Comparison of Ground Improvement Techniques

Comparison of Different Techniques Based on Technical, Environmental and Economic Aspects

Infrastructure and Environmental Engineering

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Abstract

This master's thesis compares three ground improvement techniques: deep mixing, stone columns, and lightweight fill. The methods are designed to achieve comparable settlement levels and are evaluated for two case studies with clay soils in western Sweden, representing different soil depths and conditions. In addition to settlement performance, the impact on slope stability is analysed. Furthermore, the environmental impact and cost of the techniques are assessed and compared.

The results indicate that deep mixing is generally the most effective technique in terms of settlement reduction and slope stability improvement relative to cost. However, it also exhibits by far the highest environmental impact among the studied methods. Lightweight fill, on the other hand, generally results in the lowest environmental impact and represents a competitive alternative, particularly in deep soil conditions where column-based methods would otherwise require floating solutions. Stone columns are most suitable for sites with thinner clay layers and favourable ground conditions, and they have the additional advantage of significantly reducing the consolidation time.

Overall, the findings show that the optimal ground improvement technique is highly dependent on site specific conditions, as well as the relative importance of technical performance, cost, and environmental impact.

Keywords: Ground improvement, Deep mixing, Stone columns, Leca, Foam glass, PLAXIS, GeoStudio, Settlements, Slope stability.

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Albin Carrin and Gabriel Öhgren, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CKD	Cement Kiln Dust
CPT	Cone Penetration Test
CRS	Constant Rate of Strain
EPS	Expanded Polystyrene
GL	Ground Level
GWL	Ground Water Level
HVO100	Hydrotreated Vegetable Oil 100%
LECA	Lightweight Expanded Clay Aggregate
InSAR	Interferometric Synthetic Aperture Radar
Multicem	A commercial binder consisting of cement and CKD
OCR	Over Consolidation Ratio
POP	Pre Overburden Pressure
SEK	Swedish Krona
Trafikverket	The Swedish Transport Administration

Nomenclature

Below is the nomenclature of symbols, parameters, and variables used throughout this thesis.

Parameters

Greek symbols

δ	Settlement
η	Improvement factor
γ	Unit weight
γ_{sat}	Saturated unit weight
κ^*	Modified swelling index
λ^*	Modified compression index
μ^*	Modified creep index
ν'	Poisson's ratio
ν_{ur}	Poisson's ratio for unloading–reloading
σ	Normal stress
σ'	Effective stress
σ'_c	Preconsolidation pressure
σ'_v	Vertical effective stress
σ'_1	Major effective principal stress
σ'_2	Intermediate effective principal stress
σ'_3	Minor effective principal stress
τ_f	Shear strength
$\tau_{f,col}$	Shear strength of column

$\tau_{f,soil}$	Shear strength of soil
τ_{fdk}	Characteristic drained shear strength
φ'	Friction angle

Latin symbols

B	Drainage width
E_{ref}	Reference Young's modulus
F_s	Factor of safety
H	Depth of soil to firm layer
K_0	Coefficient of earth pressure at rest in situ
K_0^{NC}	Coefficient of earth pressure at rest for normally consolidated soil
L	Length
M	Confined (1D) compressibility
M_c	Stress ratio at critical state
R	Radius of the drainage zone
S	Centre-to-centre distance
b_c	Column radius
c'	Effective cohesion
k	Hydraulic conductivity
q	External stress
r_c	True column radius
s_u	Undrained shear strength
$s_{u,inc}$	Rate of increase of undrained shear strength
z	Depth

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Introduction

1.1 Motivation

The demand for urban infrastructure is continuously increasing as a result of population growth and evolving societal needs. New buildings, roads, and bridges require suitable land. To ensure that the projects do not result in excessively large settlements, collapses, and landslides, it is of great importance that the properties of the underlying soil provide sufficient strength and stiffness. In cases where ground conditions are inadequate, particularly in soft and weak soils, ground improvement measures are required to reduce settlements and prevent failures such as collapses and landslides.

This can be done through multiple different approaches. Techniques that aim to reinforce the soil and in this way improve the buildability on poor quality soils are called ground improvement techniques, and they include different methods to improve the soil. These methods include using binders to stabilise the soil and increase the stiffness of the soil to decrease the consolidation time. Another solution is to decrease the natural loads on the site to compensate for the additional loads caused by construction. This could be done by replacing parts of the soil with materials with lower density.

This thesis investigates several ground improvement techniques and evaluates their performance under different site conditions. What should be emphasised when choosing a ground improvement technique is the importance of considering environmental and economic aspects. What ground improvement technology is the most optimal for a specific site varies depending on variations in soils and site conditions. The different techniques may also have differences in economic and environmental impacts that need to be taken into account when selecting a method to improve the ground. An illustration of how these three categories often need to collaborate is presented in Figure 1.1.

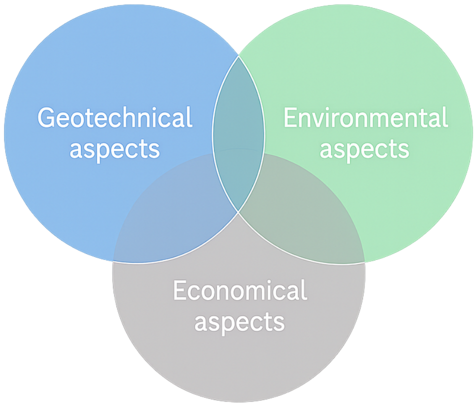


Figure 1.1: Conceptual framework of the thesis

1.2 Aim and objectives

The aim of this thesis is to analyse different ground improvement techniques and evaluate their advantages and limitations under varying soil conditions at two sites in Sweden. The selected sites represent typical clay soil profiles on the Swedish West Coast but differ in terms of soil depth and layer composition. The analysis includes the comparison of technical performance in terms of settlements and slope stability, as well as the environmental impact and cost associated with each technique.

The main objectives of the thesis are to:

- Collect and compile relevant data for the selected sites
- Design ground improvement techniques to achieve comparable settlement levels using both analytical and numerical methods
- Evaluate how the chosen designs influence slope stability
- Compare techniques with respect to environmental impact and cost
- Analyse the potential for emission reductions and perform a sensitivity analysis of cost calculations

By fulfilling these objectives, the study aims to identify how different ground improvement techniques perform under varying conditions and to assess their suitability based on technical, environmental, and economic criteria.

1.3 Societal, Ethical and Ecological impacts

The selection of a valid ground improvement technique is highly linked to societal, ethical, and ecological implications. From an ecological perspective, the choice of method dictates the environmental footprint of an infrastructure project. Deep mixing, which is a common improvement technique, is heavily based on cement and lime, whose production processes generate substantial carbon emissions, whereas lightweight fills such as foam glass use recycled materials to support circular resource management. Societally, implementing reliable ground stabilisation is critical to ensure public safety and protecting civil infrastructure from catastrophic ground failures or landslides. This is especially important in western Sweden due to the presence of quick clays. From an ethical point of view, the geotechnical responsibility of considering impacts beyond cost efficiency or short term solutions is of major importance. By evaluating potential solutions and weighing performance, cost and environmental degradation, this thesis aims to enhance and the decision framework of ground improvement applications and make future projects more sustainable.

1.4 Limitations

This study is subject to several limitations. The analysis is based on two representative sites on the Swedish West Coast, and the results may therefore not be directly applicable to other geographical conditions with different soil properties.

Only two sites are considered, which limits the variation in soil profiles. As a result, the findings may not fully capture the range of conditions encountered in practice.

The input data for the analyses are based on previous sampling results, and no additional field or laboratory testing has been carried out within the scope of this thesis. To provide sufficient ground for the comparison, a literature study will be conducted along with analyses from real projects.

The ground improvement techniques included in this study are deep mixing, stone columns, and lightweight fill. Other ground improvement techniques will not be considered.

All numerical analyses are performed using two-dimensional modelling. Three-dimensional effects are therefore not included.

For the settlement analysis, a unit cell model with singular columns is used and for the slope stability analysis, a square pattern of columns is assumed. Thus, the effect of the installation pattern and its different suitability for different purposes are not investigated.

2

Background

This chapter focuses on the background of the three selected ground improvement methods. It begins with an introduction to the core concept of ground improvement and its general purpose. This is followed by a presentation of the different techniques investigated in the thesis, including detailed descriptions of what the techniques are and how they work.

2.1 Ground Improvement

Ground improvement is defined as methods to increase the stability and stiffness of the soil in situ. The purpose of ground improvement is to improve the carrying capacity of the soil. For example, piles down to rock are not defined as a ground improvement method, as they do not improve the soil itself, even though the bearing capacity increases. Instead, piles transfer the load to solid rock or a soil layer with higher strength. In parallel, the ground improvement can modify the permeability of the system (e.g. stone columns), or indeed reduce the permeability (e.g. deep mixing is used for encapsulation of contaminants).

2.1.1 Why ground improvement

When a construction project is carried out, the site-specific properties of the soil need to be taken into account. Most often, the soil does not inherit a sufficient quality for construction, and without taking this into account, we would have instability and unacceptable deformations. In such cases, what was planned cannot be built on that site due to the ground-conditions. The alternatives then are to find another location for the construction if possible or to adapt what is to be built to the prevailing ground conditions. In many cases, this is not entirely possible, and this is where ground improvement could be used to allow construction on land that would otherwise not have been possible to build that project on.

As an alternative to ground improvement that aims to improve soil, there are foundation methods that aim to avoid an excessively weak layer of soil to carry load. Compared to foundation methods such as piling, ground improvement often means a lower cost and a wider possibility of application. Piling also has limitations when it comes to certain conditions, such as thick layers of weak soil, where ground improvement could be more useful (Kirsch & Bell, 2013).

2.1.2 Different ground improvement techniques

There are many different approaches to improving ground quality. It also varies what improvements are needed for the soil in question. It can be bearing capacity, slope stability or increased consolidation time. Today in Sweden, deep mixing is the most widely used method of ground improvement and is considered the standard solution to limit deformations and stabilise slopes in Sweden. In addition to this, lightweight fill is used as a complement. Internationally, the use of stone columns is a common technique, but there are only a few projects that have applied the method in Sweden (Rosholm, 2026).

2.2 Deep soil mixing

Deep soil mixing used in Sweden is a technique where a mixture of lime and cement is mixed into the soil, building lime cement columns. The mixture, in this case a dry powder composed of lime and cement is the so called binder. The binders react with the water in the soil and build a structure that strengthens the soil. The technique has been in use in Sweden since the middle of the 1970:s (Åhnberg & Holm, 1986). The usage of the method has increased over time and today, deep mixing with lime cement columns is the most common way of improving the strength and stability of the ground in Sweden.

Two different binder preparation methods can be used in deep mixing, dry and wet. If dry binders are used, the binders are in form of a powder before they are put into the soil, or if the wet mixing is used, the binder is in a slurry form, In both cases the binders are mixed into the soil in situ. In Sweden, dry mixing is predominantly used, while wet mixing is more common in Japan, North America, and southern Europe (Svenska Institutet för Standarder, 2005).

In northern Europe, and particularly in Sweden, dry mixing is the most commonly used technique due to the high natural water content typically found in fine-grained soils. Dry deep mixing could be installed down to 25-35 meters depth depending on machines and market (Kitazume & Terashi, 2013). The Swedish machines differs from those used in Japan and this means that the Japanese machines are capable of installing deep mixing down to a depth of around 35 meters, while 25 meters is seen as the greatest possible installation depth in Sweden (Svenska Institutet för Standarder, 2005).

The Swedish Traffic administration (Trafikverket), has requirements and recommendations that must be met for deep mixing. Design of deep mixing must be done in at least safety class 2. If buildings are planned to be built upon the improved soil, safety class 3 must be used (Trafikverket, 2023) There are also recommendations that safety class should be considered for use if the soil has a strength of less than 8 kPa before the improvement or if the embankment height exceeds 4 meters or a load of 80 kPa (Trafikverket, 2023). Trafikverket also sets requirements for the amount of binder to be used in deep mixing. A minimum of 80 kg of binder per cubic meter must be used according to Trafikverket's guidelines (Trafikverket, 2023).

2.2.1 Application

The applications of deep mixing are mainly in fine grain soils, such as natural clays. Deep mixing is possible to use in all fine grained soils, and it works when the grain size is up to around 0.2 mm (Kupryianchyk & Song, n.d.). For bigger grain sizes than that, there are better and more suitable ground improvement methods than deep mixing. This means that deep mixing mainly is effective for clay, silt and partly for sandy soils. Another factor that is important for deep mixing is that the soil has a water content of at least 20 percent, especially if dry mixing is used as commonly in Sweden, as water is needed for the dry binders to react in soil. For lower water content, there are difficulties with the reaction for the binders used in dry deep mixing, which is the technique usually used in Sweden.

Factors that prevent the installation of deep mixing includes bigger stones, rocks, roots and stumps (Peter Carlsten, 2000). This is because the mixing tool is sensitive to larger fractions in the soil and work the best in homogeneous fine-grained soils. This means also that there are problems when using deep mixing in unsorted soils or soils consisting of filling materials of different fractions. Another installation issue is ground frost that is common in Sweden during the winter. A deeper ground frost than 10 centimetres could prevent installation of deep mixing (Peter Carlsten, 2000), which could lead to unexpected and unpredictable interruptions and delays in production.

Installation of deep mixing may increase the permeability of the soil dramatically. For a fine-grained clay stabilised with deep mixing, the permeability could be 200-600 times bigger according to (Larsson, 2006). When calculating the time dependent settlements, the effect of a higher permeability is around 1000 times bigger than the original permeability of the clay (Peter Carlsten, 2000). As recommended by (Trafikverket, 2016) a factor of 1000 should be used when lime is used as binder and 500 when cement or a combination of lime and cement is used, when calculating the time dependent settlement. On the other hand, other studies indicate that the hydraulic conductivity of lime-cement column systems is highly variable and not necessarily increased in a consistent or proportional manner, or that the permeability figure is uncertain (Bozkurt et al., 2023); (Baker, 2000). This is further supported by the fact that hydraulic conductivity in column-stabilised clay is difficult to measure reliably and shows large spatial variability depending on soil conditions and installation effects. This is also motivated by that when the lime and cement react with the water in the soil and become something cement-like, which does not have a drastically higher permeability than clay. Consequently, there is no clear consensus that lime-cement column installation leads to a systematic or dramatic increase in the hydraulic conductivity of the soil mass.

2.2.2 Installation

The installation is usually carried out with different machines depending on the length of the columns. As previously noted, the different deep mixing methods are distinguished by the type of installation equipment used. For column lengths exceeding approximately 10-13m, the largest class of mixing equipment is required, enabling installation depths of up to about 25m. The column diameter is selected based on site conditions, equipment availability and the performance requirements of the soil improvement. For dry deep mixing in Sweden, the commonly used column diameters typically range between 0.5 and 1.0m (Svenska Institutet för Standarder, 2005).

Installation of dry deep mixing is carried out in five steps, as shown in Figure 2.1 (Svenska Institutet för Standarder, 2005). In the first step, the mixing tool is positioned at the place where the column should be created. In step 2, the shaft tool penetrates the soil and when reaching the desired depth, the shaft is withdrawn and during step 3, the residual soil (dry crust) is removed. In step 4, the rotation of the mixing tool starts, and the soil gets mixed with the binder. The rate of rotation and the rate at which the tool is lifted towards the surface is depending on the soil properties. In step 5, the mixing toll is withdrawn close to the ground surface, and the complete column is created.

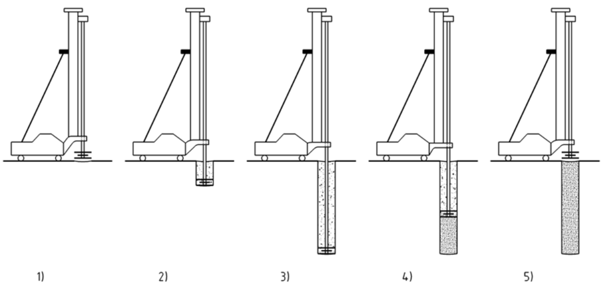


Figure 2.1: Installation of dry deep mixing (Svenska Institutet för Standarder, 2005)

The installation patters of the columns are depending on what effect of soil improvement that is required, stability or settlements. If stability is required, in particular when considering slopes, the columns are usually placed in a line perpendicular to the sliding surface where the failure is expected to provide safety for landslides. On the other hand, if decreased settlements are desired, the columns are placed in a square or triangular pattern (Svenska Institutet för Standarder, 2005). The distance between the columns, called the centre-to-centre distance, is together with the column diameter depending on the properties of the soil and load, and the improvement factor needed by installing deep mixing columns. Commonly used installation patterns are shown in Figure 2.2.

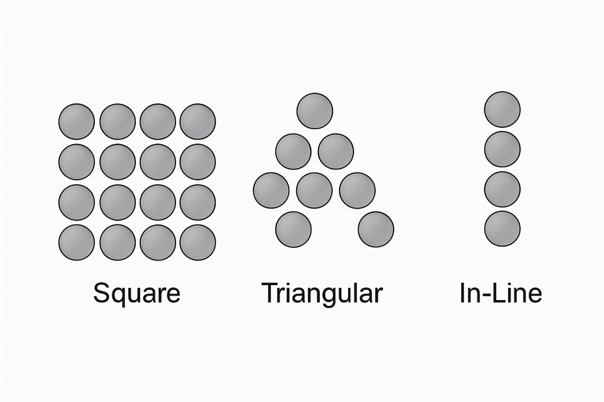


Figure 2.2: Common installation patterns of deep mixing

2.2.3 Environmental aspects

Deep mixing is regarded as a technique with a high climate impact. The environmental impact comes primarily from the production of the raw materials used in deep mixing, mainly the binders including lime and cement. Secondly, the transport and disposal of excess materials from the installation is also a factor to consider together with the climate impact of the installation itself. The production of cement means that carbon emissions are created, which cannot be avoided. The first step to produce cement is to burn limestone to obtain burnt lime (CaO). The reaction is called calcination and the formula is shown in Equation (2.1). During the process, carbon emissions are created. In addition, the calcination reaction is dependent on very high temperatures, around 1000 degrees celsius, which means high energy consumption. In the next step, the burnt lime reacts with silicon dioxide to create calcium silicate. Even this reaction is done at high temperatures, around 1450 degrees celsius. The carbon emissions of cement production are therefore dependent on the type of fuel and energy used. If fossil fuels are used, the carbon emissions from the energy use are very significant.

$$CaCO_3 + Heat \rightarrow CaO + CO_2 \tag{2.1}$$

$$CaO + H_2O \rightarrow Ca(OH)_2 + Heat \tag{2.2}$$

The other part of the binders is lime, which also has a high climate impact. Limestone ($CaCO_3$) is converted to burned quicklime (CaO) in the calcination reaction shown in Equation (2.1) above. The quicklime is then converted to hydrated lime by Equation (2.2). Both quicklime and hydrated lime could be used for deep mixing, but the Swedish Transport Administration recommends quicklime to be used (Trafikverket, 2016). If quicklime is used, it becomes hydrated lime in the soil by the reaction shown in equation above that happens in the soil. Allowing this reaction to occur in the soil has positive aspects in that it means that the column binds more water and that it contributes more quickly to higher strength in the soil (Kupryianchyk & Song, n.d.). In addition, the heat released when Equation (2.2) occurs in the soil contributes to the evaporation of water in the soil. This, together with the fact that the reaction in the equation consumes water, contributes to the drying out of the soil, which is important for the strength to increase. On the other hand, usage of quicklime places higher demands on the water ratio in the soil and using quicklime in drier soils can therefore be problematic.

In addition to the carbon dioxide related climate impact discussed above, lime quarrying is also associated with other environmental aspects that must be considered. Lime quarrying is often referred to as a threat to biodiversity at the site where the quarrying takes place. Moreover, groundwater related issues, including the impact of lime quarrying on the availability of groundwater of sufficient quality and quantity, must also be considered.

For reduction of carbon impact from deep mixing, the focus is mainly on finding alternative materials to use instead of lime and cement. Normally, a combination of 50 percent cement and 50 percent lime is used in the columns. Depending on soil and conditions, the shares of lime and cement could differ. To reduce the climate impact, other materials than lime and cements could be used in the binder. Current requirements means that the proportion of lime and cement must be at least 70 percent of the binder to call it deep mixing with lime cement columns (Trafikverket, 2016) This means that there is a possibility of using up to 30 percent of alternative materials.

One substance that partly could replace lime and cement is fly ash. Fly ash is a by-product of coal combustion which is separated from the flue gases in dust filters during combustion at high temperatures (Kupryianchyk & Song, n.d.). The availability of the material is high, and the cost of fly ash as a material is almost free, excluding transportation costs (Åhnberg & Holm, 1986). Fly ash as a binder can react with water in soil without the addition of cement or lime. However, fly ash has low reactivity, which means that the reaction takes a long time, which makes it less interesting to use fly ash alone as a binder in soil stabilisation (Kupryianchyk & Song, n.d.). Nevertheless, when fly ash is mixed with lime and cement in the binder, calcium hydroxide is released from the lime and cement, which increases the reactivity of the fly ash. This leads to fly ash gets characteristics similar to cement in soil. If fly ash is included in the mix of binders, usually a fly ash content of 5-30 percent is used together with lime and cement (Kupryianchyk & Song, n.d.). Fly ash has also characteristics to create immobilisation of some pollutants in soil, which makes it extra suitable when contaminated soil is improved.

Slag can also be used as an additive in soil improvement. It is produced when iron ore is reduced to pure iron at high temperatures, where the slag could be seen as a by-product from this process. Because slag is considered a by-product, it has a quite low climate impact. The strength of soil stabilised with deep mixing in which a part of the lime and cement has been replaced with slag varies in relation to the slag content. Tests show that some mixes with slag can get a higher strength than ordinary lime-cement columns (Kupryianchyk & Song, n.d.). On the other hand, if the slag content reaches about 50 percent of the total binders, a clear reduction in the strength of the stabilised soil can be noticed. However, soil stabilised with slag generally has a slightly higher strength than soil stabilised with fly ash of the same ratio. Like fly ash, slag can have properties that contribute to the immobilisation of certain contaminants in the soil when it is used to stabilise the soil.

Gypsum can also be used as a binder in deep mixing (Kirsch & Bell, 2013). Gypsum primarily serves as an alternative to lime in very soft clay soils.

Another product that aims to reduce the climate impact by the binders in deep mixing is Multicem, produced by Heidelberg Materials. The product means that the lime is replaced by a composition called cement kiln dust (CKD), which is a by-product that is formed when cement is produced. CKD consists of different substances that are separated from the cement by dust and gas collection during the cement production process. The main content of CKD includes unreacted or only partially reacted ingredients when cement is produced, which could be things such as lime, limestone or additives. CKD contains also a high concentration of volatile compounds, sulphates and alkalis among others. This is also the reason why CKD could not be used in cement production again, instead of the raw materials. In cement manufacturing, the residual product CKD is estimated to constitute 15-20 percent of the amount of cement produced (Al-Bakri et al., 2022).

For the mixing of the binder, instead of using a typically 50:50 distribution of lime and cement, the distribution between cement and CKD could also be 50:50. It is possible to have a CKD-mix of 50 % even though the Swedish Transport Administration only allows 30 % alternative materials in addition to lime and cement. Thus, parts of the CKD that are used are classified as materials that the Swedish Transport Administration approves in the permitted mix. Multicem has similar characteristics to those of traditional deep mixing based on lime and cement. However, some tests show that Multicem reacts slightly slower than lime and cement, which is why it takes longer to achieve the strength of the improved soil when Multicem is used (Kupryianchyk & Song, n.d.).

Regarding the climate impact for different binder materials, it should be noticed that mixing with alternative materials can mean that the total amount of binder materials needed to get the same strength in the improved soil can increase. Thus, even though alternative materials have a lower climate impact, this advantage may be limited by the fact that larger amounts of the binder is required. The amount of total binder depends on what binders are used and in what proportions, as well as current site conditions. A comparison between lime-cement columns in a 30:70 mix and Multicem shows that the total amount of binders increased by 40-110 % for the two different sites studied in the report (Kupryianchyk & Song, n.d.).

2.3 Stone columns

Another technique used to improve weak, soft soils such as loose sand or marine clays, is to install stone columns. This method is, similar to deep mixing, performed in-situ but utilises crushed rock material or compacted gravel to replace or compact existing soil, ultimately creating rigid columns that are much stiffer than the surrounding material. Today, various configurations of stone columns are available, predominantly categorized by the installation processes, as further discussed in Section 2.3.2. The most common variation of stone columns is vibrated stone columns. In order to sustain the desired properties of the finished columns, the aggregate used for vibrated stone columns shall be sufficiently stiff and chemically stable to prevent reactions occurring between the material and the surrounding soil from breaking down the fill material over time. (British Standards Institution, 2005). The use of stone columns provides a range of advantages for the soil such as increasing the overall bearing capacity and significantly reducing the magnitude of settlements (Foda et al., 2023). Furthermore, stone columns can improve slope stability and mitigate the risk of liquefaction in cohesive soils (Castro et al., 2014). Additionally, since the column material typically exhibits a higher permeability than the treated soil, the columns function as vertical drains, which implies a faster consolidation time and thus a reduction in settlements over time.

2.3.1 Application

As previously mentioned, the implementation of stone columns generally works best for soils with fine grain sizes such as soft to medium clays. For these soil types, both the addition of the fill aggregate and the compaction of the column material along with the surrounding soil works to improve the overall stability of the ground. The mechanical properties of the soil matrix, such as undrained cohesion and Young's modulus, thus increase as a result of the installation of columns (Guetif et al., 2007).

While cohesive soils are characteristic for the Swedish geological landscape, the utilization of stone columns has not yet achieved widespread adoption in the Swedish geotechnical practice. In western Sweden and the Gothenburg area, there has yet to be a project that has used stone columns as a measure of ground improvement. In fact, there are only a few projects in Sweden that have employed the strategy. Like the ongoing construction of Norrbotniabanan for instance, where an innovative programme using stone columns installed without vibrating tools is used in order to stabilise the ground for the new railway (Trafikverket, 2024b).

Soil properties is one aspect that greatly affects the possibility of using stone columns as a means of stabilisation. Although the columns work best in soils of finer grain size, too soft soils may possess a critically low undrained shear strength. As stated by (Ünver & Ünver, 2016), installing stone columns in clay with an undrained shear strength of less than 15 kPa will likely result in excessive settlements. When the lateral strength provided by the soil is not enough to support the horizontal pressure caused by the weight of the stone material, the columns can bulge and thus cause settlements instead of counteracting them. This fact suggests that the improvement technique should be approached with caution in order to avoid excessive stability or settlement issues, especially in weaker clays that are not uncommon in the Swedish geological environment.

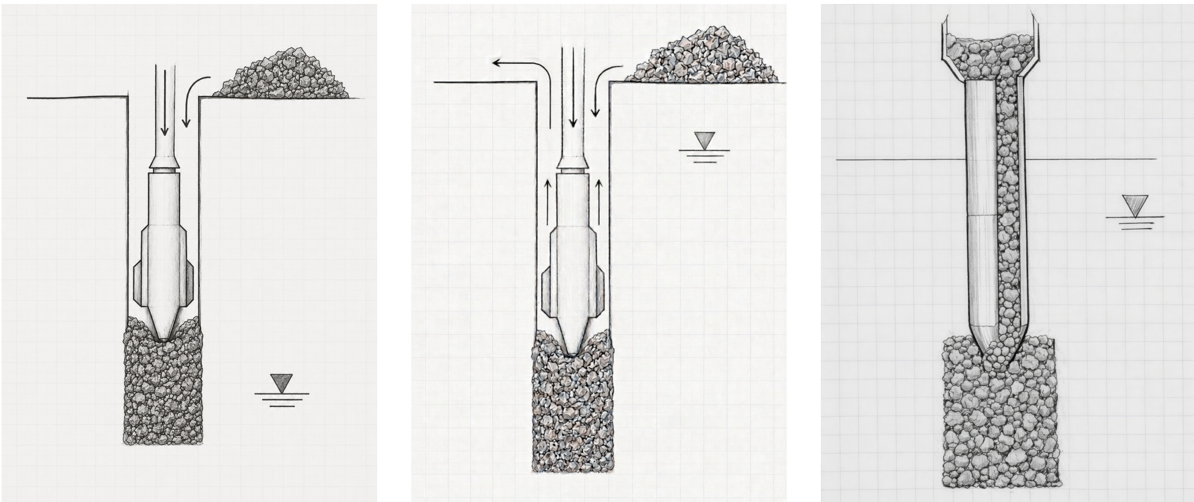
2.3.2 Installation

Installation of stone columns can be done through multiple approaches. In most cases, the installation includes some vibration to compact the material after it is discharged into the soil. These columns are referred to as vibro-stone columns. Several different approaches such as vibro-replacement or vibro-compaction can be chosen when performing this installation technique depending on site conditions (British Standards Institution, 2005). Within these two vibration categories, the stone columns can be constructed under wet or dry circumstances, constructed from the bottom up to ground level or from top to bottom.

One technique is the dry top feed, predominantly used in shallow to medium deep treatment depths and best applicable in granular fine deposits above the groundwater table. See Figure 2.3a This method involves piercing the ground using a steel probe, taking advantage of its weight along with compressed air being dispersed to make room for the fill material to be placed into the hole from the top. This is done in different stages where the vibrating probe is compacting the fill material and unifying it with the surrounding soil step by step as the probe is raised towards the ground surface. The wet top feed process is quite similar to the previously mentioned dry process. This method is commonly used at medium to deep treatment depths and when the dry method is geotechnically unsuitable due to low stability in soft cohesive deposits or simply when the installation takes place below the groundwater table (McCabe et al., 2009). The main difference between these methods is that the wet feed uses water jets instead of compressed air.

The wet top feed method, as shown in Figure 2.3b is also generally more effective for use in softer cohesive soils compared to the dry top feed. One method that nowadays is often preferred over the wet top feed is the dry bottom feed (McCabe et al., 2009). This method is effective as treatment in soils with shear strengths of well below 15 kPa, and examples in Poland and Germany for instance, it has been proven effective for soils with undrained cohesion of as low as 4-5 kPa. The vibrator in this method is, just as the previously mentioned methods, multi-functional by both vibrating the existing soil to aid the probe forming the initial hole and then vibrating the granular rock, interlocking it with the soil material.

The dry bottom feed process is visualised in Figure 2.3c. As the name suggests, it is equipped with a unique feeder that enables the column material to be displaced from the tip of the probe, thus constructing the column from bottom to top (British Standards Institution, 2005). Lesser used installation methods include bottom rammed columns, which however would neither be profitable nor safe for usage in soft cohesive soils. The diameter of stone columns differ depending on the project and treatment processes. However, the most common diameter of the columns ranges from around 0.6 to 1 meter. If larger diameters are required, coupling of column vibrators can be applied to solve these situations, which is often wanted for softer soils (Mitchell, 1981).



(a) Dry top feed process (b) Wet top feed process (c) Dry bottom feed process

Figure 2.3: Different installation/feed processes of stone column construction.

2.3.3 Environmental aspects

In order to inspect the overall sustainability of the use of stone columns as a means of stabilizing the ground, it is crucial to evaluate the environmental potential these columns can have. Embodied carbon dioxide could be described as a measure of assessing environmental impact by providing an estimate of greenhouse gas emissions. Most construction projects use some kind of economical evaluation and comparison before choosing the best possible alternatives for conducting the project, which generally will result in a certain percentage of saved resources.

According to (Egan & Slocombe, 2010), a similar approach regarding environmental perspectives show that when ground improvement alternatives are implemented it could result in significant decreases of up to 90 % of the embodied carbon dioxide. The rather simple principle reduce, reuse and recycle can provide assistance for minimising the environmental impact in many cases. This circular view on recourse management is a great tool in streamlining the usage of stone columns ensure a desired sustainability performance. Reducing the amount of raw material and other additives that is needed to construct the stone columns is an obvious point that can improve environmental sustainability since if less material is used, there will be a decrease in energy demand. Reusing existing columns is another aspect of the circular sustainability. This has been done in some cases where the stone columns have been reused on previously vibrated sites (Egan & Slocombe, 2010). Recycling material is also of importance from an environmental point of view. Instead of sourcing new raw fill materials, using recycled rock from other projects for instance both reduces produced waste and saves energy. Along with the possibility to reuse aggregate fill from sources where the material is considered as waste and thus sustaining a circular system for the material use, the displacement method (as for dry bottom feed), where the hole is created by laterally displacing the soil and therefore does not produce any excess waste that needs to be discharged at landfills. (G. T. Senthilnath & Y. Harikrishna, 2010) This is another example of how sustainability goals can be sustained.

2.3.4 Complications

Unfortunately, there may be some problems one can encounter when utilizing stone columns as a means of stabilisation. For example, clogging is a phenomenon that can occur when stone columns are installed in clayey soil. This clogging arises when the fine-grained soil particles gets stuck in the cavities along the soil-column interface. This will directly lead to a reduction in drainage capacity by reducing the permeability of the column surface (Indraratna et al., 2013). Moreover, as discussed in the installation section, installation effects could vary greatly depending on chosen method and soil properties. Aspects like potential liquefaction need to be considered and improvement of sensitive soils should be approached with great caution to avoid any effects caused by vibration or other installation impacts.

2.4 Lightweight fill

Using lightweight fill as a measure of reducing the load is another approach that can aid improving general system performance, especially considering the ambition of reduced settlements. The implementation is neither technically nor physically complicated. Commonly used for embankment and/or fill constructions, lightweight fill is something that brings several advantages. Lightweight fill is not one single material, but rather an umbrella term for several materials designed to substantially reduce pressure on underlying soil while maintaining sufficient stiffness to carry the construction above.

The choice of material varies, depending on different wanted qualities or specific site conditions. Organic fill can be used, but in order to eliminate the possibility for deterioration, inorganic material, such as expanded polystyrene, foam glass or Leca is often used.

Expanded polystyrene (EPS) is relatively common to use as a lightweight fill material and is primarily used for embankment construction such as bridge approaches. According to (Miao et al., 2013), the first project using geo-foam was in Norway in 1965 and it has since 1972 been used in many projects worldwide. Other than being stable in a biodegradable matter, benefits of using EPS as a fill material include that the production can be adjusted to obtain various properties (Peter G Nicholson, 2014). Some beneficial properties of EPS are; low compressibility, isotropy, 100 % recyclable. Additionally, the properties of the material can be modified and the material can reduce noise and vibrations. A disadvantage is the flammability and deterioration if chemicals leak to the ground e.g. due to an accident. For the applications in this thesis, EPS is not considered.

2.4.1 Foam glass

Another lightweight material that could be used as a fill material for projects with ambitions of reduced load is foam glass. It is a material that is extremely versatile with several possible applications within modern construction. Road constructions, building constructions or even for green roofs are some examples, where the material is beneficial thanks to its drainage capacity and thermal insulation (foam Glass UK Ltd, 2024). In the manufacturing process of the material, crushed recycled glass is heated and expanded to create a porous aggregate. The glass expands to about five times its previous size, resulting in a grain size of around 10 - 60 mm (Eriksson & Hägglund, 2008). The high air content in these aggregates that arises from the heating, results in a material with a high insulating ability and low density (around 200 kg/m^3).

According to (Hasopor AB, n.d.), which is the only Swedish manufacturer of the product, utilization of cellular glass has a row of different benefits in various aspects. Firstly, the material is made from 100 % recycled glass collected from households across Sweden. The potential for reusing the material is also very high, and can thus avoid the need for disposal. The reduced weight enables reduced excavation in construction projects that require removal of soil masses, which subsequently can significantly reduce construction times. Moreover, foam glass possesses an adequate drainage capability due to the high porosity of the material. Regarding overall stability of the material in the sense of an embankment or slope fill material, foam glass retains a great stability thanks to its high friction angle which can reach 45 degrees, although as recommended by (Trafikverket, 2023), at least 42 degrees shall be used in the design stages. This is important for projects concerning overall stability and further motivates the possibilities of using this material as fill aggregates in a wide range of projects.

2.4.2 Lightweight expanded clay aggregate (LECA)

Leca is a granular ceramic material that has been in use within infrastructure and geotechnical projects for over 60 years (Leca Saint-Gobain, n.d.). As the name suggests, it is a lightweight material produced from clay which, due to its manufacturing process obtains various attractive properties regarding use in various construction projects. Similarly to foam glass, the material is manufactured using ovens that both dry out and expand the material beads in order to create a porous, durable material with a grain size of around 0-32 mm. Among the various project applications for Leca, geotechnical problems such as settlement reduction from reduced excessive loads, insulation to protect the ground from frost damage or increased drainage capacity are some examples where Leca can be used in order to find desirable solutions for these cases. Thanks to its persistency, Leca is a material with a wide range of benefits. Excavating and reusing Leca enables the possibility of major environmental benefits for instance. Moreover, the environmental potential is expected to have a high potential in future uses of the material and according to (Leca Saint-Gobain, n.d.), utilizing climate-compensation, the usage of recycled Leca as a fill material can theoretically reach net-negative emissions of CO_2-equivalents for projects with strict environmental policies/ambitions.

2.4.3 Application

As a result of the wide range of lightweight fill varieties, as well as the great variation in properties of each material, the scenarios of utilizing lightweight fill are many. As previously mentioned, EPS is attractive for usage as road embankments and bridge approaches thanks to its persistent shape and low compressibility. foam glass is rewarding to use when replacing with existing soil to increase stability and reduce settlements for most kinds of construction projects, but also not uncommon to support road embankments (Eriksson & Hägglund, 2008). Further, similarly as for Leca, the insulating ability and drainage properties of the foam glass are aspects that greatly can reduce frost damage and consolidation time which makes these favourable for usage in road construction.

2.4.4 Installation

One major benefit of installing lightweight fill is the weight of the material. This makes it relatively easy to manage which enables the possibility for faster construction time and eliminates the need of staged construction (Peter G Nicholson, 2014). EPS-blocks can, for instance easily be cut into desired pieces using handheld saws and no heavy machinery or other advanced equipment is needed. When installing the geo-foam, some guidelines are important to follow. Firstly, the blocks shall be placed in an alternating pattern to minimise the risk movement among the group, both laterally and vertically. Further, it is important that the blocks are thoroughly installed and secured in place. This can be achieved using both adhesives or “gripper” plates. Installation of foam glass and Leca is usually performed by tipping the material, either to fill an excavation or as embankment material. Both materials should in most cases be enfolded by geotextile and packed to a desired stage.

2.4.5 Complications

One central disadvantage of using lightweight fill as stability improvement or settlement reduction, is due to the same cause which gives the materials their wanted properties. The extreme lightweight of the materials implies that the design or layout of the solution should be approached with great caution regarding groundwater. If the groundwater table rises above the level of which the fill is located, the fill can essentially float, and thus cause heave of the material overlying the fill. If installed incorrectly or in conflict to recommendations, the high insulating ability in the fill material could potentially cause frost damage and slippery surfaces on roads constructed on the fill.

3
Case Studies

To enable the analysis and comparison of different ground improvement techniques, two sites with somewhat varying geological conditions were selected. Both sites are located on the west coast of Sweden and are characterised by thick layers of soft clay with low undrained shear strength, which is typical for the region. At both sites, a large number of geotechnical investigations have been performed, providing the data used in the calculations presented later in this thesis. In addition to soil layer sequences and data used for settlement analyses, both sites are situated on slopes that require stability assessment. Consequently, potential landslide risks must be evaluated, which in this thesis is carried out using GeoStudio. This is especially important to enable sufficient safety for future development at the sites that cause an increase in the load on the slopes.

3.1 Case Hisingen

The first case is located on Hisingen in Gothenburg. The site contains a thick clay deposit, 40m in depth, with no penetration of frictional soil layers. The clay is overlain by a thin, approximately one meter thick layer of silty clay, and at the surface a fill layer consisting of various materials and grain size fractions is present. The geotechnical investigations done at the site claim that this fill layer consists of various soil material such as sand, clay and gravel, but also miscellaneous other material such as bricks, porcelain, glass and asphalt. A visualisation of the soil layer sequence is available in Figure 3.1.

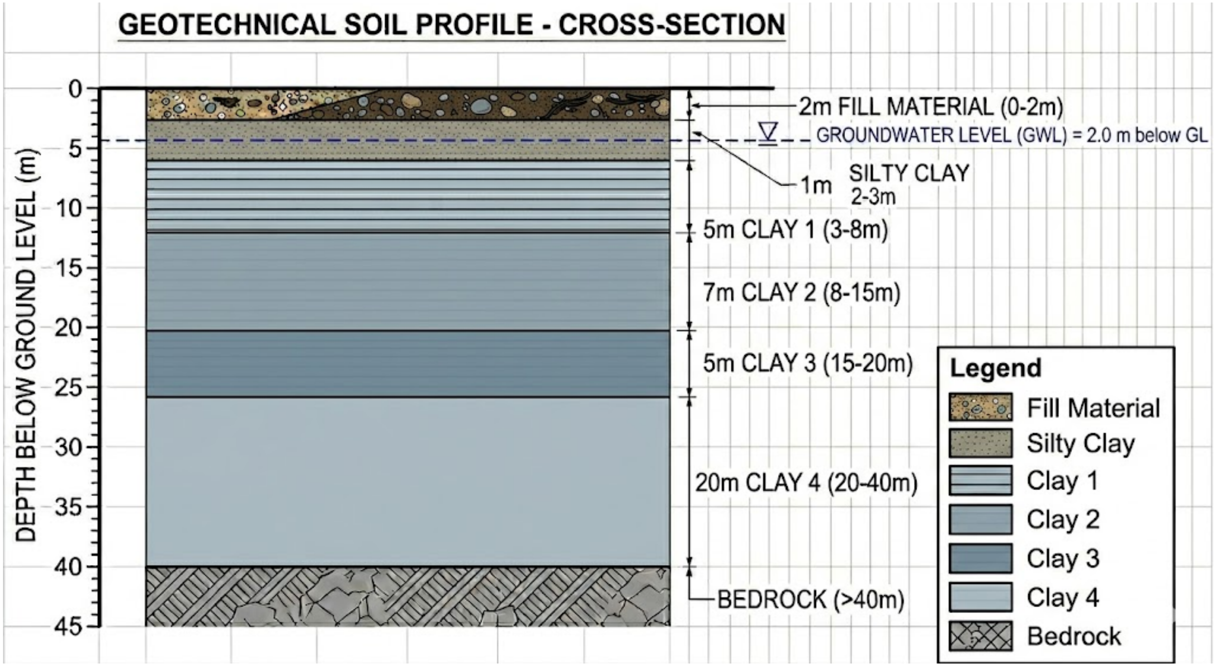


Figure 3.1: Soil layer profile at the Hisingen site

The clay at the site is divided into 4 dividing layers, based on different clay parameters and the availability of CRS tests at different soil depths. The clay also has a low undrained shear strength that are increasing with depth, shown in Figure 3.2. The site is located below the highest coastline and the clay is postglacial clay, which implies an increased salt content originating from the seawater. The geotechnical investigations claims that the clay partly has properties that classifies the clay as quick clay, and it should therefore be seen as very sensitive.

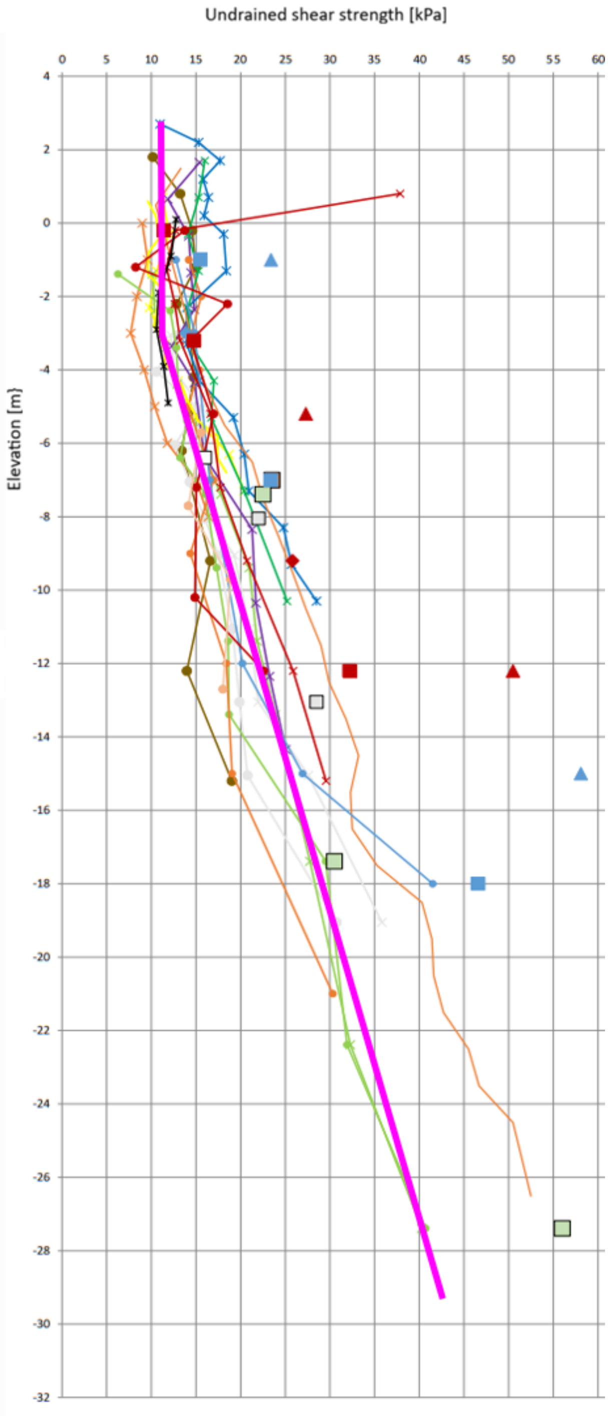


Figure 3.2: All measurements of undrained shear strength at the Hisingen site with trendline in purple

At first glance, the site appears predominantly flat, with only a slight inclination towards the river. A more detailed evaluation of topographic maps, however, indicates that the west–east slope is steeper than initially perceived. The critical section of the slope is found at the shoreline, where the ground surface descends sharply and subsequently merges with the riverbed. The cross section in Figure 3.3 represents the general slope throughout the area and is the slope that will be used later in the slope stability analysis in GeoStudio. The total vertical distance of the slope down to the riverbed is around 11 metres.

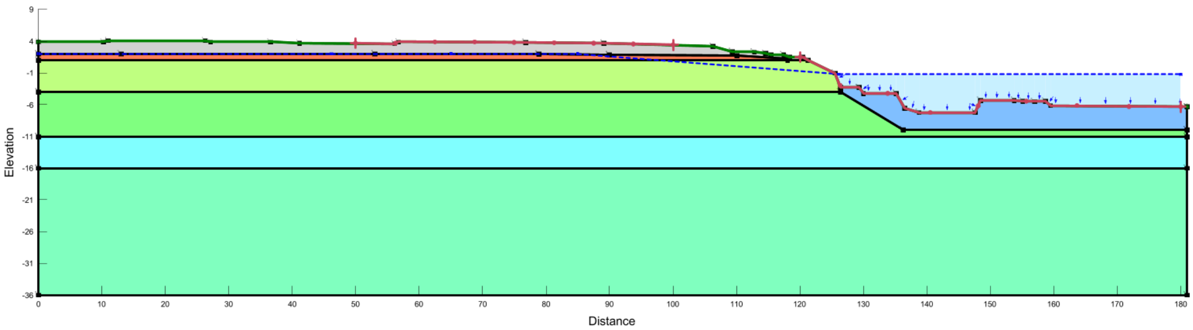


Figure 3.3: Slope profile over the Hisingen site

The measurements claim that the groundwater level is located 2 metres below the ground surface. Note that there may be variations within the area which is not measured everywhere and therefore are not considered. The groundwater level can also generally be seasonal and weather dependent, which is not taken into account in this thesis. Instead, a groundwater level of 2 metres has been assumed everywhere.

3.2 Case Uddevalla

The other case used in this thesis is located in Uddevalla, around 100 kilometres north of Gothenburg. This soil profile is mainly composed of clay deposits, although the total soil depth is significantly shallower than at the Hisingen site. The total depth is 16 metres in this case, of which 13 metres consists of clay. In addition, there is a thin layer of silt in between the clay and bedrock. Above the clay, another metre of silt is present, and the top layers consists of a 1 metre thick dry crust. The groundwater level is assumed to be located 2 metres below the ground surface across the site, which is an average from the documented measurements and the conditions at the borehole from which the data for the calculations is taken. A visualisation of the soil layer sequence can be found in Figure 3.4.

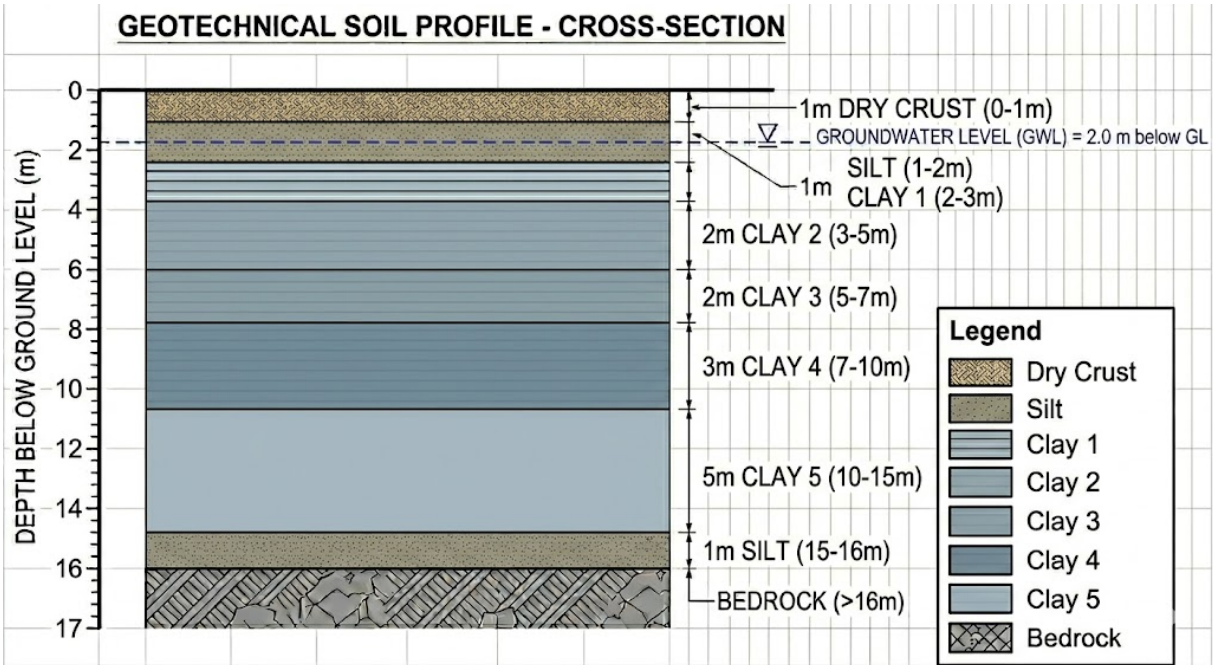


Figure 3.4: Soil layer profile at the Uddevalla site

At this site, the clay is divided into 5 different layers, that are based on the different parameters for the clay and the availability of CRS tests. The clay is generally silty but still has a low hydraulic conductivity and a low undrained shear strength that is increasing with depth, see Figure 3.5. There is also occurrence of clay classified as quick clay, especially at the bottom of the clay deposit.

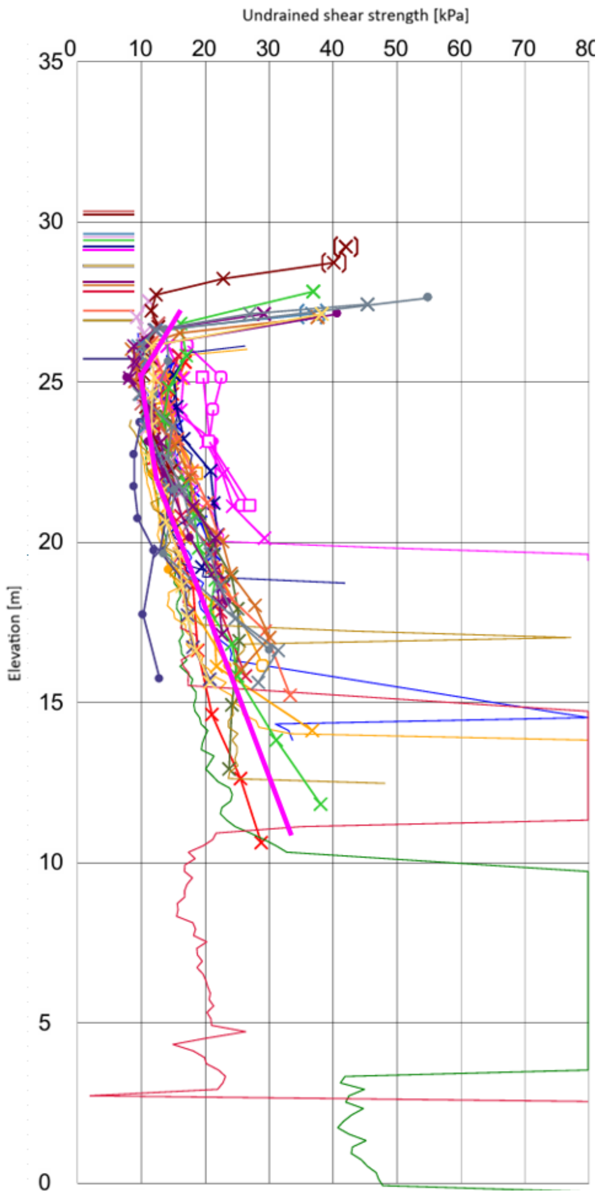


Figure 3.5: All measurements of undrained shear strength at site Uddevalla with trendline in purple

Similarly to the Hisingen site, the area does not inherit a steep slope that stretches across the area. However, on the minor gradient that is present on site and continues further north along the slope, there is a great sports complex with an aquatic centre, a football arena as well as an indoor track and field training facility. Even if not directly imposing a considerable load close to the crest, it may be worth noting this when modelling the area. With exposed bedrock north of the area and a considerable depths of clay in the south, the soft soil is expected to sit on a steep layer of bedrock. At the site of interest, just south of the sports complex, the slope does not inherit any substantial gradient. Also, at the bottom of the slope, there is a railway embankment that could potentially act as a pressure bank for the slope which likely does not inherit any critical stability issues at first glance. The cross section of the site, provided in Figure 3.6 will later be used in the GeoStudio stability analysis.

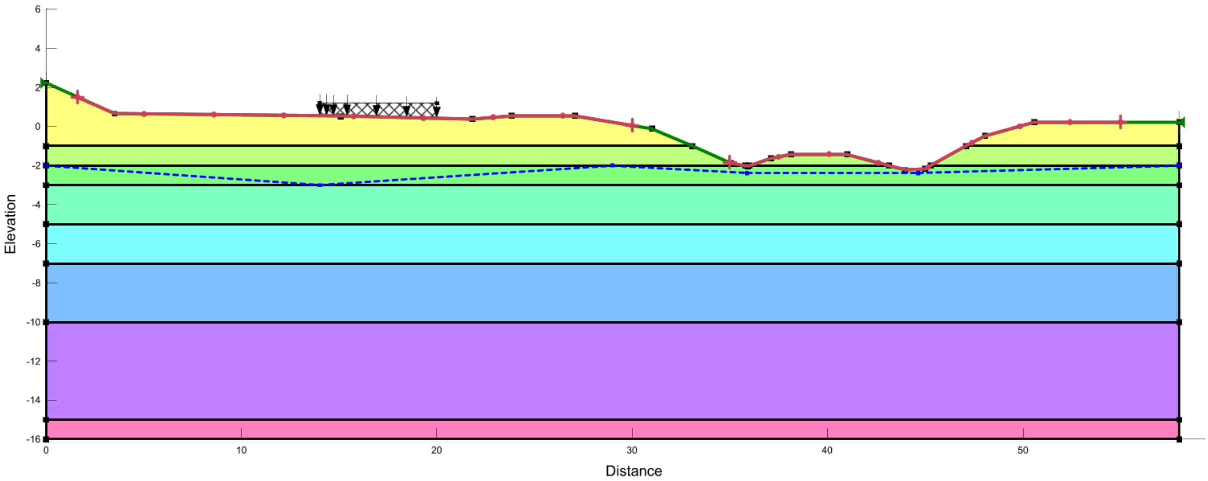


Figure 3.6: Slope profile over the Uddevalla site

3.3 General calculation information

For the settlement calculations, an on site construction of a 1.5 metre high embankment is assumed in both cases. This corresponds to a load of 28.5 kPa using parameters of the embankment, provided in tables 5.4 and 5.6. By constructing an embankment of this height, the resistance of the soil to settle during construction, loading and usage can be analysed, and its improvement needs be investigated.

For slope stability calculations, the slopes provided in Figures 3.3 and 3.6 were analysed. Here, a surcharge load of 40 kN/m^3 is used to simulate a traffic load on the road that is constructed in the Uddevalla case. At the Hisingen site, there is no additional load considered. Mostly because of the already low stability of the slope but also since no additional construction is planned for the real case that provided material properties and geometry of the site.

4

Hand calculations on settlements

Analytical settlement calculations were performed to complement the numerical simulations and to provide a reference for comparison with the results from PLAXIS.

4.1 Deep Mixing

The Swedish design method is used to calculate settlements when deep mixing is installed as a ground improvement material. According to (Trafikverket, 2023), the method assumes three different zones of the columns in the soil. Zone A is the zone closest to the ground surface, where the columns are fully plastic and carry their maximum load possible, but are not seen as fully mixed with the soil. Zone B is the zone in the middle, where the columns are seen as a composite material together with the clay and the behaviour in this zone is assumed to be elastic. Finally, zone C is the zone below the bottom of the columns, and in this zone, the load on the columns is seen as reduced by transfer of load in zones A and B. If the columns are end bearing, zone C is not considered because the bottom of the columns are in contact with a firm layer.

The soil depth at Hisingen exceeds the possible installation depths for the current technique of installing deep mixing columns. Therefore, the calculations have to be accounted for as end bearing. For Uddevalla, the soil depth is less, and the columns can be installed down to a firm layer, in this case bedrock, and can thus be assumed as end bearing in this case. Regarding the installation patterns, a square installation pattern of the columns is assumed when using this method.

The settlement is calculated with the following equations. Firstly, the volume of lime cement columns in the soils, a, is calculated using Equation (4.1).

$$a = \frac{\pi \cdot d^2}{4 \cdot S^2} \tag{4.1}$$

The volume of lime cement columns is dependent on d, the diameter of the columns, and S, the centre-to-centre distance of the columns. With this calculated volume ratio, a stiffness modulus value, M_{block}, could be calculated for the improved soil.

$$M_{block} = a \cdot E_{col} + (1-a) \cdot M_{soil} \tag{4.2}$$

M_{block} is dependent on the stiffness of the columns, E_{col} and the stiffness of the soil, M_{soil}, and both of them are material parameters.

To determine change from Zone A to B, the two following equations for $\Delta\sigma_{block}$ Equation (4.3) and Equation (4.4) for floating columns or Equation (4.5) for end bearing columns could be put equal and be solved for z, which is depth and in this case is the depth that are the border between zone A and B. σ'_{v0} are the effective stress, that are dependent on the depth, z. $c_{(u,col)}$ are a material parameter.

$$\Delta\sigma_{block,lim} = M_{block} \cdot \frac{1.5c_{u,col} + \sigma'_{v0}}{E_{col} - 1.5M_{soil}} \tag{4.3}$$

$$\Delta\sigma_{block} = \eta_{LC} \cdot q + (1-\eta_{LC}) \cdot q \cdot \frac{B}{B+z} \tag{4.4}$$

$$\Delta\sigma_{block} = q \cdot \frac{B}{B+z} \tag{4.5}$$

With the z-value at the border between Zone A and B, the value for $\Delta\sigma_{block}$ at each depth could be calculated, which is used to calculate the settlements of each zone with Equation (4.8). B in equation Equation (4.4) and Equation (4.5) are the width of the surcharge load and q are the surcharge load. η_{LC} is calculated with the following Equation (4.6).

$$\eta_{LC} = \frac{L^{\frac{1}{v}}}{H} \tag{4.6}$$

Where L is the length of the column and H is the depth of the soil down to a firm layer. If the columns are end bearing, $\eta_{LC} = 1$ always, and therefore Equation (4.5) could be used instead of Equation (4.4). With the following Equation (4.7), v is calculated for floating columns to be used in Equation (4.6).

$$v = (M_{\text{block}} - M_{\text{soil}})^{0.1} - (M_{\text{soil}} - M_{\text{block}})^{0.1} \tag{4.7}$$

Then, the settlement for each layer could be calculated. $\Delta\sigma_{block}$ in Equation (4.8) is varying depending on the depth of where the block is located, the z value, and has to be calculated with

Equation (4.4) or Equation (4.5) for all depths where there is a block/zone border. z_{block} is the thickness of the block and M_{block} is the stiffness moduli. For zones 1 and 3, M_{soil} is used for M_{block}, and for zone 2, the M_{block} value of the deep mixing material is used.

$$\delta_{a,b,c} = \Delta\sigma_{block} \cdot \frac{z_{block}}{M_{block}} \tag{4.8}$$

The total settlement is calculated with Equation (4.9).

$$\delta = \delta_a + \delta_b + \delta_c \tag{4.9}$$

If the columns are end bearing, zone Z is not included and the corresponding term is excluded from Equation (4.9).

4.2 Stone columns

One method for hand calculation of settlements using stone columns is the Priebe method.
The Priebe method is used for calculating assumed end bearing stone columns. Due to the site conditions and the large clay depth at Hisingen, it is not possible to install end bearing columns there. The Priebe method is still used however, but the results have to be handled with care and should definitely not be seen as accurate. The finite element modelling in PLAXIS is where the main results, later used for comparison, will be evaluated. The drainage capacity of stone columns is primarily affected by the fact that they are floating. Since there is no permeable layer beneath the columns, their drainage effect cannot be fully utilised in this case. Furthermore, floating stone columns can mean that the entire improved block settles into the clay beneath the columns. For the Uddevalla site on the other hand, where end bearing columns are possible to apply, the Priebe calculations could be carried out as usual.

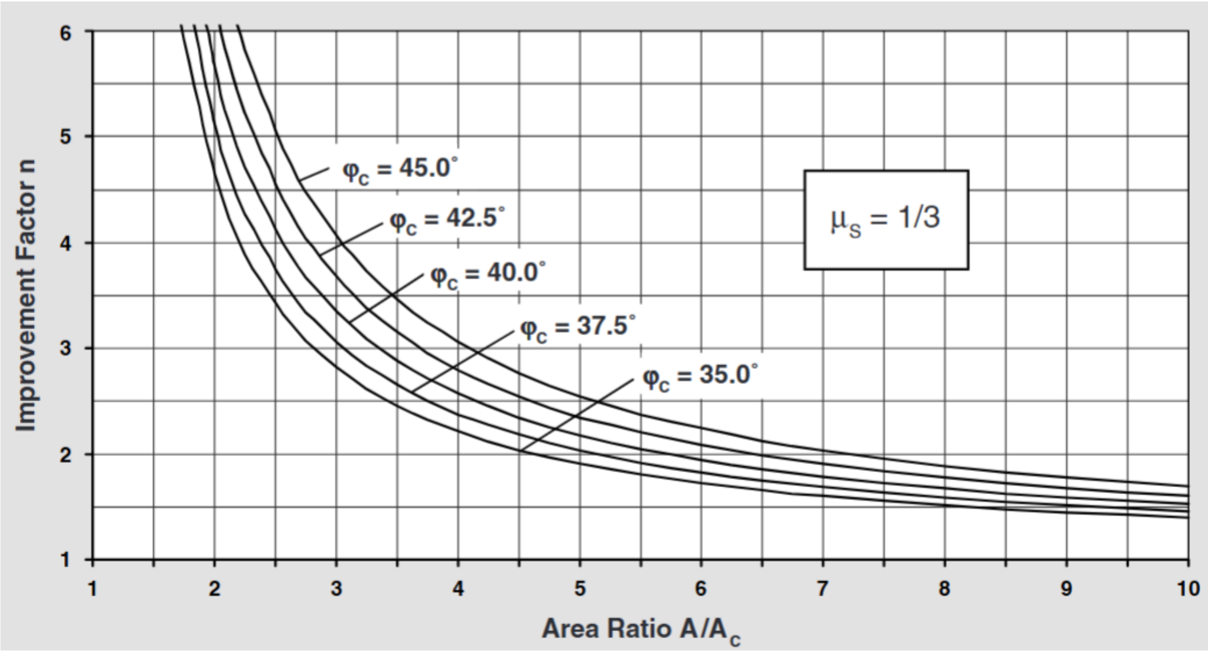


Figure 4.1: Priebe diagram for design of stone columns (Heinz et al., 1995)

With the calculated area to area column ratio and the dimensions of the column, the Priebe diagram could be used to determine an improvement factor, η, of the stone columns as shown in Figure 4.1 (Heinz et al., 1995). With this improvement factor, the settlement before improvement is divided with the improvement factor to obtain the calculated settlement after improvement, see Equation (4.10).

$$\delta_{Stone\ columns} = \frac{\delta_{No\ improvement}}{\eta} \tag{4.10}$$

As an explanation, settlement in unimproved clay is calculated in this case with the following Equation (4.11).

$$\delta_{No\ improvement} = \frac{q \cdot d}{M_{soil}} \tag{4.11}$$

4.3 Lightweight fill

The principle of lightweight fill involves substituting existing soil with a low-density material to offset the additional stress imposed by the construction. This implies that the settlement analysis for a soil body modified using lightweight fill can be conducted using the standard settlement calculation methodology. By treating the lightweight fill as a reduction in net load, the calculations then remain consistent as for those with unchanged soil and thus, ultimately limits the magnitude of settlements.

5

Numerical modelling in PLAXIS

As a complement to the hand calculations presented in the previous chapter, more detailed calculations needed to be conducted in order to provide a reliable foundation and reasonable results for proceeding with the economical and environmental calculations. These calculations were performed using the finite element method (FEM) in PLAXIS 2D. PLAXIS is a FEM software developed for analysing geotechnical engineering problems and is an effective tool for engineers wanting to analyse stability, deformations or groundwater movement in different geotechnical situations (Bentley Systems, 2025). One advantage of using PLAXIS for calculating settlements or other geotechnical interests, is that there are a lot of different methods and models that can be used in order to model the problem accurately and closely resemble the reality. This chapter will present these different approaches along with relevant material models and in short describe the influence they have on the accuracy of the settlement results. In addition, all parameters used for the models will be presented in this chapter.

Each of the two sites in this thesis was analysed using a unit cell modelling approach. In this case, a unit cell suggests a fraction of the site that is not overly complex but is still complex enough to accurately represent the behaviour of the soil reinforcement response at the site. This was done by modelling the axisymmetric unit cells as 2D strips that include the entire soil sequences plus potential improvement material, such as foam glass or stone columns. For the lightweight fill, the material was simply modelled in the top section of the unit cell, as fill materials should be modelled. However, the column materials were modelled in the unit cell by only modelling half of the columns, i.e., full column length, and radius instead of diameter. In theory, this will represent a three dimensional unit cell when it is rotated 360 degrees. This allows the unit cell to accurately represent a fraction of the improved soil body.

5.1 PLAXIS material model theory

Depending on site conditions and soil material, the modelling approaches of the unit cells vary. Geotechnical engineering can be complex and requires advanced models that take anisotropic and time dependent behaviour of the soil into account. Similarly, the different saturation phases that the soil can adopt also need to be accounted for. In order to manage these properties, and the accompanying changes, PLAXIS provides different material models that enables accurate definitions and behaviour of the soil. For frictional soils, such as sand and gravel, the Mohr Coulomb model was used. The same model was applied for all ground improvement techniques. When modelling the clay layers however, the soft soil creep model was used. This involves the consideration of over consolidation of the clay, referred to as over consolidation ratio (OCR) and pre overburden pressure (POP) in the software. To account for the time dependent creep settlements, the regular soft soil model was complemented by the soft soil creep model.

5.1.1 Mohr Coulomb model

The Mohr Coulomb model is one of the simpler models in PLAXIS, since it does not include any advanced material settings but utilises the most basic input parameters.(Bentley Systems, 2025). The model type is non linear and assumes a stress strain curve that is linear elastic - perfectly plastic. This approach means that in the software, the soil is behaving linearly elastic according to Hookes law up to a certain yield stress where it transitions into a plastic deformation and the strain increases without any additional stress.

5.1.2 Soft soil model

For analysing the long-term effects and taking consolidation ratio into account, a more advanced material model like the soft soil model is needed. The PLAXIS soft soil (SS) model is specifically designed to simulate the behaviour of normally-, and slightly over consolidated soils consisting of finer grained materials, such as clays, silty clays and peat. Fundamentally based on the modified cam-clay model, the soft soil model incorporates several adjustments to accurately capture properties such as the high compressibility that is typical for these softer soils under primary loading (Bentley Systems, 2025). The SS model define the soil stiffness through a logarithmic relationship between volumetric strain and effective stress, where modified swelling and compression indices describe the behaviour during primary loading, unloading and reloading of the soil. These indices are described in Section 5.2.2.

5.1.3 Soft soil creep model

The creep deformation is already included in the total settlement in the soft soil model in a general sense. Using the soft soil creep model however, the creep can be defined based on site specific soil test parameters and thus provide outputs that are increasingly accurate for the area in question. Here, the creep constant is used which is the only additional parameter beyond those used in the soft soil model.

5.2 General parameter determination

The following section will handle the general determination of all input parameters needed in order to conduct the PLAXIS simulations.

5.2.1 Friction angle

The friction angle is defined as a function of the compression index in triaxial compression (Karstunen & Amavasai, 2017).

$$\phi = sin^{-1}\frac{3M_c}{6+M_c} \tag{5.1}$$

M_c is the stress ratio at critical state under triaxial compression and is derived from the linear part of the p'-q plot (Karstunen & Amavasai, 2017), an example of this plot is shown in Figure 5.1. The plots used to gather the M_c values for the analyses conducted in the thesis was taken from the triaxial tests performed at each site. With the value of M_c known, the friction angle could be calculated according to Equation (5.1). After evaluating the relevant friction angles using this method, they were calibrated using the PLAXIS soil test tool. The values used in the model are shown in the chapters for each site.

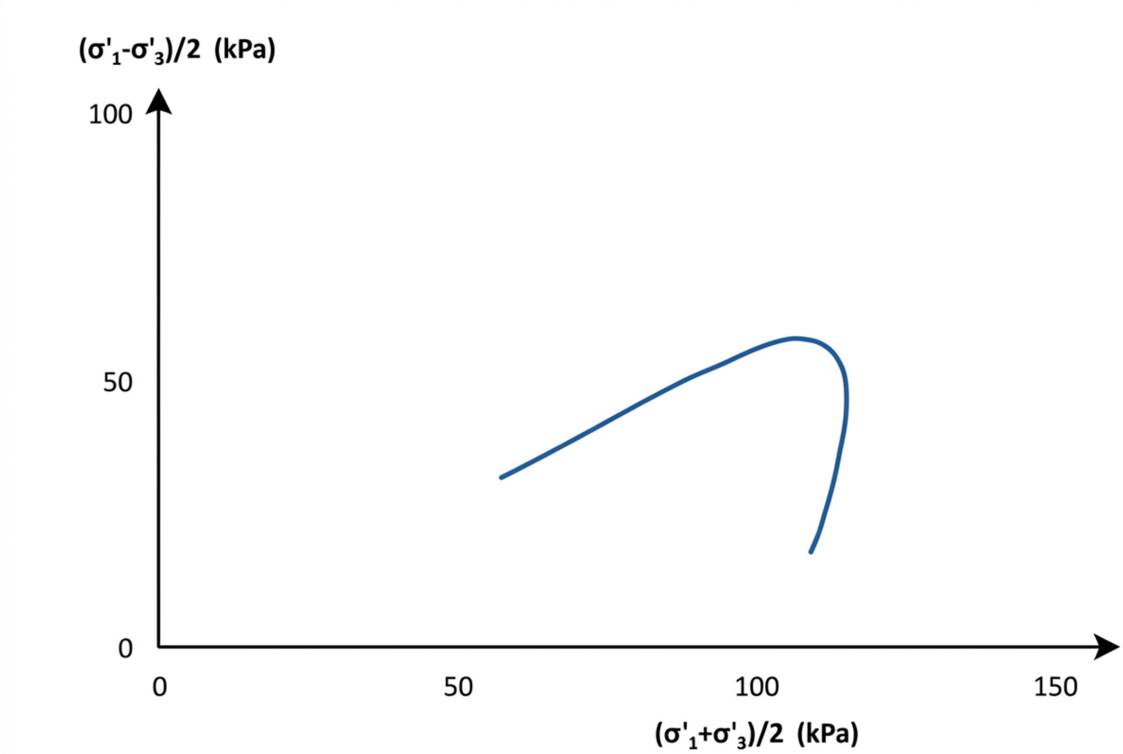


Figure 5.1: Determination of friction angle using the p'-q plot

5.2.2 Stiffness parameters

The stiffness parameters λ^* and κ^* are values used for the soft soil- and soft soil creep model in PLAXIS. They are used to define the loading and unloading behaviour and response of the clay. The stiffness parameters, including the modified swelling index κ^* and the modified compression index λ^* are determined using CRS tests and the graph of effective stress versus volumetric strain. An illustration can be seen in Figure 5.2. The stiffness parameters were after the calculation shown in the figure below also optimised by using the PLAXIS lab test which was used by matching to the loading curve from the oedometer test.

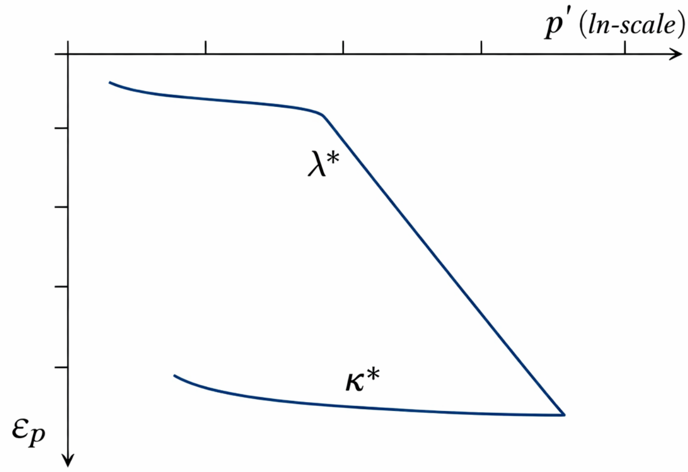


Figure 5.2: Determination of Kappa and Lambda

Another stiffness parameter used only in the soft soil creep model is the modified creep index μ^*. The modified creep index is a constant for how creep develops over time and is usually determined using incrementally loaded oedometer tests. However, no such test was performed at any of the two sites used in this thesis. Instead, a typical value for west coast clay is assumed. The same value, taken from (Tornborg, 2024) is used for both sites. Interferometric Synthetic Aperture Radar (InSAR) is a satellite based remote sensing technique used to monitor ground surface deformations over time with high spatial resolution (Statens Geotekniska Institut, 2026). This was used to further validate background creep by comparing settlements obtained from an unloaded PLAXIS model with observed ground surface deformations in the surrounding area.

5.2.3 Consolidation parameters

Depending on the geotechnical history and previous loads on the clay, the clay could be over consolidated, meaning that the clay historically has been subjected to a greater load compared to the current conditions. This is defined using (OCR) and (POP). Both OCR and POP are defined using the preconsolidation pressure and the effective stress. OCR is defined as the ratio between effective stress and preconsolidation pressure and as seen in Equation (5.2).

$$OCR = \frac{\sigma_c'}{\sigma_v'} \tag{5.2}$$

POP is defined as the difference between the effective stress and the preconsolidation pressure, using Equation (5.3).

$$POP = \sigma_c' - \sigma_v' \tag{5.3}$$

Worth noting is that both POP and OCR depend on depth and the calculation must be done at each depth with the corresponding effective stress and preconsolidation pressure. This means that it is essential to have CRS tests divided into different steps over the depth. Fortunately, this is provided for both sites which enables accurate calculation of both POP and OCR. When POP and OCR are used as input parameters for finite elements models, however, constant values should be used (Karstunen & Amavasai, 2017).

The preconsolidation pressure, σ_c', and the effective stress, σ_v', are determined from the CRS tests with effective stress plotted against deformations of the test sample.

5.2.4 Poisson's ratio

Poisson's ratio, ν_{ur} for unloading and reloading of the clay and is needed when the soft soil model is used in PLAXIS. The value is difficult to both measure and calculate. The alternative is to fine-tune the value when all other parameters are correctly set, which could be done by simulating unloading and reloading. Calibration of ν_{ur} is especially important when horizontal deformations are considered (Karstunen & Amavasai, 2017). Normally, a value of ν_{ur} between 0.1-0.2 is assumed.

When using the Mohr Coulomb model in PLAXIS, Poisson's ratio ν is used. This ratio is not necessarily the same as ν_{ur} and does, in fact often acquire a different value (Karstunen & Amavasai, 2017). In the calculations conducted in this thesis, ν is set to 0.3.

5.2.5 K_0

K_0^{NC} is determined using Jaky's formula, Equation (5.4).

$$K_0^{NC} = 1 - sin(\varphi) \tag{5.4}$$

Where ϕ is the friction angle. This value is only valid if the soil is normally consolidated. If the soil is not normally consolidated, another approach is needed. To calculate K_0 with regard to over consolidation, a factor of the root of the OCR is used to calibrate the K_0 as seen in Equation (5.5).

$$K_0 = K_0^{NC} \cdot \sqrt{OCR} \tag{5.5}$$

5.2.6 Hydraulic conductivity

The hydraulic conductivity was evaluated from CRS-tests of the clay. For soils other than clay, standardised values for the hydraulic conductivity were used since there were no available data of this to collect from the documents providing the geotechnical test data. Further, the soil was assumed to be isotropic and consequently the conductivity is defined as equal in all directions.

5.2.7 Basic soil parameters

Basic soil parameters including the stiffness modulus, E were extracted from the CPT probing performed at the each site.

5.3 Material models used in PLAXIS

The following section provides a lists all material layers used at the different sites, and what material model each layer was defined with. Return to Section 5.1 for detailed information regarding the material models.

5.3.1 Hisingen site

A list of what material models that are used for the different soil layers are provided in Table 5.1.

Table 5.1: List of materials and material models used at the Hisingen site

Material	**Material model**
Clay 1, 2, 3, 4	Soft soil creep (Undrained A)
Fill	Mohr Coulomb (Drained)
River clay	Mohr Coulomb (Undrained B)
Silty clay	Mohr Coulomb (Drained)
Deep mixing	Mohr Coulomb (Undrained B)
Stone columns	Mohr Coulomb (Drained)
Foam glass	Mohr Coulomb (Drained)
Leca	Mohr Coulomb (Drained)

5.3.2 Uddevalla site

Table 5.2 provides a list of what material models were used for the different soil layers at the Uddevalla site.

Table 5.2: List of materials and material models used at the Uddevalla site

Material	**Material model**
Clay 1, 2, 3, 4	Soft soil creep (Undrained A)
Dry crust	Mohr Coulomb (Drained)
Silt	Mohr Coulomb (Drained)
Deep mixing	Mohr Coulomb (Undrained B)
Stone columns	Mohr Coulomb (Drained)
Foam glass	Mohr Coulomb (Drained)
Leca	Mohr Coulomb (Drained)

5.4 Hisingen site parameter determination

The parameters were derived with the methods described in chapter 5.2 and were taken from the geotechnical tests performed at the site. The tables of parameters are separated according to the material model used in PLAXIS.

5.4.1 Soft soil creep model

Table 5.3: List of values for parameters of the different clay at the Hisingen site

Parameter	Clay 1	Clay 2	Clay 3	Clay 4	Unit
Depth	3–8	8–15	15–20	20–40	$[m]$
γ	15.1	15.5	15.3	16.6	$[kN/m^3]$
γ_{sat}	15.1	15.5	15.3	16.6	$[kN/m^3]$
λ^*	0.17	0.39	0.56	0.31	$[-]$
κ^*	0.020	0.015	0.015	0.013	$[-]$
μ^*	0.0016	0.0016	0.0016	0.0016	$[-]$
ν_{ur}	0.15	0.15	0.15	0.15	$[-]$
φ	26	25	27	30	$[\circ]$
K_0^{NC}	0.40	0.47	0.37	0.34	$[-]$
K_0	0.43	0.47	0.37	0.36	$[-]$
k	1.6×10^{-3}	1.6×10^{-3}	5.8×10^{-4}	4.4×10^{-4}	$[m/day]$
POP	15	0	0	20	$[kN/m^2]$
OCR	1	1	1	1	$[-]$

5.4.2 Mohr coulomb model

Table 5.4: List of the values for parameters with Mohr Coulomb model at Hisingen site

Parameter	Fill	Silty clay	Embankment	Unit
γ	18	16	19	$[kN/m^3]$
γ_{sat}	19	17	20	$[kN/m^3]$
E_{ref}	20000	12000	30000	$[kN/m^2]$
φ	32	30	35	$[\circ]$
ν	0.30	0.30	0.30	$[-]$
k	1	5×10^{-3}	1	$[m/day]$

*Material model Mohr Coulomb undrained B uses undrained shear strength instead of friction angle
**Material model Mohr Coulomb drained uses friction angle instead of undrained shear strength

5.4.3 Mesh

The mesh was generated as "very fine" in PLAXIS. Thereafter, the mesh was then refined until the refining process did not alter the final settlement. This ensured that the mesh was sufficiently fine to be used in the analysis. The final mesh used at Hisingen contained a total of 4334 elements. The mesh of the entire unit cell used at site Hisingen is presented in Figure 5.4. A view providing greater detail of the mesh is available in Figure 5.3

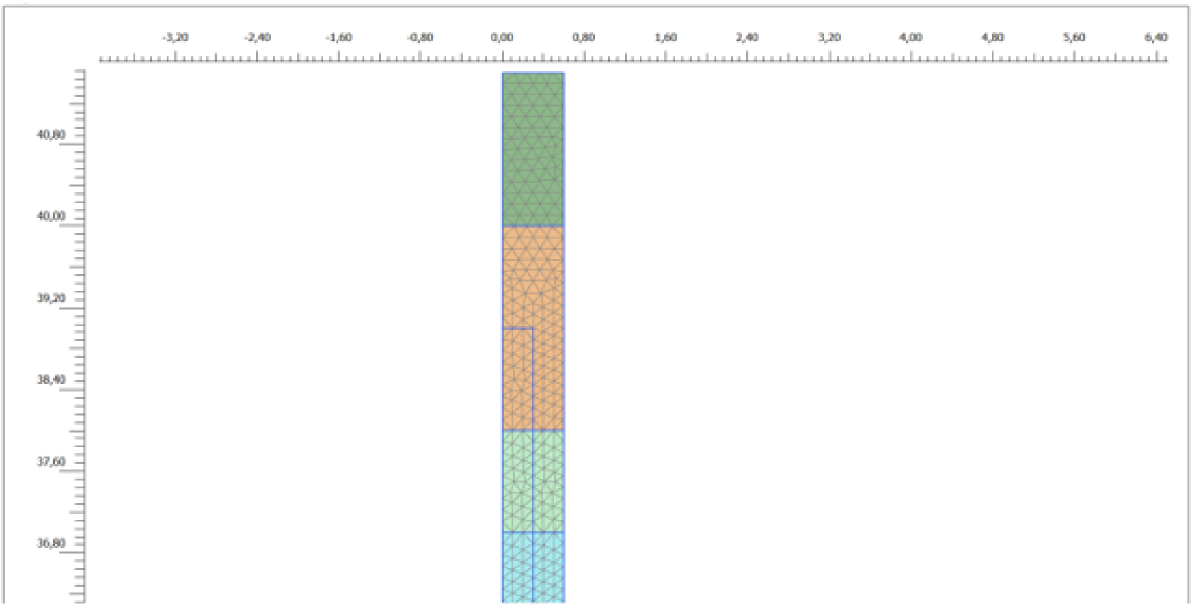


Figure 5.3: Mesh used for the Hisingen site

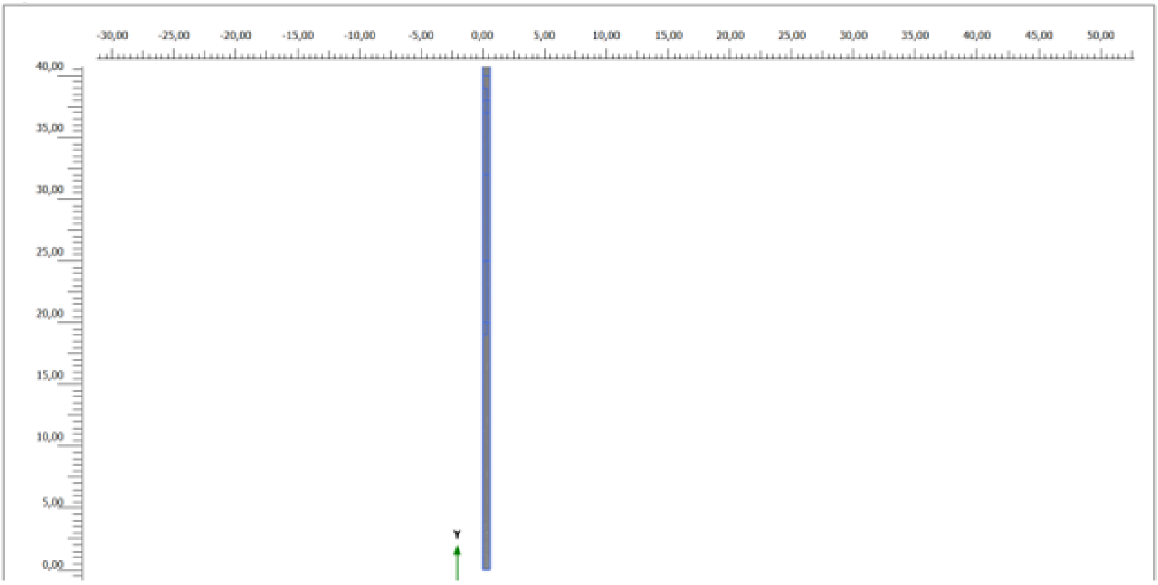


Figure 5.4: Mesh of the entire unit cell at the Hisingen site

5.5 Uddevalla site parameter determination

The following section provides information about input parameters and general properties needed in order to conduct the settlement and stability analysis at the site in Uddevalla. The parameters were derived with the methods described in Section 5.2 with input values originating from geotechnical tests performed at the site

5.5.1 Soft soil creep model

Table 5.5: List of values for parameters of the different clay at the Uddevalla site

Parameter	Clay 1	Clay 2	Clay 3	Clay 4	Clay 5	Unit
Depth	2–3	3–5	5–7	7–10	10–15	$[m]$
γ	15.8	15.4	14.8	14.6	15.8	$[kN/m^3]$
γ_{sat}	15.8	15.4	14.8	14.6	15.8	$[kN/m^3]$
λ^*	0.20	0.16	0.24	0.24	0.24	$[-]$
κ^*	0.018	0.014	0.015	0.011	0.022	$[-]$
μ^*	0.0016	0.0016	0.0016	0.0016	0.0016	$[-]$
ν_{ur}	0.15	0.15	0.15	0.15	0.15	$[-]$
φ	27	27	28	28	29	$[\circ]$
K_0^{NC}	0.55	0.55	0.53	0.53	0.52	$[-]$
K_0	0.55	0.55	0.53	0.53	0.52	$[-]$
k	8.6×10^{-4}	8.6×10^{-4}	6.9×10^{-4}	2.6×10^{-3}	2.6×10^{-3}	$[m/day]$
POP	0	0	0	0	0	$[kPa]$
OCR	1	1	1	1	1	$[-]$

5.5.2 Mohr Coulomb model

Table 5.6: List of the values for parameters with Mohr Coulomb model at Uddevalla site

Parameter	Dry crust	Silt	Embankment	Unit
γ	19	19	19	$[kN/m^3]$
γ_{sat}	20	20	20	$[kN/m^3]$
E_{ref}	15000	25000	30000	$[kN/m^2]$
φ	33	35	35	$[\circ]$
$\nu_{(nu)}$	0.30	0.30	0.30	$[-]$
k	1	1×10^{-2}	1	$[m/day]$

5.5.3 Mesh

The mesh from Uddevalla was generated with the same approach as for Hisingen, refined until the change of mesh did not cause an increase of the final settlement. The final mesh for Uddevalla consisted of 2036 elements. The mesh of the entire unit cell is presented in Figure 5.6 and is complemented with a more detailed view of the mesh in Figure 5.5.

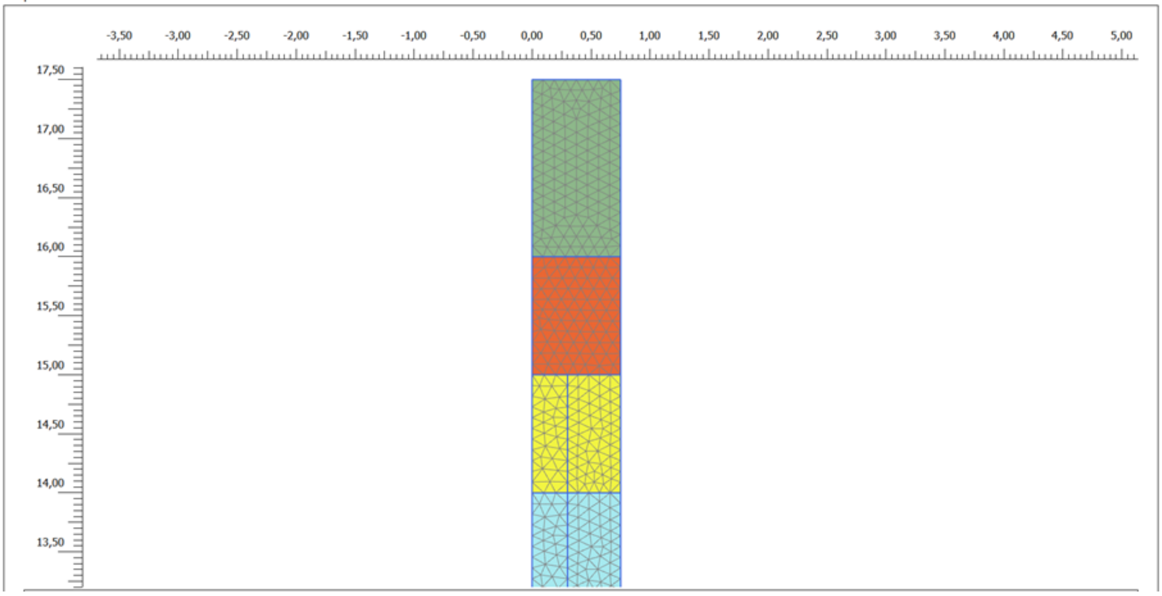


Figure 5.5: Mesh used for the Uddevalla site

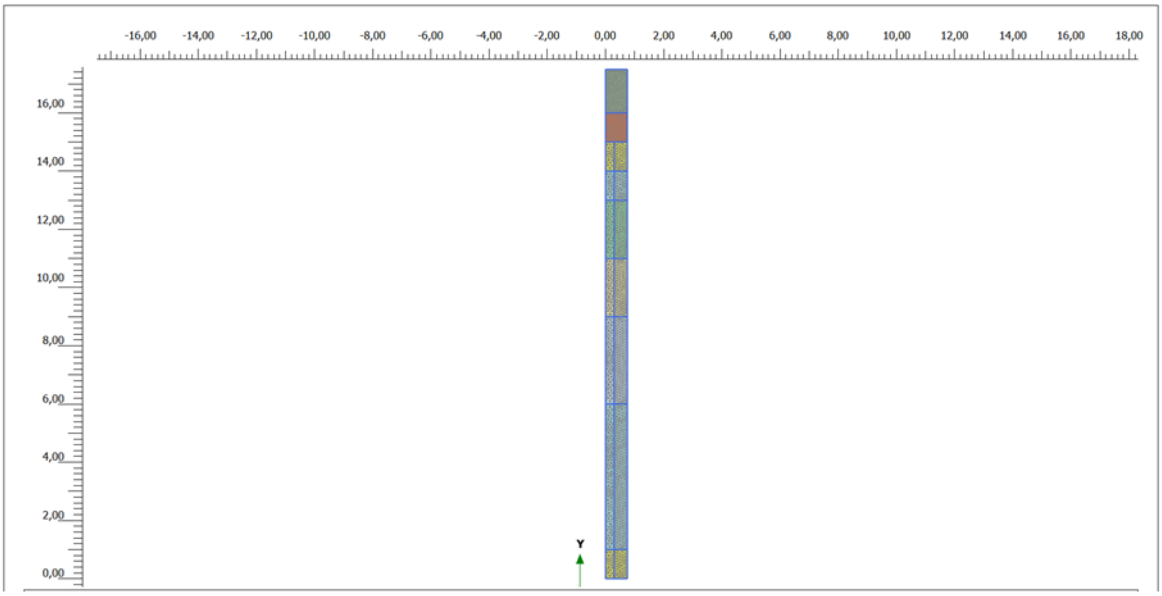


Figure 5.6: Mesh of the entire unit cell at the Uddevalla site

5.6 Deep mixing in PLAXIS

The properties for deep mixing were taken from (Trafikverket, 2023) and (Ignat et al., 2015). For the corrected undrained shear strength, a value of 100 kPa is used. However, there are tests performed at the Hisingen site that claim that the installed columns achieved an undrained shear strength of above 100 kPa. Though, the Swedish Transport Administration requires that an undrained shear strength of a maximum of 100 kPa shall be used when dimensioning for deep mixing (Trafikverket, 2023). The unit weight, Poisson's ratio and Young's modulus were taken from (Ignat et al., 2015). The hydraulic conductivity used, was an average of the surrounding clay since deep mixing does not contribute to an increase in hydraulic conductivity of the surrounding soil.

Table 5.7: Parameters used for deep mixing in PLAXIS

Parameter	Value	Unit
γ	16.5	$[kN/m^3]$
γ_{sat}	16.5	$[kN/m^3]$
E_{ref}	20000	$[kN/m^2]$
s_u	100	$[kN/m^2]$
ν	0.3	$[-]$
k	Same as surrounding clay	$[m/day]$

The columns were modelled to begin one meter below the ground surface for both sites. For site Hisingen, the columns were 20 meters long, and for site Uddevalla, 15 meters long. Since the soil depth at the Uddevalla site is 16 metres, the columns reached the bedrock in the bottom.

5.7 Stone columns in PLAXIS

All parameters used for stone columns in PLAXIS are shown in Table 5.8 and were taken from (Tan et al., 2008). The columns modelled in PLAXIS using the same approach as deep mixing, with columns starting one meter below ground surface and acquiring lengths of 15 meter in Uddevalla and 20 meters in Hisingen.

Table 5.8: Parameters used for stone columns in PLAXIS

Parameter	Value	Unit
γ	19	$[kN/m^3]$
γ_{sat}	20	$[kN/m^3]$
E_{ref}	30000	$[kN/m^2]$
φ	40	$[\circ]$
ν	0.3	$[-]$
k	10	$[m/day]$

5.8 Lightweight fill in PLAXIS

Lightweight fill was modelled using the structure element in PLAXIS, thus representing the material replacing the excavated soil. Replacing the soil with the lightweight material is therefore relatively straightforward. The main difference is the change of some properties such as stiffness, friction angle and permeability.

5.8.1 Foam glass

When modelling foam glass as a lightweight fill material, a minimum of 0.5m of overlying fill material must be placed above the foam glass according to regulations provided by (Trafikverket, 2023). The suggested unit weights and the friction angle were taken from (Trafikverket, 2023) and are provided in Table 5.9. Trafikverket does not provide any suggested value for Young's modulus or Poisson's ratio. Therefore, values from (Vinay Kumar et al., 2024) were used.

Table 5.9: Parameters used for foam glass in PLAXIS

Parameter	**Value**	**Unit**
γ	4	$[kN/m^3]$
γ_{sat}	11	$[kN/m^3]$
E_{ref}	3333	$[kN/m^2]$
φ	42	$[\circ]$
ν	0.3	$[-]$
k	1	$[m/day]$

5.8.2 Leca

The required thickness of overlying fill material above Leca depends on the intended use. In this thesis, a minimum thickness of 0.5m was adopted in accordance with (Trafikverket, 2016).

Table 5.10: Parameters used for Leca in PLAXIS

Parameter	Value	Unit
γ	4.5	$[kN/m^3]$
γ_{sat}	11	$[kN/m^3]$
E_{ref}	2520	$[kN/m^2]$
φ	35	$[\circ]$
ν	0.3	$[-]$
k	1	$[m/day]$

5.9 Staged construction

The construction was divided into several steps, each containing certain activities. The time for each activity was adapted to represent the real time span for these activities and for the last phase, to include all time dependent settlements.

Table 5.11: List of construction phases when using different kinds of ground improvement

Improvement technique	Deep mixing	Stone columns	Lightweight fill	Lightweight fill + columns
Phase 1	-	-	Excavation for fill	Excavation for fill
Phase 2	-	-	Installation of lightweight fill	Installation of lightweight fill
Phase 3	Installation of column	Installation of column	-	Installation of column
Phase 4	Embankment construction	Embankment construction	Embankment construction	Embankment construction
Phase 5	Consolidation	Consolidation	Consolidation	Consolidation

Table 5.12: Time of construction phases

Phase	Time
Phase 1	3 days
Phase 2	3 days
Phase 3	100 days
Phase 4	150 days
Phase 5	100 years

6

Slope/W modelling

Following the settlement analysis, a stability analysis of the two sites was commenced. The parameters of the different soils and improvement methods, along with dimensions of these combinations, were used in the stability analyses conducted using GeoStudio's Slope/W. The parameters and geometry were dimensioned from the PLAXIS simulations leading to similar settlement results. GeoStudio is a geotechnical software for analysing geotechnical problems such as groundwater seepage, stress deformations and evaluating slope stability in soil and rock. Slope/W which is an analysis branch in the software, is used for evaluating the slope stability of ground formations by calculating the factor of safety along with providing relevant potential slip surfaces. The process includes setting input variables, such as soil strengths and friction angles, and then defining so called entry and exit regions for the slip surface analysis. This enables the software to calculate multiple possible slip surfaces within these boundaries represented by the entry and exit points. In order to check the validity of each ground improvement method from a stability perspective, Slope/W was used in this part of the analysis.

6.1 Hisingen parameter determination

For the slope stability analysis done in GeoStudio's Slope/W, the soil parameters for the general soil sequences and properties were extracted from the same data as for the PLAXIS modelling, previously demonstrated in Table 5.3 and Table 5.4. Additional data that was not used in PLAXIS are the shear strengths of the soils and improvement materials. The undrained strengths can be seen in tables 6.1 and 6.2. For stone columns, Leca, foam glass, fill and dry crust, the strengths was defined through the friction angles in Slope/W and is thus not included in the table.

Table 6.1: Hisingen shear strength declaration

Material / Layer	Undrained shear strength [kPa]
Clay 1	11
Clay 2	17
Clay 3	24
Clay 4	32.5
Riverbed clay (Top of layer)	2.2

*Strength defined from friction angle

Table 6.2: Deep mixing shear strengths, Hisingen

Material / Layer	Undrained shear strength [kPa]
Deep mixing (No lightweight fill)	
DM Fill	37.3
DM Dry crust	43.0
DM Clay 1	28.5
DM Clay 2	33.3
DM Clay 3	38.9
DM Clay 4	45.8
Deep mixing (With lightweight fill*)	
DM Fill	39.3
Dry crust	43.0
DM Clay 1	15.4
DM Clay 2	21.1
DM Clay 3	27.7
DM Clay 4	35.8

*Doubled centre to centre distance

6.2 Uddevalla parameter determination

The same applies for the Uddevalla site, where the soil parameters used in GeoStudio can be found in Table 5.5 and Table 5.6. The undrained shear strength parameters are found in tables 6.3 and 6.4, below and the drained strengths, are once again defined using the friction angles in Slope/W.

Table 6.3: Uddevalla shear strength declaration

Material / Layer	Undrained shear strength [kPa]
Clay 1	15
Clay 2	12.5
Clay 3	11
Clay 4	15
Clay 5	22.5

*Strength defined from friction angle

Table 6.4: Deep mixing shear strengths, Uddevalla

Material / Layer	Undrained shear strength [kPa]
Deep mixing	**(No lightweight fill)**
DM Clay 1	25.7
DM Clay 2	23.5
DM Clay 3	22.2
DM Clay 4	25.7
DM Clay 5	32.2
Deep mixing	**(+ lightweight fill*)**
DM Clay 1	17.7
DM Clay 2	15.2
DM Clay 3	13.8
DM Clay 4	17.7
DM Clay 5	24.9

*Doubled centre to centre distance

6.3 Material models in Slope/W

For a slope stability analysis done in software like GeoStudio, it is crucial that all different soils and material are defined appropriately, so that the stability of a given slope neither is under- nor overestimated. When defining the properties of each soil layer, the choice of material model is important to make sure that the programme handles these properties accurately.

6.3.1 Mohr Coulomb

The frictional soil layers, as well as the material used for lightweight fill, were defined using the Mohr Coulomb material model. This model utilises the Mohr-Coulomb failure envelope, where the shear strength of the material increases with depth. Here, an initial effective cohesion is defined for the material. Then the strength increases linearly over depth depending on the effective stress and the friction angle of the material, see Figure 6.1. The drained strength of the frictional soils and fill was thus calculated using Equation (6.1).

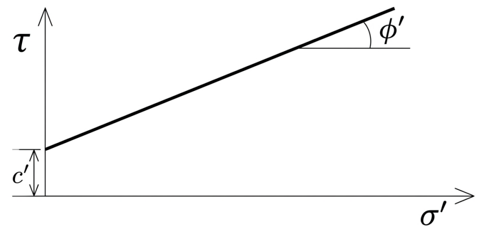


Figure 6.1: Mohr-Coulomb failure envelope

$$\tau = c' + \sigma' \cdot tan(\varphi') \tag{6.1}$$

6.3.2 Undrained (Phi=0)

The undrained model, conveniently used for cohesive soils such as clay purely defines the undrained strength properties of the material from cohesion and porewater pressure, (Seequent Limited, 2022). In contrast to the Mohr Coulomb model, the friction angle is set to zero and the strength of the soil is thus assumed to be constant across the entire layer, as shown in Figure 6.2. Using this model approach, the strength in the upper parts of the soil layers is thus easily overestimated, and the lower parts underestimated, respectively. It is therefore important to proceed with caution when choosing to use this material model, both in terms of validity for the particular case, but also to make sure not to over or underestimate the strength of the soil.

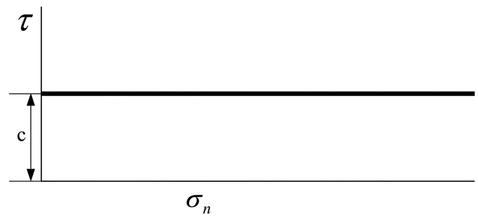


Figure 6.2: Undrained strength envelope

6.3.3 Combined, S=f(datum)

The combined model could be described, as the name suggests, as a combination of the previous two models. The model initially utilises a drained response for the strength of the soil until the undrained shear strength max is reached, where the strength remains constant for the remainder of the layer. There are two different models in GeoStudio that utilises this combined theory, S=f(datum) and S=f(depth). The former defines the strength from a given level in the soil whilst the latter is defined from the top of each soil layer. For the majority of the materials considered in this thesis, Combined, S=f(datum) is used.

6.3.4 Material models Hisingen

Table 6.5: Material models used for Hisingen

Material	**Material model Combined approach**	**Material model Undrained approach**
Fill	Mohr-Coulomb	Mohr-Coulomb
Dry crust	Mohr-Coulomb	Mohr-Coulomb
Stone columns	Mohr-Coulomb	Mohr-Coulomb
Foam glass	Mohr-Coulomb	Mohr-Coulomb
Leca	Mohr-Coulomb	Mohr-Coulomb
Clay 1-4	Combined, S=f(datum)	Undrained (Phi=0)
Riverbed clay	Combined, S=f(depth)	Undrained (Phi=0)
Deep mixing, Clay 1-4	Combined, S=f(datum)	Undrained (Phi=0)
Deep mixing, Fill	Combined, S=f(datum)	Mohr-Coulomb
Deep mixing, Dry crust	Combined, S=f(datum)	Mohr-Coulomb

6.3.5 Material models Uddevalla

Table 6.6: Material models for the combined approach, Uddevalla

Material	**Material model Combined approach**	**Material model Undrained approach**
Dry crust	Mohr-Coulomb	Mohr-Coulomb
Silt (Top & bottom)	Mohr-Coulomb	Mohr-Coulomb
Stone columns	Mohr-Coulomb	Mohr-Coulomb
Foam glass	Mohr-Coulomb	Mohr-Coulomb
Leca	Mohr-Coulomb	Mohr-Coulomb
Clay 1-5	Combined, S=f(datum)	Undrained (Phi=0)
Deep mixing, Clay 1-5	Combined, S=f(datum)	Undrained (Phi=0)
Deep mixing, Silt	Combined, S=f(datum)	Mohr-Coulomb

6.4 Modelling of deep mixing

In contrast to the unit cell model in PLAXIS, where the columns are represented as a material of its own, Slope/W modelling requires another approach in defining the shear strength improvement provided by the installation of the deep mixing. Here, the weak soil and columns are modelled as a homogeneous material and adopt a higher shear strength and stiffness compared to the untreated soil, representing an average of soil reinforced using deep mixing in the real life case. The columns will thus be modelled in the shape of a block, which will achieve its parameter calibration from the area ratio of the columns versus the drainage path/soil of the unit cell in the axisymmetric case. This method, described by (Trafikverket, 2016) is a requirement from the Swedish traffic administration and should be used when modelling simplified, plane strain models of ground improvement with deep mixing. The weighted shear strength average of the soil is achieved firstly by calculating the percentage of material being mixed into the soil. This share is then used to calculate the average weighted shear strength using Equation (6.2). This method eliminates the possibility of mistakenly overestimating the efficiency of the improvement.

$$\tau_f = a \cdot \tau_{f,col} + (1-a) \cdot \tau_{f,soil} \tag{6.2}$$

Where $\tau_{f,col}$ is the drained or undrained shear strength of the column material, and $\tau_{f,soil}$ is the drained or undrained shear strength in the soil.

For the majority of the soil layers, $\tau_{f,col}$ is defined by a constant 100 kPa, however, for the first two metres of the soil depth, where the performance of the columns usually is lower as a result of installation effects, a characteristic drained shear strength (τ_{fdk}) should be considered and is calculated according to Equation (6.3), (Trafikverket, 2016).

$$\tau_{fdk} = c' + \sigma' \cdot tan(\varphi) \tag{6.3}$$

6.5 Modelling of stone columns

As previously mentioned, the use of stone columns in Sweden today is not as widely used as lime cement or other deep mixed columns when stabilising or strengthening soil structures. To simulate scenarios in GeoStudio that accurately represent the reality, it is critical that geometry and parameters are dimensioned correctly. Since this paper is limited to 2D analyses, plane strain modelling of the columns need to be considered when conducting the stability analysis.

When a plane strain model is used in software like GeoStudio or PLAXIS, the true width of the stone columns must therefore be reduced in the simulation. The method for adjusting the stone column properties varies from the approach for deep mixing. For the slope stability analysis including stone columns, the authors used the area matching method as described by (Tan et al., 2008). Using this method to convert the column diameter, the model should provide more realistic results that compensate for an otherwise too high stiffness and weight of the improvement. The reduction in column width implies an increase of the flow path in the soil surrounding the columns. Thus, by taking this approach, other material parameters like hydraulic conductivity for instance, does not need to be modified.

To achieve the reduced areas of the columns for the plane strain analysis in GeoStudio, Equation (6.4), introduced by (Tan et al., 2008) was used.

$$b_c = B \cdot \frac{r_c^2}{R^2} \tag{6.4}$$

Here, b_c is the column radius that was used in PLAXIS and r_c is the true column radius. R is the radius of the drainage zone for the axisymmetric unit cells and was defined depending on the centre-to-centre distance of the columns from the current site. R was then calculated using Equation (6.5).

$$R = \frac{s}{\sqrt{\pi}} \tag{6.5}$$

The final drainage width, B of the columns that should be used in the modelling, is finally calculated from the assumption that the columns are placed in a square-grid and dependent on R, using Equation (6.6).

$$B = \frac{R}{1.13} \tag{6.6}$$

6.6 Foam glass

When modelling foam glass as a lightweight fill material, the configured settlement analysis was dimensioning in defining key parameters, such as the thickness of the fill layers. Furthermore, designing the layout of the fill material was done in accordance with the recommendations and requirements from (Trafikverket, 2023). For instance, foam glass must be overlaid with a wearing course with a minimum thickness of 0.5 metres, which mainly is to avoid frost development on the ground surface. The material was further defined with the drained Mohr-Coulomb material model, with a unit weight of 4 kN/m^3 and a friction angle of 42 degrees, according to Table 5.9. In addition, the material was strictly limited to being placed above the groundwater table for both sites in the analysis. This was done to avoid the risk of heave of the material due to the unit weight being considerably lower than that of waters.

6.7 Leca

Similarly for Leca, the design and layout of the material was governed by the settlement analysis. The regulations by (Trafikverket, 2023) suggests a unit weight of 4.5 kN/m^3 and a friction angle of 35 degrees. Similarly to the foam glass, the requirement of a minimum of 0.5 metres to the ground surface applies here as well.

6.8 Dimensions of ground improvement at each site

Dimensions corresponding to each site, used for conducting accurate stability analyses, were taken from the results of the settlements calculation, displayed in Table 8.1 for site Hisingen and Table 8.5 for site Uddevalla.

7

Environmental and economical assessment methodology

In this chapter, the environmental impact and cost of the different ground improvement techniques for the two sites were calculated. The calculations were based on the dimensions used for achieving similar settlements. First, it is explained which parts affect the environmental impact and cost of the ground improvement processes, and into which categories they are divided. Thereafter, the exact cost and climate impact of the different material and processes needed for the ground improvement projects are provided. Together with the calculated amounts of ground improvement needed, derived from Chapter 8, the total climate impact and cost for the different ground improvement techniques could be calculated.

In order to carry out the calculations, a number of assumptions had to be made. First, in the calculations, both sites are assumed to be located in central Gothenburg. This made the environmental and economical costs generated from transports for instance, comparable and easier to calculate.

Furthermore, a large area of 10,000 square metres was chosen to be improved and used as the basis for the calculations for the comparison. This is so that the actual costs of the improvement itself would guide the comparison and not the costs for establishment and, for example, work platforms and the installation of machines.

In the case of lightweight fill and embankment construction, a category called savings has been included in both the environmental and economic calculations. This is because lightweight filling of embankments reduces the amount of construction material for the embankment, leading to a reduction in transport needs. When improving slope stability, there are no possibilities of placing lightweight fill in a bank, but the soil needs to be excavated and replaced with lightweight fill. This means that no possibilities for savings arise. Instead, the environmental burden increases the costs of excavation work and the disposal of excavated materials. Therefore, the results for slope improvement and settlement reduction are presented in separate diagrams.

7.1 Environmental calculations

The environmental aspect was assessed by comparing emissions of CO_2-equivalents. This was also the sole aspect regarding environmental aspects that was considered in the thesis and no other environmental aspects such as effects on biodiversity for instance, was investigated.

7.1.1 Climate impact from ground improvement

For the environmental comparison, the total amount of CO_2-equivalents generated by each improvement process was calculated with the Swedish traffic administration's climate calculating tool; (Trafikverket's Klimatkalkyl) to an as large extent as possible. The calculation tool contains information on emissions for lime cement columns and lightweight fill materials such as Leca and foam glass. The calculating tool also contains values and calculation support for the climate impact of transport of materials. In addition to this, EPD:s from the material manufacturers was used to determine the climate impact. This was used for crushed rock and foam glass among others, see Table 7.1, Table 7.2, Table 7.3 and Table 7.4 for sources of all data for the calculations.

The climate impact of geotechnical ground improvement techniques could be divided into three parts. Firstly, the production of the materials used. For example, production of lime, cement or foam glass. This is often the part of the process with the largest carbon footprint, which also means that this is where the savings potential is the greatest. For example, by making effective material choices and optimizing constructions to limit material use.

The next part of the climate impact for ground improvement is the transport of the material from the production factory to the site where the material is installed. This factor is heavily dependent on the distance of the intended transport, but also the quantities and weights of the improvement material needed. In addition, the choice of transportation mode and fuel have an impact. To limit the climate impact from transports of materials, materials produced near the site can be used to limit the transportation distance. Furthermore, switching from transport by trucks to ships or trains and replacing fossil fuels with renewables such as HVO100 or electricity can imply a reduced environmental impact. At the same time, it should be remembered that transportation accounts for a smaller part of the ground improvement's climate impact in relation to material production, so trading materials to reduce climate impact transportation may not be a good strategy.

The third part of the climate impact caused by ground improvement is the installation stage. This includes practical work steps when the improvement is implemented. Among other things, emissions occur from excavators and deep mixing machines. This category includes environ-

mental impacts arising from the establishment of the construction site and other emissions that are added to make construction possible.
In addition to these factors, there are some aspects that are not directly linked to the improvement material itself but are consequences of the improvement itself. This applies, for instance, to material surplus when the soil is treated. The amount of material depends, among other things, on which ground improvement technique was used. The use of lightweight fill materials often means that the existing material need to be excavated, either entirely or partially. The excavated material then needs to be transported from the site and in many cases, handled at a landfill. This itself can have a major climate impact, and to which extent depends on whether the soil is contaminated or not. Even techniques such as deep mixing and stone columns can result in excess soil that needs to be transported away. The amount is usually not as large as for lightweight fill, but excess masses can also be generated when using these techniques. To achieve a complete and comprehensive climate calculation of ground improvement, it is important to include these parts as well.

Soil that is excavated and transported away is by definition classified as waste and is often treated or disposed at landfills according to regulations. The definition states that everything that the responsible company disposes of is classified as waste (Trafikverket, 2024a). The use of soil classified as waste varies depending on a pollution level and if the soil could be used for something else in the same project or nearby projects. Such as using crushed rock from blasted bedrock in stone column construction. In order for the soil to be reused, its contamination level must be determined, as well as for what purpose it is planned. The Swedish Transport Administration has different categories depending on how contaminated the soil is and what it will be used for (Trafikverket, 2024a). However, handling excavated material does have an environmental impact in the form of transportation and disposal or reuse of the material. The greatest environmental impact occurs if the material is considered heavily contaminated and needs to be disposed of in a hazardous waste landfill, which is not uncommon for projects where the land has had a previous purpose.

In addition, other factors that can affect a ground improvement climate impact, for example the transport of machinery such as excavators and deep mixing machines to the site. The climate impact from these aspects of course depends a lot on the location of the site and the conditions that prevail on the site.

7.1.2 Values used for environmental calculations

In the following tables, the values used for the calculation of the climate impact of the different ground improvement techniques are shown. In Table 7.1, the CO_2 emissions generated from materials for ground improvement are shown. The values are taken mainly from (Trafikverket,

2026) climate calculating tool. It should also be noted that these values are based on the use of virgin material. In some cases, it is possible to use recycled material, which is the case for Leca, which implies a reduction in climate impact compared to using virgin material.

Table 7.1: Climate impact by materials and fuels used for ground improvement

Material	Emissions	Unit	Source
Lime	1.45	$[kgCO_2/kg]$	(Trafikverket, 2026)
Cement	0.87	$[kgCO_2/kg]$	(Trafikverket, 2026)
Multicem	0.393	$[kgCO_2/kg]$	(Trafikverket, 2026)
Crushed rock	0.002	$[kgCO_2/kg]$	(NCC, 2021)
Foam glass	16.1	$[kgCO_2/kg]$	(Trafikverket, 2026)
Leca	36	$[kgCO_2/kg]$	(Trafikverket, 2026)
Recycled Leca	8	$[kgCO_2/kg]$	(Leca Saint-Gobain, 2025)

Different fuels have different levels of impact on the climate. In addition, the energy content of these differs. This means that for example, one litre of diesel is not equivalent to one litre of HVO100 or one kWh of electricity in terms of energy content. All values are shown in Table 7.2 and was taken from the swedish traffic administrations climate calculator (Trafikverket, 2026). The value for electricity is for the Swedish electricity mix.

Table 7.2: Climate impact and energy content for fuels

Material	Emissions $[CO_2$-eq]	Unit	Energy content	Unit	Source
Diesel	2.75	$[kgCO_2/l]$	43.25	$[MJ/l]$	(Trafikverket, 2026)
HVO100	0.46	$[kgCO_2/l]$	40.8	$[MJ/l]$	(Trafikverket, 2026)
Electricity	0.047	$[kgCO_2/kWh]$	7.27	$[MJ/kWh]$	(Trafikverket, 2026)

Different modes of transport have different energy needs per unit of distance, usually defined as megajoules per tonne-kilometre (MJ/tkm). This could then be used together with the energy content of the fuels to calculate the need of fuels and thereafter the total climate impact. This information was taken from Trafikverkts klimatkalkyl and is shown in Table 7.3 (Trafikverket, 2026).

Table 7.3: Climate impact by transport

Transport mode	Energy consumption	Unit	Source
Truck (Local distribution)	2.5	$[MJ/tkm]$	(Trafikverket, 2026)
Truck (Regional transport)	1.5	$[MJ/tkm]$	(Trafikverket, 2026)
Ship (Coast traffic)	0.3	$[MJ/tkm]$	(Trafikverket, 2026)

In Table 7.4, the fuel consumption of different machines at the construction site needed for the implementation of ground improvement is shown. In this case, the data is presented in units of diesel consumption per unit of work done. This was done because the information about consumption from the sources was provided in these units. However, alternative fuels, such as HVO100 could also be used for these activities, and to calculate the consumption and the climate impact of these fuels, it had do be done backwards by first calculating the energy content of the diesel consumption, and then recalculate it to consumption of alternative fuels.

Table 7.4: Climate impact by construction machines

Work steps	Fuel consumption	Unit	Comment	Source
Excavator works	0.19	$[l/m^3]$	All work with excavators included	(SGI, 2022)
Deep mixing machine	0.41	$[l/m]$	Per meter of column installed	(SGI, 2022)
Stone column machine	2.5	$[l/m]$	Per meter of column installed	(G. T. Senthilnath & Y. Harikrishna, 2010)

7.2 Economical calculation

This section covers certain fundamentals regarding the cost of the different techniques such as material purchases or transportation costs. Aspects that do not vary to to a sufficient degree between techniques, such as payouts to employees, are not considered due to these mall differences.

7.2.1 Economy in ground improvement

The economical aspects of ground improvement are mainly related to similar processes as the environmental aspects. The costs of ground improvement originates from the material used for improvement as well as installation- and transportation costs of the material. In addition to this, there is often a charge for using landfills or cleaning excess materials from the project, which has a greater impact on the economic than the environmental calculation.

7.2.2 Values used for the economical comparison

The used cost for different materials and services used for ground improvement are presented in Table 7.5.

Table 7.5: Costs for various materials for ground improvement

Material or service	Cost	Unit	Comment
Deep mixing cost/m	80	$[SEK/m]$	Installation and transport included
Deep mixing base price/column	90	$[SEK/st]$	Installation and transport included
Crushed rock 0-63	90	$[SEK/tonne]$	For working platform
Crushed rock 32-63	130	$[SEK/tonne]$	For stone columns
Stone columns inst.	100	$[SEK/m]$	Big uncertainty in Sweden
Foam glass	640	$[SEK/m^3]$	
Foam glass transportation	120	$[SEK/m^3]$	
Leca	690	$[SEK/m^3]$	Transport included
Landfill	240	$[SEK/tonne]$	

During implementation of the ground improvement technologies, considerable work is done using various construction machinery. These are in many cases rented and charged for by the hour. Together with their capacity and working pace, the total cost of the installation process could be calculated. It should be noted here that it is not reasonable to assume that the machines can operate at their maximum capacity constantly. The calculations need to take downtime and similar aspects into account in order to not overestimate the total running time of the machine versus renting time. In Table 7.6, the cost for certain machinery is shown, taken from Skanska Schakt och Transport. Although the price includes machine operator and fuel, if HVO100 is to be used instead of diesel, there is an additional fee.

Table 7.6: Rental cost for different machines needed for ground improvement

Machine	Cost	Unit	Comment
Excavator	1560	$[SEK/h]$	40-tonne excavator
Truck	140	$[SEK/h]$	35-tonne capacity
Roller	600	$[SEK/h]$	7-tonne roller

8
Results

In this chapter, the results of the calculations are presented. The results are presented separately for the two different sites analysed in the thesis. First, the results from the settlement analyses are introduced, including both PLAXIS simulations and the corresponding hand calculations. This is followed by the results from the slope stability analyses conducted in GeoStudio. Additionally, the results from the environmental and economic comparison of the different techniques are presented after the settlement and slope stability results. The results are then presented, where the results for the Hisingen site are found in Chapter 8.1, and the results for the Uddevalla site, in Chapter 8.2.

In Chapter 8.3, the impact of potential savings on the environmental and economic calculations is presented. Finally, a sensitivity analysis of the economic results is presented in Chapter 8.4. This section examines, among other aspects, how variations in material and fuel prices influence the total costs and environmental impact, with the aim of identifying the primary sources of cost-related uncertainty in the calculations.

As pointed out in the aim of the calculations, the ground improvement should be dimensioned to have a similar settlement. In this case, the ambition is to match the final settlement, and the time period is set to 100 years. To achieve this, the centre-to-centre distance and the thickness of the lightweight fill were adjusted to match the predicted settlements. These dimensioning settlement calculations were carried out using the finite element method in PLAXIS, as previously described.

Based on the dimensions of the different ground improvement techniques that result in similar settlements, slope stability analyses were subsequently carried out. The purpose of this was to be able to see whether the dimensions of the different techniques that give a similar settlement also provided a similar increase in the safety factor regarding slope stability. Alternatively, to be able to see if any of the techniques is better for reducing settlements or for increasing slope stability or vice versa.

8.1 Results Hisingen

Firstly, the results from the Hisingen site are presented. In Section 8.1.1, the settlements calculated using PLAXIS are shown. This is followed by the settlement results obtained from hand calculations in Section 8.1.2, the slope stability analysis in Section 8.1.3, and the environmental and economic comparison of the techniques in Sections 8.1.4 and 8.1.5, respectively.

8.1.1 Results from PLAXIS

In Figure 8.1, the development of the settlements over time for the different ground improvement techniques is presented, from which the final settlements can also be observed as the end of each curve after 100 years following the construction of the embankment. All ground improvement techniques were designed to achieve the same or a similar final settlement after 100 years. This was done by adjusting their geometrical parameters, centre-to-centre distance and diameter. All techniques, except for stone columns, resulted in similar calculated settlements, although the final settlements differ by a few centimetres. These variations arise from the need to define the centre-to-centre spacing of the columns and the thickness of the lightweight fill in whole decimetres to ensure buildability. The final settlements of all improvement techniques, except stone columns, differ by at most 7 centimetres.

For stone columns, it was not possible to achieve a settlement reduction comparable to that of the other techniques. This is regardless of how much the dimensions and share of column material in ground were increased by reducing the centre-to-centre distance between the columns. The shown final settlement for stone columns in Figure 8.1 are the least possible final settlement by using stone columns. Thus, the most optimal dimensions for centre-to-centre distance between the stone columns were used. These are shown in Figure 8.1.

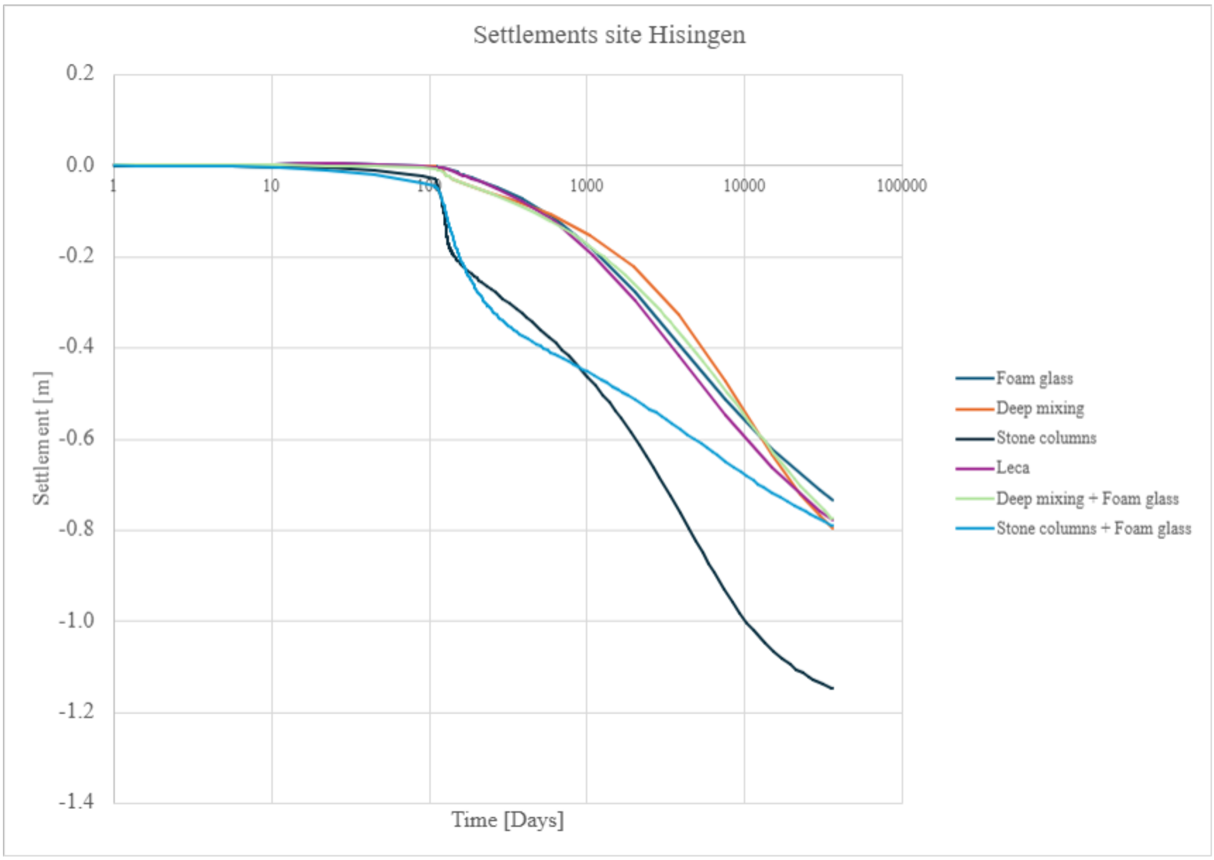


Figure 8.1: Settlement over time for the different ground improvement techniques at the Hisingen site

For all techniques, except stone columns and stone columns combined with foam glass, the settlement development over time is similar, as shown in Figure 8.1. Both stone columns and stone columns combined with foam glass exhibit a faster settlement process than the other techniques. In addition, stone columns alone result in a significantly larger final settlement compared to the other techniques.

In Table 8.1, the exact final settlements are shown. In addition, the dimensions for the different ground improvement techniques are shown.

Table 8.1: Results from PLAXIS for the Hisingen site

Ground improvement	**Diameter (Column)** [m]	**Thickness (L-weight fill)** [m]	**Centre-to-centre distance (Column)** [m]	**Settlement [m]**
No improvement	-	-	-	2.14
Deep mixing	0.6	-	1.2	0.80
Stone columns	0.8	-	2	1.15*
Foam glass	-	1.2	-	0.73
Leca	-	1.2	-	0.78
Deep mix. + Foam glass	0.6	0.7	2.4	0.78
Stone col. + Foam glass	0.8	0.9	4	0.79

*Stone columns can't limit the settlement to around 0.75m. Thus, stone columns used as the only improvement technique are not recommended for this site.

To compare the settlements of improved and unimproved ground, the predicted settlement without improvement is included in Figure 8.2.

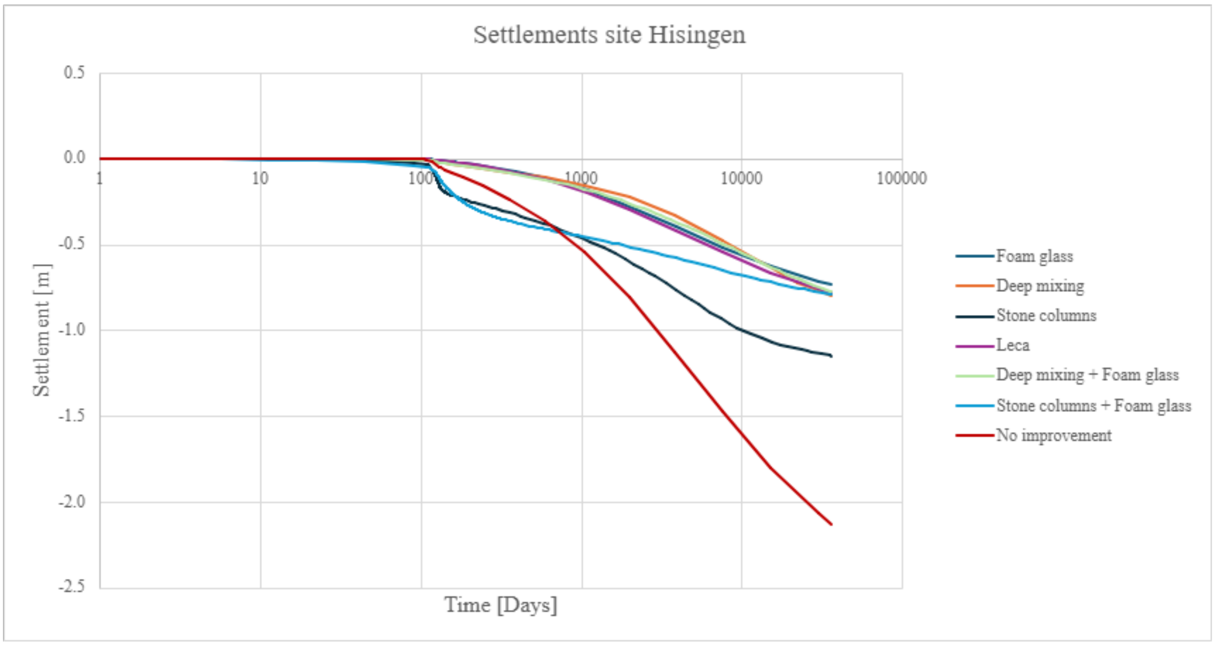


Figure 8.2: The settlement over time compared with the settlement without ground improvement in the Hisingen site

Figure 8.2 shows that all ground improvement techniques reduced the settlements and Table 8.2 shows the improvement factor for all the improvement techniques. As seen in the table, the improvement factors generally lie between 2.7-2.9, which is generally quite low for usually is expected regarding improvement.

Table 8.2: List of improvement factor of the different ground improvement techniques at the Hisingen site

Ground improvement	Improvement factor
Deep mixing	2.7
Stone columns	1.9
Foam glass	2.9
Leca	2.7
Deep mixing + Foam glass	2.7
Stone columns + Foam glass	2.7

8.1.2 Results from hand calculations

The settlement results of the hand calculations for Hisingen are shown in Table 8.3. Worth noting is that the settlements are generally somewhat greater than those obtained from PLAXIS, except for deep mixing combined with foam glass. A similar trend in settlement behaviour is observed as in the PLAXIS results, where, for example, stone columns give the largest settlements among the different ground improvement techniques.

Table 8.3: Settlements using hand calculations for the Hisingen site

Ground improvement	Settlement [m]
No improvement	2.85
Deep mixing	0.96
Stone columns	2.04
Foam glass	0.94
Leca	1.04
Deep mixing + Foam glass	0.42
Stone columns + Foam glass	-

8.1.3 Results from GeoStudio

In Table 8.1, all the calculated safety factors for slope stability are presented. The entry and exit range for the stability analysis is set to include the most critical slip surface. As highlighted in the table, the critical slip surface for deep mixing in the combined model deviates in size and shape from the other cases but is complemented by a safety factor corresponding to a slip surface that is more similar to the others.

Table 8.4: Safety factors from GeoStudio for the Hisingen site corresponding to the critical slip surfaces.

Ground improvement	Combined model	Undrained model
No improvement	0.96	0.89
Deep mixing	1.26*	1.36
Stone columns	1.07	1.01
Foam glass	1.12	1.06
Leca	1.13	1.03
Deep mix + Foam glass	1.19	1.12
Stone col. + Foam glass	1.15	1.06

*Greater slip surface, see Figure 8.5. For similarly sized slip surface, SF=1.39

In Figure 8.3 and Figure 8.4 below, the slip surfaces and their corresponding factor of safety are shown for the best and worst performing slope, respectively, at the Hisingen site. Each slip surface reaches a maximum depth of about 14 metres and has a radius of about 30-40 metres. The slip surfaces for all methods and material models can be found in Appendix B.

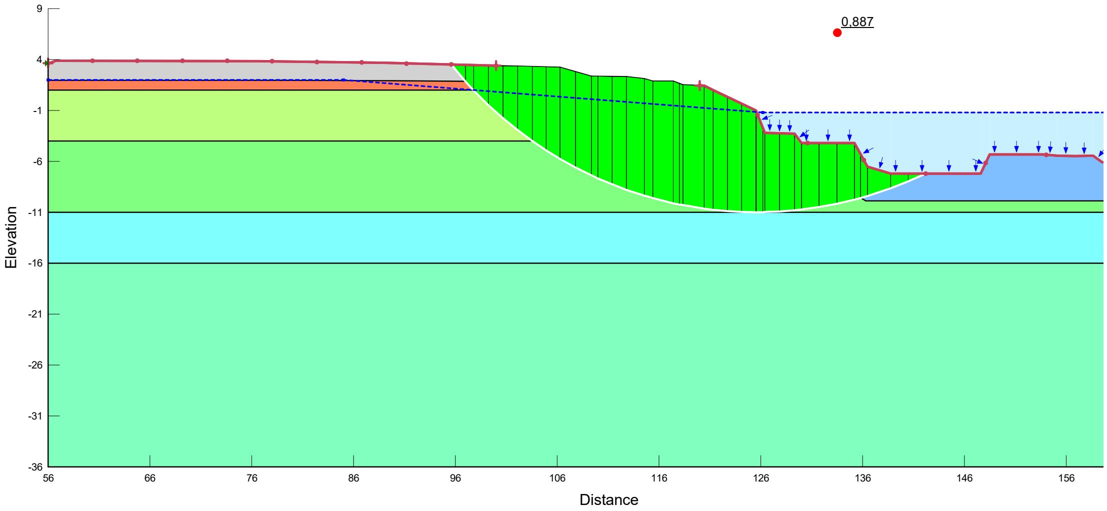


Figure 8.3: Critical slip surface for Hisingen without improvement, from undrained material model

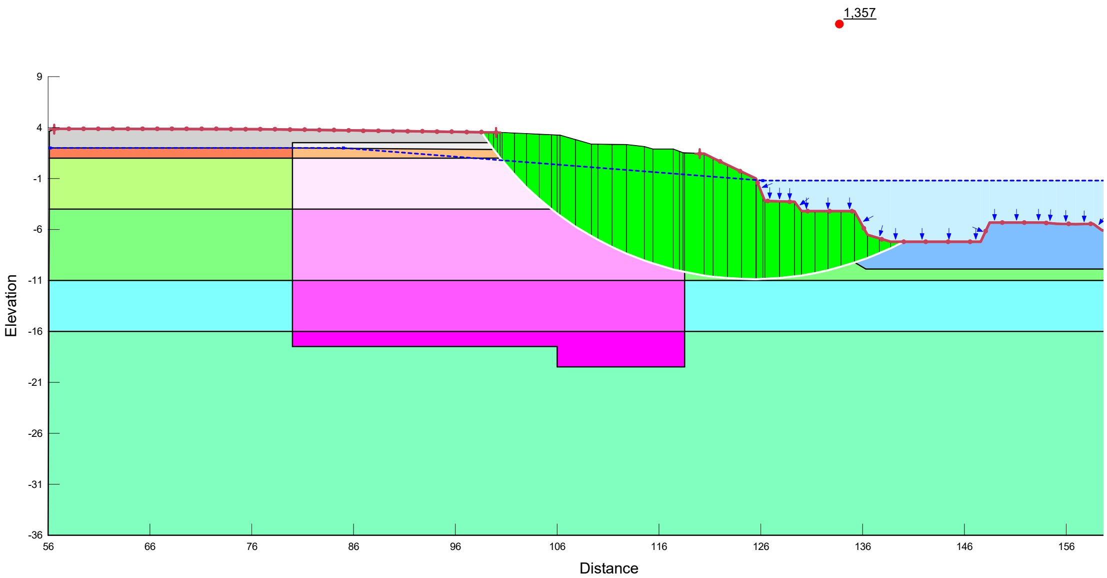


Figure 8.4: Critical slip surface for Hisingen with deep mixing, from undrained material model

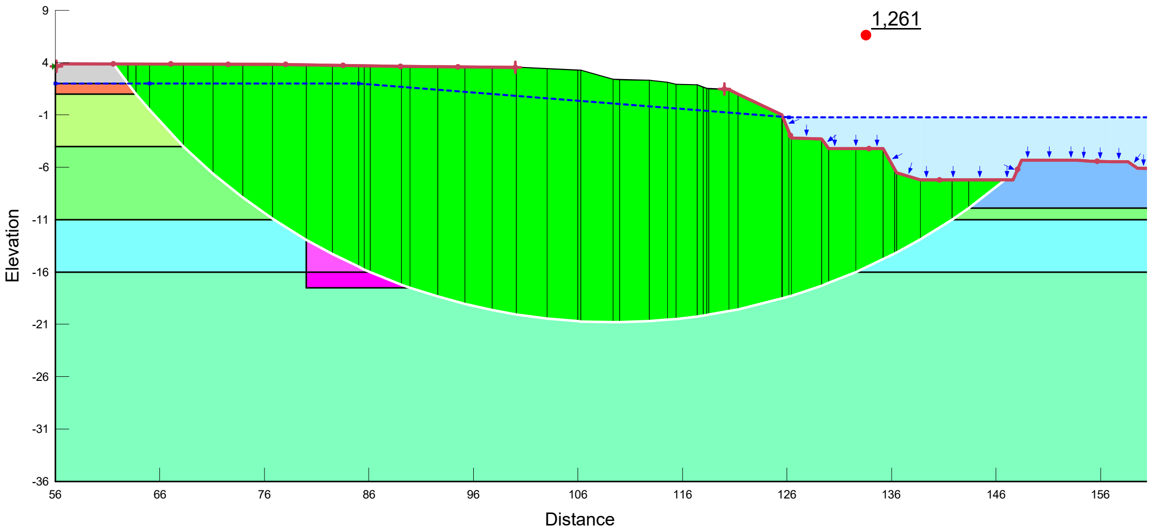


Figure 8.5: Critical slip surface for Hisingen with deep mixing, from combined material model, Greater slip surface

8.1.4 Environmental comparison

Figure 8.6 shows the results of the comparison of climate impact in emissions of CO_2-equivalents for the different ground improvement techniques. The results are based on the values for climate impact for the different techniques presented in chapter 7 and are valid for an improved area of 10,000 square metres. It should be noted that the values for deep mixing reported in the results assume that Multicem with a mixture of 50 percent cement and 50 percent CKD is used as a binder with a mixing ratio of 120 kg/m^3.

Although the techniques are designed with the same dimensions for both slope and soil improvement beneath an embankment, the differing applications result in different conditions for the use of lightweight fill. For embankment applications, all or part of the lightweight fill can be incorporated within the embankment, whereas for slope stability improvement, a larger amount of soil must be excavated to accommodate the lightweight fill. This difference influences both the environmental impact and the cost estimates.

The results presented in Figure 8.6 indicate that deep mixing has by far the greatest climate impact, several times higher than the other techniques. Among the remaining techniques, the differences are smaller, with lightweight fill in the form of foam glass yielding the lowest climate impact in both cases. Although Figure 8.6 refers to embankment conditions, a similar pattern is observed for slope applications, and the results are therefore not presented separately.

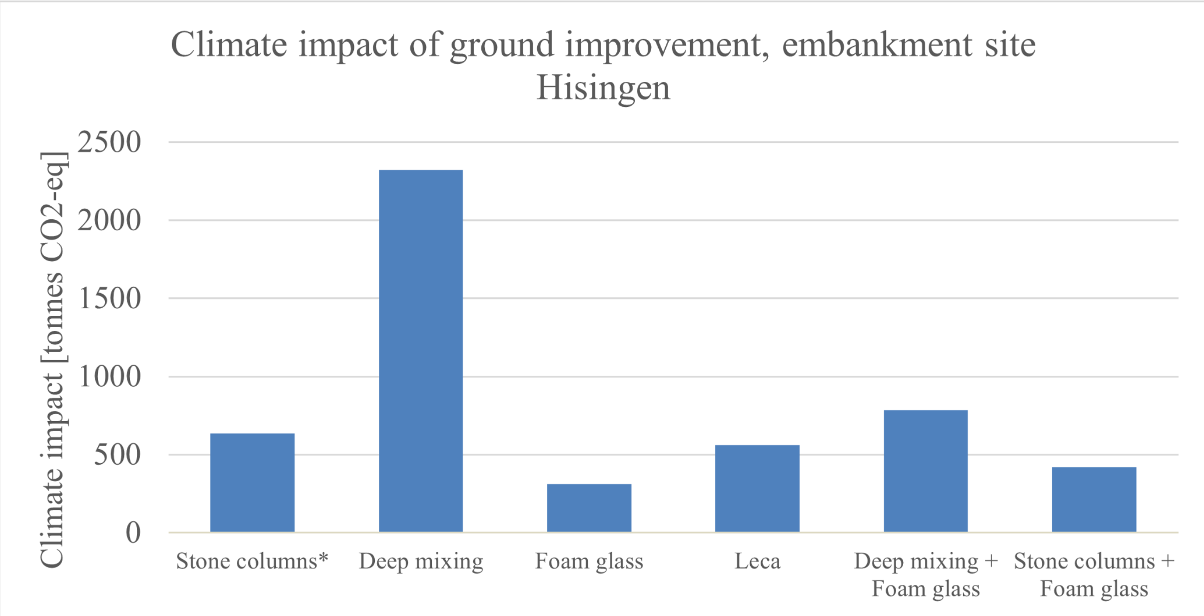


Figure 8.6: Climate impact of ground improvement at the Hisingen site (embankment)

*Stone columns can't limit the settlement to around 0.75m. Thus, stone columns used as the only improvement technique are not recommended for this site.

To enable a more detailed analysis of the results and support efforts to minimise the environmental impact of ground improvement, the total impact has been divided into different categories, as shown in Figure 8.7. The source of climate impact has been divided into the following categories: materials, transport, workplace and savings. Materials represent all raw materials used in the construction process. Transport includes all transportation activities, such as the delivery of materials from the production sites to the construction site, as well as the transport of waste for recycling or landfill. Workplace refers to the use of machinery and other activities carried out at the construction site. Savings, as previously described, refer to the reductions associated with the decreased need for embankment material when parts of the embankment are replaced with lightweight fill.

Figure 8.7 shows that the main contributor to emissions for all ground improvement techniques is the production of materials. This is also where the largest differences between the techniques are observed, as the material used for deep mixing alone results in approximately twice the emissions compared to the combined emissions from all categories for the other techniques. Emissions related to transport are of a similar order of magnitude across all techniques. In contrast, emissions associated with the workplace are highest for stone columns and deep mixing, and lower for lightweight fill. It should be noted that Figure 8.7 refers to ground improvement beneath an embankment. The distribution of climate impact for slope improvement is not presented separately, as it largely follows the same pattern, with the difference being that the savings are eliminated.

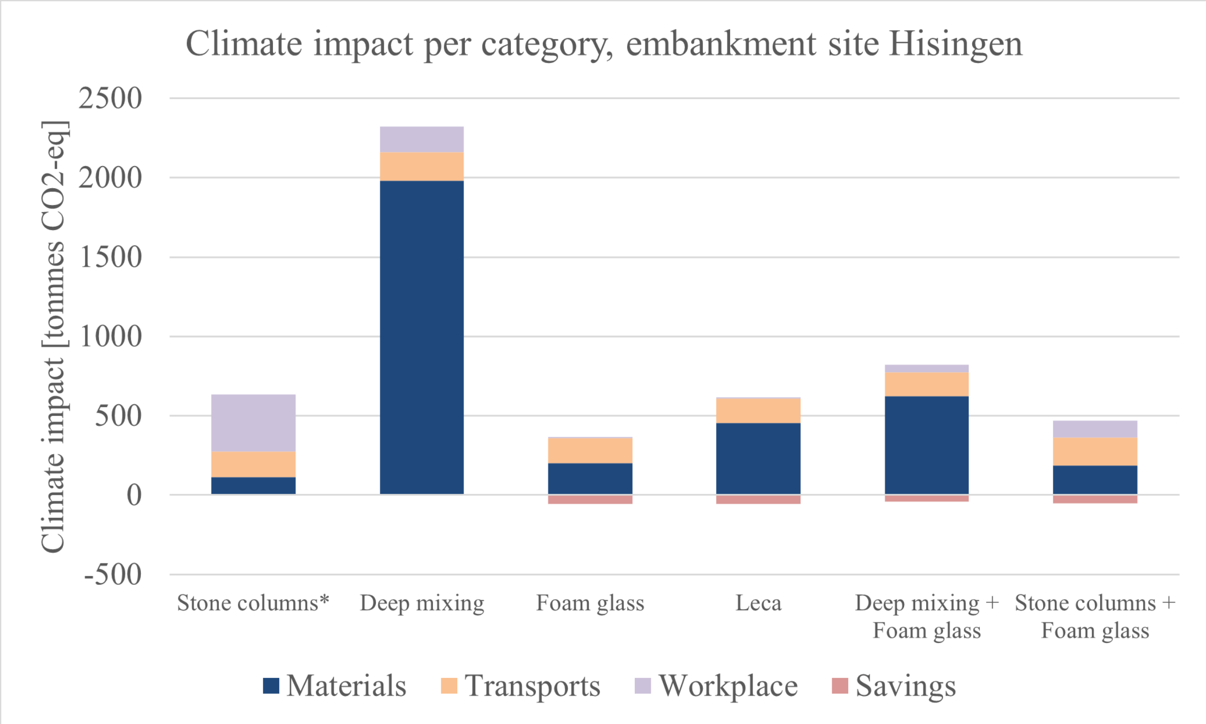


Figure 8.7: Climate impact per category, embankment at the Hisingen site

*Stone columns can't limit the settlement to around 0.75m. Thus, stone columns used as the only improvement technique are not recommended for this site.

8.1.5 Economical comparison

The calculated costs for each ground improvement technique are shown in Figure 8.8 and Figure 8.9. The results are divided according to application, where Figure 8.8 presents the costs for ground improvement beneath an embankment, and Figure 8.9 presents the costs for slope improvement.

The results show that lightweight fill, in the form of foam glass and Leca, as well as in combination with deep mixing, has the lowest cost for embankment construction. However, for slope improvement, lightweight fill is less cost-effective, with deep mixing representing the most economically profitable alternative.

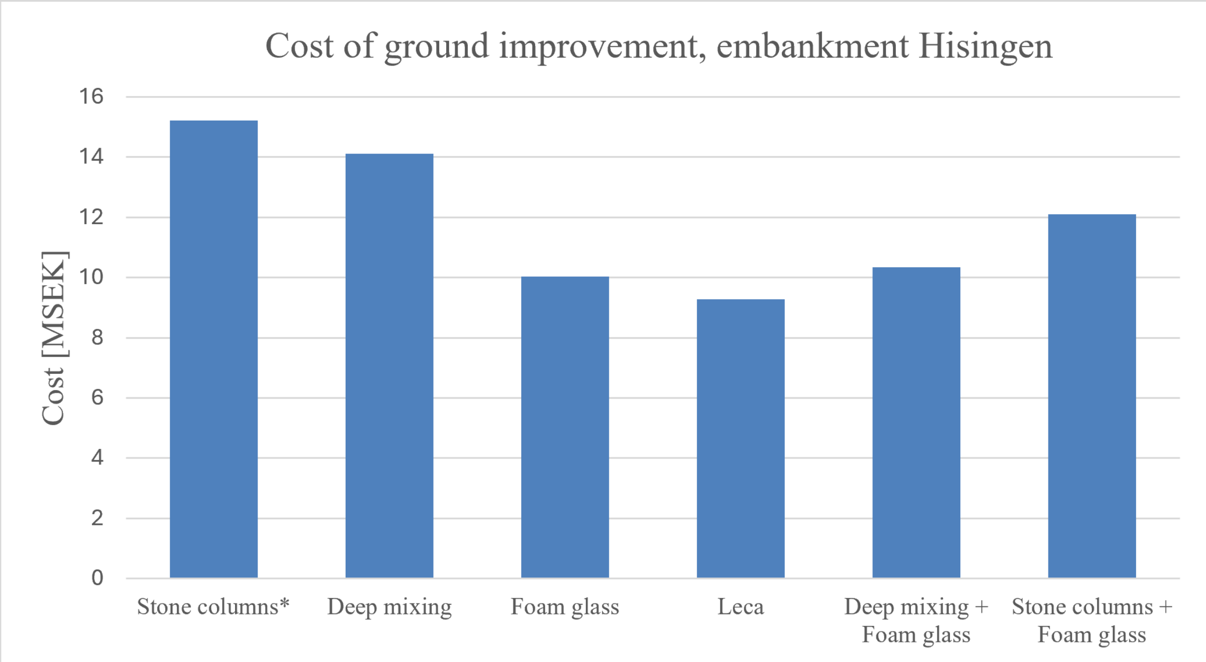


Figure 8.8: Cost of the different ground improvement techniques at site Hisingen (Embankment)

*Stone columns do not reduce settlement as much as other methods. Please note that settlement with stone column is higher than with other techniques.

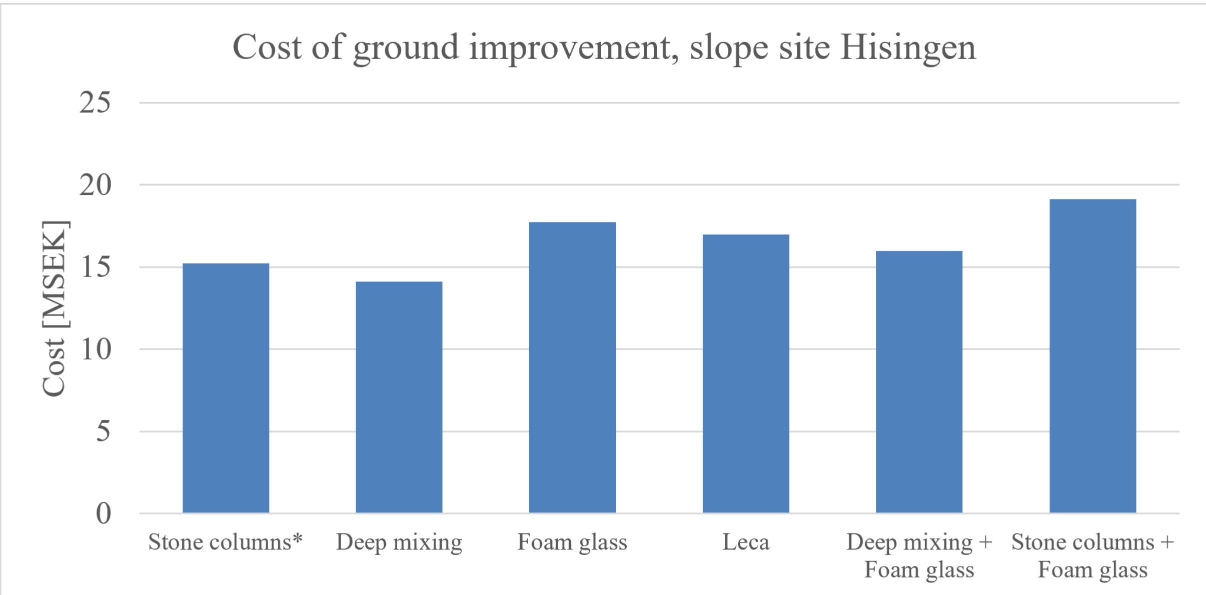


Figure 8.9: Cost of the different ground improvement techniques at site Hisingen (Slope)

*Stone columns do not reduce settlement as much as other methods. Please note that settlement with stone column is higher than with other techniques.

To enable further analysis of the main cost drivers, the costs have, similarly to the environmental impact assessment, been divided into different contributing factors. These are presented in Figure 8.10 for embankment applications and in Figure 8.11 for slope applications.

Similarly to the environmental impact, materials account for the largest share of the total cost. However, the proportion of cost attributed to materials is smaller than their contribution to the overall environmental impact. It should also be noted that for deep mixing, the installation and binder costs are included within the material category, meaning that the actual material cost is lower than indicated in Figure 8.10 and Figure 8.11. Furthermore, as shown in Figure 8.10 and Figure 8.11, the higher cost associated with lightweight fill in slope applications compared to embankment applications is primarily due to increased waste management costs.

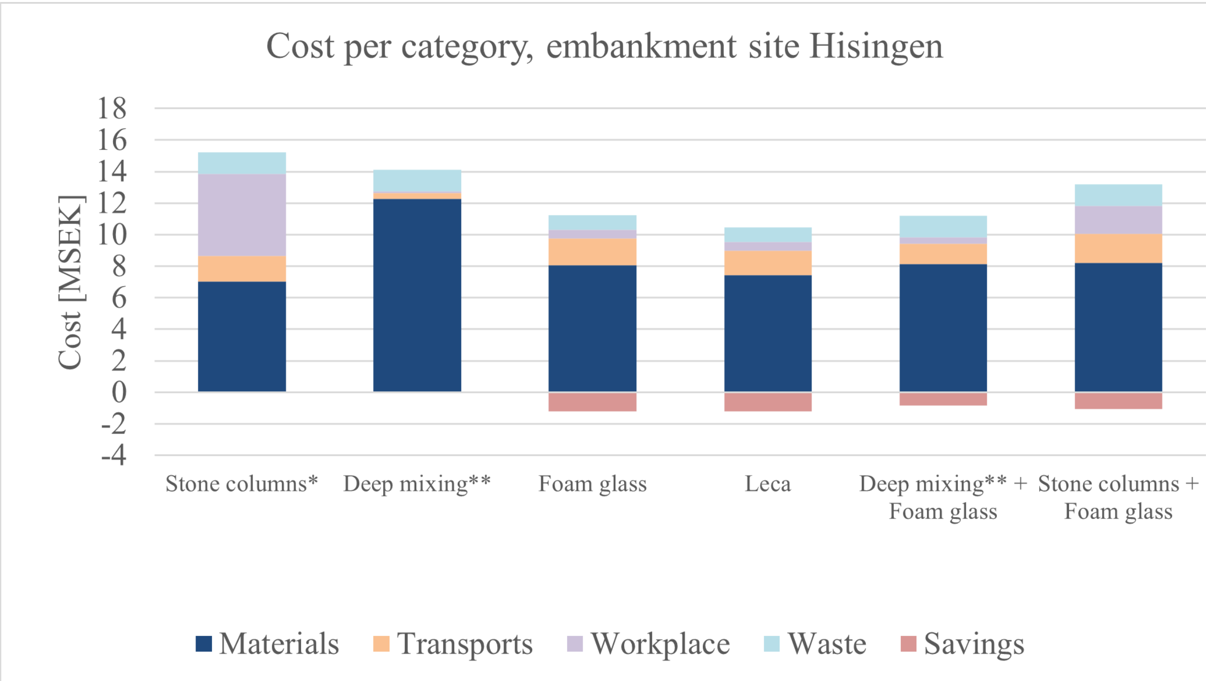


Figure 8.10: Cost per category, embankment at the Hisingen site

*Stone columns do not reduce settlement as much as other methods. Please note that settlement with stone column is higher than with other techniques.
**For deep mixing, installation cost and transport cost of the binders are included in the material cost.

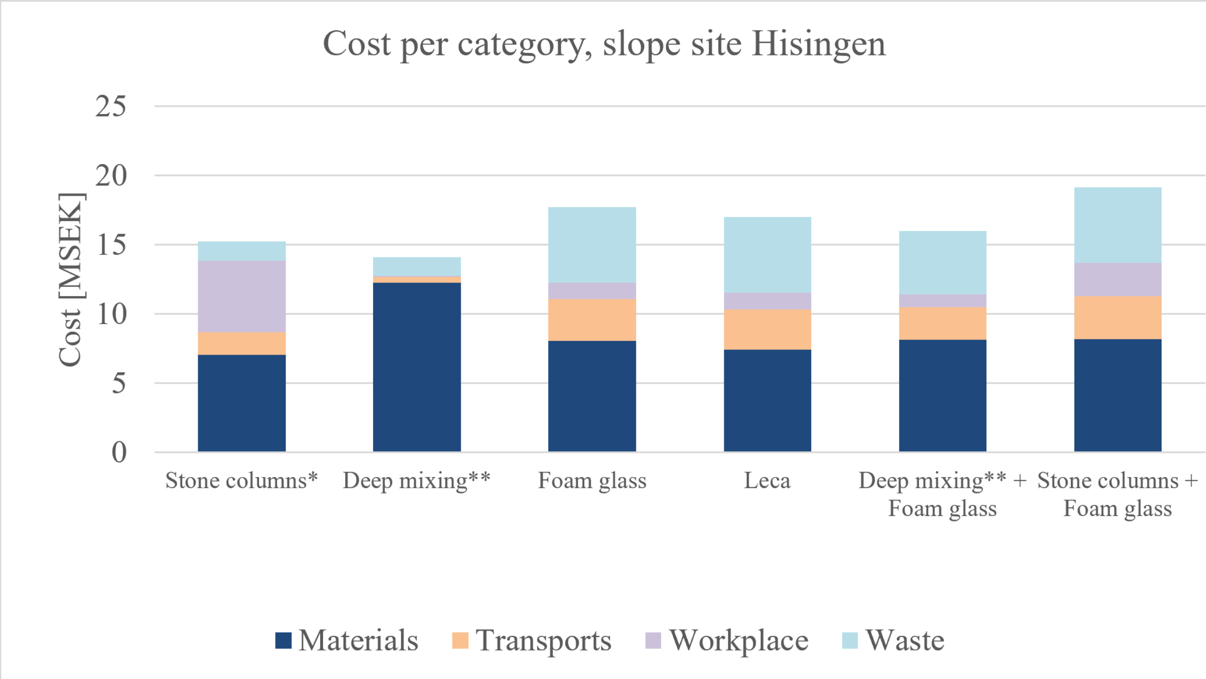


Figure 8.11: Cost per category, slope at the Hisingen site

*Stone columns do not reduce settlement as much as other methods. Please note that settlement with stone column is higher than with other techniques.
**For deep mixing, installation cost and transport cost of the binders are included in the material cost.

8.2 Results Uddevalla

The results from Uddevalla are presented in the same way as the results from site Hisingen. First, the results from the settlement calculation in PLAXIS are presented.

8.2.1 Results from PLAXIS

Figure 8.12 presents the calculated settlements for the different techniques and combinations of techniques, including their development over time. It should be noted that the settlements are not identical, as achieving this would require highly detailed dimensioning of the ground improvement measures. Instead, the design is based on centre-to-centre spacing and the thickness of the lightweight fill being defined in whole decimetres to ensure practical buildability. As a result, the calculated settlements differ by approximately 7 centimetres between the techniques that result in the greatest and the least settlement.

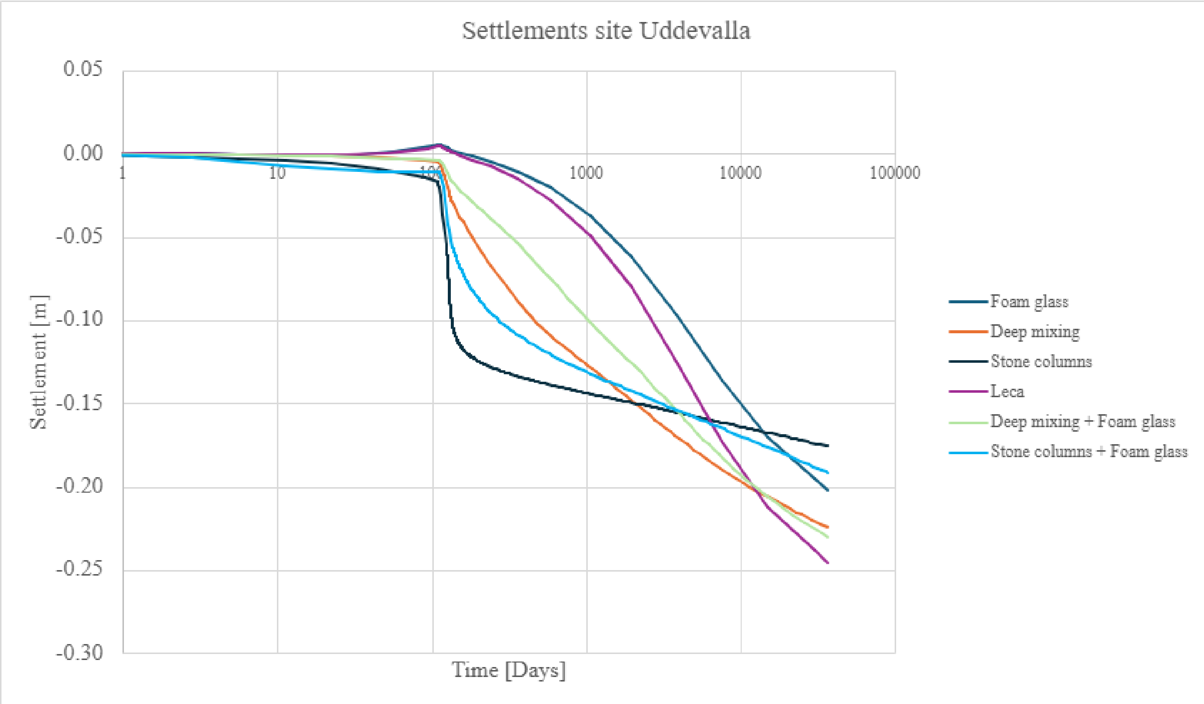


Figure 8.12: Settlement over time for the different ground improvement techniques at the Uddevalla site

In Figure 8.12, the development of settlements over time is presented. Stone columns, in particular, exhibit rapid primary settlement, followed by an early transition into creep settlement. When combined with foam glass, the rate of settlement is reduced compared to stone columns alone, but remains significantly faster than for the other ground improvement techniques. A notable difference compared to the Hisingen site should be highlighted, where stone columns do not show a similarly accelerated settlement process, which is clearly observed at the Uddevalla site. Furthermore, deep mixing exhibits an intermediate behaviour, with characteristics of both relatively fast and slow settlement development. For the lightweight fill techniques, foam glass and Leca, the initial rate of settlement is lower than for the other techniques. However, over longer time periods, the rate becomes greater than for the other techniques. This behaviour can be explained by the reduced load applied to the ground when using lightweight fill, resulting in smaller immediate settlements compared to the other techniques.

The dimensions of the ground improvement techniques used to achieve the similar settlements presented in Figure 8.12 are provided in Table 8.5. The corresponding final settlements are also presented in that table.

Table 8.5: Results from PLAXIS for the Uddevalla site

Ground improvement	**Diameter (Column)** [m]	**Thickness (L-weight fill)** [m]	**Centre-to-centre distance (Column)** [m]	**Settlement [m]**
No improvement	-	-	-	1.30
Deep mixing	0.6	-	1.5	0.23
Stone columns	0.8	-	1.7	0.18
Foam glass	-	1.9	-	0.20
Leca	-	1.9	-	0.25
Deep mixing + Foam glass	0.6	1.4	3	0.23
Stone columns + Foam glass	0.8	1.5	3.4	0.19

Figure 8.13 presents the settlement over time for both the unimproved case and the cases with different ground improvement techniques. It is evident that all techniques result in a substantial reduction in settlement. The final settlement after 100 years is reduced from approximately 1.3 metres to around 20 centimetres.

Compared to the Hisingen site, the settlements at the Uddevalla site are lower for both the unimproved case and the cases with ground improvement. This is observed despite the fact that the applied load, in the form of a 1.5 metre high embankment, is the same at both sites. The settlement without improvement is approximately one metre greater at the Hisingen site than at the Uddevalla site. Furthermore, the settlements with ground improvement are approximately three times higher at the Hisingen site than at the Uddevalla site. This trend is observed even though the dimensions of several ground improvement techniques are larger at the Hisingen site. For example, deep mixing at the Hisingen site is characterized by a smaller centre-to-centre spacing, while still resulting in significantly greater settlements.

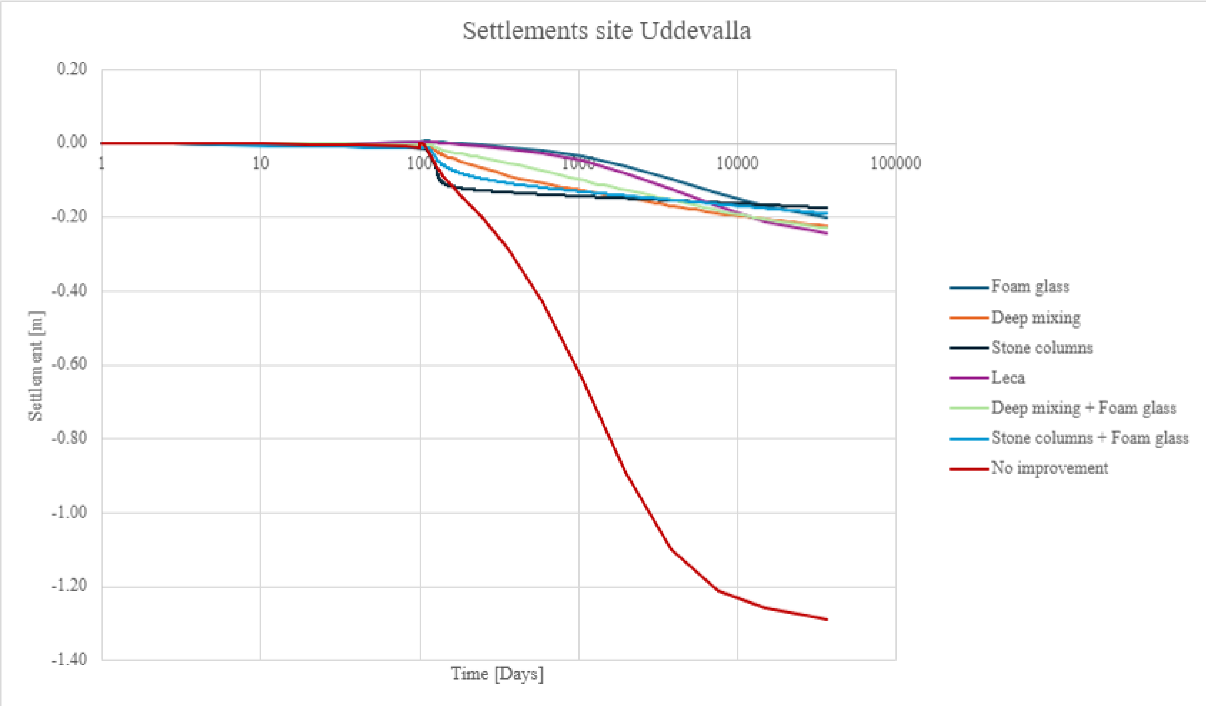


Figure 8.13: The settlement over time compared with the settlement without ground improvement at the Uddevalla site

In Table 8.6, the improvement factors for the different ground improvement techniques are presented. The values are generally in the range of 6–7, indicating a relatively high level of settlement reduction.

Table 8.6: List of improvement factor of the different ground improvement techniques at the Uddevalla site

Ground improvement	**Improvement factor**
Deep mixing	5.9
Stone columns	7.2
Foam glass	6.5
Leca	5.2
Deep mixing + Foam glass	5.7
Stone columns + Foam glass	6.8

A comparison of the improvement factors at the Uddevalla and Hisingen sites shows that the values are significantly higher at Uddevalla. The improvement factors at the Uddevalla site is approximately twice that of the Hisingen site. The underlying reasons for this difference are further addressed in the Discussion.

8.2.2 Results from hand calculations

The settlement results from the hand calculations for the Hisingen site are presented in Table 8.7. In general, the calculated settlements are somewhat lower than those obtained from PLAXIS, except for stone columns. In particular, the lightweight fill techniques yield significantly lower settlements in the hand calculations compared to the PLAXIS results.

Table 8.7: Calculated settlements from hand calculations for the Uddevalla site

Ground improvement	**Settlement** [m]
No improvement	1.14
Deep mixing	0.25
Stone columns	0.54
foam glass	0.03
Leca	0.07
Deep mixing + Foam glass	0.14
Stone columns + Foam glass	-

8.2.3 Results from GeoStudio

The factor of safety for all scenarios is presented in Table 8.8. Equivalently to the Hisingen site, the entry and exit regions were dimensioned by the slip surfaces when modelling the site in Uddevalla.

Table 8.8: Safety factors from GeoStudio for the Uddevalla site. **Entry: 1-30, exit: 35-55**

Ground improvement	Combined model	Undrained model
No improvement	1.31	1.39
Deep mixing	1.64	1.70
Stone columns	1.67	1.74
Foam glass	1.36	1.40
Leca	1.35	1.40
Deep mixing + Foam glass	1.46	1.52
Stone columns + Foam glass	1.58	1.64

Figures 8.14 and 8.15, below presents the critical slip surfaces of the slope in Uddevalla, both with the best performing stability improving method, and without any improvement. Both slip surfaces reach a depth of around 8-9 metres and their corresponding radii are about 22 metres.

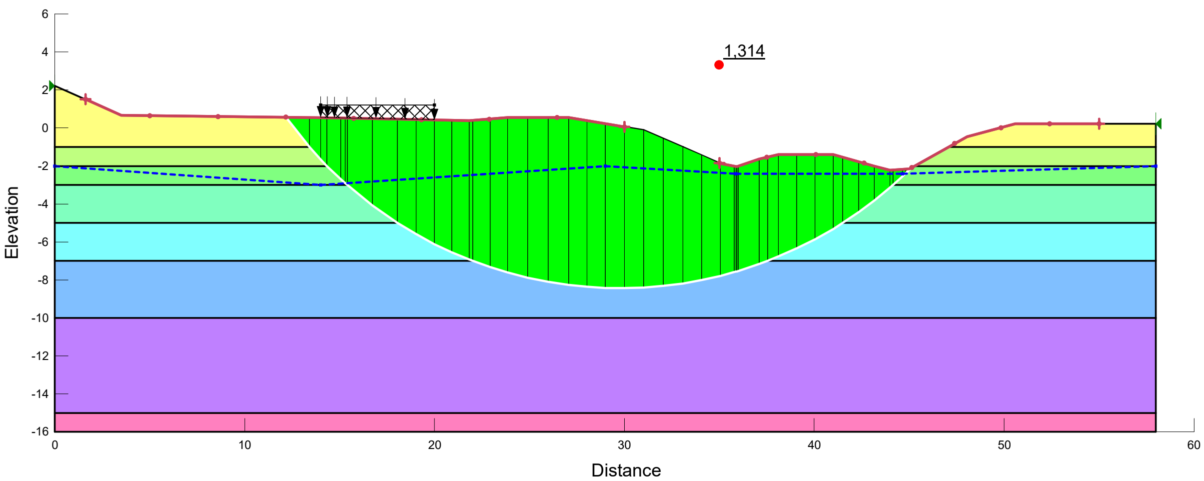


Figure 8.14: Critical slip surface for the scenario without any ground improvement in Uddevalla, combined model

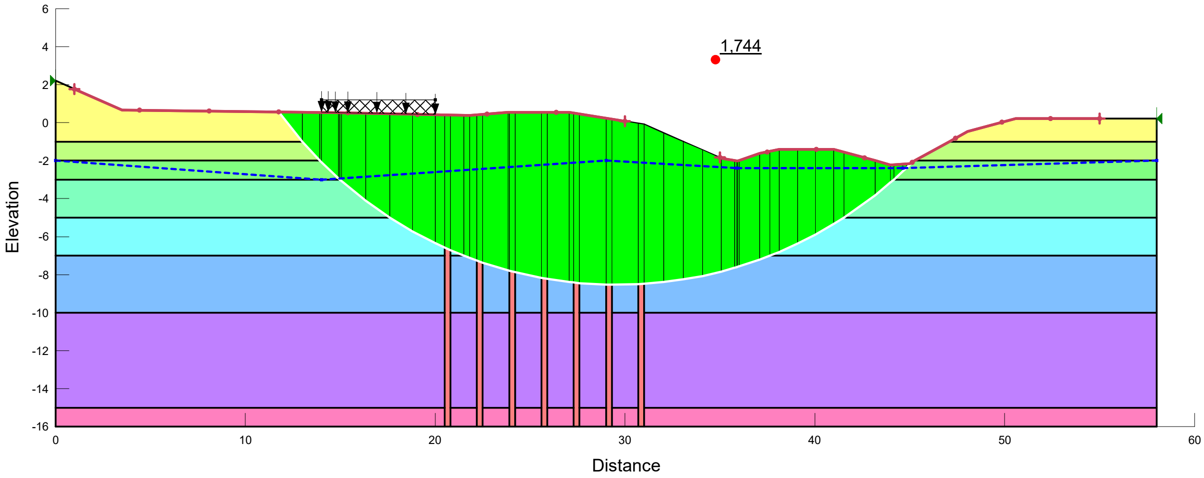


Figure 8.15: Critical slip surface for the scenario with stone columns as ground improvement, undrained material model

8.2.4 Environmental comparison

Figure 8.16 presents the climate impact values for the different ground improvement techniques. The figure refers to embankment conditions; however, similar results are observed for slope applications, and are therefore not presented separately.

In contrast to the Hisingen site, the climate impact is more evenly distributed among the different ground improvement techniques. Although deep mixing still exhibits the highest climate impact, the differences between the remaining techniques are less pronounced than at the Hisingen site. Foam glass yields the lowest climate impact for embankment applications, while stone columns result in the lowest climate impact for slope applications. It should also be noted that the values reported for deep mixing are based on the assumption that Multicem, consisting of 50% cement and 50% CKD, is used as a binder with a mixing ratio of 120 kg/m^3.

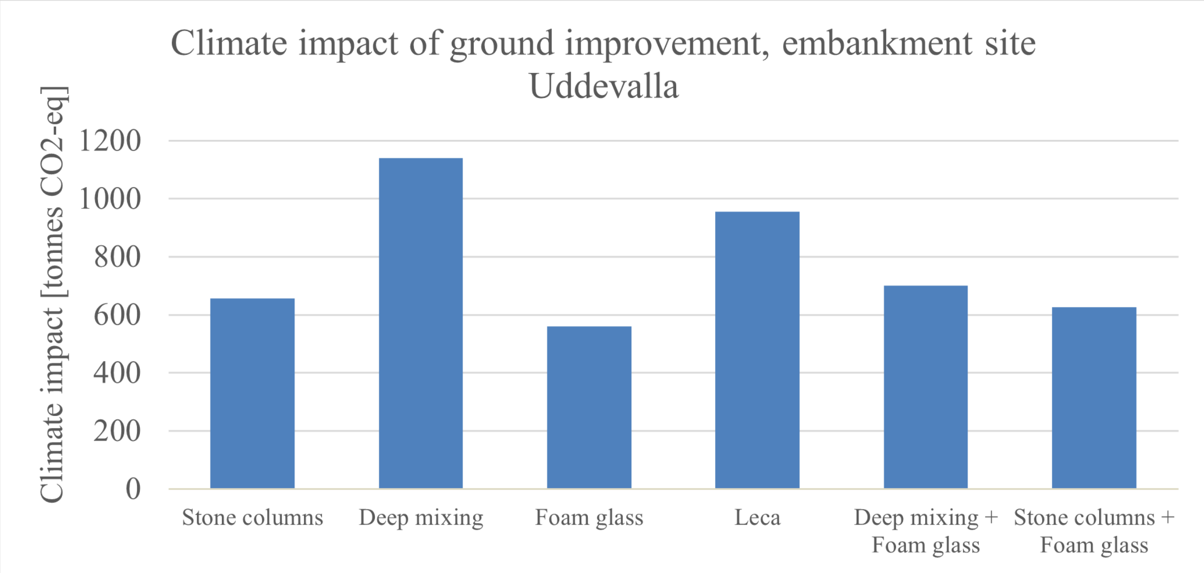


Figure 8.16: Climate impact for the different ground improvement techniques at the Uddevalla site (embankment)

Regarding the distribution of environmental impact by category, as shown in Figure 8.17, the variation at this site is greater than at the Hisingen site. Material-related emissions remain the dominant contributor for all ground improvement techniques, with the exception of stone columns. However, the transport of lightweight fill constitutes a significant share of the total climate impact in this case. For stone columns, transport and, in particular, workplace activities contribute a larger proportion of the emissions compared to material production.

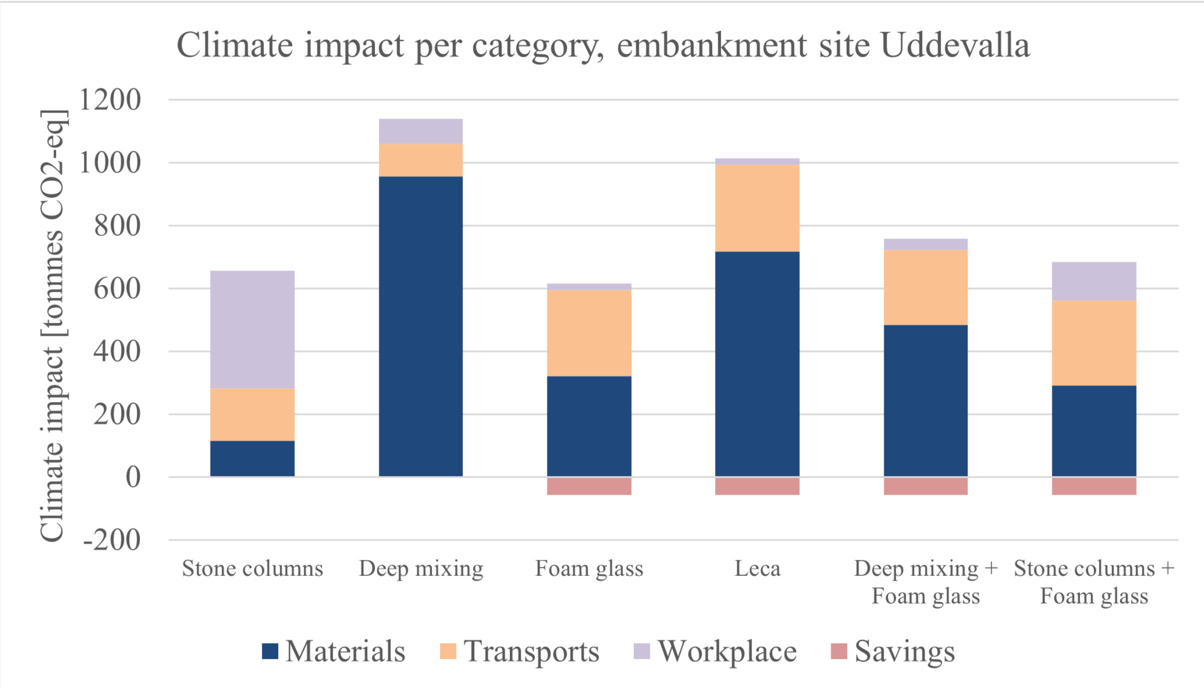


Figure 8.17: Climate impact per category, embankment at the Uddevalla site

8.2.5 Economical comparison

Figure 8.18 and Figure 8.19 present the costs of the different ground improvement techniques at the Uddevalla site for embankment and slope applications, respectively. In this case, deep mixing is by far the most cost-effective technique, followed by stone columns. Lightweight fill exhibits a considerably higher cost for embankment applications, which increases further in comparison to stone columns and deep mixing in slope applications.

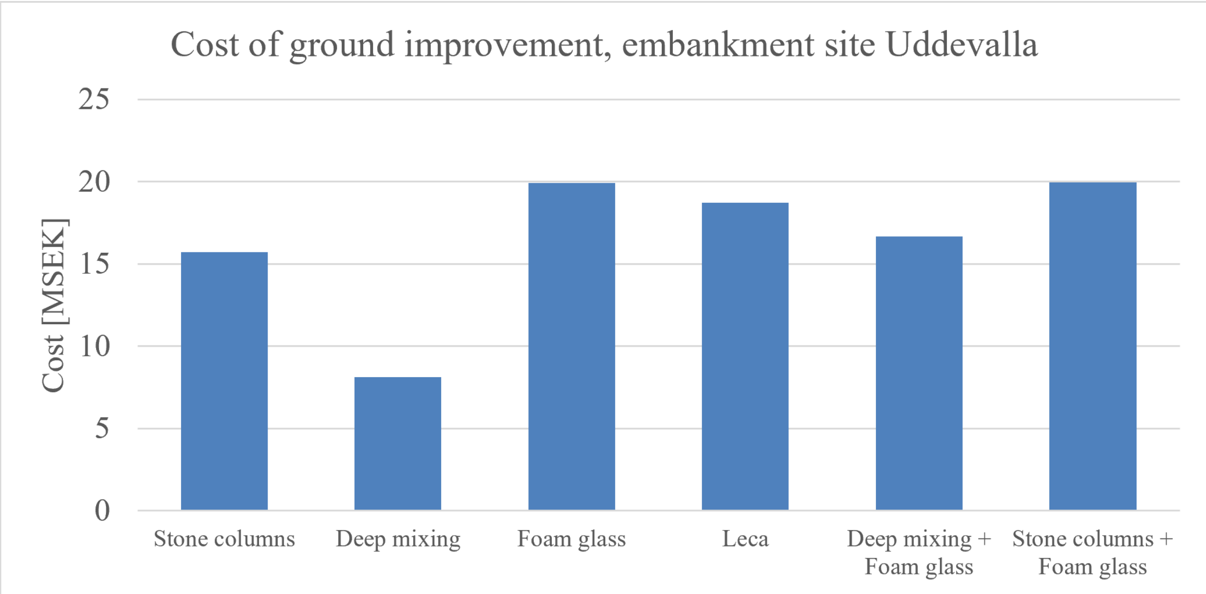


Figure 8.18: Cost of the different ground improvement techniques at the Uddevalla site (embankment)

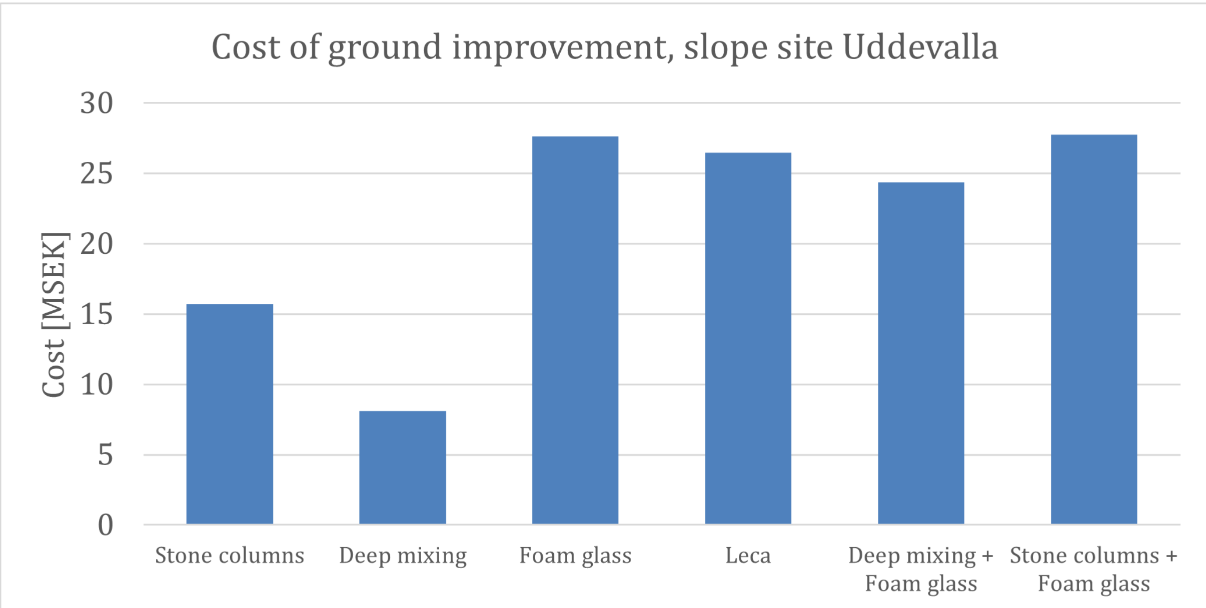


Figure 8.19: Cost of the different ground improvement techniques at the Uddevalla site (slope)

Regarding the cost distribution presented in Figure 8.20, the total cost is dominated primarily by material costs, particularly for deep mixing. For stone columns, installation costs constitute an important component, while for lightweight fill, transportation costs represent a significant share.

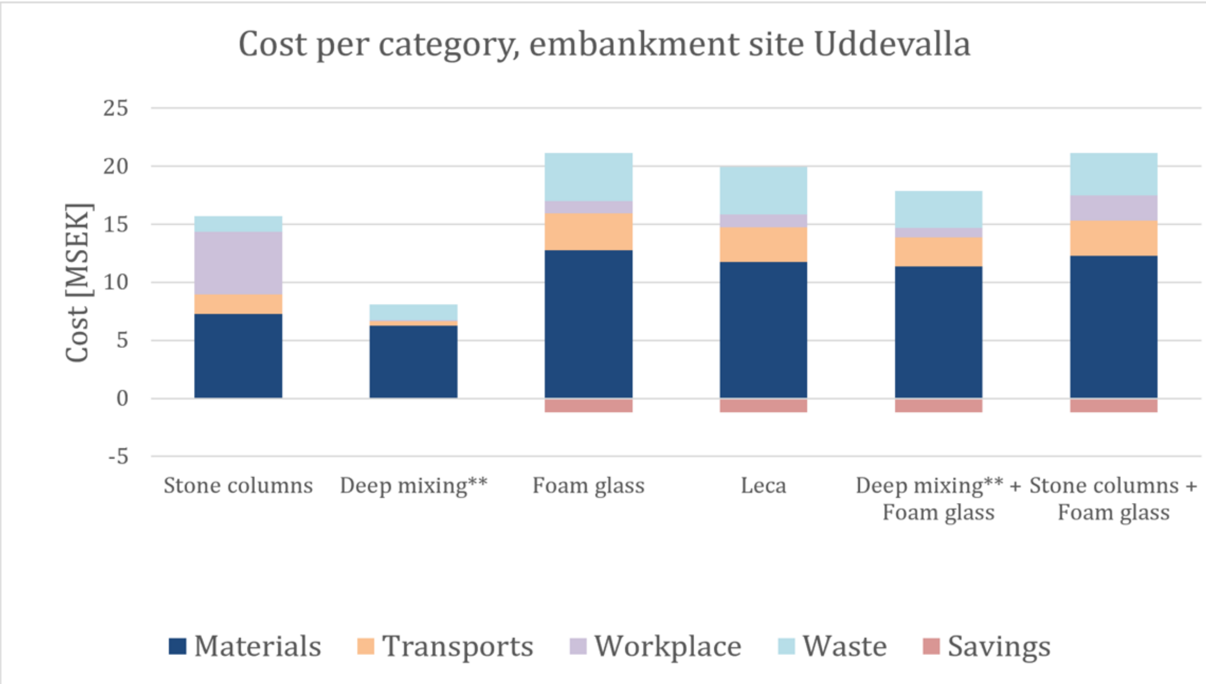


Figure 8.20: Cost per category, embankment at the Uddevalla site

**For deep mixing, installation cost and transport cost of the binders are included in the material cost.

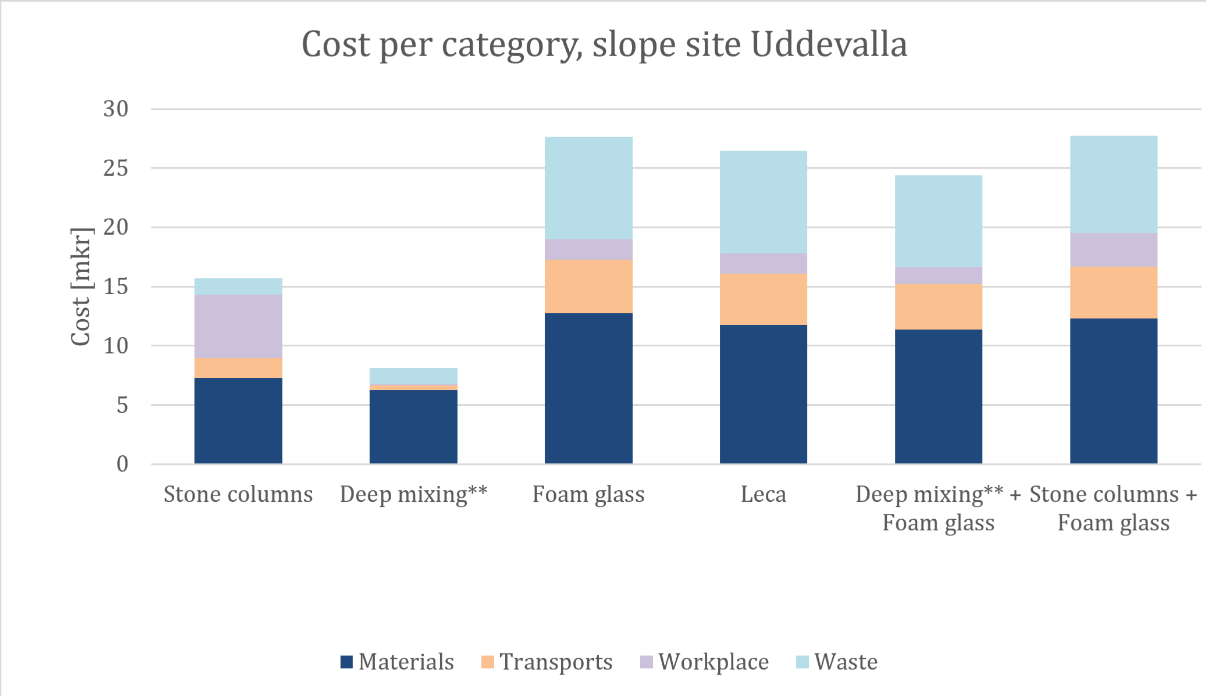


Figure 8.21: Cost per category, slope at the Uddevalla site

**For deep mixing, installation cost and transport cost of the binders are included in the material cost.

8.3 Potential savings

Based on the distribution of environmental impact and costs across different categories in Section 8.1, materials generally account for the largest share, followed by transport and workplace activities. The results indicate that there is potential for reducing material-related impacts; however, the extent of achievable reductions varies between techniques. For deep mixing, where a more environmentally optimised binder mix including CKD is already assumed in the calculations, the potential for further reductions in either cost or environmental impact is limited.

For stone columns and the two lightweight fill techniques, a greater reduction potential can be identified through the reuse of materials. In many earthworks projects, blasting operations generate excess rock. By crushing this material to suitable grain size, it can be reused in stone columns and as material for working platforms for installation equipment. This contributes to reductions in both environmental impact and cost, while also decreasing the need for material transport.

For lightweight fill, there are also opportunities to reuse material from earlier, now demolished projects, thereby reducing both costs and environmental impact compared to the use of virgin materials depending on the location of the site.

In Figure 8.22, the climate impact for the Uddevalla site is presented with the effect of material reuse taken into account. It can be observed that the difference in climate impact between deep mixing and the other techniques increases compared to the results shown in Figure 8.17.

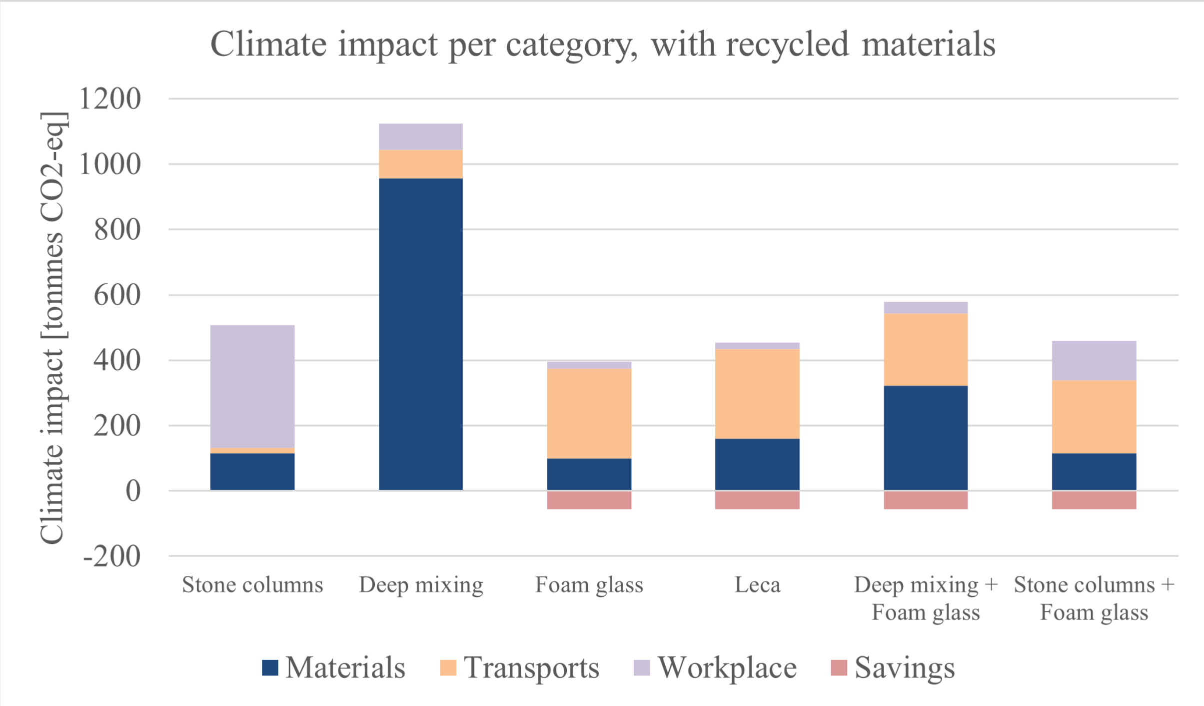


Figure 8.22: Climate impact per category for embankment at site Uddevalla, with recycled materials

Regarding costs, the reuse of locally crushed surplus rock results in cost reductions. These savings arise from both reduced material purchases and decreased transportation requirements, leading to lower transportation costs. As a result, the cost of stone columns is significantly reduced compared to the other techniques, as shown in Figure 8.23. However, deep mixing remains the most cost-effective technique, although its cost is also slightly reduced due to the use of surplus rock for the working platform.

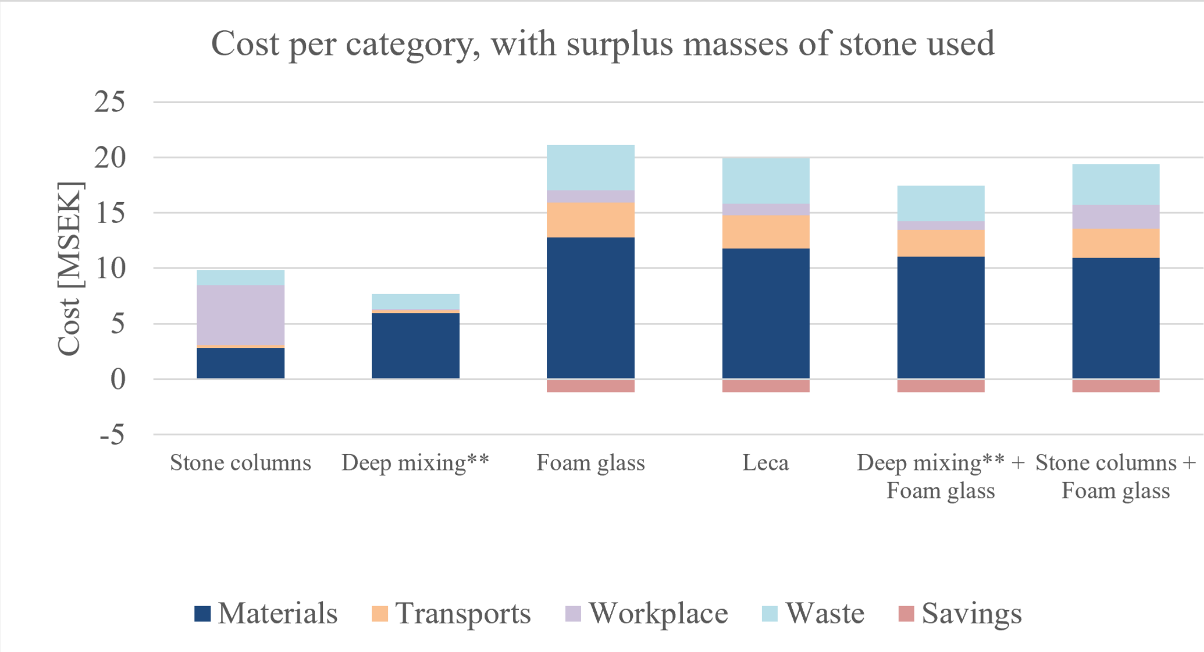


Figure 8.23: Cost per category for the embankment at the Uddevalla site, using surplus stone masses

**For deep mixing, installation cost and transport cost of the binders are included in the material cost.

After accounting for potential reductions in material-related emissions, transport and workplace activities contribute to the majority of the climate impact for the different ground improvement techniques, excluding deep mixing, as illustrated in Figure 8.22. A large share of these emissions originates from energy-intensive processes, which in the base case are assumed to rely on fossil diesel. By replacing diesel with HVO100 for all workplace machinery and transport, with the exception of maritime transport, a reduction in emissions can be observed.

Figure 8.24 shows the climate impact from Uddevalla when HVO100 is used as fuel instead of diesel, in addition to savings related to materials. The figure should therefore be compared with Figure 8.22 to see the reductions in emissions through the use of HVO100.

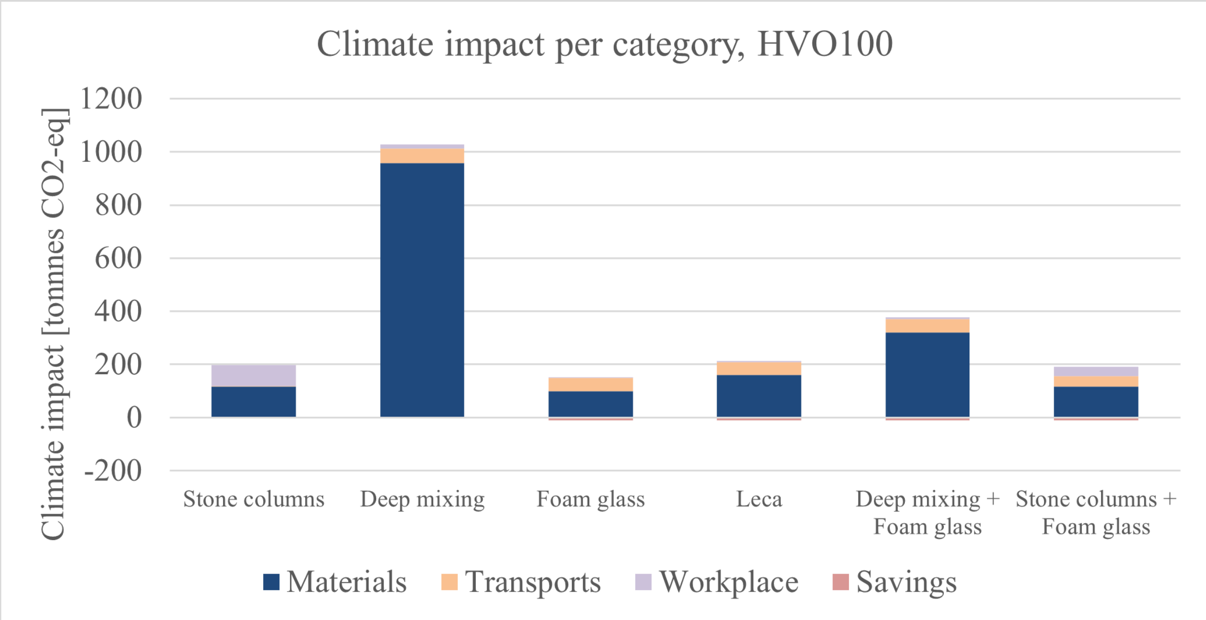


Figure 8.24: Climate impact per category for embankment at the Uddevalla site, using HVO100 instead of diesel

Further reductions in emissions can be observed when electricity is used as an energy source instead of HVO100. If all workplace activities and transport, excluding maritime transport, are powered by electricity, the resulting climate impact is illustrated in Figure 8.25, which can be compared with Figure 8.24 and Figure 8.22. The results indicate that the additional reduction achieved by replacing HVO100 with electricity is relatively small.

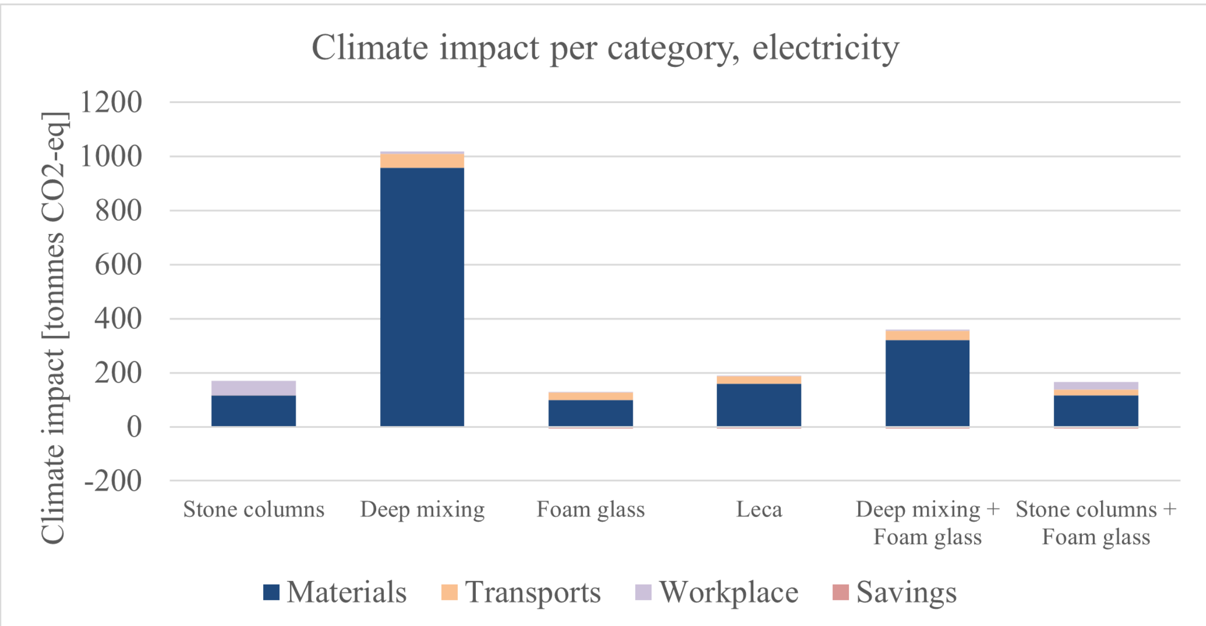


Figure 8.25: Climate impact per category for embankment at the Uddevalla site, with electricity instead of diesel or HVO100

To allow for a comparison of the different environmental savings, the reduction in CO_2-equivalents emissions associated with each measure is expressed as a percentage of the total emissions for each technique. This allows the relative efficiency of the measures to be assessed. The results are illustrated in Figure 8.26 while the corresponding numerical values are provided in Appendix Table A.2.

The results indicate that the measures with the greatest impact are the use of recycled lightweight fill, particularly for techniques incorporating Leca and foam glass. For stone columns, the largest reduction potential is associated with replacing diesel with HVO100 or electricity for the installation machines.

Overall, when combining all considered measures, the largest reduction potential is observed for Leca, corresponding to an emission reduction of approximately 80 percent, as presented in Figure 8.26. For the other techniques, the relative reduction in emissions is of a similar magnitude when expressed as a percentage of total emissions, with the exception of deep mixing. It should be noted, however, that the use of Multicem instead of a lime–cement mix is already assumed in the calculations. As previously described, this substitution results in an emission reduction of approximately 65 percent, which is not included in the values presented in Figure 8.26.

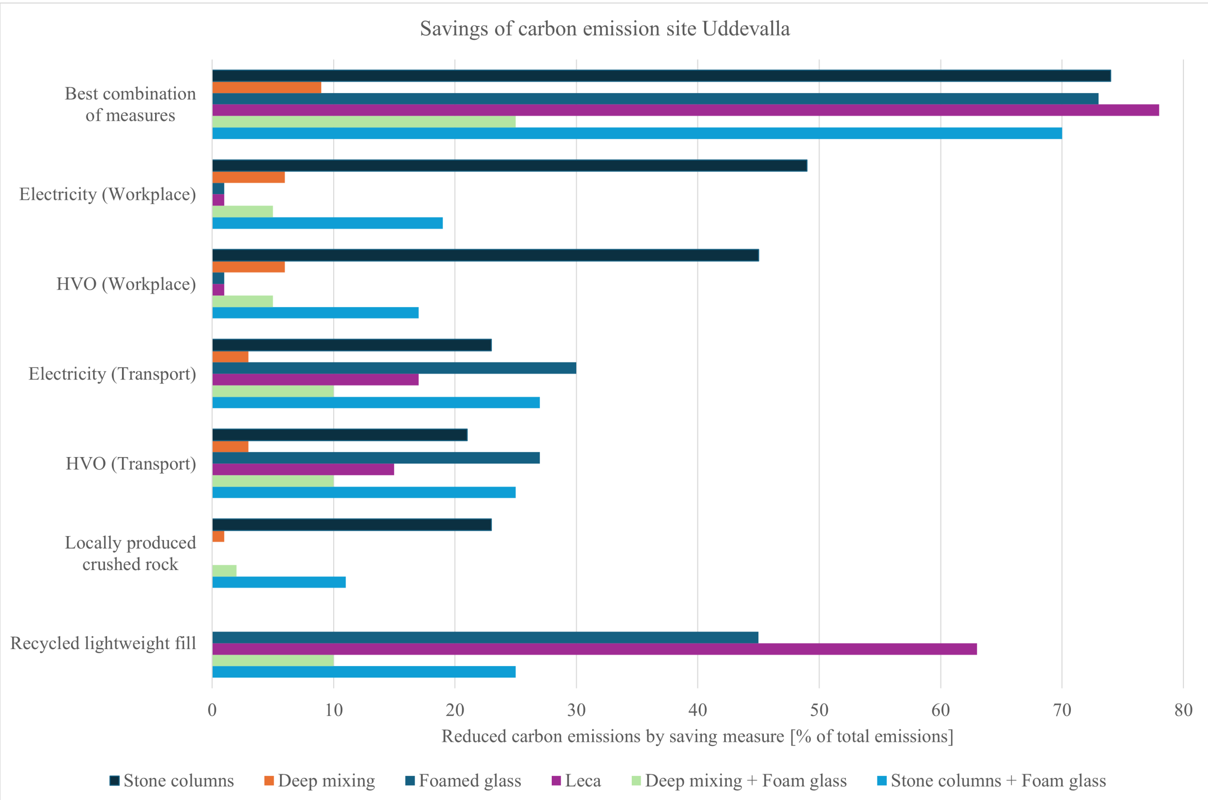


Figure 8.26: Potential savings of carbon emission for the Uddevalla site

The impact of the considered savings on emissions is presented only for the Uddevalla site. For Hisingen, the corresponding results are largely similar, with only minor differences. The associated table and figure are provided in Appendix Figure A.1.

In the above results, Multicem has been assumed as a replacement for lime–cement as the binder in deep mixing. To account for the differences between Multicem and lime–cement, a comparison is presented in Figure 8.27, which includes the climate impact for embankment applications at both the Hisingen and Uddevalla sites. The two binder types are directly compared in this figure. The results indicate that Multicem results in approximately 2–3 times lower total emissions than the lime–cement alternative. At the same time, it should be noted that this calculation assumes that the same binder content is used for both lime-cement and Multicem. This is not always the case in practice, sources indicate that the use of Multicem can require more binders to achieve the same strength, which means that the differences in climate impact may be smaller than estimated.

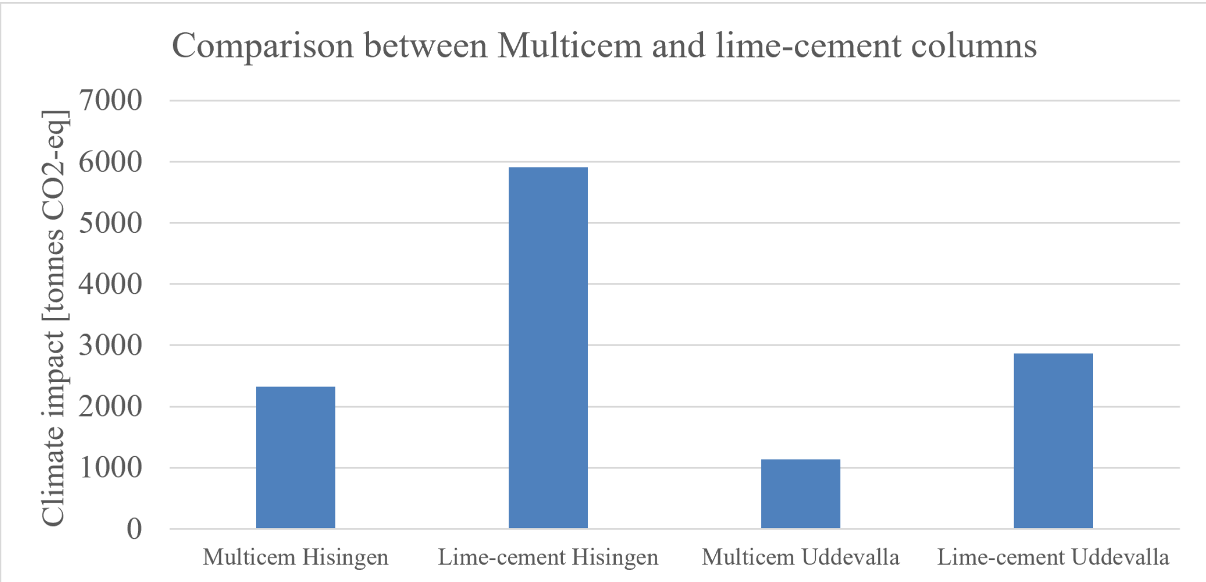


Figure 8.27: Comparison between Multicem and lime-cement columns

8.4 Sensitivity analysis

To evaluate the sensitivity of the cost calculations and the effect of variations in input prices on the total cost, a cost-based sensitivity analysis was conducted. The results presented here are only valid for the Uddevalla site. For the Hisingen site, the results follow a similar pattern with only minor differences and are therefore excluded in this section. The corresponding results for Hisingen are provided in Appendix Figure A.2.
The results of the sensitivity analysis are presented in Figure 8.28, and show the percentage

change in total cost resulting from the specified variations in input prices. The analysis was carried out separately for each ground improvement technique and for each type of cost variation. The corresponding numerical values are provided in Appendix Table A.4.

The results shown in the diagram indicate that lightweight fill is the cost component most sensitive to a 50 % price increase. However, this only applies to techniques that incorporate lightweight fill. For the other techniques, the most sensitive cost components vary. For example, for stone columns, the cost of crushed rock and installation are the most influential factors. In addition, the results indicate that landfill costs have a greater impact on the total cost than, for example, machine rental or fuel price increases of 5 SEK per litre.

It should also be noted that the cost components with the greatest impacts are associated with varying levels of uncertainty. Therefore, the probability of the price developments underlying the sensitivity analysis should also be considered to provide a more comprehensive interpretation of the results.

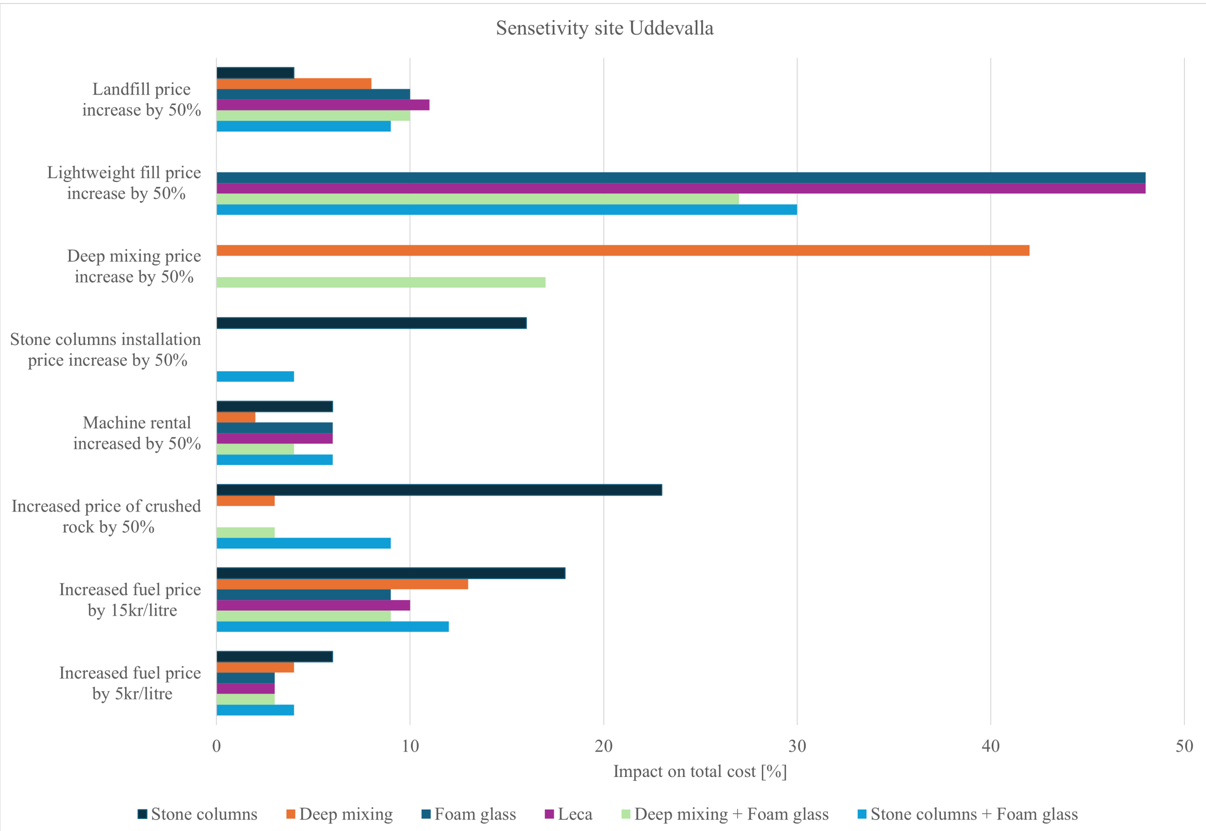


Figure 8.28: Sensitivity of the costs for the Uddevalla site

9

Discussion

The discussion chapter is divided in to three different parts. Firstly, the calculated settlements are discussed. Thereafter, the next part of the chapter are about the slope stability calculations. Finally, the economical and environmental analysis is discussed.

9.1 Discussion about the technical results regarding settlements

The higher settlements observed at Hisingen presented in Figure 8.2 site compared to the Uddevalla site presented in Figure 8.17 can primarily be explained by the significantly greater soil depth. At the Hisingen site, the clay layer extends to approximately 40 m, whereas the corresponding depth at the Uddevalla site is around 16 m. Although other parameters, such as OCR and POP, differ slightly between the sites, these variations are not sufficient to offset the effect of the increased soil thickness. This is despite the fact that the Soft Soil Creep model in PLAXIS is known to be highly sensitive to even small variations in OCR or POP. The results therefore indicate that soil depth is the dominant factor governing settlement behaviour in this study.

The differences between the sites become even more pronounced when ground improvement is applied. The improvement factors from Uddevalla are approximately twice as high as those from Hisingen site, and can be considered high compared to typical values reported in practice. In contrast, the improvement factors observed at the Hisingen site are relatively low. This difference can largely be attributed to the soil profile in Uddevalla, where the clay layer is sufficiently shallow to allow deep mixing and stone columns to function as end-bearing systems. This means that no settlement zone occurs under the columns, which the hand calculations for site Hisingen verify. In addition, the presence of a thin silt layer beneath the clay at the Uddevalla site enables double-sided drainage, which significantly enhances consolidation. This effect is absent at the Hisingen site, where the clay layer is underlain by less permeable material. Together, these factors explain the higher efficiency of ground improvement techniques at the Uddevalla site.

The efficiency of the different techniques also depend on their governing mechanisms. For deep mixing, the improvement factor from the Uddevalla site is approximately twice as high compared to from the Hisingen site, despite a larger centre-to-centre spacing. This can be explained by the fact that the columns in Uddevalla are end bearing, allowing load transfer to the underlying bedrock. At the Hisingen site, the columns only have an improvement impact in the upper part of the clay layer, resulting in a settlement of the entire improved soil mass in the underlying clay. Since deep mixing primarily increases shear strength and does not significantly affect permeability, differences in drainage conditions have a limited influence on its performance.

For stone columns, the difference between the sites is even more pronounced. At the Uddevalla site, stone columns achieve a high improvement factor of 7.2, whereas at the Hisingen site their performance is considerably lower, with an improvement factor of only 1.9. This behaviour can be explained by two main factors: the end-bearing conditions in Uddevalla and the improved drainage capacity associated with stone columns. The high permeability of the column material accelerates consolidation, particularly under the favourable double-drainage conditions provided by the silt layer at the Uddevalla site. In contrast, at the Hisingen site, the columns are floating and do not penetrate the full soil depth, which limits both load transfer and drainage efficiency. Stone columns are usually not used as floating columns. As a result, the improvement is primarily reflected in reduced settlement time rather than reduced final settlement.

For lightweight fill, the differences are not that big between the two sites. Although higher improvement factors are obtained at the Uddevalla site, this requires a substantially thicker fill layer. If a similar thickness was applied at the Hisingen site, comparable or even greater improvement could be achieved. This behaviour is expected, as lightweight fill reduces the applied load rather than improving the mechanical properties of the soil. Consequently, its effectiveness is less dependent on soil conditions and more related to the magnitude of load reduction. This also explains why lightweight fill is relatively more effective in deep soft soil profiles, such as at the Hisingen site, where other techniques are less efficient.

The combined ground improvement techniques are more complex to interpret, as their behaviour reflects a combination of the underlying mechanisms of the individual methods. In this case, their technical performance largely follows that of the dominant technique, and their evaluation is therefore more relevant from an environmental and economic perspective.

A comparison between hand calculations and numerical modelling shows that the general trends are similar, although some differences can be observed. This can partly be explained by the simplified assumptions used in the hand calculations, where several parameters, including OCR, POP, and creep effects, are not considered. At Hisingen, this results in higher settlements from the hand calculations compared to the PLAXIS simulations, where overconsolidation is taken

into account. In Uddevalla, where the clay is largely normally consolidated, this difference is less pronounced. Nevertheless, this comparison highlights the benefits of each calculation approach where initial hand calculations may provide insight whether or not the area is in need of improvement, and where PLAXIS simulations is recommended for providing reliable settlement results.
One notable discrepancy is observed for lightweight fill at the Uddevalla site, where the hand calculations predict lower settlements than the numerical model. This may be partly explained by creep effects, which are included in the PLAXIS simulations but not in the analytical approach. Since long-term creep occurs even without external loading, as indicated by InSAR measurements, its exclusion in the hand calculations contributes to an underestimation of settlement.

9.2 Discussion of slope stability results

Reviewing the slope stability results, it is clear that the choice of material model is a deciding factor for the different outcomes. The reason behind the differences is most likely how each model treats the soil properties, what is included and what is not. As mentioned in Chapter 6, the use of the undrained model, could be attractive for short term analyses but may underestimate the total strength in the soil, which could lead to the amount of reinforcement being unnecessarily large.

One takeaway that can be derived from the results is that the choice of material model is rather important when trying to analyse the stability of a slope using GeoStudio. Since the choice of appropriate material model enables the possibility of some margins of error, both undrained and combined approaches were considered when conducting the simulations. Before comparing the results, it is important to remember that the settlement analysis was dimensioning for the geometry of each scenario. This implies that the improvement measures were not optimised in a stability manner. Either way, the improvement method that appeared to be superior for both modelling approaches at the Hisingen site regarding slope stability was deep mixing. Here, when using the undrained model, the safety factor was increased by about 50 % when deep mixing was implemented, compared to unimproved ground. The combined model approach, however, provided an increase of around 30 %, where deep mixing still appeared the most effective. For slip surfaces representing each specific case, see Appendix B

Interestingly, all scenarios except for the deep mixing actually sustained lower safety factors in the undrained analysis compared to the combined analysis. This is probably due to how the undrained model handles the definition of the shear strengths in the soil. As previously described, the undrained model assumes that each undrained soil layer retains a constant average undrained strength over the entire layer, where parameters such as friction angle and effective strength are not used to define shear strength. This most likely results in an underestimation of the strength in the clay layers which thus leads to a, although conservative, possibly too low safety factor. The reason why the deep mixing scenario contradicts this pattern may be due to how the shear strength is defined in the clay layers with deep mixing. As seen in Figure 8.5 the critical slip surface for deep mixing in the combined model extends deeper and wider than all other scenarios. Important to notice, is that the slip surface does not penetrate the third clay layer in the undrained model, which may be due to the high strength at the top of the layer. This could be one flaw that the undrained model fails to acknowledge, that is not disregarded in the combined model. Here, the lowered shear strength is probably too low at the top of the layer which allows for a greater slip surface to occur. One could argue that this should happen in all combined cases as well, but since the deep mixing is modelled as a solid block with average stiffness properties, it may be one of the root causes of this instance.

The remaining techniques all exhibited some stability improvement but neither of them were conspicuous, as can be seen in Table 8.4. Regarding the soil sequence in Uddevalla, apart from having a generally higher safety factor compared to the other case, the differences between material models are not significant. Here, the improvement methods that had the worst performance were the lightweight fill materials, where neither the foam glass nor the Leca managed to increase the computed safety factor of the slope even by 5 %. In contrast to this, the best performing stability increasing method in this case was the stone columns, where for the undrained model, the safety factor could be increased by 26 %.

When comparing Uddevalla with Hisingen, the improvement at Hisingen had the biggest change in stability in terms of the safety factor, even though the values may be considered a bit too low regarding construction. However, most of the slip surfaces in Uddevalla provided acceptable factors of safety. The reason why the improvement did not have as big of an impact compared to the Hisingen case is likely due to the massive difference in soil depth and local drainage conditions.

The difference in performance of the stone columns between the two sites, is most likely due to the bearing conditions. At Hisingen, the stone columns are floating and cannot fully utilise their drainage potential or transfer the load down to bedrock. This hinders the columns from reaching a desired stiffness, which would imply an increase in shear strength and bearing capacity of the reinforced soil. However, at the site in Uddevalla, the shallow depth allows for end bearing columns to be used. This enables the possibility of a full load transfer down to bedrock, and the columns can fully utilise their stiffness potential.
Worth mentioning is that changes on the entry and exit regions for the slip surfaces in Slope/W most likely has a slight impact on the magnitude of the safety factor as a result of less ideal

parts of the slope being prone to landslides occurring. However, most of these instances consist of small, locally triggered landslides that generally could be considered as erosional impacts caused by the river, especially due to the fact that the majority of these slip surfaces are located by the shoreline. See Figure B.1 for reference.

9.3 Discussion about environmental and economical comparison

The results highlight a clear trade-off between economic and environmental performance among the studied ground improvement techniques. Deep mixing is in most cases the most cost-effective solution, while at the same time exhibiting by far the highest environmental impact.

The high environmental impact of deep mixing can primarily be attributed to the production of binders, particularly lime and cement-based materials. Despite the use of Multicem and partial replacement with CKD, the binder remains the dominant source of emissions. This indicates that the environmental performance of deep mixing is strongly constrained by the current availability of low-emission binders. For deep mixing to become a competitive alternative from an environmental perspective, further development of binder materials with substantially lower emissions is required.

From an economic perspective, deep mixing is generally the most favourable technique. The only notable exception is observed for deeper clay layers, such as at the Hisingen site, where lightweight fill solutions can provide a lower cost. However, this reduced cost must be considered in relation to the lower improvement in slope stability compared to deep mixing. This illustrates that the economically optimal solution may not always coincide with the technically most effective one.

Lightweight fill materials, Leca and especially foam glass, demonstrate significantly lower environmental impact compared to deep mixing. This is especially evident in deep soil profiles, where the reduction of load becomes an efficient strategy. Furthermore, the possibility of using recycled materials introduces a substantial potential for further reductions in emissions. However, the benefits of lightweight fill are partly offset by the need for transportation of relatively large volumes of low-density material. Since these materials are produced at limited locations in Sweden, transport distances can be significant, which increases both cost and emissions. Both Leca and foam are only manufactured by one supplier each in Sweden with exclusive rights, which takes place in central Sweden and this involves a transport distance of around 300 kilometers to Gothenburg. This highlights the importance of material sourcing and logistics in evaluating the overall sustainability of ground improvement solutions.

Stone columns represent a more context-dependent alternative. Their applicability is limited by technical constraints, particularly the requirement for sufficient soil strength and favourable installation conditions. From both an economic and environmental perspective, access to locally available surplus rock is a key factor for making stone columns competitive. Reuse of such materials can significantly reduce both costs and emissions. Furthermore, the price of installing stone columns is an major uncertainty. Since the number of stone column installations that have been carried out in Sweden is still small, it is difficult to say a reasonable price for the installation on the Swedish market. The price used in the calculations is instead from a more international perspective, which increases the uncertainties as the conditions differ geographically and thus also costs. In addition, the installation process is both energy and time-consuming compared to installing deep mixing, which is why it is difficult to achieve the low installation costs found there. The also means that the installations has a high carbon footprint.

Regarding potential environmental savings, material-related measures appear to have the greatest impact. In particular, the use of recycled lightweight fill provides the largest reduction in emissions among the considered options. Fuel substitution, such as replacing diesel with HVO100 or electricity, also contributes to noticeable reductions, although to a lesser extent. The largest gains are achieved when transitioning from fossil diesel to HVO100, while the additional benefit of electrification is comparatively limited.

However, the practical feasibility of these measures varies significantly. While HVO100 can be implemented relatively easily using existing machinery, the adoption of fully electric construction equipment is currently limited by availability and cost. Consequently, although electrification offers theoretical environmental benefits, its short-term applicability remains constrained. In contrast, HVO100 represents a more immediately feasible solution, albeit at a moderate increase in project cost.HVO100 is in many cases already implemented or more easily feasible because it is possible to refuel existing machines with a higher fuel price as a consequence. At an HVO100 price of 5 SEK higher than the diesel price, it affects the total cost of the project by between 3-6 percent depending on which ground improvement technique is used.

It should be noted, however, that this comparison only takes into account the emissions related to the type of fuel. For biofuels such as HVO100, the emissions during combustion are of a similar magnitude to those of fossil diesel. However, they are considered lower in the calculation due to the use of renewable feedstock, which is assumed to be part of a short-term carbon cycle. In contrast, electricity is produced with fewer actual emissions during production and usage than biofuels. This difference is not included in the comparison, but is something that needs to be taken into account when it comes to biofuels and their specificities when compared to electricity. It should also be noted that the availability of biofuels is limited in a long-term and system wide perspective, whereas electricity production has a greater potential for scaling. This may influence the feasibility of large scale substitution when comparing HVO100 and electrification.

This is related to the sensitivity analysis and the effects that a change in the cost of an individual product or raw material has on the total cost of the project. It is also important to take into account in this comparison that different cost changes have different probabilities of occurring. For example, the price for installing stone columns is very uncertain in Sweden and deviations from the used price are very likely. The same applies to excavation materials that are to be sent to landfill. There, the cost depends strongly on the degree of contamination of the materials, and the differences in price can be large. In cases where the uncertainties are lower, there is, among other things, the price for deep mixing, since the technology is well used and many suppliers are on the Swedish market. The price also includes many parts, both the price for the machine, raw materials and wages, which reduces the effect of a price adjustment for one of the parts. This means that deep mixing is not as sensitive in terms of price, even though it is shown in Figure 8.28 as one of the factors where a price increase has the greatest impact on the total cost. Instead, for example, the installation cost of the stone columns or the landfill prices are a greater uncertainty even if they are not considered as sensitive in Figure 8.28.

10

Conclusion

The results of this study demonstrate that the selection of ground improvement technique is strongly dependent on site specific conditions. No single method can be identified as universally optimal, as the technical performance, cost, and environmental impact vary significantly with soil profile, depth, and project requirements.

Deep mixing generally provides the most favourable combination of cost efficiency and technical performance, offering effective reduction of settlements as well as significant improvements in slope stability. However, its major drawback is the high environmental impact associated with binder production, which represents the dominant source of emissions. This limitation highlights the need for the development of binder materials with lower emissions if deep mixing is to remain a sustainable long term solution.

Lightweight fill materials, such as Leca and foam glass, represent viable alternatives in cases involving deep soft clay layers where column-based methods must rely on floating solutions. These techniques are particularly attractive from an environmental perspective, as they reduce applied loads rather than relying on energy-intensive material production. However, their effectiveness is highly dependent on transport conditions and material availability, as large volumes of material with low density must often be transported over significant distances.

Stone columns may provide an attractive alternative in projects involving thinner clay layers, where end bearing conditions can be achieved. Under such conditions, they offer a potentially favourable combination of low environmental impact and competitive cost. However, their applicability in Sweden is currently limited by technical constraints, uncertainties in installation cost, and potential risks associated with installation in sensitive soils.

Overall, the results of this study demonstrate that the selection of ground improvement technique must be based on a project specific evaluation of soil conditions, required technical performance, environmental impact, and cost. As these factors are often in conflict, no single method can be considered optimal in all cases. Instead, the choice of ground improvement technique requires a balanced assessment, where trade-offs between efficiency, sustainability, and economic feasibility are explicitly considered.

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A

Savings and Sensitivity

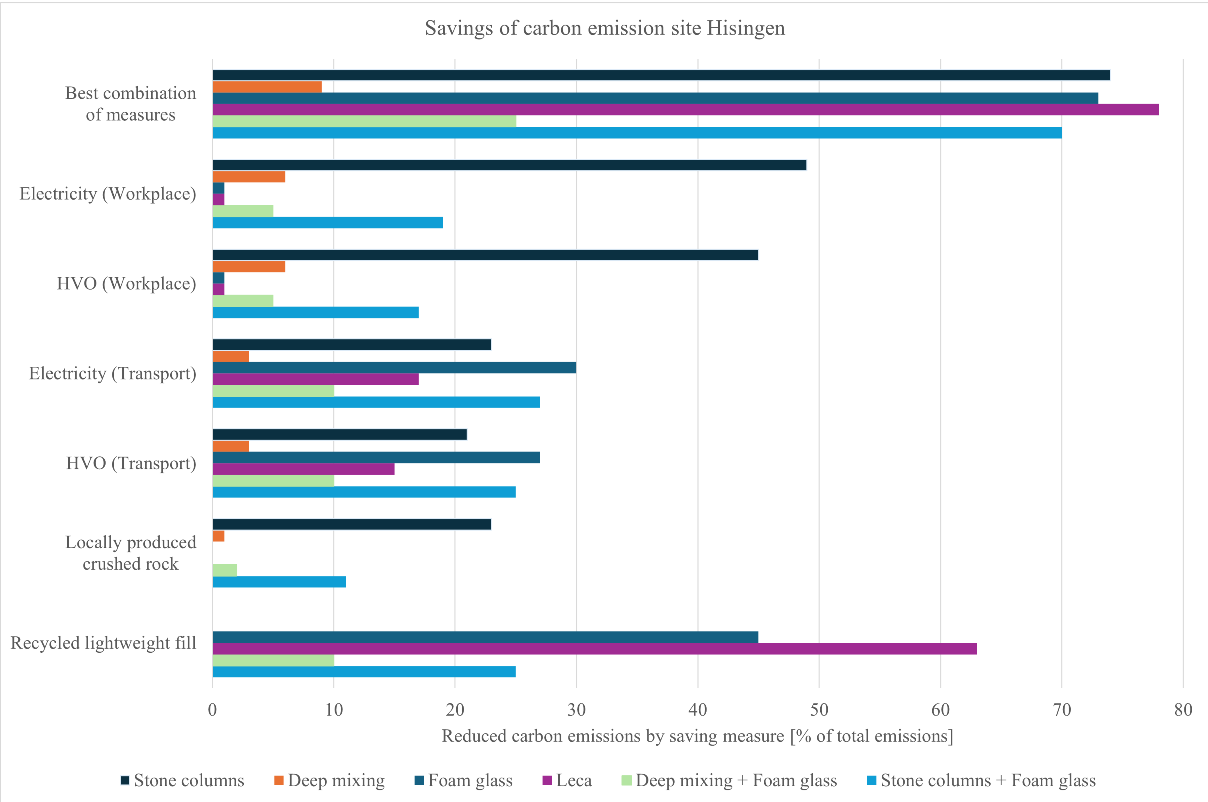

Figure A.1: Savings site Hisingen

Table A.1: Potential savings in percent for embankment at site Hisingen

Savings measures [%]	Stone columns	Deep mixing	Foam glass	Leca	Deep mixing + foam glass	Stone columns + foam glass
Recycled lightweight fill	0	0	45	63	10	25
Locally produced crushed rock	23	1	0	0	2	11
HVO (Transport)	21	3	27	15	10	25
Electricity (Transport)	23	3	30	17	10	27
HVO (Workplace)	45	6	1	1	5	17
Electricity (Workplace)	49	6	1	1	5	19
Best combination	**74**	**9**	**73**	**78**	**25**	**70**

Table A.2: Potential savings in percent for embankment at site Uddevalla

Savings measures [%]	Stone columns	Deep mixing	Foam glass	Leca	Deep mixing + foam glass	Stone columns + foam glass
Recycled lightweight fill	0	0	40	58	23	28
Locally produced crushed rock	23	1	0	0	2	8
HVO100 (Transport)	21	4	33	19	20	29
Electricity (Transport)	23	4	36	21	22	32
HVO100 (Workplace)	45	6	2	1	4	13
Electricity (Workplace)	49	6	2	1	4	14
Best combination	**74**	**11**	**78**	**81**	**50**	**74**

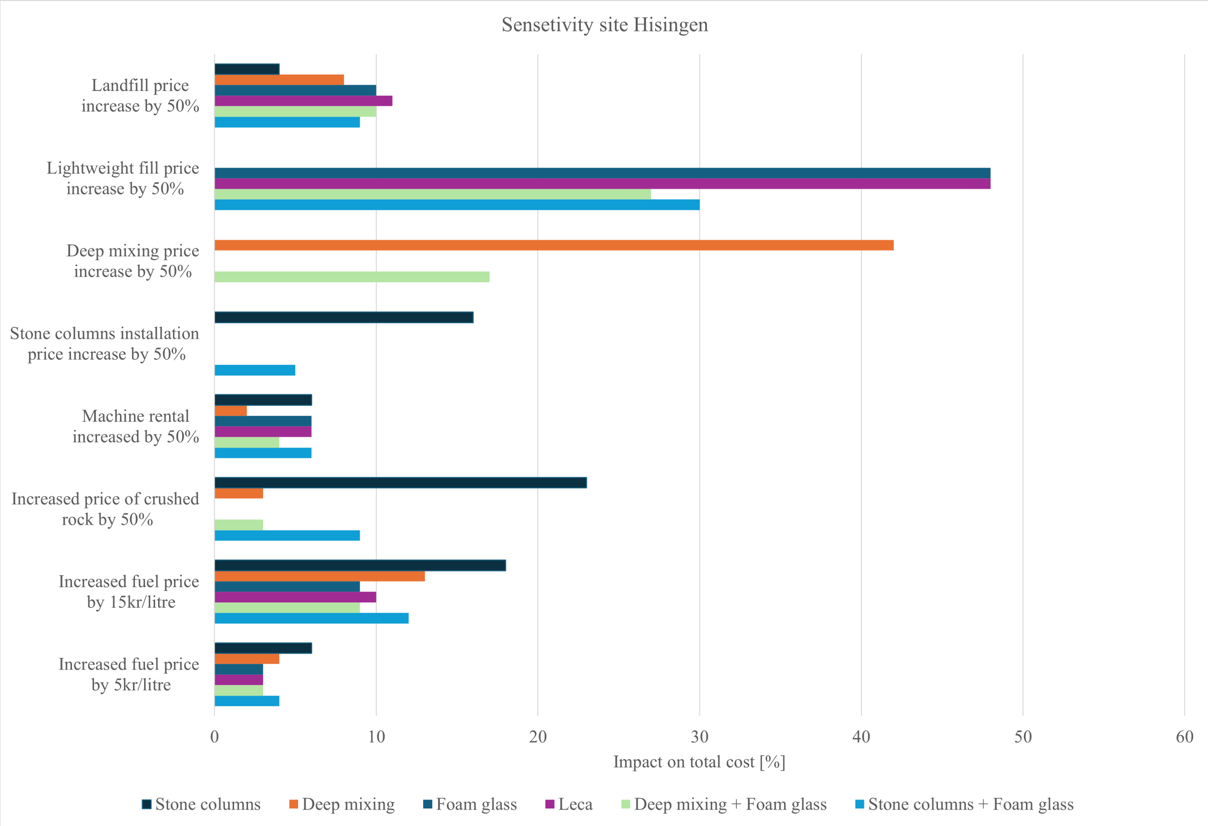

Figure A.2: Sensitivity of the costs for the Hisingen site

Table A.3: Sensitivity site Hisingen

Changes [%]	**Stone columns**	**Deep mixing**	**Foam glass**	**Leca**	**Deep mixing + foam glass**	**Stone columns + foam glass**
Increased fuel price by 5kr/litre	6	4	3	3	3	3
Increased fuel price by 15kr/litre	18	12	8	8	9	10
Increased price of crushed rock by 50%	23	3	0	0	2	6
Machine rental increased by 50%	6	2	2	2	1	2
Stone columns installation cost increase by 50% *	16	0	0	0	0	4
Deep mixing price increase by 50%	-	35	-	-	4	-
Lightweight fill price increase by 50%	-	-	38	37	34	30
Landfill price increase by 50 %	5	5	5	5	7	6

Table A.4: Sensitivity site Uddevalla

Changes [%]	**Stone columns**	**Deep mixing**	**Foam glass**	**Leca**	**Deep mixing + foam glass**	**Stone columns + foam glass**
Increased fuel price by 5kr/litre	6	4	3	3	3	4
Increased fuel price by 15kr/litre	18	13	9	10	9	12
Increased price of crushed rock by 50%	23	2	0	0	3	9
Machine rental increased by 50%	6	2	6	6	4	6
Stone columns installation cost increase by 50% *	16	0	0	0	0	5
Deep mixing price increase by 50%	-	42	-	-	17	-
Lightweight fill price increase by 50%	-	-	48	48	27	30
Landfill price increase by 50 %	4	8	10	11	10	9

B

GeoStudio

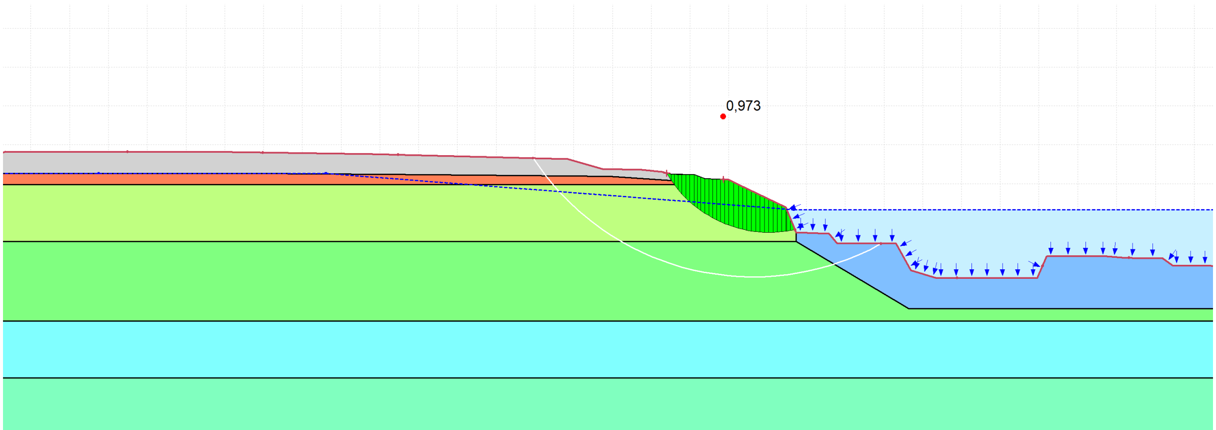

Figure B.1: Slip surface with erosional impact

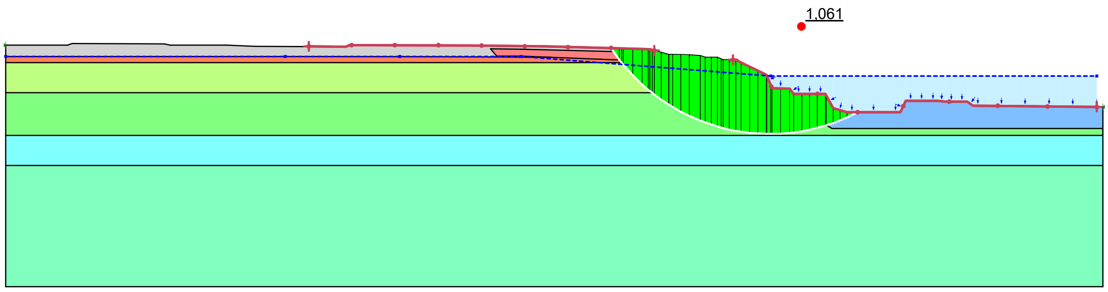

Figure B.2: Foam glass Hisingen, Undrained model

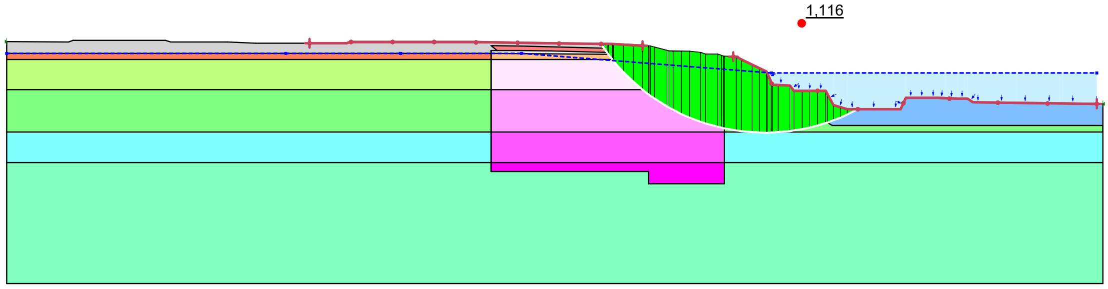

Figure B.3: Deep mixing + Foam glass Hisingen, Undrained model

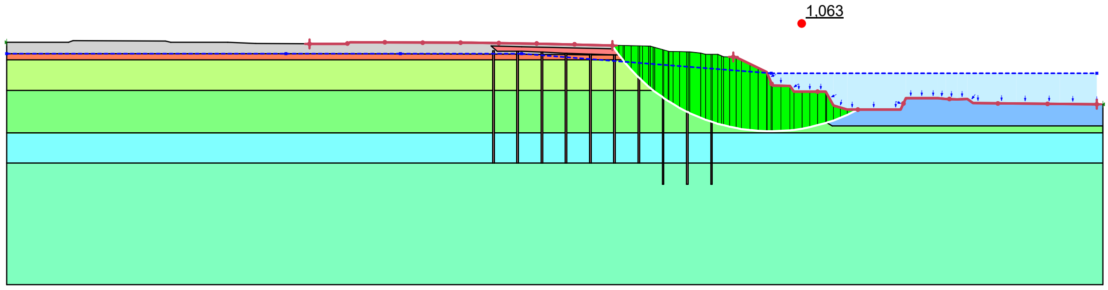

Figure B.4: Stone columns + Foam glass Hisingen, Undrained model

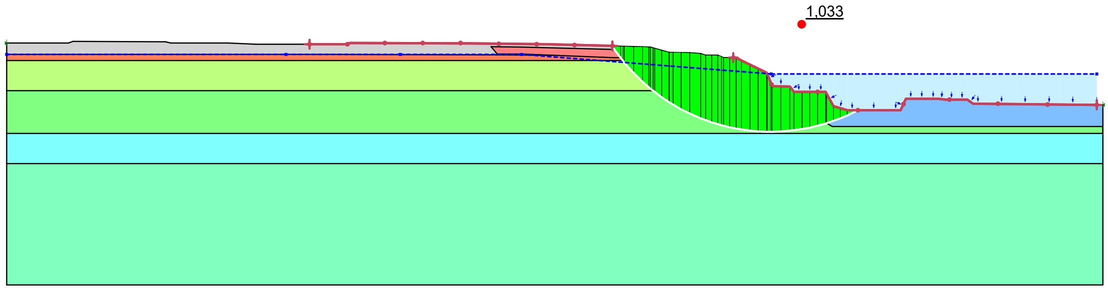

Figure B.5: Leca Hisingen, Undrained model

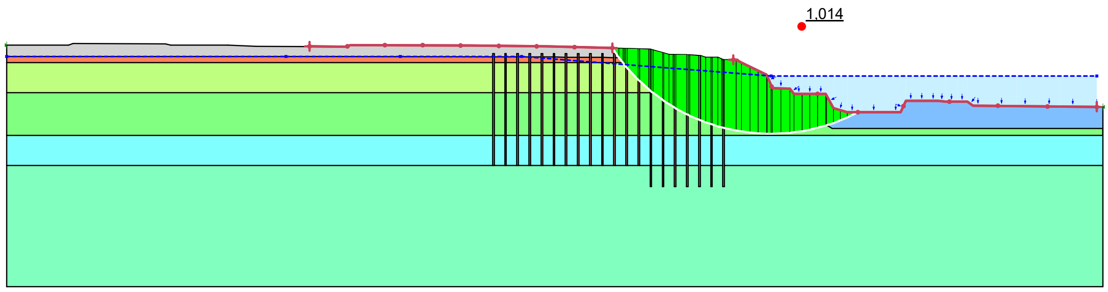

Figure B.6: Stone columns Hisingen, Undrained model

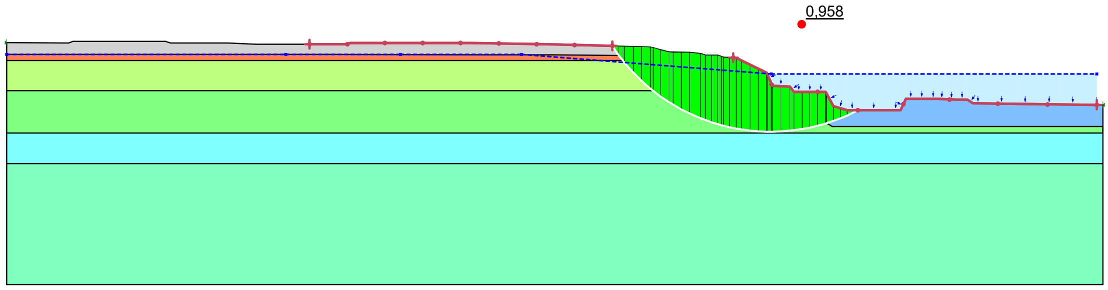

Figure B.7: No reinforcement Hisingen, Combined model

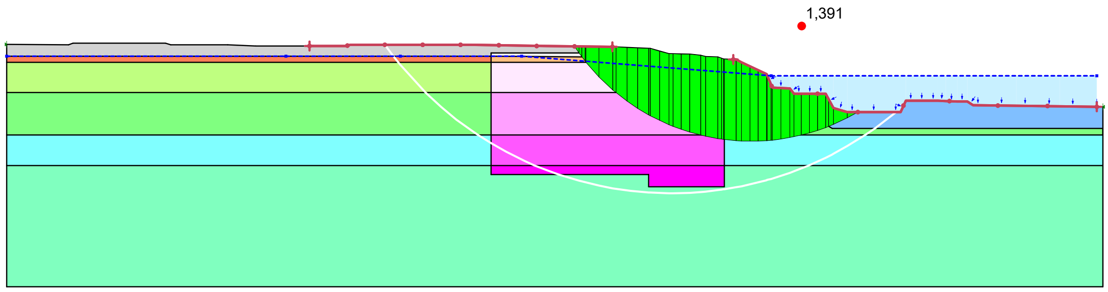

Figure B.8: Deep mixing Hisingen, Combined model

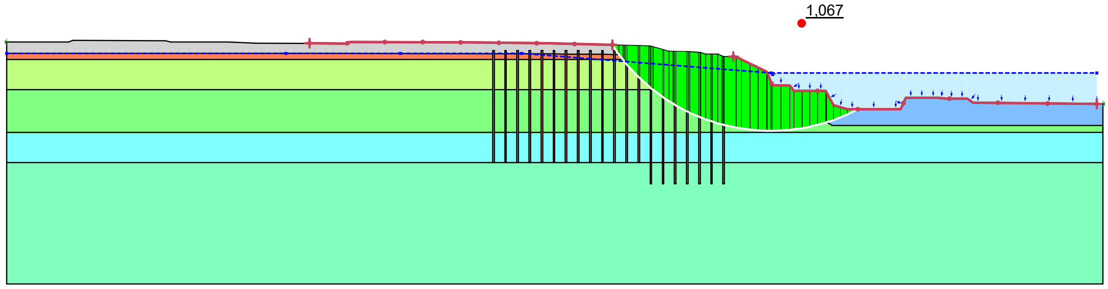

Figure B.9: Stone columns Hisingen, Combined model

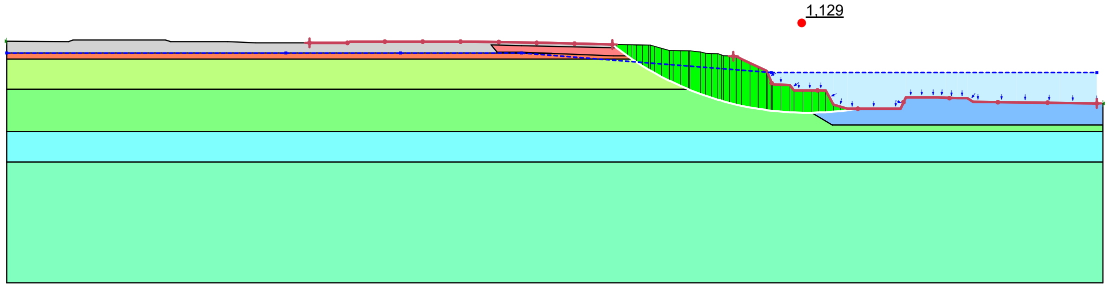

Figure B.10: Leca Hisingen, Combined model

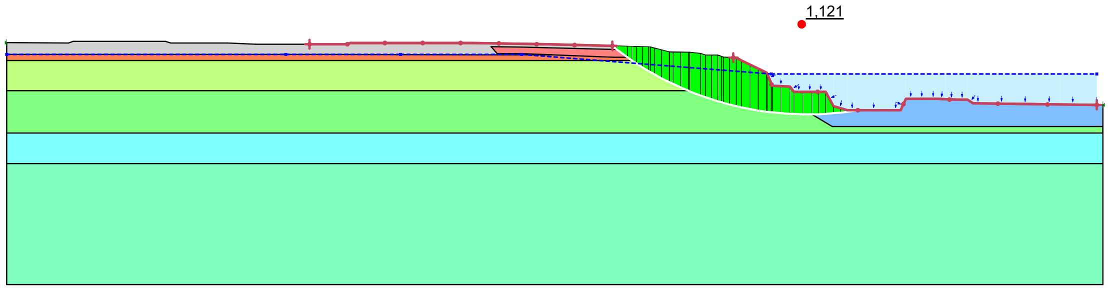

Figure B.11: Foam glass Hisingen, Combined model

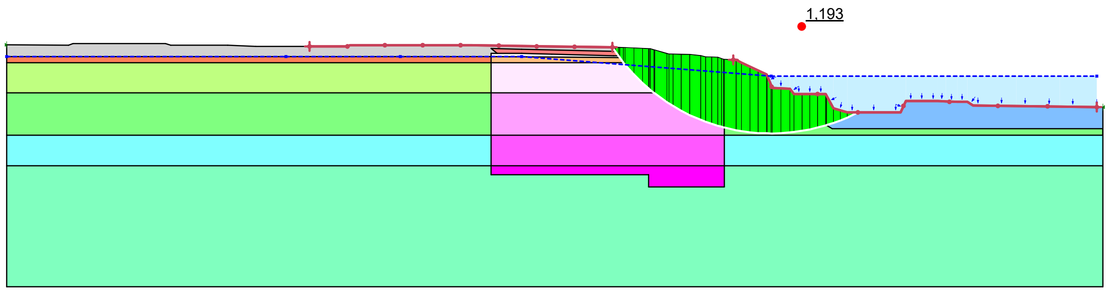

Figure B.12: Deep mixing + Foam glass Hisingen, Combined model

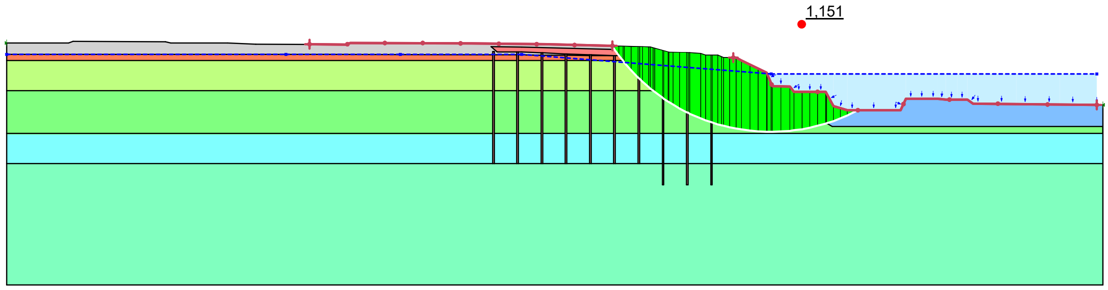

Figure B.13: Stone columns + Foam glass Hisingen, Combined model

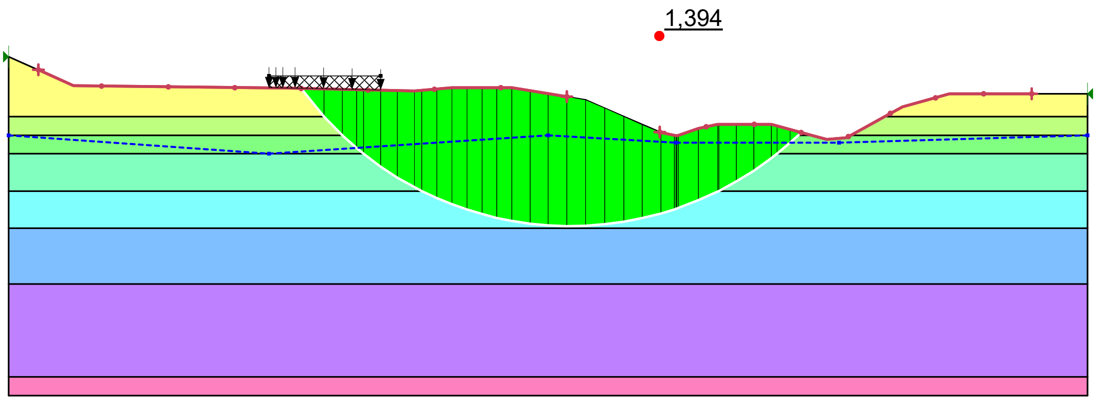

Figure B.14: No reinforcement Uddevalla, Undrained model

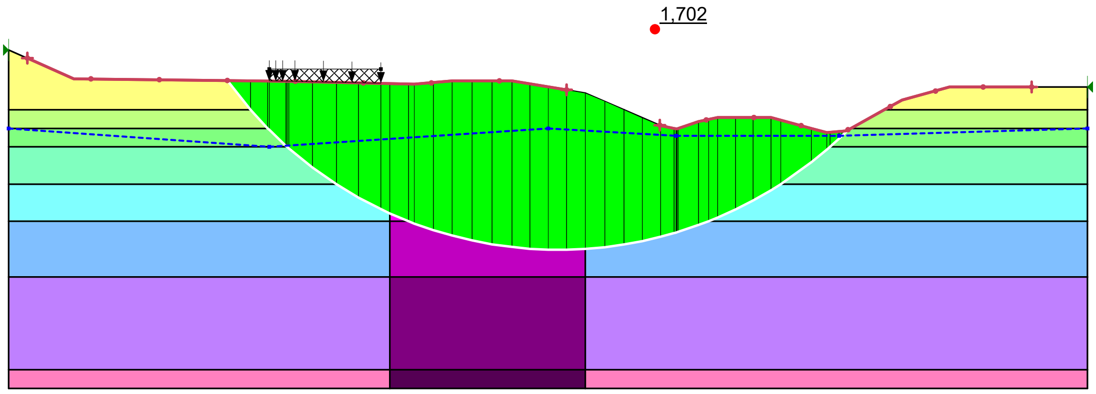

Figure B.15: Deep mixing Uddevalla, Undrained model

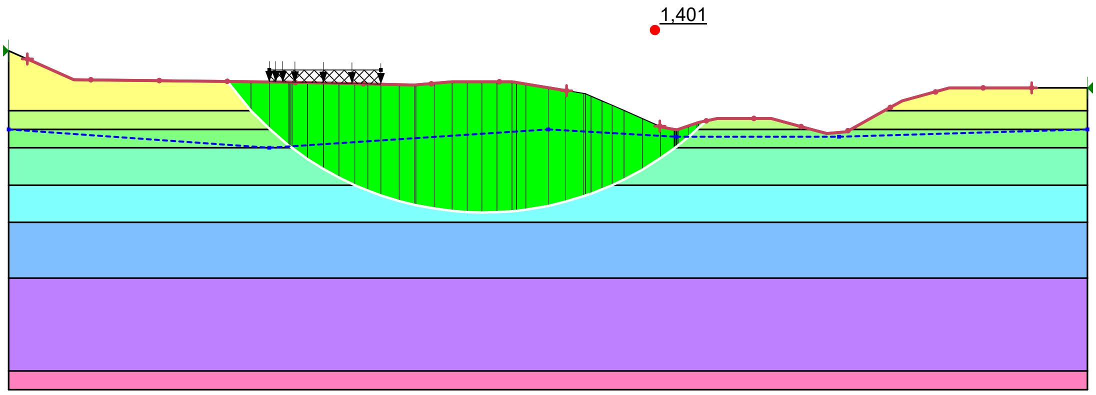

Figure B.16: LECA Uddevalla, Undrained model

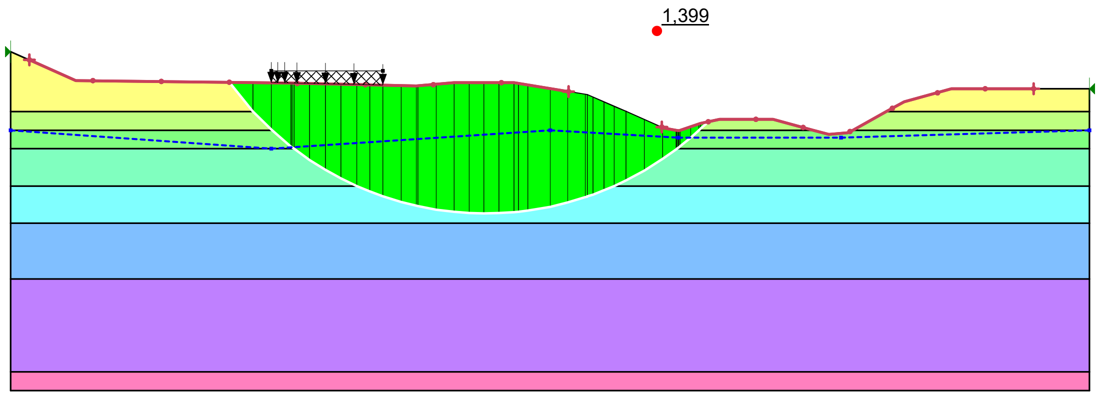

Figure B.17: Foam glass Uddevalla, Undrained model

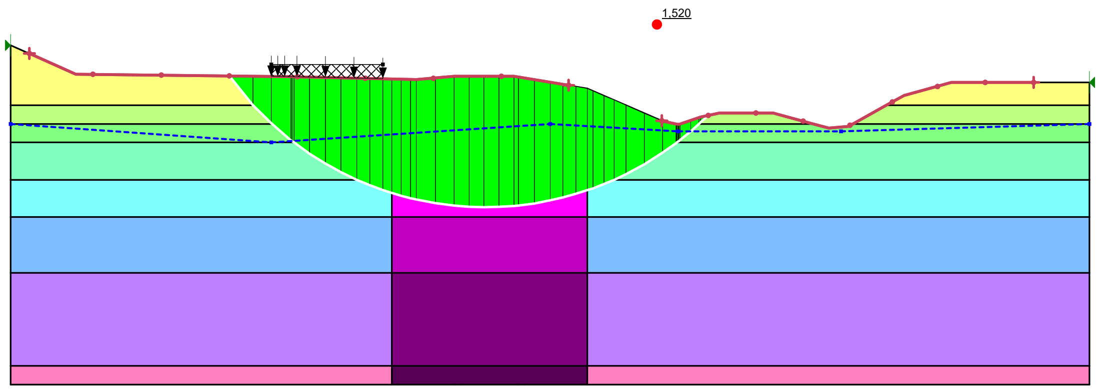

Figure B.18: Deep mixing + Foam glass Uddevalla, Undrained model

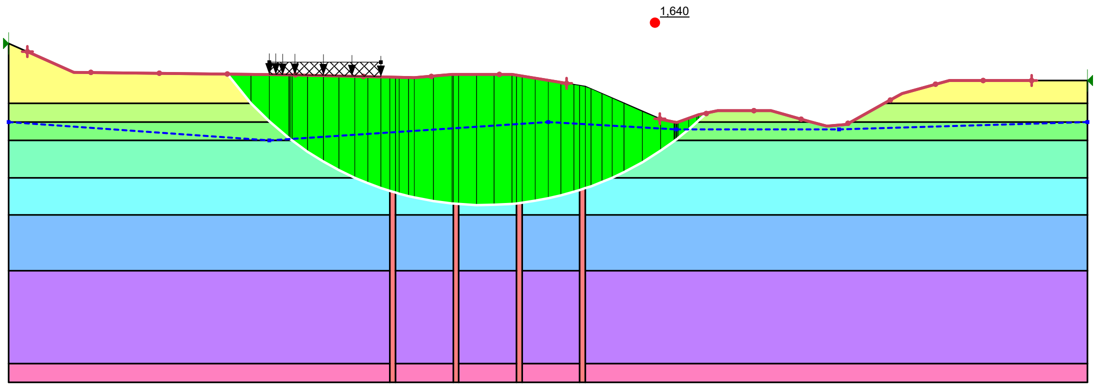

Figure B.19: Stone columns + Foam glass Uddevalla, Undrained model

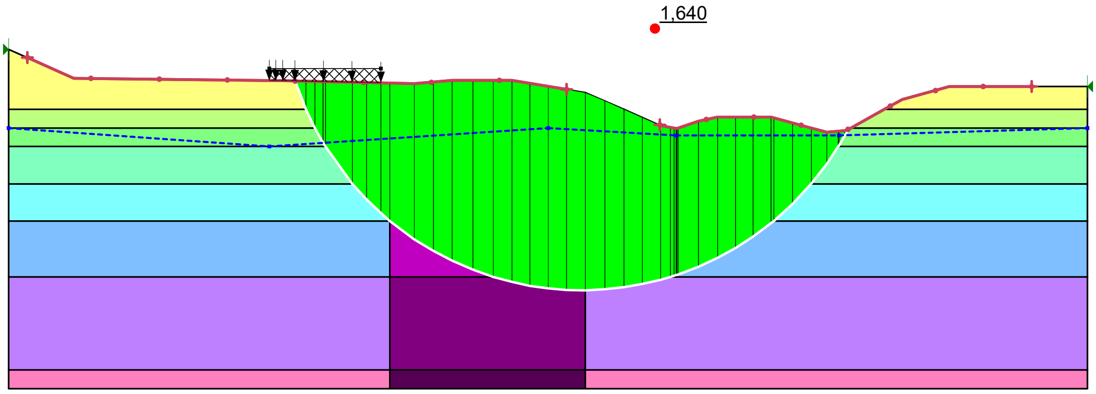

Figure B.20: Deep mixing Uddevalla, Combined model

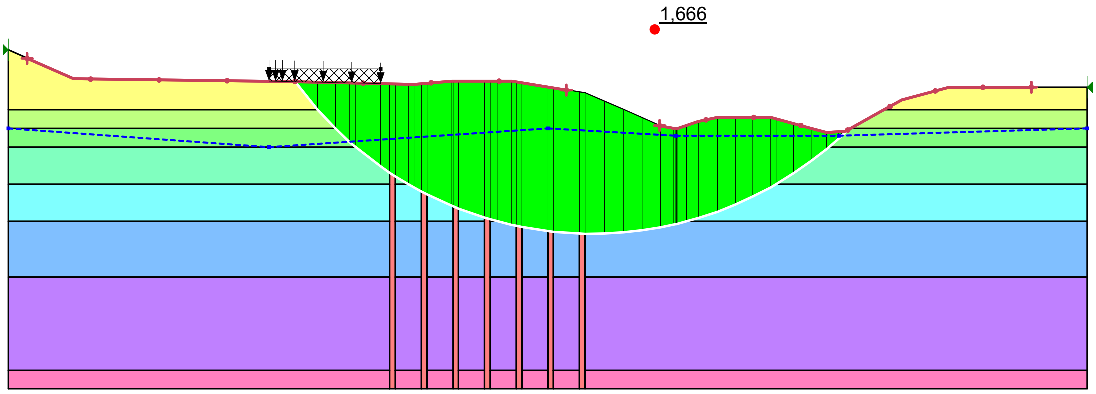

Figure B.21: Stone columns Uddevalla, Combined model

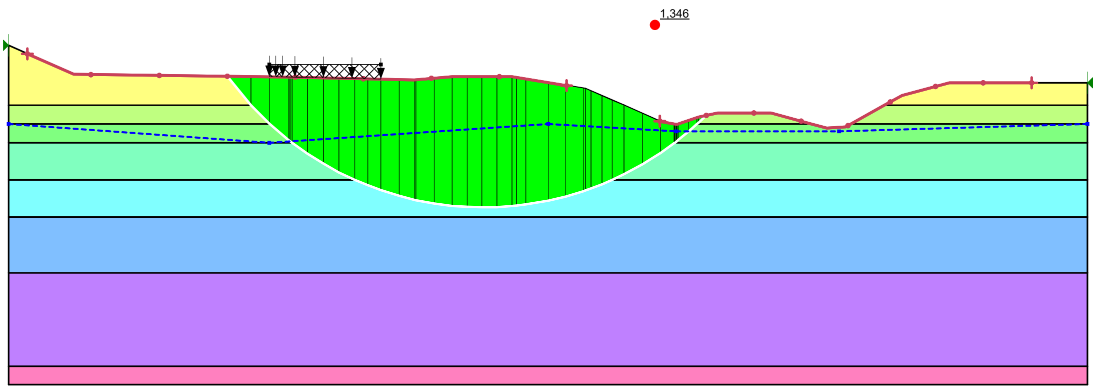

Figure B.22: Leca Uddevalla, Combined model

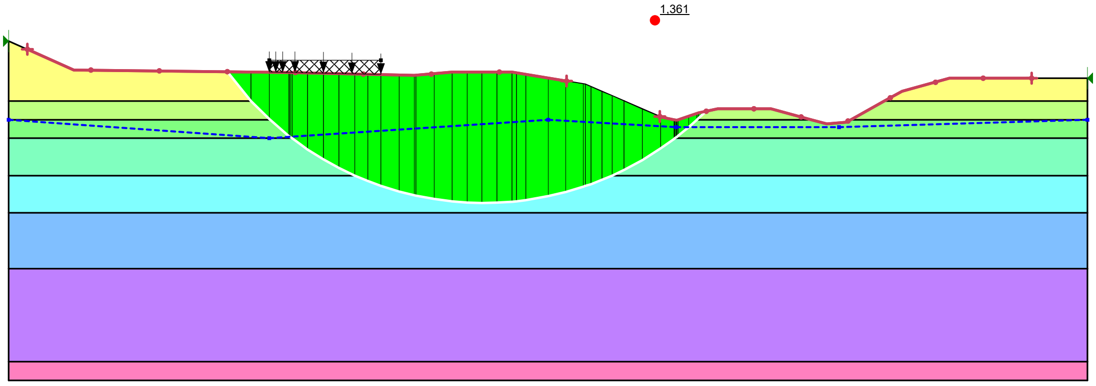

Figure B.23: Foam glass Uddevalla, Combined model

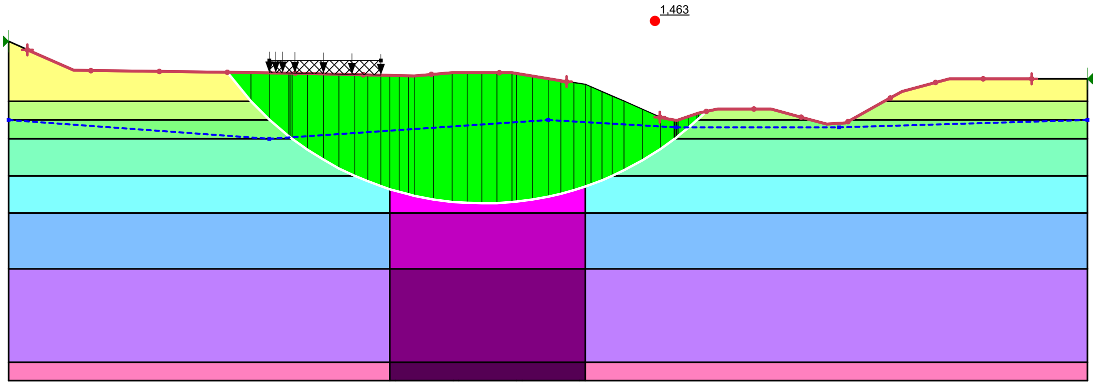

Figure B.24: Deep mixing + Foam glass Uddevalla, Combined model

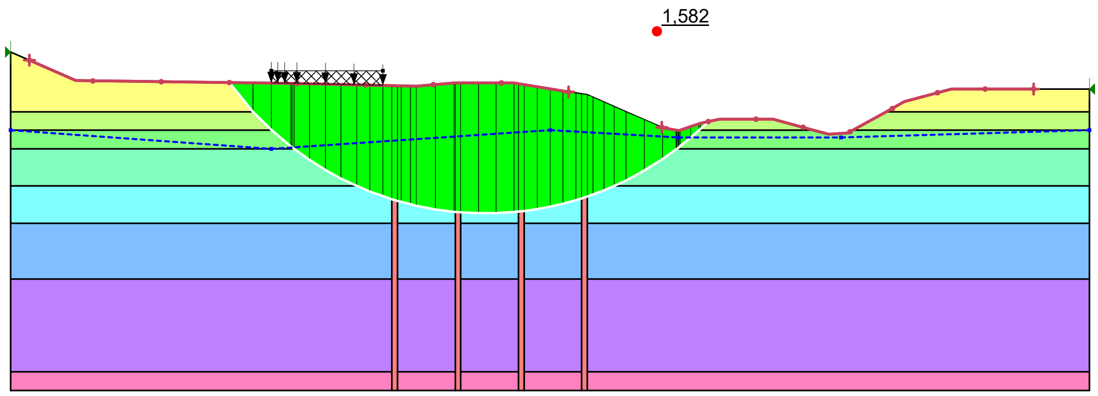

Figure B.25: Stone columns + Foam glass

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