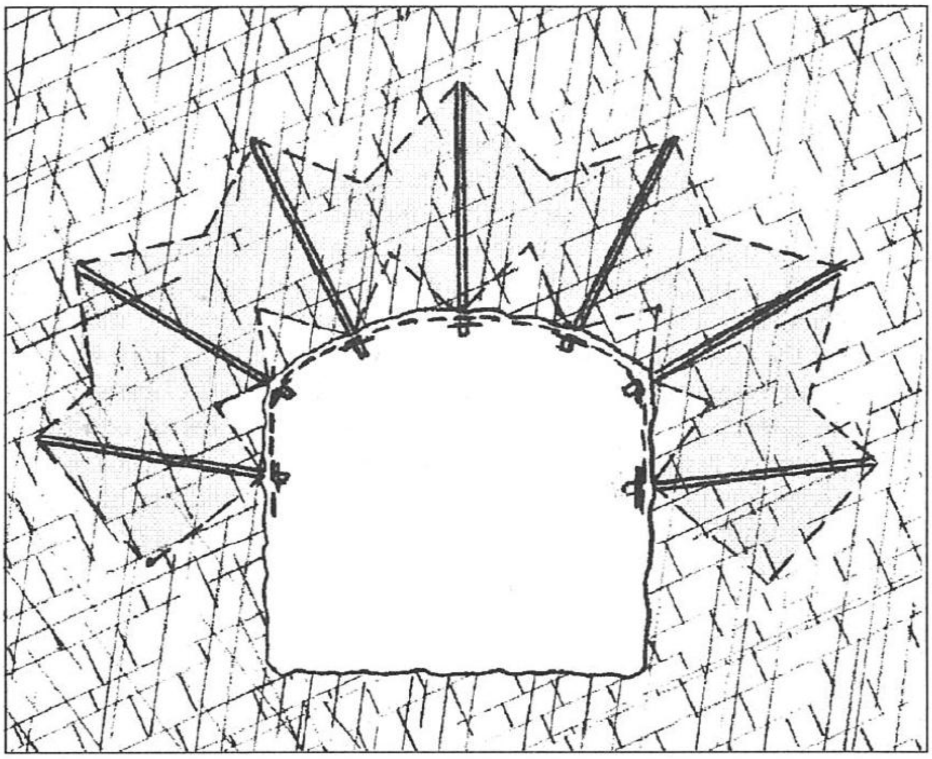

*Figure 3: Rock bolts installed in tunnel roof. The area surrounded with a dashed line show where the rock is exposed for compressive stress where the rock pieces interlocks and a self-supporting arch is formed. The white areas between the bolt heads are at risk of falling out, and should be secured with a mesh or shotcrete (Hoek et al., 2000).*

There are mainly three types of rock bolts in use today: un-tensioned cement injected bolts, pre tensioned bolt and friction bolts. (Lindblom, 2010)

### 3.2.1.1 Un-tensioned cement grouted bolts

A cement injected bolt is a steel rod which is inserted into a, with cement prefilled, borehole in the rock. They are usually used as permanent reinforcement since the bolt is effectively protected against corrosion in the cement. The bolt can be threaded in the end and combined with a washer and nut to tension the rock bolt. Figure 4 shows what a typical cement grouted rock bolt looks like, and Figure 5 describes a mechanically anchored rock bolt with cement grouting made possible in the construction.

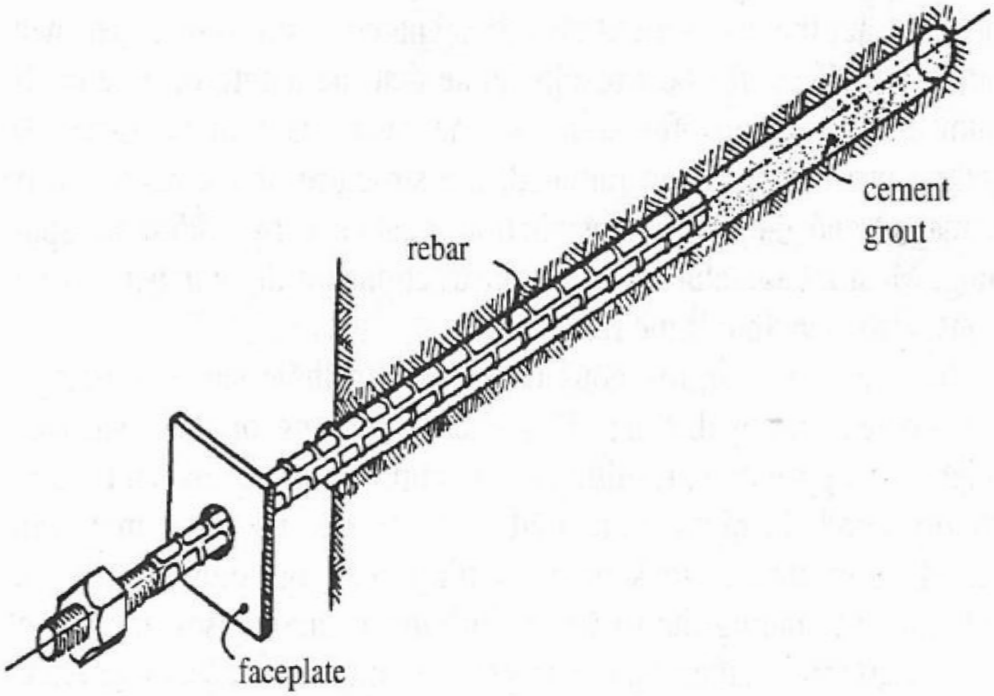

*Figure 4: Cement grouted bolt (Hoek et al., 2000).*

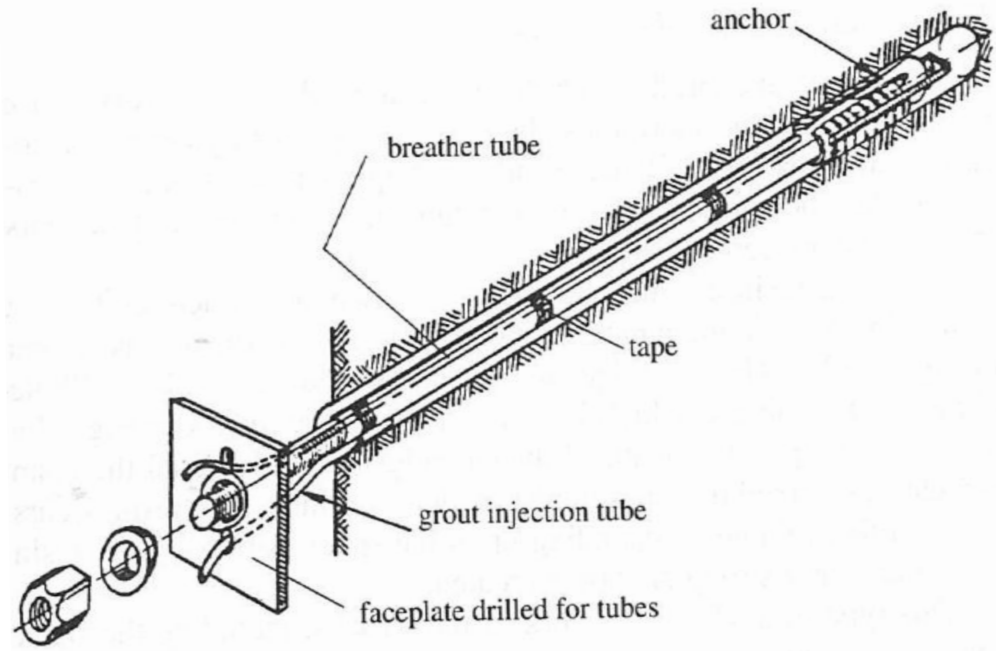

*Figure 5: Mechanically anchored rockbolt for pre tensioning and with grout injection arrangements (Hoek et al., 2000).*

When steel is coated with cement slurry it becomes passivated due to the high pH of the cement. This passivation is a very good protection against corrosion as long as the pH is high enough. (Ellison, 1992).

If a bolt is grouted in a proper way, it is well protected against corrosion. If the environment around the bolt is dry the bolt is in no need for maintenance. If the environment around the bolt is wet only a few needs to be replaced every 25th year. If the bolt is poorly grouted and subjected to water it will probably corrode and about 20% needs to be replaced every 10th year. There are methods to control the quality of the grouting with ultra-sonic sound (Boltometer test). (Lindblom, 2010).

#### 3.2.1.2 Pre tensioned bolt

If the bolt is anchored in the bottom of the borehole and then tensioned, the strength in the bolt can be increased, see *Figure 5*. The bolt is anchored with expanding metal or embedded in cement or other chemical compound such as plastic compounds. If expanders are used the strength in the bolt is instant from the moment it is tensioned and therefore it is useful as reinforcement during construction. (Lindblom, 2010).

#### 3.2.1.3 Frictions bolts

Friction bolts combine properties from the two bolt types above and is useful when the construction area is being reinforced. The friction bolt is often made of thick sheet metal which is forced to the surface in the borehole with water pressure (Swellex) or spring tension (splitset, the borehole diameter is less than the bolt, so the bolt is pushed by great forced into the hole). The working forces are friction between the bolt surface and the surface in the borehole and axial forces due to shortening of the bolt when it is expanded. The long-time resistance against corrosion is not very well known for this bolt type why it is not used as permanent reinforcement (Lindblom, 2010). Figure 6 shows a friction bolt of the make “Swellex”. However the sustainability of friction bolts and its use as final support are questioned, since the thickness of material is less due to its hollowness, and it is not protected in a cement paste environment. Therefore, the friction bolt is often used for temporary support.

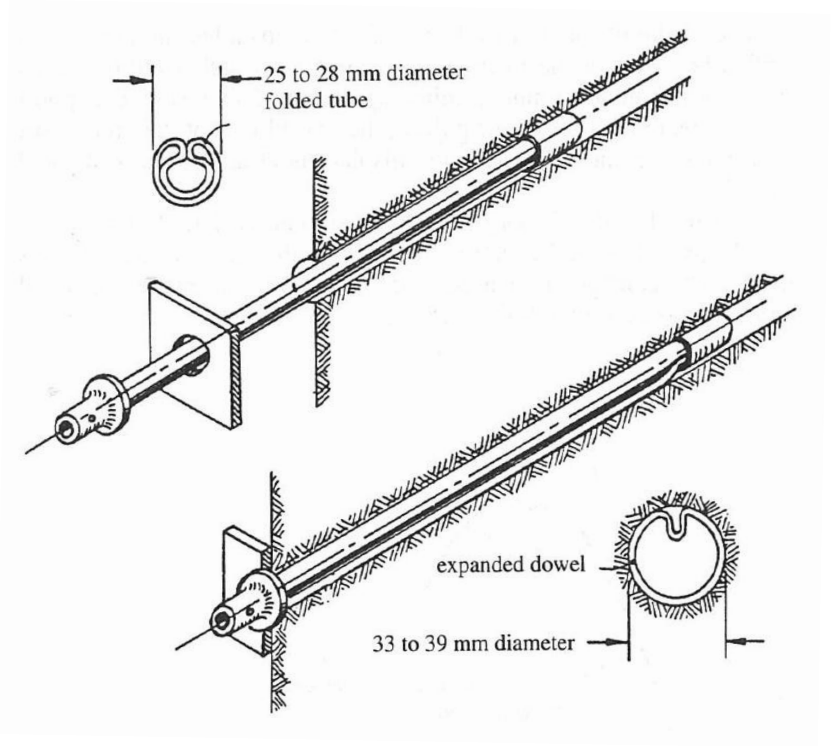

*Figure 6: An example of friction bolt is the Atlas Copco Swellex bolt where the sheet metal collar is expanded in the borehole with high water pressure (Hoek et al., 2000).*

### 3.2.2 Sprayed concrete

Sprayed concrete or shotcrete is used to hinder parts of crushed rock to fall into the tunnel and when applied in greater thickness to create a bearing structure. Shotcrete is applied with high pressure and can either be dry or wet mixed (Lindblom, 2010). Due to working environmental aspects normally wet mixed are used in underground constructions.

The major problem with shotcrete is the way it is applied to the tunnel wall – it is difficult to get an even thickness and quality which may lead to varying quality and inhomogeneous structure and hence the shotcrete is easily leached out. The rock surfaces varies along the tunnel, some surfaces are damp or even wet, some consist of fresh rock or heavy fractures and some parts consists of crushed rock or even rock weathered to soil. This and recrystallization may lead to poor adhesive abilities and much of the positive properties of the shotcrete is lost. Often excessive use of accelerator is used to get an instant stiff concrete mixture on the tunnel wall, but this also makes the concrete structure different to what it would be without the accelerator (Lagerblad, 2007).

If the shotcrete is performed with high quality on dry rock the need for maintenance is rather small; only minor parts of the shotcrete needs to be replaced every ~25th year. If the shotcrete is of average quality applied on damp rock or sealed zones ~10% of the shotcrete needs to be replaced every 15th year. If these kind of conditions are known it should be controlled every 5th year. Poor shotcrete applied to wet rock or weak zones needs a 25% replacement every 5th year. If the shotcrete is applied in layers thicker than 40 mm, the deterioration rate is substantially lowered (Lindblom, 2010).

# 4 Life Cycle Cost

## 4.1 LCC in general

Life Cycle Cost (LCC) is used to calculate the total life time cost for a product. The purpose is to give information on decisions regarding the product to make the quality of the product good enough, at such a low price as possible. A thorough analysis of the life time cost includes everything from retrieval of raw material used in production to disposal of the product when its technical life is at end. The main part of the analysis often regards cost of the production itself and the cost for use during the life time.

One of the definitions of LCC is:

> *"LCC is a comparison of a system's or equipment's total economic impact throughout its life with some simplifications and exclusions made to facilitate the use of the comparative figures."* (Wååk, 1992)

From this it is clear that a life cycle cost analysis is conducted to give a total life cost for a component including every cost the component is associated with, such as planning, construction, maintenance, management and disposal. Often the model is used to compare two or more alternatives to decide which one should be chosen.

A related idea is the LCA (Life Cycle Assessment), which is used to determine the environmental impact instead of economic cost for a product. It can for example be emissions of greenhouse gases or the total amount of a certain mineral that is used. Everything from energy used in the making of the product to transport of it and disposal is taken into account. The LCA can then be used to choose another solution or product which has a lower environmental impact

### 4.1.1 Net present value (NPV)

Since most cost is associated with a time when it occurs, the model also has to take into account the net present value of the cost. The NPV is a method for estimating the value of a certain amount of money today with the future. This gives the opportunity to decide if an investment should be made or not: if the value is less in the future, with respect to interests and inflation, the investment will not pay off. If the value is greater the investment will pay off and the investment should be carried out. The net present value is commonly used in economics, and is calculated as follows:

$$NPV = \frac{R_t}{(1+r)^t}$$

*Equation 1: Net Present Value*

Where:

$R_t$ = cash flow at current time
$r$ = discount rate
$t$ = time of cash flow

### 4.1.2 The LCC summation

The LCC model itself can be very simple; it is just a matter of summation. The base model that this thesis will evaluate and use is the following:

$$LCC = \sum_{x}^{t=0} I_x + \sum_{x}^{t=0-n} K_x + \sum_{t} S_t = I + \sum_{x}\sum_{t=0}^{t=n} K_{xt} * \beta t + \sum_{t=0}^{t=n} s_t * \beta t$$

*Equation 2: The parts included in the LCC summation*

Where:
$LCC$ = the summation of technical components with maintenance demand
$I_x$ = cost of investment for component *x* at time *t*=0
$K_x$ = net present value of future maintenance of component *x* from time *t*=0 to *t*=*n*, see Equation 1 above.
$S_t$ = net present value of future stoppage due to inspection, maintenance and incidents
$I$ = cost of investment for all components at construction
$K_{xt}$ = cost of maintenance of component *x* at time=*t*
$s_t$ = cost of stoppage *t* years after start of usage
$\beta_x$ = capitalisation factor. Depends on interest and inflation

*Figure 7* gives an overview of what the accumulated costs during a lifetime might look like. Every major cost (investments, large repairs, disposal etc.) makes a big impact on the LCC, while smaller running costs contribute less to the total cost, at least if they are considered apart from each other. It can also be noted that the increase in LCC is smaller at a later state even though the cost itself is larger. This is the effect from that money is in general thought of as “less worth” in the future than today.

Note: in *Figure 7* the stoppage cost is not present. This is the social cost for not being able to use a tunnel during maintenance (tunnels for roads or trains). This cost is often omitted but is a large portion of the total cost when maintaining these kinds of tunnels, see chapter 4.2.3.

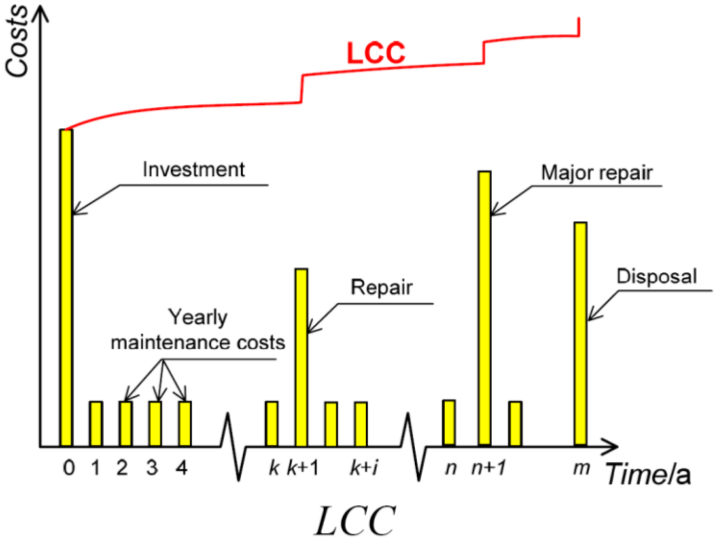

*Figure 7: Costs are summed up during a lifetime (Course memorandum for Operation and maintenance of bridges and tunnels, LCC and LCA, KTH, 2009).*

## 4.2 LCC in this project

When applying LCC to the maintenance of rock reinforcements in tunnels, the purpose is to choose what kind of reinforcement that is necessary to have at as low total cost over a lifetime as possible. This can be divided into two parts. The first concerns the construction of the tunnel with suitable reinforcement. The other concerns the maintenance of the tunnel. Both parts are associated with high costs, and the LCC can be used to optimize both building cost and maintenance cost. The aim is to reduce the total cost, even if the cost seems to be higher in an initial stage.

To be able to conduct a LCC model, the need for data which tells us when and what needs to be done when maintaining a tunnel is of great extent. The data should tell us costs for different actions as well as how often they need to be carried out. If the model is too complex it will be complicated to interact with. A LCC model is often used to compare different alternatives rather then get the true cost.

To make an analysis of the life time cost the operator must know what kind of reinforcements that is used, how often they need maintenance, how much of the different reinforcements that are installed and the cost of maintenance for each part. Apart from this, some qualified guess regarding the interest for the future needs to be done.

### 4.2.1 Maintenance cost

In this case five main categories are considered and introduced to the model, with 12 different costs associated with a maintenance frequency. When designing a tunnels need for reinforcement the rock quality should be taken into consideration and thus indirectly is included into the model. The main and sub categories are:

- Free rock surface
    - Dry surface
    - Wet surface
- Shotcrete
    - Good quality
    - Average quality
    - Poor quality
- Bolts
    - Good quality
    - Poor quality
- Drains
    - Drains in active ground water
    - Drains with water containing biological/chemical precipitate
- Inspection
    - Synoptic
    - Thorough
    - Detailed
- Setup of work equipment for all maintenance actions

From Lindblom (2009) the following chart of estimated maintenance actions and frequencies can be found (*Table 1*).

*Table 1: Estimated maintenance actions and frequencies for different types of rock support.*

| **Maintenance** | | **Action** | **Part that needs action** | **Years between actions** |
|---|---|---|---|---|
| **Free surface:** | | | | |
| | dry conditions, good rock | scaling | limited | 10 |
| | wet conditions, good rock | scaling | limited | 5 |
| **Shotcrete:** | | | | |
| | high quality shotcrete, good rock | replacement | limited | 25 |
| | average quality at damp rock or seals zones | replacement | 10% | 15 |
| | poor quality at weak zones with wet rock | replacement | 25% | 5 |
| **Bolting:** | | | | |
| | high quality injected in dry rock | none | | |
| | high quality injected in wet rock | replacement | limited | 25 |
| | poor quality injected in wet rock | replacement | 20% | 10 |
| **Drains:** | | | | |
| | chemical and biological inactive groundwater | none | | |
| | biological active groundwater | flushing | 100% | 0,25-0,5 |
| | chemical active groundwater | flushing | 100% | 0,25-0,5 |
| | biological active groundwater | replacement | 10% | 10 |
| | chemical active groundwater | replacement | 25% | 10 |

### 4.2.2 Construction cost

To model the life cycle cost the construction cost must be known and used in the calculation. Diverse rock types with different fracture sets and the varying layouts of the tunnel gives different costs, and to be able to calculate the construction cost accurately these (and more) parameters needs to be known.

An estimation of the construction cost is 350 to 450 SKR/m$^3$. This estimation of the construction cost is courtesy of Stefan Sidander[2] and is applied for a tunnel with a cross section area of 75 m$^2$. For the derivation of this cost, see appendix IV.

### 4.2.3 Stoppage cost

When maintenance is performed in a tunnel which carry traffic (cars, trucks or trains with goods or passenger traffic) the traffic often needs to be stopped partially or fully and diverted in another way, which is longer and the reason why the tunnel was built

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[2] Stefan Sidander, NCC Construction Sverige AB, e-mail 28th of October, 2010

in the first place. The increased time it takes to travel the new route together with increased risk of accidents, tear of vehicles and environmental effects is the cost generating actions associated with stoppage. If the maintenance will go on for a long time the environmental and disturbing impact can have some influence and might be necessary to account for in the analysis.

The extra travel time can be calculated and is transferred to a cost for the society. Let’s make an example:

> 10 000 cars/day needs to take another way through a tunnel while maintenance is performed. The new route takes 5 minutes longer to drive, and the cost for the delay for each car is 72 SEKR/hour. The maintenance is going on for 14 days. The cost for the society is then 10000*14*(5/60)*72=840 000 SEK (delay costs from SIKA 2005).

The example above is very simple; a more thorough analysis of the cost for stops would be another thesis, but it is obvious that even a small tunnel with low flow and short detours costs a lot of money why it is important to always make stops in traffic tunnels as short as possible.

A tunnel should be constructed so that maintenance can be made with the tunnel still in use (part of the tunnel), and in such manner that installations easily can be inspected and worked with.

If stop costs need to be estimated SIKA (2005) is a good resource for Swedish traffic costs. It is a memorandum that gives guidance when calculating the community cost for example stoppage and delays

# 5 The Excel model

When all basic parameters are decided the operator can make up to 5 alternatives (more alternatives can be added) which can be compared in the LCC model developed in this thesis.

The net present value equation is presented in chapter 4, *LCC,* and is interpreted into Excel as a function as follows:

```
Function NPV(lifespan, maintfreq, interest, cost)
  If maintfreq = 0 Then
      NPV = "Frequency cannot be 0!"
    Else
    For i = 0 To lifespan Step maintfreq
      NPV = NPV + (cost / ((1 + interest) ^ i))
    Next i
  End If
End Function
```

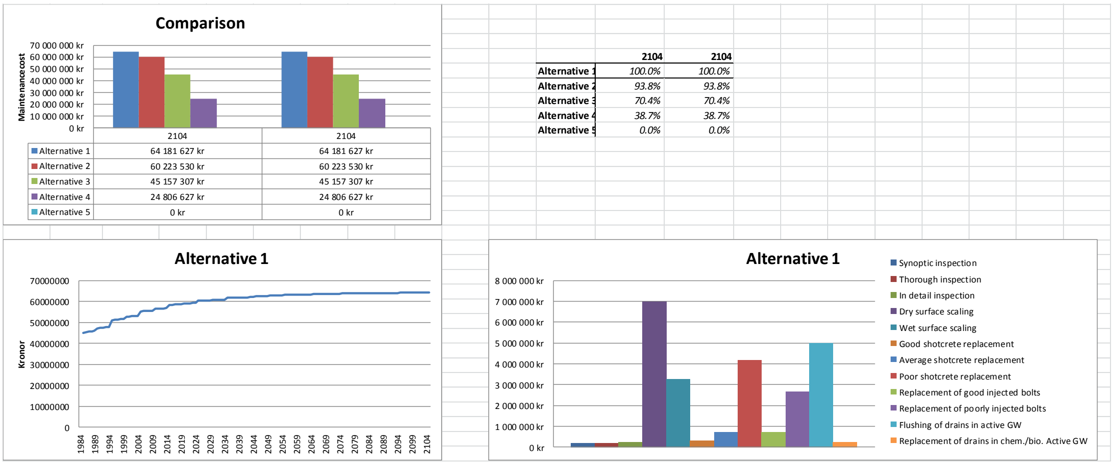
First of all the function is declared as the function NPV with the four inputs *lifespan, maintfreq, interest* and *cost*. The if-statement tells the function not to run if the frequency is zero. If the frequency is not zero the for-loop makes repeated net present value calculations and accumulates them in the variable NPV. This is made with the maintenance frequency as input variable (*i* in the loop). When the loop is finished the variable NPV is outputted into the current working cell.

## 5.1 Users guide for the Excel model

The excel file containing the LCC-model consists of six work sheets. The first five work sheets are used to give the model input data regarding tunnel properties and maintenance frequencies and costs (see *Figure 9*). All parameters can be changed in each and every one of the five sheets to be able to make a user defined comparison.

The last sheet, called “*Comparison*” (see *Figure* 8) contains comparison data and total costs for all five alternatives, together with a cost for an arbitrary year, defined by the user in sheet 1, “*Alternative 1*”. There are also two graphs for each alternative displayed in the comparison sheet. Those graphs give information about the cost development over the life time and the distribution of maintenance cost.

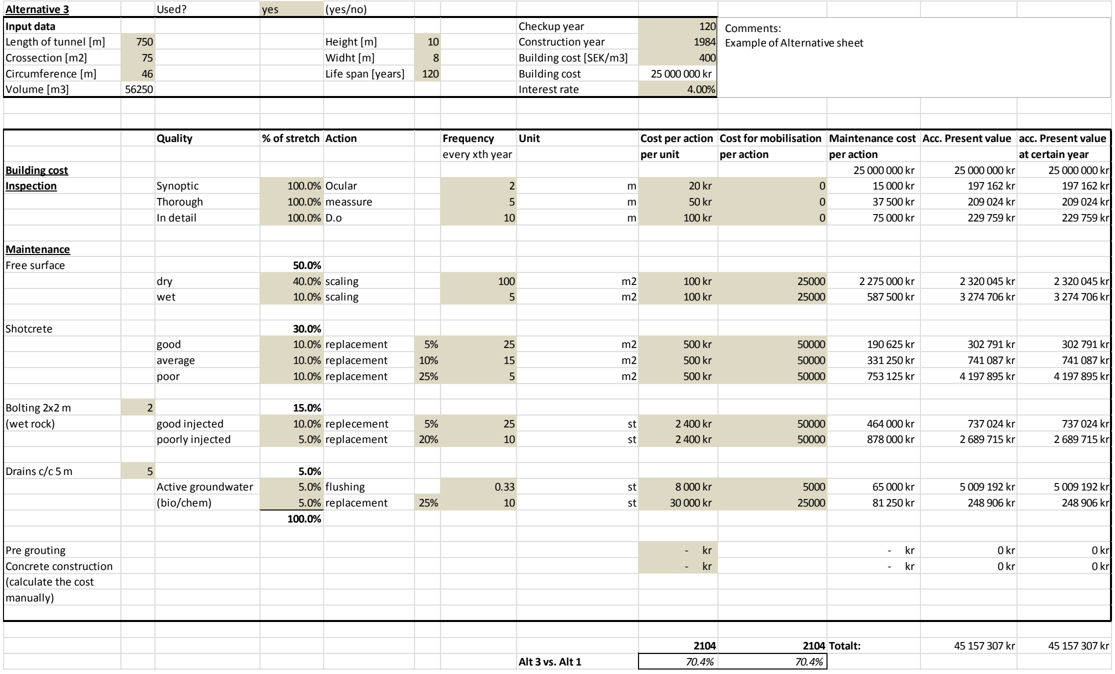
In the alternative sheet the operator can specify all input for the maintenance. The parameters that should be altered are marked in a beige colour. Do not alter any other cells; it will change the model.



| | 2104 | 2104 |
|---|---|---|
| Alternative 1 | 64 181 627 kr | 64 181 627 kr |
| Alternative 2 | 60 223 530 kr | 60 223 530 kr |
| Alternative 3 | 45 157 307 kr | 45 157 307 kr |
| Alternative 4 | 24 806 627 kr | 24 806 627 kr |
| Alternative 5 | 0 kr | 0 kr |

| | 2104 | 2104 |
|---|---|---|
| Alternative 1 | 100.0% | 100.0% |
| Alternative 2 | 93.8% | 93.8% |
| Alternative 3 | 70.4% | 70.4% |
| Alternative 4 | 38.7% | 38.7% |
| Alternative 5 | 0.0% | 0.0% |

*Figure 8: The summary work sheet with details regarding all five alternatives and compare them.*



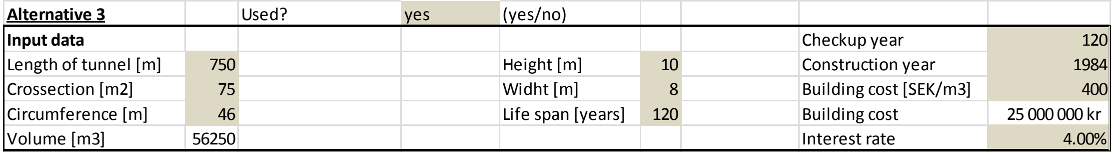
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Alternative 3 | | Used? | yes | (yes/no) | | | | |
| Input data | | | | | | Checkup year | 120 | Comments: |
| Length of tunnel [m] | 750 | | | Height [m] | 10 | Construction year | 1984 | Example of Alternative sheet |
| Crossection [m2] | 75 | | | Widht [m] | 8 | Building cost [SEK/m3] | 400 | |
| Circumference [m] | 46 | | | Life span [years] | 120 | Building cost | 25 000 000 kr | |
| Volume [m3] | 56250 | | | | | Interest rate | 4.00% | |

| | | Quality | % of stretch | Action | | Frequency every xth year | Unit | Cost per action per unit | Cost for mobilisation per action | Maintenance cost per action | Acc. Present value | acc. Present value at certain year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Building cost | | | | | | | | | | 25 000 000 kr | 25 000 000 kr | 25 000 000 kr |
| Inspection | | Synoptic | 100.0% | Ocular | | 2 | m | 20 kr | 0 | 15 000 kr | 197 162 kr | 197 162 kr |
| | | Thorough | 100.0% | meassure | | 5 | m | 50 kr | 0 | 37 500 kr | 209 024 kr | 209 024 kr |
| | | In detail | 100.0% | D.o | | 10 | m | 100 kr | 0 | 75 000 kr | 229 759 kr | 229 759 kr |
| | | | | | | | | | | | | |
| Maintenance | | | | | | | | | | | | |
| Free surface | | | 50.0% | | | | | | | | | |
| | | dry | 40.0% | scaling | | 100 | m2 | 100 kr | 25000 | 2 275 000 kr | 2 320 045 kr | 2 320 045 kr |
| | | wet | 10.0% | scaling | | 5 | m2 | 100 kr | 25000 | 587 500 kr | 3 274 706 kr | 3 274 706 kr |
| | | | | | | | | | | | | |
| Shotcrete | | | 30.0% | | | | | | | | | |
| | | good | 10.0% | replacement | 5% | 25 | m2 | 500 kr | 50000 | 190 625 kr | 302 791 kr | 302 791 kr |
| | | average | 10.0% | replacement | 10% | 15 | m2 | 500 kr | 50000 | 331 250 kr | 741 087 kr | 741 087 kr |
| | | poor | 10.0% | replacement | 25% | 5 | m2 | 500 kr | 50000 | 753 125 kr | 4 197 895 kr | 4 197 895 kr |
| | | | | | | | | | | | | |
| Bolting 2x2 m | 2 | | 15.0% | | | | | | | | | |
| (wet rock) | | good injected | 10.0% | replecement | 5% | 25 | st | 2 400 kr | 50000 | 464 000 kr | 737 024 kr | 737 024 kr |
| | | poorly injected | 5.0% | replacement | 20% | 10 | st | 2 400 kr | 50000 | 878 000 kr | 2 689 715 kr | 2 689 715 kr |
| | | | | | | | | | | | | |
| Drains c/c 5 m | 5 | | 5.0% | | | | | | | | | |
| | | Active groundwater | 5.0% | flushing | | 0.33 | st | 8 000 kr | 5000 | 65 000 kr | 5 009 192 kr | 5 009 192 kr |
| | | (bio/chem) | 5.0% | replacement | 25% | 10 | st | 30 000 kr | 25000 | 81 250 kr | 248 906 kr | 248 906 kr |
| | | | 100.0% | | | | | | | | | |
| | | | | | | | | | | | | |
| Pre grouting | | | | | | | | - kr | | - kr | 0 kr | 0 kr |
| Concrete construction | | | | | | | | - kr | | - kr | 0 kr | 0 kr |
| (calculate the cost | | | | | | | | | | | | |
| manually) | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | 2104 | 2104 | Totalt: | 45 157 307 kr | 45 157 307 kr |
| | | | | | | | Alt 3 vs. Alt 1 | 70.4% | 70.4% | | | |

*Figure 9: One of the alternative work sheets. In this view all input data for the tunnel and the input data regarding the rock support maintenance are entered.*

### 5.1.1 What needs to be known?

To be able to make a calculation the properties of the cross section of the tunnel needs to be known. This is altered at every alternative sheet (to give the operator the opportunity to make different alternatives of cross section and length). See *Figure 10*. This box is also where the interest rate, construction cost, construction year and comparison year are typed. The construction year has no real values for the model more than to show a correct year in the graphs and to give the operator a hint on how far in the future costs appear. If the operator wishes to see the time from today, just type “0” as construction year.



| **Alternative 3** | | Used? | yes | (yes/no) | | | | |
|---|---|---|---|---|---|---|---|---|
| **Input data** | | | | | | | Checkup year | 120 |
| Length of tunnel [m] | 750 | | | Height [m] | 10 | | Construction year | 1984 |
| Crossection [m2] | 75 | | | Widht [m] | 8 | | Building cost [SEK/m3] | 400 |
| Circumference [m] | 46 | | | Life span [years] | 120 | | Building cost | 25 000 000 kr |
| Volume [m3] | 56250 | | | | | | Interest rate | 4.00% |

*Figure 10: Basic input data box where the basic data regarding tunnel dimensions, service time, construction cost and interest rate are defined.*

The comparison year is used to pinpoint a certain year and see the costs for this year. This is shown in the last sheet. Note that both construction year and comparison year only should be modified in alterative 1.

Below the basic data input box is the maintenance specification box. All information regarding the maintenance is noted in the first column where the main categories of the maintenance actions are.

The two coloured cells in the second column is the C-C distance between bolts and drains, accordingly.

The quality of the applied reinforcement method is shown in the third column (and also the inspection method).

In the fourth column the operator specifies how large part of the tunnel that is exposed to the different measures. This is divided into subcategories, and is written as per cent of that specific part. The percentages of all subcategories add up to a “total” percentage of that category. All categories together should add up to 100%; otherwise the model will prompt this to the user. These fractions are used to calculate the appropriate costs for the specific maintenance action and are important. See *Table 1* for a hint of what replacement frequencies that is suitable. Do not modify the bold percentages.

The kind of maintenance action is shown in the fifth column, for example replacement and flushing. This is just a note to the operator.

In the sixth column the percentage of how much of column fives measures that needs to be dealt with are shown, i.e. inspected/replaced/flushed etc.

In the seventh column the maintenance frequency for each action should be specified. This is also important for the calculation to be right.

In column eight the unit (i.e. m, $m^2$, $m^3$ or quantity) for the measures specified in column one, three and five are noted.

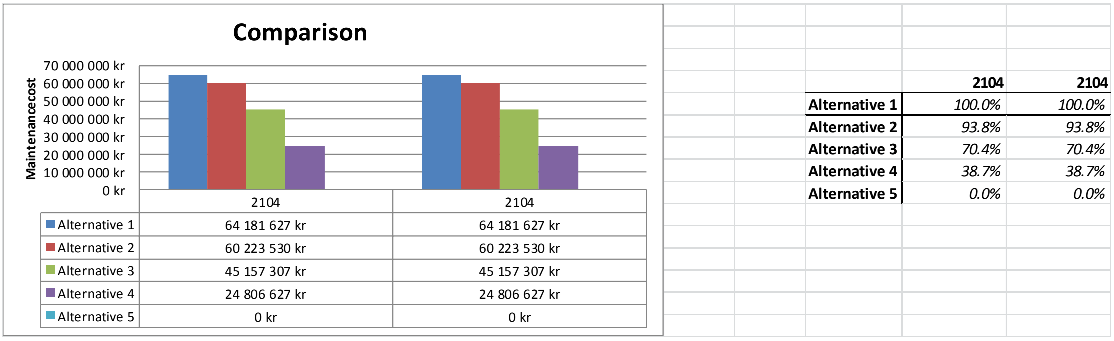
The ninth column contains the cost for each unit specified in column eight.

In the tenth column the setup cost for that rows maintenance action are specified.

In the three following columns the operator can read the maintenance cost for every occurring maintenance action, the total (accumulated) maintenance cost for each category (each row), and the accumulated maintenance cost for each category up to a specific year, namely the comparison year specified in the basic input data box.

### 5.1.2 The comparison sheet

At the last sheet a comparison is made for the five alternatives. The summary is divided into two parts; a total comparing part where the alternatives are compared (see *Figure 11*) and an individual part where every alternative is described by a total life cost graph and a distribution chart where the impact of the different maintenance measures are shown as a percentage of total maintenance cost for the last year (construction year + life time), see *Figure 12*.



| | 2104 | 2104 |
|---|---|---|
| 🟦 Alternative 1 | 64 181 627 kr | 64 181 627 kr |
| 🟥 Alternative 2 | 60 223 530 kr | 60 223 530 kr |
| 🟩 Alternative 3 | 45 157 307 kr | 45 157 307 kr |
| 🟪 Alternative 4 | 24 806 627 kr | 24 806 627 kr |
| 🟦 Alternative 5 | 0 kr | 0 kr |

| | 2104 | 2104 |
|---|---|---|
| **Alternative 1** | *100.0%* | *100.0%* |
| **Alternative 2** | *93.8%* | *93.8%* |
| **Alternative 3** | *70.4%* | *70.4%* |
| **Alternative 4** | *38.7%* | *38.7%* |
| **Alternative 5** | *0.0%* | *0.0%* |

*Figure 11: Part one of the comparison work sheet where the total costs at the last life time year and an arbitrary "checkup year" is found. This information is compiled from alternative sheet 1 to 5.*

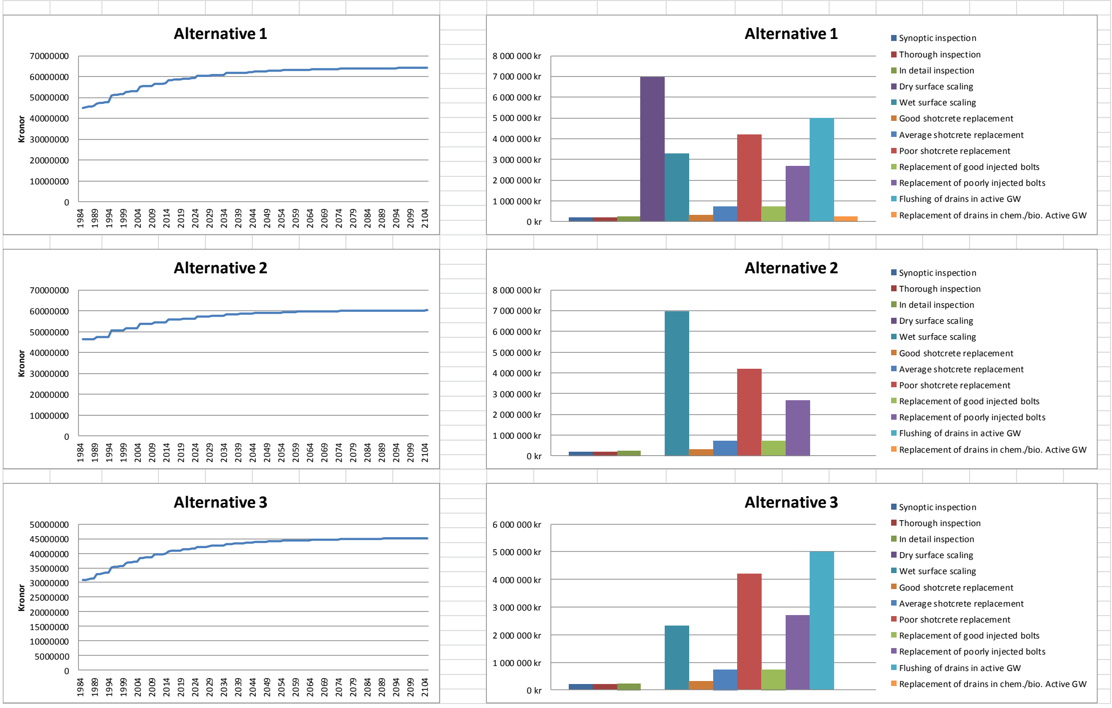


*Figure 12: Part two of the comparison sheet with a graph describing the growth of the total (accumulated) life cost for every year, and a pie chart describing the percentage distribution between different maintenance measures.*

In *Figure 11* a bar graph and a small chart can be seen. The bar graph describes the total life costs both with numbers and as bars, for both the last year and for the comparison year. The chart describes *alternative 2* to *5* compared with *alternative 1* (which is assumed to be the base alternative) as percentages. For example the cost for *alternative 2 is* 93.8% of the cost for *alternative 1* for the last year. In the second column the comparing year is shown.

### 5.1.3 What are all the numbers in the alternatives?

Next to the input boxes in *alternative 1* to *5* are a lot of numbers (not shown in any figures and coloured white in the sheets. They are still there, though). This is the costs for every maintenance action distributed for every year. Below all those costs is a sum for that year. These costs are used to plot the graphs, and due to the nature of excel they need to be written instead of hidden away in a variable.

## 5.2 Some practical examples

The examples in this chapter aim to give some guidance on what kind of analyses the Excel model is capable of and how to do them. It is important to remember are that all data used in the calculations are estimations from literature. The results in this chapter should not be used as absolute truths, but should rather be used for relative evaluation of different maintenance methods.

Therefore, it is more interesting to look at the maintenance cost alone instead of adding construction cost and maintenance cost which is difficult to estimate correctly. But on the other hand a different maintenance alternative often does affect the building cost. One way to see this difference is to use the expected change in construction cost as the construction cost in the model rather than the estimated total construction cost.

If the tunnel is already built, the construction cost is known and should be used.

### 5.2.1 Fracture zones: drains and shotcrete versus no drains and concrete lining

According to chapter 3.1, one of the most important tasks during construction is to hinder groundwater to flow into the tunnel. Groundwater in the tunnel is unwanted and is associated with high costs since the groundwater can break down reinforcements and can create icicles wintertime. Both are great safety concerns for those using the tunnel.

One common way of divert the inflowing groundwater is to install drains at the rock surface of the tunnel. The drain dissipates the groundwater to where it can be transported out of the tunnel through pipes or canalizations. Drains should only be used to get rid of groundwater leakage that occurs after the tunnel has been put into operation since the maintenance of drains is a very costly task.

In this example shotcrete and drains are compared to concrete lining and the parameters are changed to decrease the reinforcement needed since the lining is also a support structure which helps to keep the tunnel intact.

#### 5.2.1.1 Alterative 1: drains and shotcrete

Drains divert inflowing groundwater from the surface of the tunnel wall to the sewer in the tunnel where it is taken care of accordingly. Drains function well if no biological or chemical activity is present in the groundwater, but if they do it tend to clog the drains and the groundwater will still be present in the tunnel. Also the drains do not solve the fundamental problem, namely that groundwater is flowing into the tunnel from the beginning. Due to the biological and chemical activity the related clogging makes the drains need to be flushed once or several times per year.

Assume that a tunnel has 5 % poor rock which carries water. The analysis is made on a 750 meter long distance. This gives 37.5 meter of poor rock. The tunnel is 8 meter wide, and 10 meter high, has a cross section of 75 $m^2$ and a circumference of 46 meter. This is equal to a standard train tunnel that fits one pair of rails.

In alternative 1 shotcrete is used for reinforcement.. According to Lindblom (2009) 25% of this shotcrete would probably need to be replaced every 5th year. Drains are used to divert incoming water to the sewer, and those drains needs to be flushed 3 times every year, and 10% needs to be replaced every 10th year, since the ground water has biological activity. The construction cost for this alternative is assumed to be 39 375 kSEK, which is based on the costs shown in appendix IV, and includes pre grouting.

#### 5.2.1.2 Alternative 2: no drains and concrete lining

The concrete lining is used where fracture zones is found during construction, and aims to hinder groundwater inflow through the fracture zone and also acts as a support structure for permanent rock stabilization of the tunnel roof and walls during the tunnels use phase.

In alternative 2 a concrete structure is built which is assumed to be constructed in such way that no maintenance is needed during the lifetime. To fit the larger concrete structure the tunnel needs to be wider where the fracture zones are situated. The increased construction cost is assumed to 3000 SEK/$m^3$ concrete and 1 $m^3$ concrete covers approximately 2 $m^2$ of tunnel wall according to Dahlström[3]. The extra concrete for the 5% poor rock will cost 1300 kSEK (0.5 x 46 x 37.5 x 1500 SEK). The construction cost for this alternative is then 40 675 kSEK, which includes pre grouting.

#### 5.2.1.3 Result

Since the concrete structure together with thorough grouting prevents inflowing water and also is structural strengthening this is assumed to generate a lower life time cost, even though it has a higher initial cost.

The two alternatives are compared in the excel model with all parameters constant, except those explained above. The interest rate is set to 4%.

When the total cost after 120 years is calculated, alternative 1 costs approximately 64 181 kSEK while alternative 2 costs approximately 60 224 kSEK. This is equivalent with a cost for alternative 2 that is 93.8% of the cost for alternative 1 If construction cost is set to 0 and only the maintenance cost are regarded, alternative 2 costs 84.0% of alternative 1.

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[3] Lars-Olof Dahlström, NCC Construction Sverige AB, interview 29th of April, 2010

In *Table 2* the total costs for alternative 1 and alternative 2 can be seen for every 10th year from the construction year. Break even, or the point where alternative 1 costs more than alternative 2, is around year 7. This means that after 7 years, alternative 2 is preferable in front of alternative 1.

*Table 2: Costs for alternative 1.1 and 1.2 every 10th year from year 0.*

| Year | Alternative 1 | Alternative 2 |
|---|---|---|
| **0** | 45 128 250 kr | 46 282 000 kr |
| **10** | 51 092 806 kr | 50 586 090 kr |
| **20** | 55 310 440 kr | 53 677 711 kr |
| **30** | 58 386 047 kr | 55 989 733 kr |
| **40** | 60 244 466 kr | 57 316 764 kr |
| **50** | 61 636 560 kr | 58 362 082 kr |
| **60** | 62 508 849 kr | 58 999 211 kr |
| **70** | 63 081 647 kr | 59 408 360 kr |
| **80** | 63 516 887 kr | 59 736 804 kr |
| **90** | 63 785 748 kr | 59 933 242 kr |
| **100** | 63 975 256 kr | 60 072 352 kr |
| **110** | 64 098 758 kr | 60 162 964 kr |
| **120** | 64 181 627 kr | 60 223 530 kr |

### 5.2.2 Grouting: pre grouting versus post grouting

This example will deal with the same problem as the example in chapter 5.2.1, but with another solution. Instead of lining the groundwater inflow will be limited with excessive pre grouting. The object of this measure is that thorough grouting prevents groundwater flow through the fractures in the rock mass.

#### 5.2.2.1 Alternative 1: divert groundwater with drains

Alternative 1 is equal to alternative 1 in chapter 5.2.1.

### 5.2.2.2 Alternative 2: minimize groundwater inflow with grouting

More grouting is used, which gives a higher construction cost. The cost for the pre grouting is calculated to approximately 3737 kSEK and is based on the costs presented in *Table 6* in appendix IV. The grouting fan is assumed to have 36 holes, 25 meters long each. The borehole is 64 mm in diameter, and the overlap between the fans is 2.5 meters, see *Table 3* for all data.

*Table 3: Estimated grouting costs for example 2.2*

| | | |
|---|---:|---|
| Length of borehole in grout fan | 25 | m |
| Overlap | 2,5 | m |
| Bore diameter | 64 | mm |
| Boreholes in grout fan | 36 | pc |
| Bore cost | 40 | SEK/m |
| Cement grout cost | 9 | SEK/kg |
| Density of cement grout | 2850 | kg/$m^3$ |
| Cement grout in fractures/bore hole | 2 | l |
| Total volume of grout in fan | 2.967 | m3 |
| Cement grout cost per fan | 76 111 | SEK |
| Boring cost per fan | 36 000 | SEK |
| Total cost per fan | 112 111 | SEK |
| **Total cost per tunnel** | **3 737 034** | **SEK** |

### 5.2.2.3 Result

As can be seen in Table 4, the total cost for a lifetime of 120 years is 64 182 kSEK for alternative 1, and 62 661 kSEK for alternative 2. The total cost is approximately 1 521 kSEK cheaper for the extra grouting alternative (alternative 2) compared with the drains alternative (alternative 1). Break-even is reached at year 31.

The total cost for alternative 2 is 97.6 % of the total cost in alternative 1.

Table 4: *Costs for alternative 2.1 and 2.2 every 10th year from year 0.*

| **Year** | **Alternative 1** | **Alternative 2** |
|---|---|---|
| **0** | 45 128 250 SEK | 48 719 000 SEK |
| **10** | 51 092 806 SEK | 53 023 090 SEK |
| **20** | 55 310 440 SEK | 56 114 711 SEK |
| **30** | 58 386 047 SEK | 58 426 733 SEK |
| **40** | 60 244 466 SEK | 59 753 764 SEK |
| **50** | 61 636 560 SEK | 60 799 082 SEK |
| **60** | 62 508 849 SEK | 61 436 211 SEK |
| **70** | 63 081 647 SEK | 61 845 360 SEK |
| **80** | 63 516 887 SEK | 62 173 804 SEK |
| **90** | 63 785 748 SEK | 62 370 242 SEK |
| **100** | 63 975 256 SEK | 62 509 352 SEK |
| **110** | 64 098 758 SEK | 62 599 964 SEK |
| **120** | 64 181 627 SEK | 62 660 530 SEK |

# 6 Sensitivity analysis

One of the major problems with this kind of economic analysis is the uncertainty with the interest. If the interest is too low the estimated cost will be too high, and if the interest is too high the total cost will be under estimated. According to Lundman[4], the estimated long time interest rate is chosen to be 4 % for large projects in Sweden today.

It is also tough to estimate future costs for the different maintenance measures. Those costs are depending on for example the global economic development and future material cost, which in turn is dependent on the raw material asset.

The frequency of maintenance measures does also influence the total maintenance cost. This is shown in example 1 in chapter 5.2, where the cost is reduced if the high frequency cost for drain flushing is removed. Therefore it is not possible to identify parameters that influence the total cost only by looking at the individual cost, but the frequency also needs to be taken into account.

A sensitivity analysis can be seen as a way to find weaknesses in a model and to see which changes that make the largest impact on the models result. If the simple mathematic *Equation 3* is looked upon, it is instinctively clear that a change in $x^2$ will have larger impact on the change of $(x, y)$ , than a change in $y$, hence the term $x^2$ in the equation above is more sensitive to the equation (our "model") than $y$:

$$f(x, y) = x^2 - 6y + 9 \; where \; 1 < x < -1$$

*Equation 3: Simple second degree equation*

If we have a more complex model, one way of finding which parameters that makes impact on the result is to change one and only one parameter at the time, and make notes of the change of result. This kind of simulation is made in the LCC-model described in this thesis, and the result is presented in this chapter.

To perform this sensitivity analysis Excel is programmed to make small changes to one parameter at a time, and then plot the parameter change to the change in total cost.

## 6.1 Analysed parameters in the LCC model

Three different parameters have been chosen to be included in the analysis. The first one is the maintenance frequency. It is shown that this parameter is the most sensitive and a small change in the maintenance frequency can have a large influence to the total cost; if a maintenance action is performed too often the total cost will be substantial large, but within a limit it does not affect the total cost much at all, why the maintenance frequency may be designed in such a way that it is made "often, but not too often".

---

[4] Peter Lundman, Trafikverket, e-mail conversation 23rd of September, 2010

Another parameter that has a large influence on the total cost is the interest rate, and it is also an uncertain parameter since changes in global economy may alter the calculated interest rate used in the beginning of a far-going project.

The cost for every maintenance action and mobilisation cost can also be changed when analysing the sensitivity. The setup cost does relatively small impact to the total cost even though the setup cost is rather large. This is due to that this cost only occurs once for every maintenance action.

### 6.1.1 Maintenance frequency

When multiple simulations are made, where one parameter at the time is changed in small steps and the result is noted and plotted, a trend can be seen when changing to different frequencies; the “change curve” does always have the form as shown in *Figure 13* below.

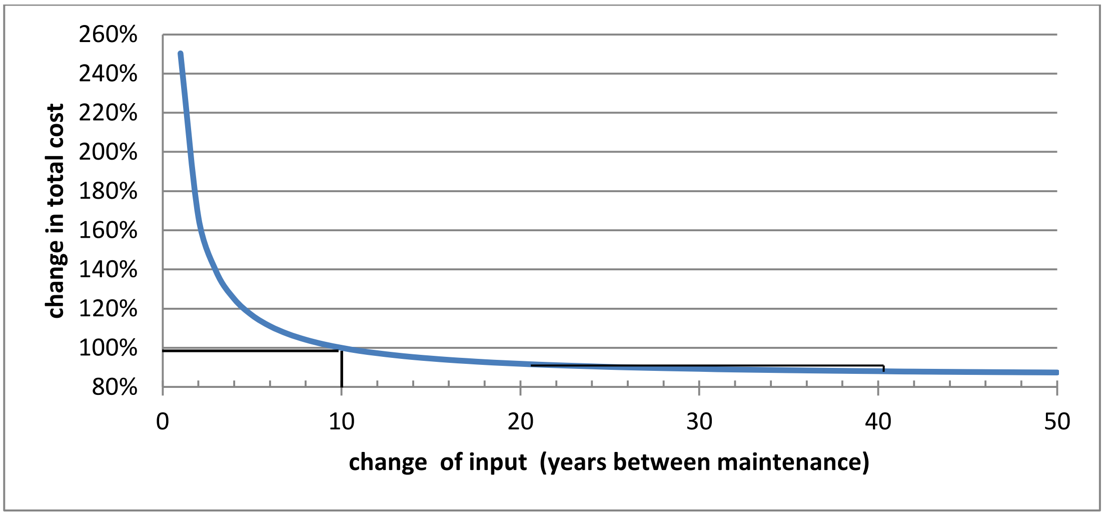

*Figure 13: Change in total cost when the time between scaling is changed.*

As can be seen in *Figure 13*, the result changes dramatically when the frequency is higher (maintenance is made with short intervals/period) and flattens out when the frequency is lower (maintenance is made with longer intervals/periods). The reason for this behaviour is that if maintenance is made every 2nd year, 60 maintenance actions which generates cost is made during a total lifetime of 120 year. But if maintenance is made every 20th year, only 6 maintenance actions generates cost during the same time span.

One interesting note is that the total cost is almost the same if maintenance is conducted every 20th year as if it were made every 40th year; the difference is 4 % units, from 92 % to 88 % of total cost compared with 10 years. Therefore, there is no reason to have longer time between maintenance than necessary from a lifetime cost perspective.

### 6.1.2 Interest rate

Since this model takes the economic interest rate into the calculation, it is probable that the interest is one parameter that is significant for the total cost. When the interest rate is changed *Figure 14* is acquired. The lines in the figure indicate the interest rates 2 % and 4 % which gives an increase of total cost with 72 % units, from 100 % to 172%.

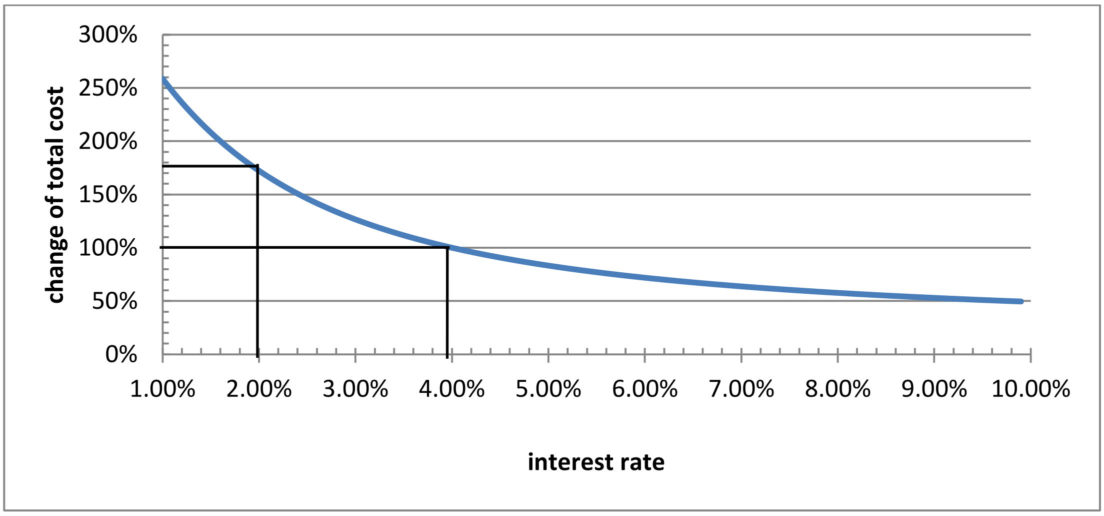

*Figure 14: Change in total cost when changing the interest rate.*

### 6.1.3 Cost per unit and action, and setup cost for every maintenance action

When changing parameters such as cost per unit and the setup cost for every maintenance action it appears to have a linear behaviour, see *Figure 15* and *Figure 16*. The unit cost might have a large impact on the total cost, if the cost itself is large and the unit is of a kind that has large quantity, such as surface area of the tunnel walls.

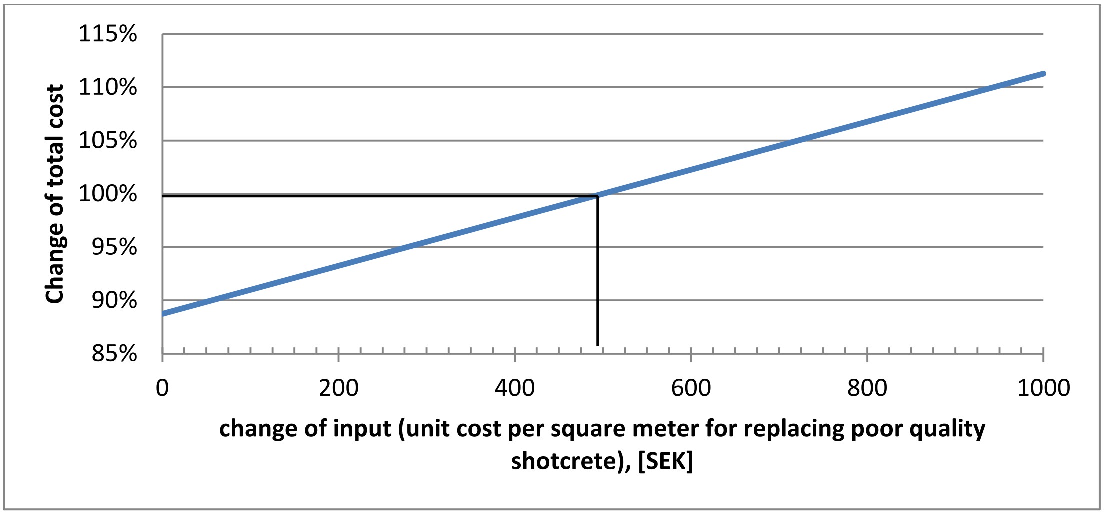

*Figure 15: Change in result when changing the unit cost per square meter replaced poor quality shotcrete.*

The setup cost is less prone to have a large influence on the total cost. This cost only occurs once for every maintenance action (see *Figure 16*). If the setup cost is doubled from 25000 SEK to 50000 SEK the change in total cost is 0,46 % units.

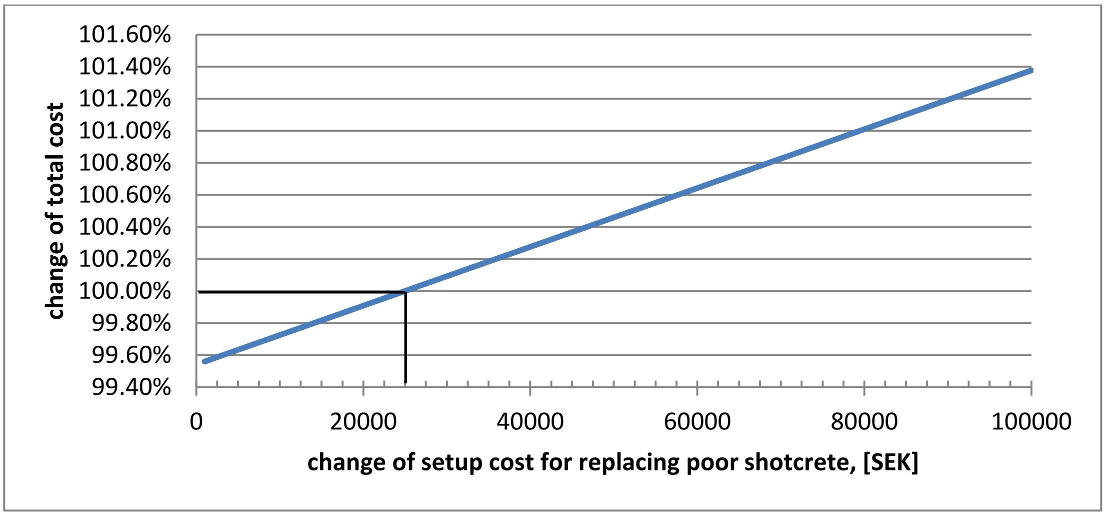

*Figure 16: Change in result when changing setup cost for a specific maintenance action.*

# 7 Discussion and conclusions

To be able to make an accurate analysis of a tunnel Life Cycle Cost, a lot of accurate data is needed. The access and accuracy of available data differs from type of project and from project to project. During the work with this thesis it has become clear that tunnel owners in Sweden in generally do not, in a comprehensive way, save data about their maintenance work and maintenance cost of tunnels for future needs. Without accurate data regarding maintenance actions, costs and what has previously been done, it is difficult to make a perfectly correct analysis. In the LCC model for tunnels developed in this thesis, input data regarding maintenance work, maintenance frequency and estimated costs is collected by using information from experienced tunnel owners, tunnel construction companies and consultants. Based on these input data, estimates may be performed that are useful for comparison of different investment alternatives.

The interest rate is decided by the economy market, and is controlled by the “Riksbank” (the Sweden’s central bank) who makes estimates of how the interest rate will develop in the near future. Over long time however, the interest rate is hard to estimate accurately, and it cannot be affected when planning for a project. For example the financial crisis 2008 affected the interest rate a lot in the short time perspective (a few years’ time). How the crisis is going to affect the long term rate can only be told by the future. Since the interest rate cannot be controlled by the tunnel owner it is a factor with a large uncertainty.

One interesting note is that the total cost for tunnel maintenance is almost equal if maintenance is conducted every 20th year as if it were made every 40th year, see *Figure 13* in chapter 6.1.1. *Figure 13* shows that the cost for maintenance every 20th year is 92% of the total cost, while the cost for maintenance every 40th year is 88% of the total cost. This could mean that there are no economic incentives to have longer time between maintenance then necessary, as long as it is not performed “too often”. Therefore a too long time between maintenance would only cause larger and unnecessary degradation of the facility and a higher maintenance cost.

The examples in chapter 5.2 show that drains are a very costly alternative to use for control of inflowing groundwater, mainly because they require maintenance often. Even if the cost for each flushing of the drain is low, the total cost increase much due to the high maintenance frequency compared with other maintenance demanding structures in the tunnel. See also chapter 3.1.2 about drains.

When designing a tunnel it may be appropriate to consider different technical solutions, both from a technical (which solution is the most suitable for this application?) and economical perspective. As stated above, the cheapest alternative, which costs little to maintain and install may not be the most economical in the long run. It can be summarized as the long known truth "the cheapest is not always the best”.

The societal cost for disturbance of traffic can be very high if the maintenance cannot be made without influencing the traffic. Trafikanalys (Traffic analysis, a Swedish authority, former SIKA, Statens Institut för TrafikAnalys or National Institute for Communications Analysis) develops methods to calculate and estimate the socioeconomic cost for many types of scenarios, including costs for delay in traffic due to reroutes or stops. If the tunnel maintenance is assumed to create delays in traffic this cost should be included in the analysis to get the true total cost for the maintenance. Since the owner of traffic tunnels often is the government this cost should be a concern, since the ambition is to keep the societal cost at a minimum. See chapter 4.2.3 about stoppage costs.

## 7.1 Conclusion

When this thesis was thought of and initialized a few years ago no hands-on model for calculation the total life time costs of tunnels reinforcement structures and its maintenance existed. The development of this LCC model is a first step towards being able to predict and compare those costs.

The model has been developed to a point where it is usable and can be used to give a good foundation for comparison between different reinforcement alternatives. The model makes it possible to predict the total life time costs of tunnels reinforcement's maintenance. The models strength is to comparing two different alternatives with each other to evaluate the best reinforcement for the studied object. It also gives a synoptic view of the costs and their distribution with the help of charts.

With some basic knowledge in Excel usage, this model is easily adaptable for other types of structural reinforcements to get a better fitting model for each use. In essence it comes down to adding a few rows and to quantify the new reinforcement in regard to the tunnels geometric properties.

It has become clear that maintenance that occur often has a large total cost, probably higher than expected, although the particular cost for each instance is low. This is the case for drains which can be flushed several times every year to a low cost and in the end is one of the largest costs regarding the total life time cost.

When a fictive project is calculated it can be shown that it is often less expensive to invest more in reliable reinforcement with a low maintenance interval and maintenance costs, for example there is belief that lining a tunnel (high investment costs) gives lower maintenance costs then a cheaper reinforcement alternative with "ordinary" reinforcements such as sprayed concrete, drains and rock bolts. When adding the accumulated costs for the maintenance with building cost and transferring the costs with net present value calculation, the total cost is lower.

One important thing to remember when using a model like this is that it is a pure calculation process; if the quality of the input data or assumptions is insufficient, the result will reflect that. On-going research is attempting to give good and reliable information regarding tunnels reinforcement structures and their need for maintenance which hopefully will result in accurate result from models like this and others.

## 7.2 Further work

To further development the model, the stoppage cost is one of the most important costs that were left out of this thesis. The stoppage cost is not always present when performing maintenance work, but when it is, it may well be the dominating part of the total cost.

Further a compilation of a database containing maintenance information of different tunnel types could help making more accurate and complex analysis. A database of this kind could include costs for maintenance of all the reinforcements and sealing methods mentioned in chapter 3, and the conditions (rock types, fractures, groundwater pressure, dimensions of tunnel etc.). This kind of work can usefully be made continuously as a collaborative project between tunnel constructors and tunnel maintainers. This work also includes make accurate definitions of costs and lifetime for different reinforcements.

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# List of Appendices

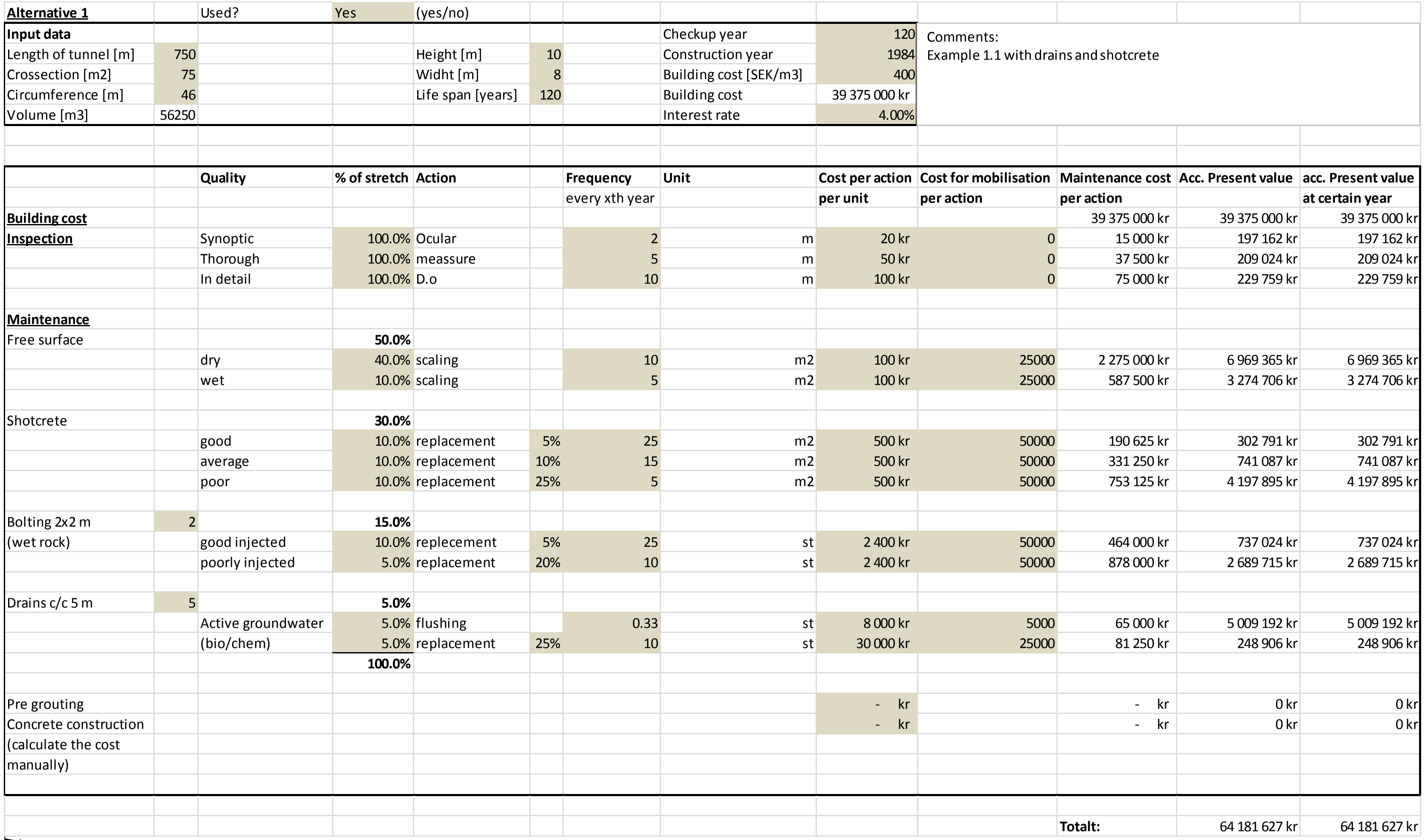
A.I Alternative 1 which chapter 5.2.1 is referring to

A.II Alternative 2 which chapter 5.2.1 is referring to

A.III Charts of changing total costs

A.IV Construction cost for tunnel in hard rock

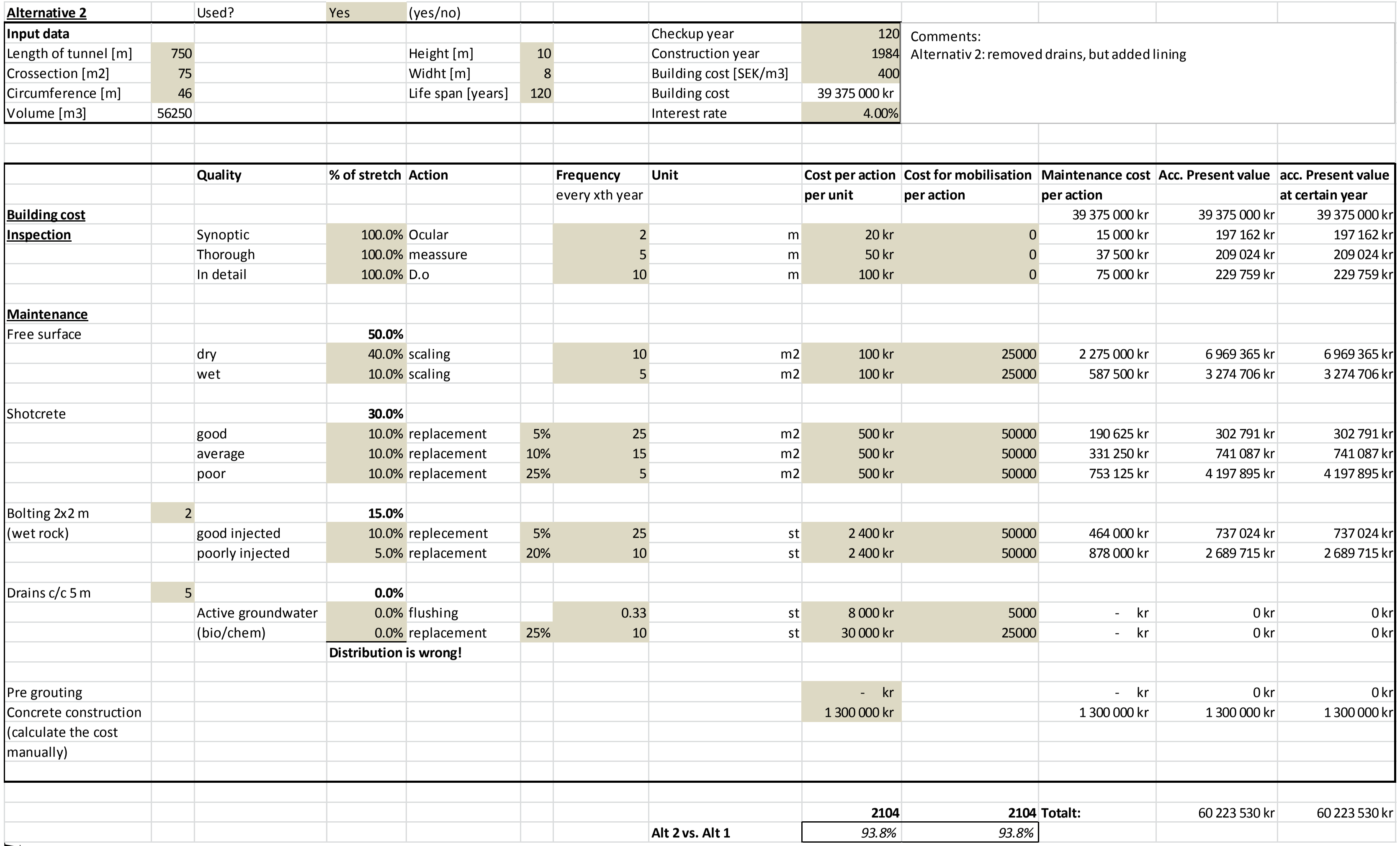
# Appendix I



| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alternative 1** | | Used? | Yes | (yes/no) | | | | | | | | |
| **Input data** | | | | | | | Checkup year | 120 | Comments: | | | |
| Length of tunnel [m] | 750 | | | Height [m] | 10 | | Construction year | 1984 | Example 1.1 with drains and shotcrete | | | |
| Crossection [m2] | 75 | | | Widht [m] | 8 | | Building cost [SEK/m3] | 400 | | | | |
| Circumference [m] | 46 | | | Life span [years] | 120 | | Building cost | 39 375 000 kr | | | | |
| Volume [m3] | 56250 | | | | | | Interest rate | 4.00% | | | | |
| | | | | | | | | | | | | |
| | | **Quality** | **% of stretch** | **Action** | | **Frequency** every xth year | **Unit** | **Cost per action per unit** | **Cost for mobilisation per action** | **Maintenance cost per action** | **Acc. Present value** | **acc. Present value at certain year** |
| **Building cost** | | | | | | | | | | 39 375 000 kr | 39 375 000 kr | 39 375 000 kr |
| **Inspection** | | Synoptic | 100.0% | Ocular | | 2 | m | 20 kr | 0 | 15 000 kr | 197 162 kr | 197 162 kr |
| | | Thorough | 100.0% | meassure | | 5 | m | 50 kr | 0 | 37 500 kr | 209 024 kr | 209 024 kr |
| | | In detail | 100.0% | D.o | | 10 | m | 100 kr | 0 | 75 000 kr | 229 759 kr | 229 759 kr |
| | | | | | | | | | | | | |
| **Maintenance** | | | | | | | | | | | | |
| Free surface | | | **50.0%** | | | | | | | | | |
| | | dry | 40.0% | scaling | | 10 | m2 | 100 kr | 25000 | 2 275 000 kr | 6 969 365 kr | 6 969 365 kr |
| | | wet | 10.0% | scaling | | 5 | m2 | 100 kr | 25000 | 587 500 kr | 3 274 706 kr | 3 274 706 kr |
| | | | | | | | | | | | | |
| Shotcrete | | | **30.0%** | | | | | | | | | |
| | | good | 10.0% | replacement | 5% | 25 | m2 | 500 kr | 50000 | 190 625 kr | 302 791 kr | 302 791 kr |
| | | average | 10.0% | replacement | 10% | 15 | m2 | 500 kr | 50000 | 331 250 kr | 741 087 kr | 741 087 kr |
| | | poor | 10.0% | replacement | 25% | 5 | m2 | 500 kr | 50000 | 753 125 kr | 4 197 895 kr | 4 197 895 kr |
| | | | | | | | | | | | | |
| Bolting 2x2 m | 2 | | **15.0%** | | | | | | | | | |
| (wet rock) | | good injected | 10.0% | replecement | 5% | 25 | st | 2 400 kr | 50000 | 464 000 kr | 737 024 kr | 737 024 kr |
| | | poorly injected | 5.0% | replacement | 20% | 10 | st | 2 400 kr | 50000 | 878 000 kr | 2 689 715 kr | 2 689 715 kr |
| | | | | | | | | | | | | |
| Drains c/c 5 m | 5 | | **5.0%** | | | | | | | | | |
| | | Active groundwater | 5.0% | flushing | | 0.33 | st | 8 000 kr | 5000 | 65 000 kr | 5 009 192 kr | 5 009 192 kr |
| | | (bio/chem) | 5.0% | replacement | 25% | 10 | st | 30 000 kr | 25000 | 81 250 kr | 248 906 kr | 248 906 kr |
| | | | **100.0%** | | | | | | | | | |
| | | | | | | | | | | | | |
| Pre grouting | | | | | | | | - kr | | - kr | 0 kr | 0 kr |
| Concrete construction | | | | | | | | - kr | | - kr | 0 kr | 0 kr |
| (calculate the cost | | | | | | | | | | | | |
| manually) | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | **Totalt:** | 64 181 627 kr | 64 181 627 kr |

*Figure 11.1: Alternative 1 which chapter 5.2.1 is referring to*

# Appendix II



| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alternative 2** | | Used? | Yes | (yes/no) | | | | | | | | |
| **Input data** | | | | | | | Checkup year | 120 | Comments: | | | |
| Length of tunnel [m] | 750 | | | Height [m] | 10 | | Construction year | 1984 | Alternativ 2: removed drains, but added lining | | | |
| Crossection [m2] | 75 | | | Widht [m] | 8 | | Building cost [SEK/m3] | 400 | | | | |
| Circumference [m] | 46 | | | Life span [years] | 120 | | Building cost | 39 375 000 kr | | | | |
| Volume [m3] | 56250 | | | | | | Interest rate | 4.00% | | | | |
| | | | | | | | | | | | | |
| | | **Quality** | **% of stretch** | **Action** | | **Frequency** | **Unit** | **Cost per action** | **Cost for mobilisation** | **Maintenance cost** | **Acc. Present value** | **acc. Present value** |
| | | | | | | every xth year | | **per unit** | **per action** | **per action** | | **at certain year** |
| **Building cost** | | | | | | | | | | 39 375 000 kr | 39 375 000 kr | 39 375 000 kr |
| **Inspection** | | Synoptic | 100.0% | Ocular | | 2 | m | 20 kr | 0 | 15 000 kr | 197 162 kr | 197 162 kr |
| | | Thorough | 100.0% | meassure | | 5 | m | 50 kr | 0 | 37 500 kr | 209 024 kr | 209 024 kr |
| | | In detail | 100.0% | D.o | | 10 | m | 100 kr | 0 | 75 000 kr | 229 759 kr | 229 759 kr |
| | | | | | | | | | | | | |
| **Maintenance** | | | | | | | | | | | | |
| Free surface | | | **50.0%** | | | | | | | | | |
| | | dry | 40.0% | scaling | | 10 | m2 | 100 kr | 25000 | 2 275 000 kr | 6 969 365 kr | 6 969 365 kr |
| | | wet | 10.0% | scaling | | 5 | m2 | 100 kr | 25000 | 587 500 kr | 3 274 706 kr | 3 274 706 kr |
| | | | | | | | | | | | | |
| Shotcrete | | | **30.0%** | | | | | | | | | |
| | | good | 10.0% | replacement | 5% | 25 | m2 | 500 kr | 50000 | 190 625 kr | 302 791 kr | 302 791 kr |
| | | average | 10.0% | replacement | 10% | 15 | m2 | 500 kr | 50000 | 331 250 kr | 741 087 kr | 741 087 kr |
| | | poor | 10.0% | replacement | 25% | 5 | m2 | 500 kr | 50000 | 753 125 kr | 4 197 895 kr | 4 197 895 kr |
| | | | | | | | | | | | | |
| Bolting 2x2 m | 2 | | **15.0%** | | | | | | | | | |
| (wet rock) | | good injected | 10.0% | replecement | 5% | 25 | st | 2 400 kr | 50000 | 464 000 kr | 737 024 kr | 737 024 kr |
| | | poorly injected | 5.0% | replacement | 20% | 10 | st | 2 400 kr | 50000 | 878 000 kr | 2 689 715 kr | 2 689 715 kr |
| | | | | | | | | | | | | |
| Drains c/c 5 m | 5 | | **0.0%** | | | | | | | | | |
| | | Active groundwater | 0.0% | flushing | | 0.33 | st | 8 000 kr | 5000 | - kr | 0 kr | 0 kr |
| | | (bio/chem) | 0.0% | replacement | 25% | 10 | st | 30 000 kr | 25000 | - kr | 0 kr | 0 kr |
| | | | **Distribution is wrong!** | | | | | | | | | |
| | | | | | | | | | | | | |
| Pre grouting | | | | | | | | - kr | | - kr | 0 kr | 0 kr |
| Concrete construction | | | | | | | | 1 300 000 kr | | 1 300 000 kr | 1 300 000 kr | 1 300 000 kr |
| (calculate the cost | | | | | | | | | | | | |
| manually) | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | **2104** | **2104** | **Totalt:** | 60 223 530 kr | 60 223 530 kr |
| | | | | | | | **Alt 2 vs. Alt 1** | *93.8%* | *93.8%* | | | |

*Figure 11.1: Alternative 2 which chapter 5.2.1 is referring to*

# Appendix III

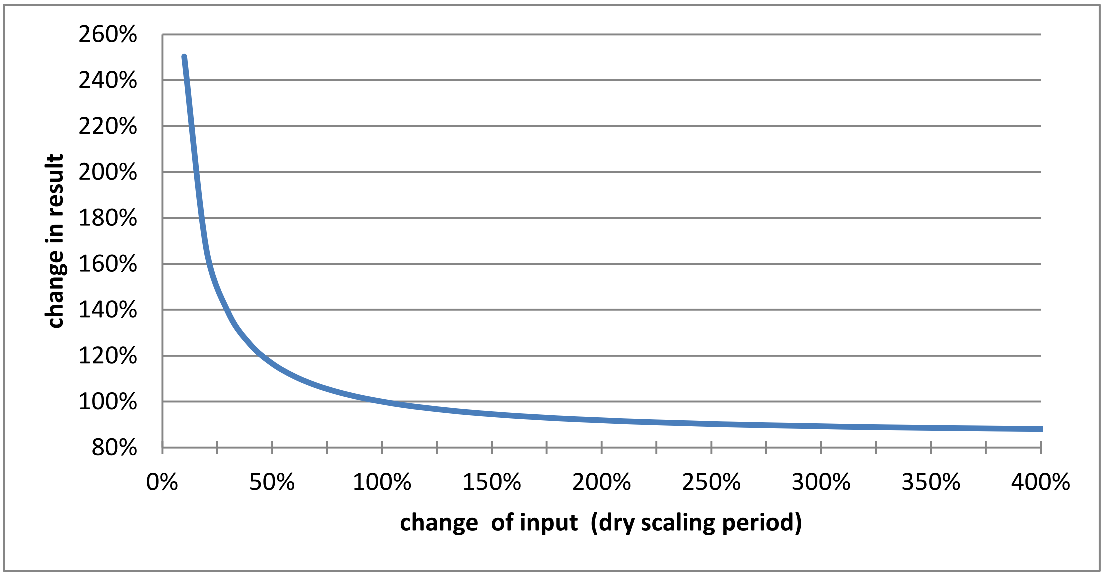


*Figure 17: Change in result when scaling period is changed. Scaling every 10th year is equal to 100 % change of input.*

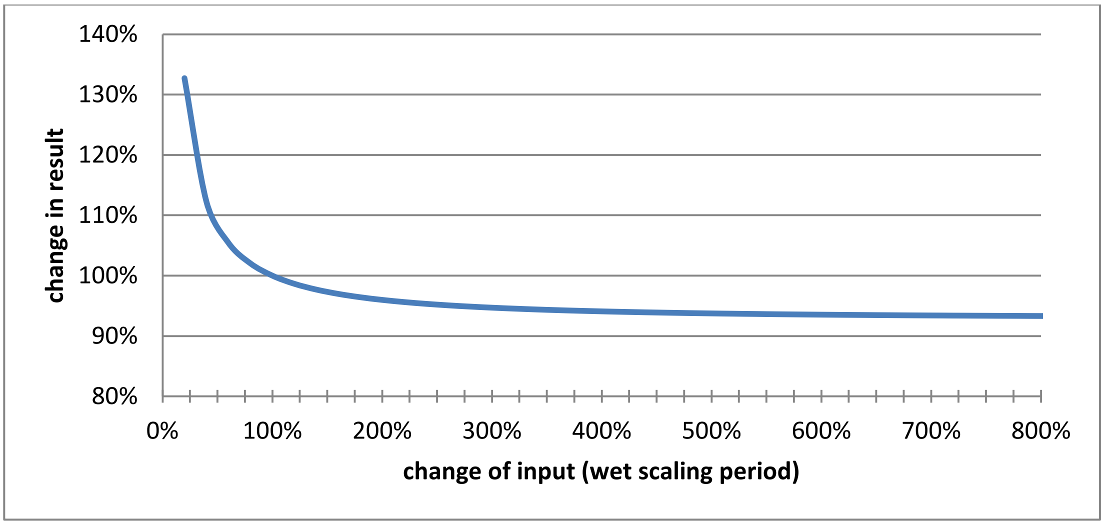


*Figure 18: Change in result when scaling period is changed. Scaling every 5th year is equal to 100 % change of input.*

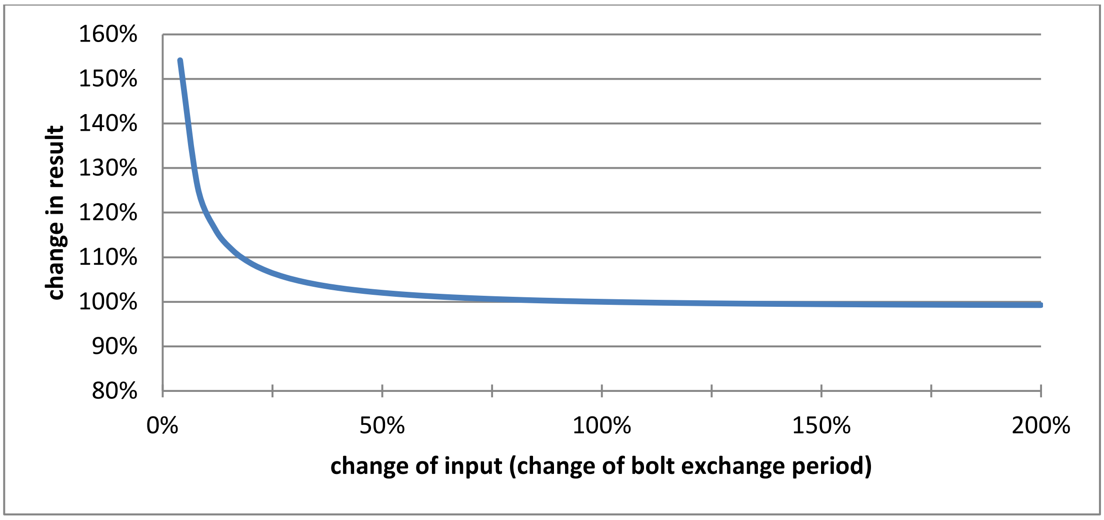


*Figure 19: Change in result when bolt replacement period is changed. Change every 25th year is equal to 100 % change of input.*

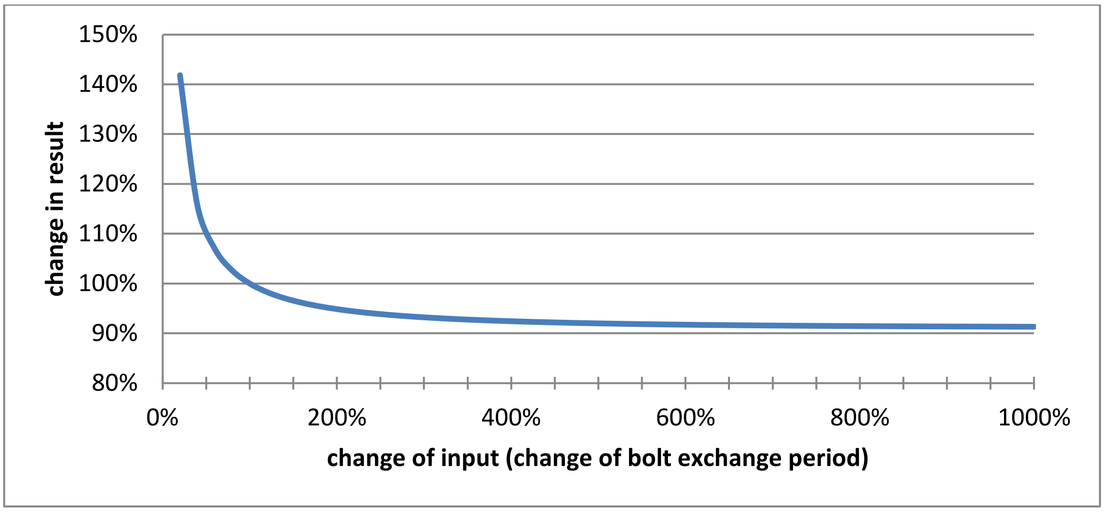


*Figure 20: Change in result when bolt replacement period is changed. Change every* 5th *year is equal to 100 % change of input.*

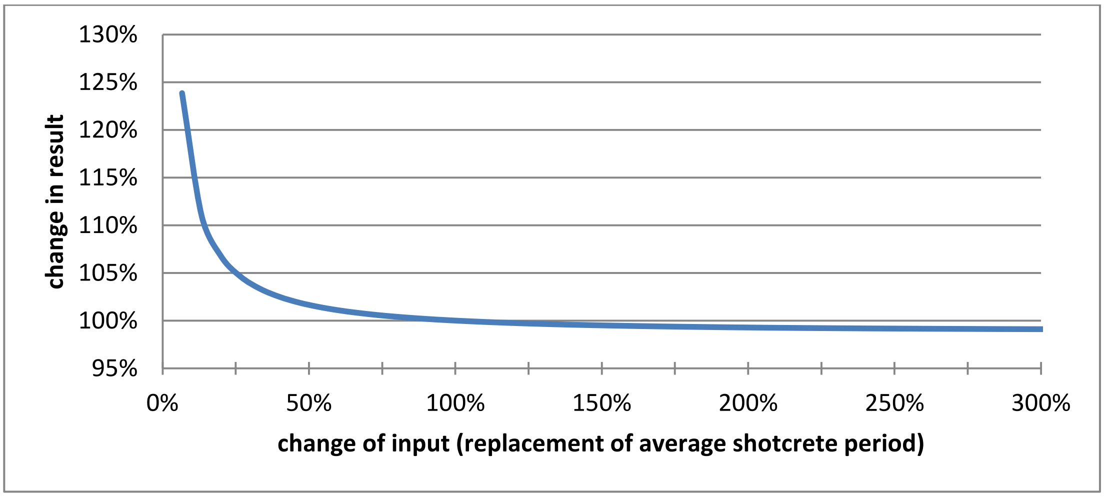


*Figure 21: Change in result when replacement of average quality shotcrete period is changed. Change every* 15th *year is equal to 100 % change of input.*

# Appendix IV

*Table 5: Construction costs for a tunnel with cross section area of 75 $m^3$. Source: Stefan Sidander, NCC construction.*

| | | | | |
|---|---|---|---|---|
| **Borrning** | | | kr/enhet | kr/m3 |
| Borrvagn | | | | 60 |
| Borrstål- och kronor | borrm/m3 | 2 | 4 | 8 |
| Reservdelar | borrm/m3 | 2 | 8 | 16 |
| Diesel | l/m3 | 0,1 | 9 | 0,9 |
| **Laddning** | | | | |
| SSE | kg/m3 | 2 | 9 | 18 |
| Primer | st/m3 | 0,25 | 7 | 1,75 |
| Tändare | st/m3 | 0,2 | 25 | 5 |
| Personal | tim/m3 | 0,11 | 525 | 57,75 |
| Lastning | | 25-35 | | 30 |
| Bergtransport | | 100-200 | | 150 |
| maskinskrotning | | 20-40 | | 30 |
| | | | | ***377,4*** |

*Table 6: Costs for grouting, shotcrete and rock bolts. Source: Stefan Sidander, NCC construction.*

| | undre gräns | medel | övre gräns |
|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Injekteringsborrning | 40 kr | 40 kr | 40 kr | kr/m2 |
| Injektering | 6 kr | 8 kr | 9 kr | kr/kg |
| Bult 3m combicoated | 400 kr | 450 kr | 500 kr | kr/st |
| Bult 4m combicoated | 500 kr | 550 kr | 600 kr | kr/st |
| Fiberbetong 50 mm | 350 kr | 375 kr | 400 kr | kr/m2 |
| Fiberbetong 75 mm | 500 kr | 550 kr | 600 kr | kr/m2 |