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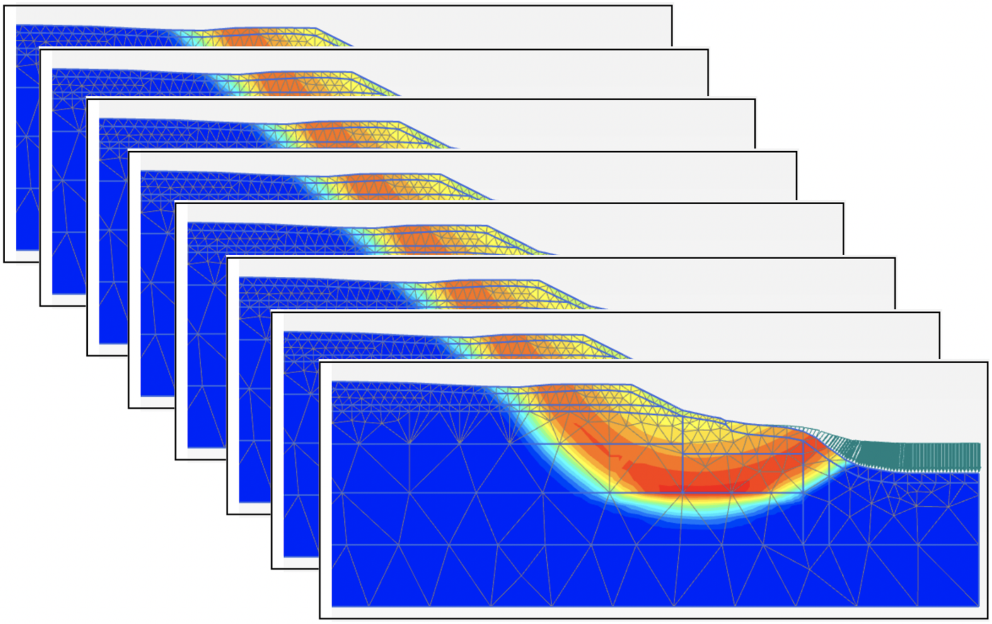

Automation of Slope Stability Calculations

A comparison between Conventional Slope/w Analysis and Plaxis Analysis Controlled by Python code

Master's thesis in Architecture and Civil Engineering

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Cover: Visualisation of multiple results of the automated method of slope stability calculations in Plaxis

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Abstract

This project aims to develop and evaluate an automated method for undrained slope stability investigations, offering a modern approach to examining slope stability more efficiently over a larger area in less time. A comparison is made between the traditional limit equilibrium analysis using Slope/w and the finite element method-based slope stability analysis using Plaxis. The objective is to create comparable geotechnical models in both programs and develop a Python code to automate the modelling in Plaxis to see the variance in safety factors in already investigated areas. The research combines quantitative methods by collecting previously conducted slope stability investigations in the Göta River investigation and qualitative methods through interpretations and assumptions.

The conclusions highlight the comparison between manual slope stability analysis using Slope/w and Plaxis with the automated Plaxis analysis. While the project does not aim to replicate reality, it successfully develops and tests a Python code for automating slope stability analysis in Plaxis. The differences between Slope/w and Plaxis lie in their determination of the critical slip surface and calculation of the safety factor, with Plaxis offering more comprehensive capabilities. Safety factors obtained from the analyses serve as a reference point for comparison and indicate that Slope/w tends to calculate higher safety factors compared to Plaxis. The automation of Plaxis analysis fulfills the objective of enabling efficient analysis of multiple sections and investigating future scenarios. The developed code is specific to the selected main sections and requires adjustments for other slope sections. Further development can focus on enhancing code flexibility and making it less sensitive to file formatting. The project concludes that Plaxis can be controlled through Python code, presenting limitless possibilities for future applications.

In summary, this project provides a valuable contribution to slope stability analysis methods, demonstrating the potential of automation while acknowledging the limitations and customization required. Plaxis offers advantages in handling complex cases and soil response, while Slope/w remains practical for combined analyses and intuitive material modelling. The project opens avenues for further research and improvement, highlighting the endless possibilities offered by controlling Plaxis through Python code.

Keywords: Automated slope stability analysis, limit equilibrium method, finite element method, Slope/w, Plaxis, Python code, Python-controlled Plaxis analysis.

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Thank you!

Frida Andersson & Emma Möller, Gothenburg, June 2023

List of Acronyms

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

API	Application programming interface
CSV-file	Comma separated values file
DXF-file	Drawing exchange format file from AutoCAD
FEM	Finite element method
GÄU	Göta River investigation
LEM	Limit equilibrium method
OCR	Over-consolidation ratio
SGI	Swedish geotechnical institute

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Chapter 1 – Introduction

The fourth industrial revolution has introduced automatic approaches to processing data using technical advancements such as artificial intelligence, robots, and programming (Lund, 2021). Within the civil engineering industry, one branch with great potential of becoming more digitised is geotechnical engineering (Yogatama & Tirta, 2021). Using Python programming language as a tool in geotechnical stability modelling can lead to more adaptable and efficient analyses. For a long time, the geotechnical industry has used the same methods based on the equilibrium of shear strength and stresses to investigate slope stability (Salunkhe, Chvan, Bartakke, & Kothavale, 2017). In Sweden, the Swedish geotechnical institute (SGI) are responsible for conducting slope stability investigations in terms of landslide risk (SGI, 2018a). Landslide risk is a combination of probability of landslide and the consequence of it happening (Odén & Thorén, 2023). This project will focus on the probability of landslide, more specifically the safety factors of slopes that can be used to determine the stability. In collaboration with Norconsult AB, this project will develop an automated approach for calculating safety factors. This will be done using Python coding in the finite element software Plaxis, and evaluate the results against the traditional manual limit equilibrium method in Slope/w. The hope is to justify that the automated method gives a comparable result for slope stability analysis and that it can be used to investigate a greater amount of sections more efficiently. Another aspect of using the automated method within slope stability is that it can be used to simplify the testing of predicted future scenarios due to climate change.

1.1 Background

In 2008, the Swedish government gave SGI a commission to map the risks of landslide along the Göta älv valley (hereinafter called the Göta River) to investigate the impact of increased erosion due to greater water flows in the river caused by climate changes (SGI, 2012a). Also, the probable increased demand to drain Lake Vänern in case of flooding risks leads to the need to investigate how Göta River will be affected. The name of the investigation is *Göta älvutredningen*, *Göta River investigation* in English, and will in this project be referred to as GÄU. The investigation is extensive and the mapping was done in collaboration with several consultants, one being Norconsult AB which are the industry advisory of this project. The investigated areas nearby the river have varied geological conditions, land use, and topography, which means that the probability of landslide and the consequences of it will be diverse along the river. Landslides can have an impact on many of the values along Göta River including buildings and other socially important functions such as railways, highways, waterworks, and power supplies, which is why the investigation was suggested by the Swedish government. The investigations were broken down into 10 subareas and included 240 sections, see figure 1.1. The results of the investigation were summarised in a map showing the landslide risks along the river, based on consequences and probability of landslide. The 200 km long shoreline of Göta River, was divided into different areas, based on geological conditions and topography, which were subjected to one of the sections in the evaluation of landslide risk(SGI, 2012b). The soil stratigraphy along the Göta River valley is characterised by various depths of loose clay covered by a layer of dry crust with various thickness along the river, from a couple of decimetres to several meters at some places (Rydell, Persson, Blied, & Rankka, 2009).

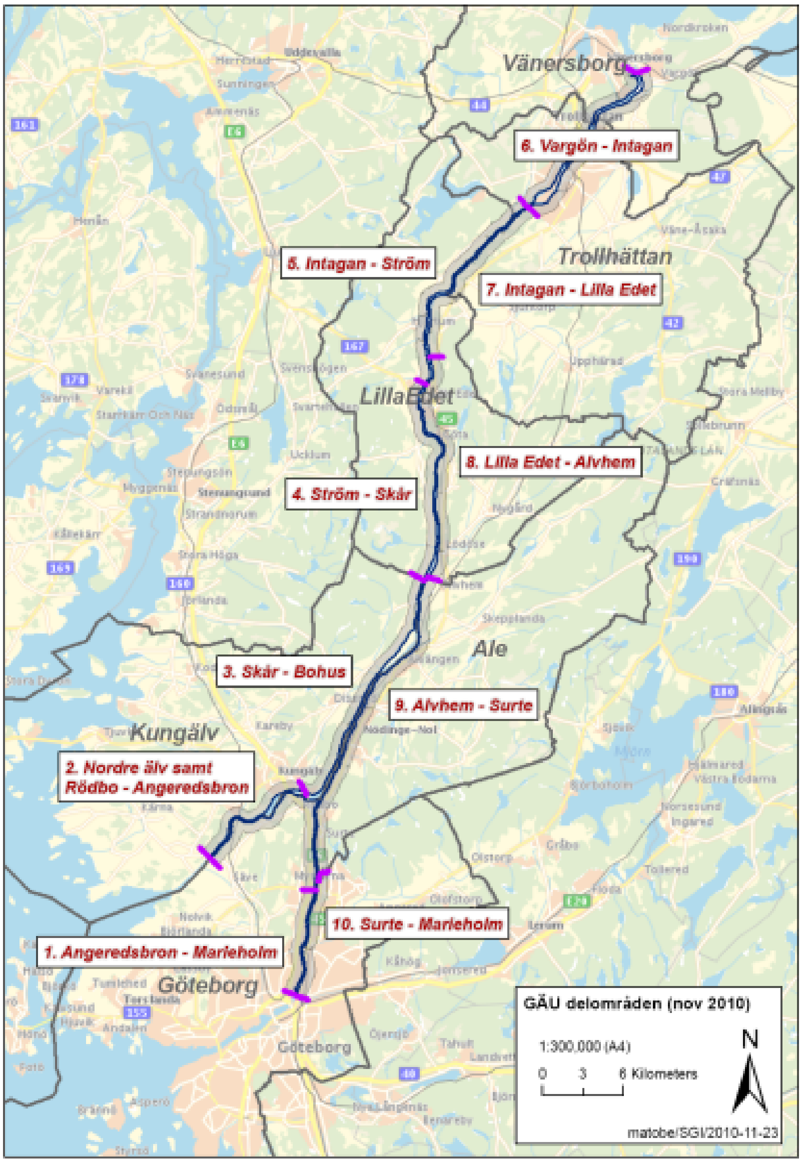


Figure 1.1: Göta älv valley divided in 10 subareas (SGI, 2012b).

Slope stability analysis in Sweden is generally done with both an undrained and a combined analysis. This is something that is requested by SGI in their guideline for slope stability analysis (Odén & Thorén, 2023). The ground rule is that the analysis generating the lowest safety factor is governing. In an earlier SGI guideline written by Larsson (1983) it is explained that for normally- and slightly over-consolidated clays, undrained total stress analysis will give reasonable results. However the undrained analysis does not take increased pore water pressures into account, which can cause errors in the calculation, especially for over-consolidated clay. In these cases, drained effective stress analysis has shown results that are more like the reality. This was also explained in Odén and Thorén's report (2023), that for clays with OCR over 2, the drained analysis will be governing and vice versa for more or less normally consolidated clays. In other words, which analysis type that will be most appropriate is influenced by the inspected soil profile, and therefore SGI requests both analyses to be carried out if it isn't obvious that one or the other will be governing. In GÄU it was concluded that the drained analysis was of higher importance for superficial slips, but that generally the increase of pore water pressures has a low impact on the overall stability (SGI, 2012b). Worldwide, the use of combined analysis in slope stability is not as common, and therefore this project focuses on the undrained analyses.

Calculations of safety factors in the undrained and combined analyses in GÄU were conducted in Slope/w or GeoStuide (SGI, 2012b). Slope/w adopts the theory of limit equilibrium which is the most common approach to use for slope stability analyses (Khalkhali & Koochaksaraei, 2019). The software is known as an intuitive and conventional approach that calculates a factor of safety from known soil strength theories. There are other more comprehensive, but well-established programs that use finite element methods to investigate slope stability. A finite element software that provides opportunities to calculate everything from slope stability to complex geostructures is Plaxis (Bentley, 2022). The reason that this program is not used as the conventional program for stability analysis in many countries is because of its comprehensive material models and the expensive investigations needed to gain the proper material parameters (Khalkhali & Koochaksaraei, 2019). Furthermore, for slope stability analysis, the simplicity of the limit equilibrium softwares is seen as more essential than the complexity of finite element programs. However, SGI states in their slope stability analysis guideline (2023) that limit equilibrium analysis as well as finite element analysis softwares are both appropriate to use, but must be used so that the main purpose of a stability analysis is fulfilled. For Plaxis this means that when doing a combined analysis the model geometry must be generated so that the boundary between drained and undrained shear strength is defined, and this can be somewhat complicated. Although in this project only undrained analysis will be investigated, it is important to note that there is a possibility to conduct combined analysis also in Plaxis even if this is complicated considering the soil models offered today. A quality that Plaxis holds, essential for this project, is the ability to handle Python programming language which is a generic way to implement an automated approach (Bentley, 2022).

1.2 Aim and Objectives

The aim of this project is to develop and evaluate a new method that automates parts of undrained slope stability investigations and from that propose a modern way of examining slope stability more effectively over a larger area in less time. An objective is to compare the traditional and conventional method, limit equilibrium analysis in Slope/w, with finite element method-based slope stability analysis in Plaxis. This is crucial to the project as the aim is to find ways to create comparable geotechnical models in both programs and from that develop a Python code that can automate the modelling in Plaxis. This project will be carried out using both quantitative and qualitative methods. Quantitative in the way that previously carried out slope stability investigations in GÄU will be collected, but also qualitative because of the interpretations and assumptions needed to be done in the project.

1.3 Research Questions

Based on the aim and objectives of this project, the following research questions have been established:

- How can slope stability investigations adopt an automated method to build and calculate geotechnical models?
- Can an automated method be used to the same extent as the traditional methods for slope stability analysis?
- Can a variance in safety factors be observed with the automated method in an already investigated area?
- Are there any possibilities or risks with using an automated method for slope stability investigations?

1.4 Limitations

The project needs to have limitations to the extent of the research and investigation in order to follow the time frame. These demarcations are listed below:

- The automated method will be applied on a few selected sections along the Göta River which is limiting how general the conclusions can be. Simplifications are done to the sections in order to make the automation more feasible.
- Plaxis is the chosen program to apply the automated method on. This is done because it is a conventional and trusted program within the finite element method-based softwares in geotechnical engineering, but other programs might also be applicable.
- Compared to the previous GÄU, the landslide risk will not be evaluated in this project. Only the safety factor, indicating the probability of landslide will be investigated.

- Only undrained analysis will be considered in this project despite the request from SGI that slope stability analysis should also be done in a combined analysis in Sweden. This limitation is necessary as there is no simple way of conducting combined analysis in Plaxis.
- It is assumed that the soil stratigaphy for all sections analysed with the automated method is the same as in the corresponding main section.

Chapter 2 – Theory

This section presents the relevant theory for the project. Most fundamental is the difference between the limit equilibrium- and finite element approaches in slope stability analysis. More specifically, the softwares Slope/w and Plaxis that adapts these two different methods are explained. This is necessary to understand the different settings and inputs in the programs in order to find the similarities and differences to use further in the project. Additionally, a study of previous research within the area of automated Plaxis analysis is also done, including the basic theory of Python programming.

2.1 Slope Stability Analysis

To determine the slope stability, the safety against the collapse of a slope, is often done by calculating the relationship between the sliding and resting forces in the slope (SGI, 2018b). The soil of the sliding mass has a shear strength, τ, that explains how much stress the soil can resist before deformation or yield (Lanza & Newsom, 2013). The method to investigate the slope stability is to find a factor of how much the shear strength must be reduced for the sliding mass to be just on the verge of instability i.e. when the shear strength is the same as the shear stress (Geo-Slope, n.d.-a). This factor is called the safety factor and refers to the ratio of sliding and resting forces. The slope is stable if the safety factor > 1, and unstable if the safety factor < 1 (Knappett & Craig, 2019).

2.2 Mohr-Coulomb Failure Criterion

The Mohr-Coulomb failure criterion describes the conditions that leads to the failure of an isotropic material and is written as a function of major and minor principal stresses, or normal and shear stresses (Labuz & Zang, 2012). This is illustrated in figure 2.1. The theory emanates from the original proposal made by Coulomb in 1776 that the limiting strength of soil is the internal friction, ϕ', related to the roughness of the shear plane (Knappett & Craig, 2019). Coulomb's model does not involve the interlocking of particles in densely packed materials, for example clay, which makes the frictional resistance higher than expected if only considering the friction alone. Increased normal stresses in dense materials will however break the interlocking effect and the strength becomes purely frictional which makes slips more likely. The failure envelope in figure 2.1 shows the combinations of shear strength and normal forces that will lead to failure. The interlocking effect more realistically contributes with non-linearity to the failure envelope, but an approximation of linearity is made with the effective cohesion, $c^{'}$. To describe the stress states on all possible planes for a soil element, Mohr circles are used. They define every state a soil particle can be in various planes and are particularly defined by the principal stresses (Sivakugan & Das, 2010). For the critical combinations of shear and normal stresses, the soil element will touch the failure envelope meaning that the soil will fail. The shear strength in drained conditions is described with equation 2.1, expressed as a function of the effective normal stress at failure because shear stress in the soil can only be resisted by the skeleton of solid particles (Knappett & Craig, 2019). In an undrained analysis, where the pore water is influencing the soil strength, equation 2.2 is applied with total stress parameters.

$$\tau = c' + \sigma_f^{'} tan\phi' \quad [kPa] \qquad (2.1)$$

$$\tau = c + \sigma tan\phi \quad [kPa] \qquad (2.2)$$

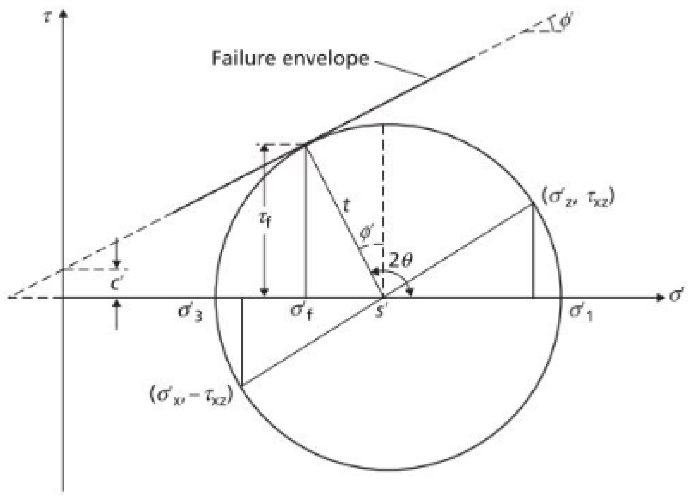


Figure 2.1: Mohr Coulomb failure criterion in drained conditions (Knappett & Craig, 2019).

2.3 Limit Equilibrium Method

The limit equilibrium method is the traditionally applied approach for slope stability analysis (Salunkhe et al., 2017). As seen in figure 2.2, a potential sliding mass is divided into several vertical slices, whereas force and moment equilibrium is solved for each slice. The limit equilibrium method has not always been as rigorous as present methods. First introduced by Petterson in 1916, versions that are more mathematically complex and rigorous, including moments, and vertical-, horizontal- and inter-slice forces, have been developed to be applied to more complex problems (Krahn, 2004). Limit equilibrium methods adopt fundamental theories from statics, aiming to find the point at which resisting and sliding horizontal and vertical forces, and moments around any point, are in equilibrium (Firincioglu & Ercanoglu, 2021).

At this equilibrium, the shear strength in all slices is assumed to be fully mobilised and the safety factor can be determined as the factor that the shear strength must be reduced for the sliding mass to be on the verge of instability (Krahn, 2004). This is described with the relationships in equation 2.3.

$$\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \Sigma M_0 = 0 \tag{2.3}$$

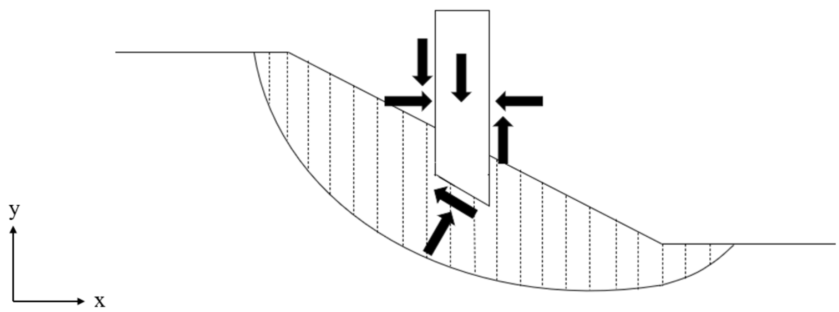


Figure 2.2: Illustration of method of slices.

2.3.1 Slope/w

One of the software that was used to evaluate the safety factor in GÄU, Slope/w, uses the principles of the limit equilibrium method. Slope/w offers many of the known limit equilibrium methods: Bishops, Spencer and Morgenstern-Price, etc. In GÄU, the used practice was the rigorous Morgenstern-Price method (SGI, 2012b). This method has its roots in Fellenius's simple method of slices and is a popular geotechnical practice because of the stricter equations of equilibrium that are used (Ouyang, Liu, & Yang, 2022). With this method, both shear and normal inter-slice forces are considered. The user specifies the inter-slice function in Slope/w, where the half-sine function is commonly used. The Slope/w manual written by Krahn (2004) explains the different options in the methods, how they should be used, and how they affect the results. Below is a short description of the most important modelling options in Slope/w for this project.

The key matter in a stability analysis is to find the position of the slip surface that gives the lowest safety factor (Krahn, 2004). In Slope/w this is done in an iterative process where many possible critical slip surfaces are tested. Slope/w has a selection of different methods that defines the shape and positions of the trial slip surfaces, however, the resemblance is that they all require conscious guidance by the user. In the Slope/w manual, it is explained that the user must consider the soil stratigraphy in order to define the location of the potential critical slip surface. Two common slip surface procedures are the grid and radius, and the entry and exit slip surface options. Traditionally the slip surface in slope stability analysis is of a circular shape (Geo-Slope, n.d.-b). However, some research propose that the circular slip surface is idealised and that the slip surface rather should be optimized to be more realistic (Malkawi, Hassan, & Sarma, 2001). Traditional slip surface methods, as those mentioned above, change the entire slip surface when forming different potential critical slips (Krahn, 2004). This means that the procedures just test different positions for the arc of a circle and finds the lowest safety factor among them. The optimization option available in Slope/w that was used in GÄU uses the critical circular slip surface and then optimizes it in order to find a lower safety factor.

To determine the safety factor in limit equilibrium methods, considering only the static equilibrium equations is not enough because the problem will be statically indeterminate (Lin, Zhong, Xiong, & Tang, 2014). Therefore, the limit equilibrium method, and hence Slope/w, adopts the Mohr-Coulomb theory to explain the soil strength. Slope/w does not make any distinction between total and effective parameters if using the Mohr-Coulomb material model. For example, if pore water pressure is defined, it assumes that the input parameters are effective and therefore require careful input by the user (Geo-Slope, n.d.-c). To make the distinction clearer, Slope/w offers material models that emerge from the Mohr-Coulomb theory, but are modified to more intuitively fit different types of materials. For instance, there's an undrained material model with a friction angle of 0 as default, which is a great practice for undrained materials with a constant shear strength. There are also material models that can take the increase of undrained shear strength into account, from either a specified datum or the top of a soil layer in slopes. Which one of the material models is appropriate to use hence depends on the current soil layers consolidation- and erosion conditions. The pore water pressure conditions, which influence the effective stresses in drained conditions, can be defined in various ways in Slope/w. Two options are offered in Slope/w, a piezometric line with hydrostatic pressure increase with depth, or from a spatial head function that accounts for irregularities in the pore water pressure (Geo-Slope, n.d.-d). Compared to using the piezometric line to define the pore water pressures, a spatial head function can give a more accurate representation.

2.4 Finite Element Method

The limit equilibrium methods are appropriate when the geometries are not too complicated, but with more complex problems with nonlinear behaviour, the finite element approach can be used instead (Khalkhali & Koochaksaraei, 2019). According to the SGI guideline for slope stability evaluation (2023), a complex problem is when the topography, or geological- and groundwater conditions are complicated. Using finite element method in geotechnology, can offer more than just calculations of slope stability, it includes the stress and strain relationship which indicates for example movements and deformations (Krahn, 2004). This method divides sections into simpler parts, called finite elements, that consist of both nodes and stress points (Bentley, 2022). The elements are connected with the nodes, and the greater number of nodes, the more accurate the calculations will be.

There are several advantages to use finite element methodology as an approach on slope stability investigations, where one of them is that no assumption of neither the shape nor the location of the failure surface is needed (Basir, Halder, & Imam, 2016). There are typically two ways of determining the slope stability with the finite element method. Either it is to reduce the soils strength parameters until failure or to increase the gravity loading until failure. However, there are still some disadvantages using finite element method for slope stability investigations. Just as for limit equilibrium methods, the factor of safety will vary in result depending on which conditions that are chosen in the model (Khalkhali & Koochaksaraei, 2019). Using the finite element method in slope stability is more time demanding, for example, if a small mesh is generated it will increase the computational time. This in turn leads to more costly investigations.

2.4.1 Plaxis

One program that uses finite element method for slope stability calculations is Plaxis, which is a software specially designed for geotechnical investigations and modelling (Bentley, 2022). This means that the program can be used to investigate the soil response to stresses, for example deformations and pore water pressure changes, and can handle complex reinforcement structures. As already described, the finite element method divides the model into smaller elements, which are generated by Plaxis as the mesh of the model. It is up to the user to choose the coarseness of the mesh, the finer the mesh, the more accurate result will be established. The soil profile is modelled with either 6- or 15- noded elements, depending on requirements on the model (Abdullah, 2021). The 15-noded element will generate more accurate results on stress problems, because it is a more complex model than the 6-noded model (Bentley, 2022).

To define a new soil material in Plaxis, the user needs to choose between several different constitutive soil models that explains the soils behaviour, but also choose the drainage type of the soil (Bentley, 2022). Depending on which soil type that is analysed as well as how much input data that is available, the different soil models will have various accuracy. As already described, the Mohr-Coulomb failure criteria is a well established theory of soil strength and is one of the soil models that can be chosen in Plaxis. Cohesion, c, and friction angle, ϕ, are parameters in the Mohr-Coulomb failure criteria, but in the soil model in Plaxis the elasticity modulus, E, is also needed as input parameter. This is to analyse the soils deformation behaviour, however the parameter has been proven to not have impact on the safety factor (Basir et al., 2016). The elasticity modulus can be an expensive parameter to investigate, and instead, estimation of this parameter is done by either applying the empirical relationships in appendix A for undrained materials or appendix B for drained materials . The drainage type that is chosen depends on what kind of analysis is to be performed, undrained- or drained analysis. When short-term soil behaviour is examined it is sufficient to apply undrained behaviour (Bentley, 2022) of the soil. For undrained analysis in Plaxis, there are two drainage type options that are suitable, undrained B or C. Both of these consider total strength parameters and the difference is that B applies effective stiffness parameters whereas C applies total stiffness parameters.

Plaxis calculations are set up in different phases. There is always an initial phase as a start, which is a calculation process to compute the initial stress generation in the soil profile (Bentley, 2022). The stress generation is influenced by the weight of the soil and if there are any previous formations in the soil. In cases where the surface layer is not horizontal, the gravity loading calculation type is accurate to use as initial stress generation. Thereafter other phases can be added where the calculation type *safety* is used to determine global safety factors of the model. It is a phi-c reduction, meaning that the soil strength parameters are gradually reduced until collapse of the slope is unavailable. The safety factor is therefore defined as the ratio of the initial and final strength parameters, see equation 2.4.

$$\Sigma M_{sf} = \frac{tan\phi'_{input}}{tan\phi'_{reduced}} = \frac{c_{input}}{c_{reduced}} \quad [-] \tag{2.4}$$

There is no possibility to calculate a safety factor < 1 for global failures in Plaxis. If the output can be confirmed to be a soil collapse, this can be assumed to be an unstable slope, just as slopes with a safety factor < 1 in Slope/W. The failure mechanism, comparable to the critical slip surface in Slope/w, can be visualised as the displacements or strain of the soil, even if the magnitude of these are of no interest for the stability (Kim & Lee, 1997).

2.5 Differences in Slope Stability Calculations for LEM and FEM

Despite the limit equilibrium methods being dependable and a good enough way of calculating safety factors and evaluating slope stability, it holds some limitations that must be considered. One important notation was made by Krahn (2004) that the use of limit equilibrium methods in softwares might have been pushed beyond the initial purpose. Meaning that the method was developed to look at simple problems where the slope stability was only affected by gravity, and including aspects like complex reinforcement or analysing deformations is not possible. This is because the limit equilibrium methods do not include a stress-strain relationship describing displacements, often leading to incorrect stress distributions. Instead, the soil is assumed to behave perfectly plastic, meaning that the strain is the same along the whole slip surface, and that the shear strength is fully mobilised along the slip (Duncan, 1996). However, this does not affect the global safety factor (Krahn, 2004). On the other hand, the calculations in Plaxis will give information on stresses, displacement, and pore pressures and are appropriate in complex situations (Odén & Thorén, 2023). Studies have shown that this stress-strain relationship might make the safety factor more accurate (Sulaiman, Miniandi, Yusoff, Ayob, & Kasa, 2019). Slope stability analysis in a finite element-based software as Plaxis is beneficial because the variation of shear and normal stresses, and strengths along the critical slip surface can be predicted without the need for assumptions of inter-slice functions as in limit equilibrium methods (Zou, Williams, & Xiong, 1995). However, calculations of the safety factor in Plaxis is not influenced by the stresses and strains, and only come down to a phi-c reduction (Bentley, 2022). Therefore the use of a phi-c reduction in Plaxis gives similar results to those from limit equilibrium methods. From previous research, it can also be stated that the factor of safety is calculated to be somewhat lower in the finite element method compared to the limit equilibrium approach (Khalkhali & Koochaksaraei, 2019; Iravanian & Shlash, 2020). This does however not necessarily mean that the stability, or probability of failure, is lower but is a great representation of the differences in the calculations. Another important difference is that in finite element-based slope stability analyses it is only the most critical slip surface that is presented as a result, while in limit equilibrium methods it is possible to see how the safety factor varies in different potential slip surfaces (Odén & Thorén, 2023). However, an extension to Plaxis called *PLAXIS 2D - Limit Equilibrium converter* has been developed by Bentley (van der Sloot, 2023), that makes it possible to open a Plaxis file in Slope/w, and vice versa, and in that way be able to visualise possible slips instead of only the critical. It is important to note that this tool is not further inspected in this project, and that therefore the limitations of it have not been looked into.

2.6 Python Coding in Plaxis

For the automated method of slope stability investigations in this project, Python coding was used. Coding can be applied to many areas and is usually interpreted in softwares using an application programming interface, also known as an API (Reddy, 2011). An API enables different applications to communicate with each other by setting up a set of rules that transfers data between the systems (IBM, n.d.). In other words, an API can be used as a way for one system to use the resources of another system.

2.6.1 Plaxis Remote Scripting API

Plaxis provides an API so that Plaxis input and output can be defined and used by a remote scripting server (van der Sloot, 2022). The API allows the user to activate the remote scripting server in Plaxis, and connect to a source code editor from which the model can be created and calculated. According to Bentley (2022) there are some prerequisites that are needed to use the API:

- A Bentley Geotechnical SELECT Entitlement license.
- An editor where python scripting is enabled. In Plaxis the SciTE text editor is provided, but other source code editors such as VS Code or Jupyter Notebook can be used as well.
- No firewall blockage of the Plaxis environment to accessing the internet, or blockage of using other applications to communicate with the remote scripting server in Plaxis.

There is a Plaxis scripting language, plxscripting.easy, that must be used in order for the source code editor to be able to communicate with Plaxis (van der Sloot, 2022). This language package is already connected in Plaxis if using the default SciTE editor but must be called on in the code for other source code editors to work as a Plaxis interpreter (Demir, 2021). The plxscripting.easy scripting language corresponds to the command line references found in the Plaxis help menu (van der Sloot, 2011).

2.6.2 Visual Studio Code

One source-code editor program available on the market is Visual studio code (VS-code), where different languages can be used and Python is one of them (Microsoft, n.d.). It is an interactive editor downloaded as an application on the computer. Because it can use Python code, VS-code can be used to run the Plaxis remote scripting API to activate the Plaxis environment.

2.7 Previous Research

Introducing Python programming into calculations within the geotechnical area will generate benefits compared to using old conventional methods, according to a study by Yogatama and Tirta (2021). By implementing Python in the geotechnical design, more reliable and economically beneficial methods can be developed. Python is a beginner-friendly and flexible coding language that can be used for many different applications. The authurs have listed different areas within geotechnics where Python code can be applied. One that they call "Automatic model creation for geotechnical software" covers parts of this project's automation. With conventional methods, it will be time-demanding to conduct several geotechnical models for a project manually. The steps of reading the input data, conducting and running the model and finally visualising the results can be simplified with the help of Python. The authors describe several different projects where the application of Python automation has been used, and they concluded that it is important to have uniform data templates to conduct appropriate analyses. Not only the data templates form but also the irregularities in the data format. Sometimes data is presented by a CSV-, XLSX-, DXF- or TXT file which makes the automated process more complex if the user does not have great knowledge of programming. This lack of knowledge of programming is common for many civil engineers, even if programming language courses have become a permanent curriculum at many universities. However, they state that when more and more people in the geotechnical branch become more fluent in the programming language, many of the repetitive tasks will be replaced by code. While this makes the geotechnical design process more effective, it does not overwrite the importance of the geotechnical engineer. Instead using Python coding can be viewed as a data-driven decision-making tool that helps the geotechnical engineer make economically and reliable designs.

Bailie, Baker, Kottke and Richmond (2020) developed a tool to automate parts of the design process of the Euston crossover tunnel and the Euston Cavern in London. Their aim was to find locations of critical sections by using automated modelling in Plaxis, instead of relying on individual engineering judgement and experience to point out the relevant sections in advance and only performing the analysis on them. The automation was done with Python code with the Plaxis remote scripting API tool, where geometries are extracted from a BIM model and combining those with soil parameters, structural properties and construction phases in an excel spreadsheet that can be read in Plaxis. How the excel spreadsheet was constructed mainly commenced from what is written in the graphical user interface, command window, in Plaxis when manually creating a test model. The authors made a simple manual model in order to see the commands needed to define polygons, create materials etc. and created the spreadsheet from that. When performing the automation, the run time duration was longer compared to manually. This is because in the automation there are more sections analysed, every 10 m, compared to fewer if the investigation was to be done manually. However, the time spent on manually inputting the model properties is reduced. Although they found that their automatic approach worked well, the authors highlight that learning to understand the Plaxis remote scripting API tool and create the Python code needed to successfully create the models initially is a time consuming activity. In reward the number of manual inputs are reduced and in the long term, the total time for the analyses are cut. The purpose for Bailie et al. (2020) was to minimise the risk of makeing incorrect engineering judgement when certain sections should be chosen for a project, and this by automating the calculations to find the most critical in an effective way. Would the same investigation be done by manually calculate each section, it would have been to time-demanding compared to this automated process. The research also shows that it is possible to use the remote scripting API tool in Plaxis, which is crucial for this project.

Chapter 3 – Method

This section describes the methodology for the project. Figure 3.1 below shows a schematic view of the methods performed and how they are connected. As described in the aim, one of the main purposes is to develop a code that can be used to automate slope stability calculations, this will be mentioned as the automated method further.

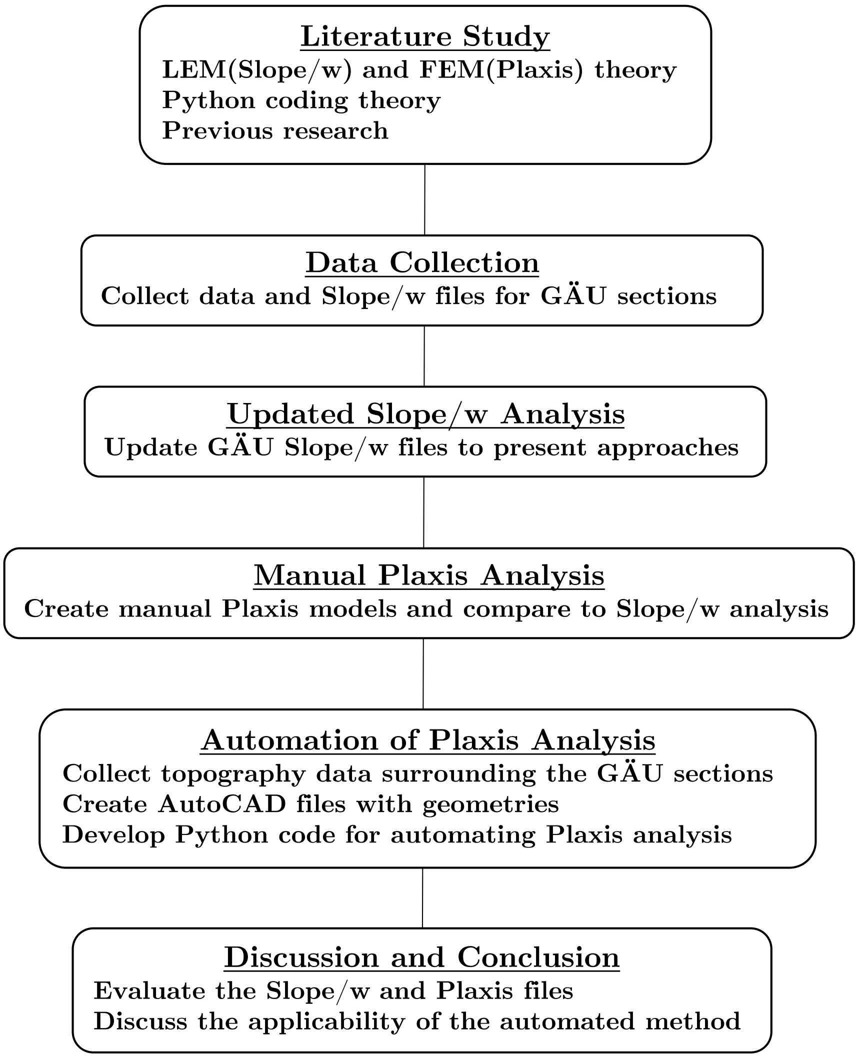


Figure 3.1: Schematic method overview.

3.1 Literature Study

A literature study of relevant theory was carried out in order to gain knowledge about the ulterior theories and principles of the methods and software investigated in this report. The theory behind the slope stability programs, Slope/w and Plaxis was conducted with great focus on the different types of analyses, material models, drainage types, pore water pressure definition, etc. This theory was used to perform the studies in this project as a way to create numerical models in the two softwares that are corresponding to each other. The focus of the literature study was to compare the similarities and differences of Slope/w and Plaxis, not evaluate which is more appropriate for slope stability investigations.

The literature study also focused on finding previous research within the area of automation of Plaxis investigations and explaining the basic principles of how coding can be applied to geotechnical investigations.

3.2 Data Collection

The comparison of Slope/w and Plaxis, and the development of the automated method, is applied on sections from GÄU. The investigation involves 240 sections, where two were chosen to focus on in this project. To choose two appropriate sections to perform the automated method on, some requirements were set up to find a location with interesting characteristics:

- One section with flat topography and a thick clay layer where only the shear strength will control the failure.
- One section with varying topography and a thick clay layer where both the varying geometry and soil shear strength will control the failure.

The available sections were found from the landslide risk map that was created from the results in GÄU at the SGI open database (SGI, 2021). The map provides the calculated risk for each section, from the consequence and probability of landslide, but also contains files showing the safety factor calculation in both undrained and combined analysis. In this project, only the undrained analysis was of interest. When two sections had been chosen based on the requirements above, more data was collected from SGI with help from Karin Odén and Axel Grahnström (Personal communication, February 13, 2023). For example, the complete Slope/w files with the safety factor calculation and other important documentation were collected. These files were then evaluated and updated as explained below.

3.3 Updated Slope/w Analysis

With help from the theory behind the limit equilibrium program Slope/w, the slope stability calculation files obtained from SGI for each section were studied and modified to be accurate to today's ways of performing slope stability calculations in Sweden. This was necessary because the obtained Slope/w calculations in GÄU were carried out 10 years ago. To be able to generate a comparable model in Plaxis, and later automate the procedure, it is crucial to understand how the Slope/w modelling was performed. This gives a better understanding of the parameters used as input data as well as the chosen settings in the program, and how the results was affected. Another aspect to the update of the Slope/w calculations was to make some simplifications necessary in the step of automation, considering the time span of this project.

3.4 Manual Plaxis Analysis

To be able to use an automated method, it is required that the program applied can be programmatically controlled. As mentioned before, Plaxis is one of the suitable programs because it can be controlled by a Python script, which Slope/w cannot (Bentley, 2022). In order to confirm that Plaxis provides comparable results to those from the Slope/w analyses, a manual investigation in Plaxis with the same properties from the chosen sections was carried out. Meaning that the theory behind both programs was applied to find corresponding input in Plaxis. From this manual model in Plaxis, the calculated safety factors were compared to the safety factors found in Slope/w. In the comparison, the theory behind both programs was also confirmed. Another aspect to conduct manual models in Plaxis was to see what appears in the graphical user interface command window when the model was conducted. This was required to be able to formulate the code needed for the automation part.

3.5 Automation of Plaxis Analysis

After manually modelling the two main sections in Plaxis, and comparing with the results from Slope/w, the automation of Plaxis input and calculation was developed. With help from Norconsult AB, AutoCAD models were created for each section. SGI (personal communication, March 17, 2023) provided topography and batymetry for approximately 1 km up- and downstream of each main section, from which subsections could be created every 200 m. The soil stratigraphy in the main sections was applied to the respective subsections. In other words, the varying parameter for the subsections is the topography and batymetry. The geometries for each subsection were saved as DXF files containing the coordinates of the soil polygons, line loads, and water levels. These DXF files were then read in a Python code connected to Plaxis via API, created in VS code. The code was developed to create soil polygons in Plaxis, create and assign materials, define external loads and pore water pressure, generate mesh, set up the calculation process, and finally calculate the safety factor for each subsection.

3.6 Discussion and Conclusion

The final step of the project was to evaluate the results of the different methods. The safety factors from the Slope/w analysis, and the manual and automated Plaxis analysis was compared to see if the new automated method is appropriate in geotechnical studies. In this part of the project, it was also important to evaluate and discuss the risks and possibilities of using this new method, and when it is appropriate or not to use.

Chapter 4 – Results

This section presents the results following the method explained in the section. First, the chosen sections from the previous GÄU will be presented and the Slope/w calculations are updated according to present approaches and with necessary simplifications. This is followed by an explanation and presentation of the manual Plaxis analyses for the two sections, and lastly a description of the automation method that is developed.

4.1 Data Collection and Chosen Sections

The two chosen sections are located in different areas along the river. One is located in subarea 9, more south and the other in subarea 7, in the northern part, see figure 4.1.

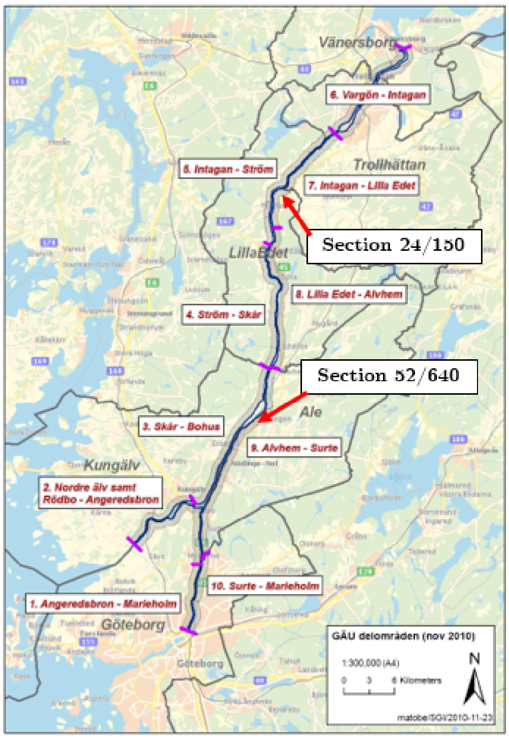


Figure 4.1: Overview of the chosen sections, modified from SGI (SGI, 2012b).

4.1.1 Section 52/640

The first chosen section to be evaluated is section 52/640 which lies within subarea 9. It is a section located nearby the small community of Älvängen and includes both a railway and an industrial area (Bengtsson, 2011a). See figure 4.2 where the soil section from Slope/w is presented. It is noted in the geotechnical PM for subarea 9 written by Bengtsson (2011a) that the area around the Älvängen industry was prior to GÄU known to have low stability conditions. The area around section 52/640 has a flat topography because of the land use, and the soil beneath is represented by thick layers of loose clay. Soundings were performed up to 80 m without encountering bedrock or other material, indicating great clay depths. The clay is covered by a 1 m thick layer of fill, and there is a 2 m layer of mud at the river bottom with considerably low shear strength. It is concluded in the PM that this section generally has low undrained shear strengths for all clays. Closest to the river, at the underwater slope, there is a 0.5 m thick erosion protection.

SGI requested, as stated in the slope stability guideline (2023), both an undrained- and combined analysis for all sections. However, for this section, it was concluded that because of the deep layers of clay and the low undrained shear strength that the undrained analysis would be governing and therefore no combined analysis was carried out (Bengtsson, 2011a). It is also concluded that this section is very sensitive to erosion at the underwater slope and the riverbed, meaning that the future scenarios of climate change can have a large impact on the stability. The analysis shows that the safety factor of the slope is 1.24, meaning that it is stable.

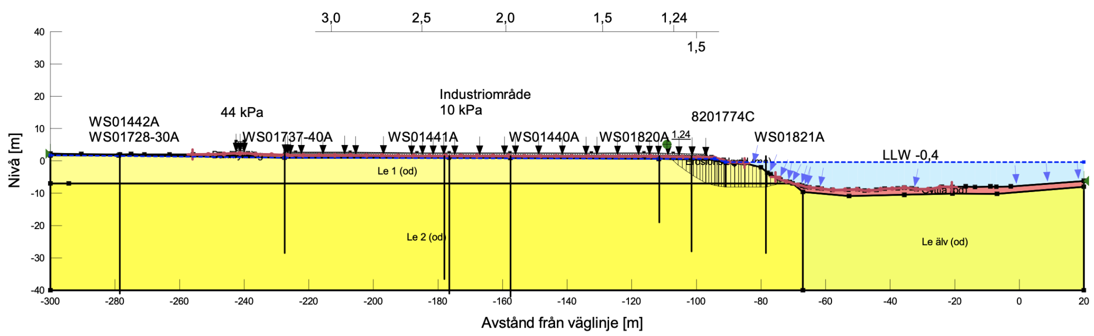


Figure 4.2: Section 52/604, subarea 9. Safety factor = 1.24 (Bengtsson, 2011b).

4.1.2 Section 24/150

The second section, 24/150, is located further north along the river than section 52/640. Figure 4.3 shows the soil section modelled in Slope/w. The section is located 12 km south of Trollhättan, just under the mouth of the river Slumpån (Löfroth, 2011). The area above the shoreline is used for agriculture, and there are no buildings or infrastructure within the section. Compared to section 52/640, the topography for this section is more varied at the slope. The slope crest is at +18 m and there is a difference of 7 m down to the toe of the slope, which results in an inclination of 1:3. Thereafter there is an underwater shelf that is flat for some meters after which there is an additional under water slope with an inclination of 1:1.5 down to the riverbed. In the surrounding areas, both south and north from the section, there are traces of previous landslides. Hence, the slope is reinforced with erosion protection closest to the river. However this layer was neglected in the calculations.

The field investigations showed that the section consists of a 6 m silt and sand layer with elements of mud and plants (Löfroth, 2011). Under this follows different layers of clay, where at the top there are still some elements of loam, sand and mud, but at 12 m depth and further, the clay is more homogeneous. The soundings were performed down to 45 m closest to the river without reaching bedrock. The clays are evaluated to vary from high-sensitive to medium-sensitive, but the clays are never considered to be quick-clay (Löfroth, 2011). Both an undrained and a combined analysis was carried out for this section, where the combined analysis showed a lower safety factor of 0.91. However, this project focuses only on the undrained analysis which for this section resulted in a safety factor of 0.92 (Schälin, 2011).

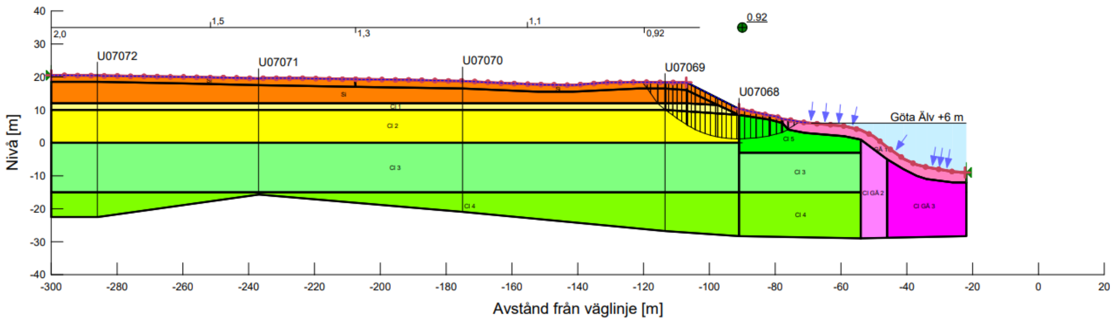


Figure 4.3: Section 24/150, subarea 7. Safety factor = 0.92 (Schälin, 2011).

4.2 Updated Slope/w Analysis

Calculations of safety factors for the sections in GÄU were done in Slope/w. These Slope/w files for sections 52/640 and 24/150 were provided by karin Odén and Axel Grahnström at SGI (Personal comminication, February 13, 2023). In this project, the Slope/w undrained analyses for both sections were updated to match the present methods. These changes are also done to simplify the models for future work with the automation.

Both sections were analysed with the Morgenstern-Price analysis type, with a Half-sine side function (Bengtsson, 2011b; Schälin, 2011). Furthermore, the entry and exit method, from left to right because the section are located east in the river, was applied in both sections to find the location of the critical slip surfaces. The critical slip surfaces were set to be optimized, which is a practice that is not presently advantageous to use according to Swedish standards. Therefore, this option was neglected when updating the two section's Slope/w analyses, and only circular slip surfaces are considered.

4.2.1 Section 52/640

The material properties that were used in GÄU for section 52/640 can be found in appendix C. The same parameters were used in this project's updated version, except that in GÄU an erosion protection layer is placed closest to the river which was neglected in this project. Instead, the soil layers closest to the erosion protection were extended to replace the erosion protection layer. For the fill and embankment, the Mohr-Coulomb material model was used. The undrained material model was used for the mud whereas the clays were modelled with S=f(datum) to account for the increased cohesion. Pore water pressure conditions were defined from a piezometric line located right under the fill and down to a level of -0.4 m (ref. system RH2000) at the river (Bengtsson, 2011a). The safety factor is calculated to 1.28 which is slightly higher than the safety factor calculated in GÄU, 1.24. However, in GÄU the erosion protection is included and the slip surface was optimized.

4.2.2 Section 24/150

The material models and parameters used in the Slope/w calculation for section 24/150 are presented in appendix D. In GÄU, this section had pore water pressures defined from a pressure head spatial function determined from field investigations. However, in this project's updated Slope/w calculation, the pore water pressure was instead defined from a piezometric line in order to ease the automation later on. In Löfroths (2011) report, it was explained that the pore water pressures for the spatial head function were taken from a nearby section. In this project, these values were instead used to convert the spatial head function to a piezometric line, see appendix E for the pore water pressure values. This resulted in an assumption that the piezometric line is at 2 m depth at the slope crest followed by 1 m depth further away from the river. The water level in the river is at + 6 m (ref. system RH2000).

As already mentioned, there is an erosion protection in the shoreline, but this was already neglected in the original Slope/w analysis. Therefore there was no need to replace the erosion protection with surrounding materials in the updated analysis. The updated calculation results in the same safety factor as in GÄU, 0.92. The updated calculation did not use the optimized slip surface option and had changes in the pore water pressure definition. Using a circular slip surface should make the safety factor somewhat higher, but the use of the piezometric line as pore water pressure generation has in this case made the factor of safety lower. This coincidentally made the updated analysis gain the same safety factor as the previous one.

4.3 Manual Plaxis Analysis

To validate the use of Plaxis as an approach that gives comparable results of slope stability to those found in the GÄU and updated Slope/w analyses, manual analyses of the two sections were done in Plaxis. It is important to make the Plaxis analyses manual before developing the automated method to identify which soil models in Plaxis that generate soil behaviour that corresponds to the behaviour in Slope/w.

Both section's geometries in terms of x and y coordinate points were extracted from the Slope/w files and imported to Plaxis via the Import geometry option so that there would be no difference between the two software analyses. This section will explain the development of the manual modelling in Plaxis for both sections and present the results of the safety calculations.

The Slope/w analyses in GÄU was done as total safety analysis for both sections. This means that characteristic values was used as input without the use of any partial factors. In Plaxis, total safety analysis is also done so no modifications to the given input parameters was required. Both sections are modelled as plain strain models with 15-noded elements. As already done in the updated Slope/w analyses, the thin erosion protection layers are neglected in both Plaxis models because these might cause difficulties with the meshing. The geometries used in Plaxis are the same as the Slope/w geometries, with some slight changes for section 24/150 explained below.

To model the soil behaviour for all soils in both sections, the Mohr-Coulomb soil model is used. Because the material models in Slope/w originate from the Mohr-Coulomb theory, it was a relevant choice to use the Mohr-Coulomb soil model in Plaxis. The safety calculation in Plaxis comes down to friction angle and cohesion as the relevant parameters, and therefore a more complex soil model would be unnecessary for this case. The material properties used in Plaxis can be found in appendix C and D. Many of the parameters are identical to those used in Slope/w but were also extended with additional parameters required to make the materials valid in Plaxis. The input parameters in GÄU did not contain an unsaturated unit weight for the undrained materials, and therefore the saturated unit weight was applied there as well. For the drained materials the reference and increasing cohesion, c'_{inc}, were set to 0 kPa. Values of the stiffness was not predefined in the Slope/w analyses, so these parameters was derived as described in appendix A with the empirical relation between cohesion and stiffness. The same equations was applied for the increased stiffness, calculated from the increasing cohesion in the undrained materials. For the drained materials where no cohesion was defined in Slope/w, the stiffness was instead determined from the friction angle according to the tables in appendix B. To model the undrained behaviour of the clays and mud, the Undrained B option was used because of the total strength parameters provided from the GÄU Slope/w analyses. The silt and fillings were modelled as drained materials.

After defining the geometry and material parameters, the mesh was generated for each section. A very fine mesh was generated and then refined 6 times at the slope. The pore water pressures were defined from the same piezometric lines as in the updated Slope/w analyses with a hydrostatic pressure increase of 10 kPa/m. Calculation of the models in Plaxis can be divided in different phases. The phases vary between the two sections but mainly follows this procedure: Initial phase that defines the initial stresses, an additional nil-phase that makes sure that the horizontal stresses are continuous (Oberhollenzer, Tschuchnigg, & Schweiger, 2018), followed by a safety calculation phase. The initial phase uses the gravity loading procedure to calculate the in-situ stresses. For the safety factor calculation, the safety analysis loading type was chosen to incremental multipliers.

4.3.1 Section 52/640

The refined numerical model, see figure 4.4, for section 52/640 resulted in 28 639 nodes and 3491 elements, the mesh can be seen in appendix F. This section has two external line loads that was put into Plaxis with the same magnitudes and location as in the Slope/w analysis, 10 kPa for the industrial area and 44 kPa for the railway. The presence of line loads in Plaxis require an extra phase to be added after the extended initial phase. This phase is added to activate the line loads after the initial stress generation so that they are counted for in the stability calculation.

The unrefined calculation resulted in a safety factor of 1.18 for section 52/640. This is a lower value compared to 1.28 in the Slope/w analysis which is reasonable according to the theory in section 2.5. It could be seen that with the refined mesh in the slope resulted in a bit lower safety factor, 1.17, which is not a remarkable difference. The figure shows the total displacement of the soil, and the most movement is located in line with the critical slip surface that was observed in the Slope/w analysis.

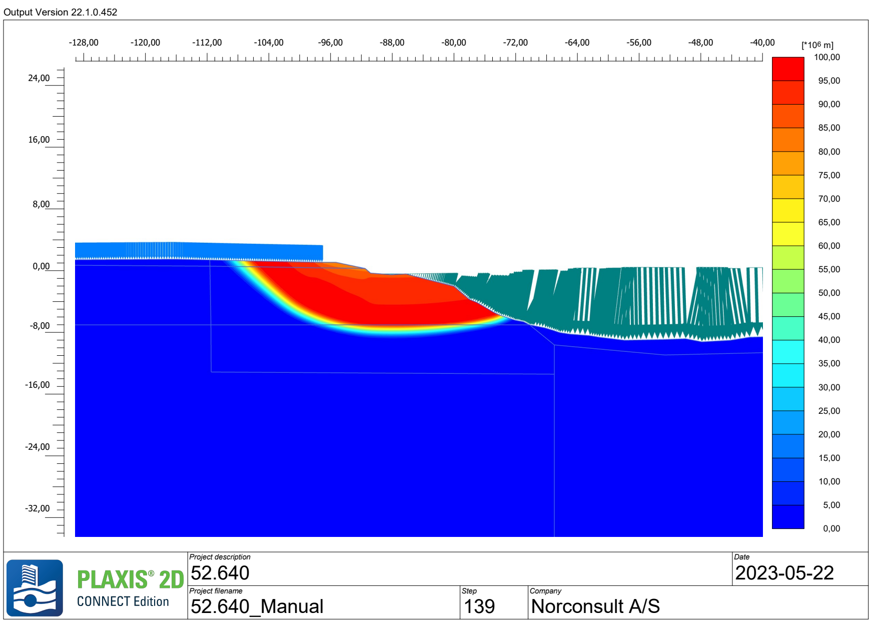


Figure 4.4: Refined manual modelling in Plaxis section 52/640. Safety factor=1.17.

4.3.2 Section 24/150

When analysing section 24/150 in Plaxis, some geometry changes were required. It can be seen that some changes to the geometry, compared to the Slope/w geometry, were necessary in order to complete the calculation. In order to avoid errors in the stiffness matrix, bedrock was placed under the soil layers furthest down in the section. The Plaxis model for the section can be found in figure 4.5.

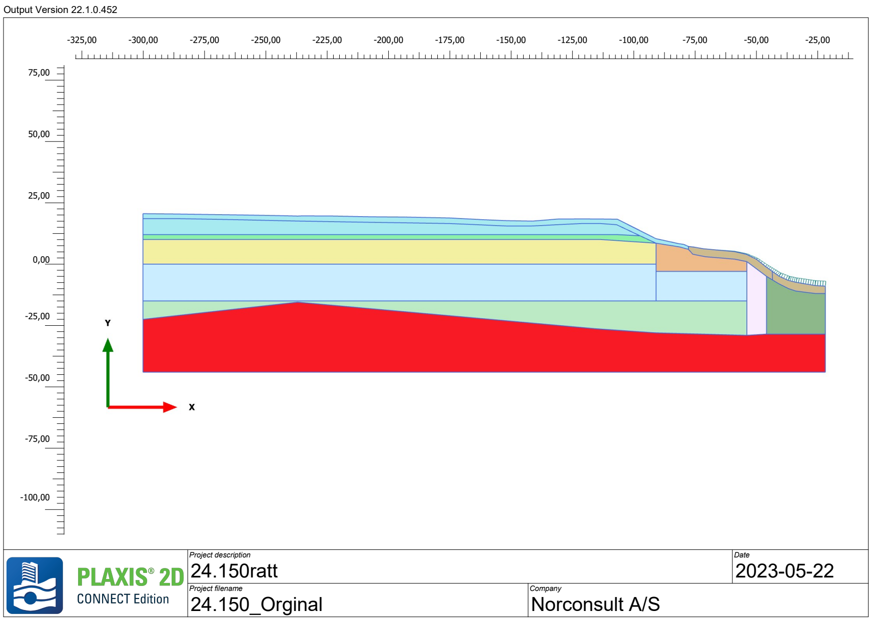


Figure 4.5: Changed geometry of section 24/150.

The refined numerical model, see figure 4.6, for section 24/150 resulted in 52 073 nodes and 6456 elements, the mesh can be found in appendix G. The material parameters for section 24/150 can be found in appendix D. In this section with more varying topography, it was of high importance to consider how the geometry will affect the increased cohesion. The riverbed, *ClG*ä1, was modelled with the S=f(depth) material model in Slope/w, which assumes that the cohesion increases from the top of the soil layer even if it has varied topography. This is not as easily applied in Plaxis, because there is no soil model that matches these criteria. There are different ways of solving this in Plaxis, for example, the riverbed can be divided into several smaller parts where the elevation of the top of the layer, from which the cohesion should increase, is subsequently changed to match each part. However, in this project, it was assumed that using the average cohesion of the *ClG*ä1 would give an acceptable representation of the layer's cohesion. This is because it is only around 2 m thick.

The expected outcome for this section in Plaxis is a failure of the calculation because the safety factor calculated in Slope/w is < 1. As expected, the Plaxis calculation fails before going through all phases with the error message "Soil body seems to collapse" which in the output can be seen to be caused by a slip in the slope near the river, see figure 4.6. The slip surface is located at the same spot and is of the same magnitude as the one in the Slope/w calculation.

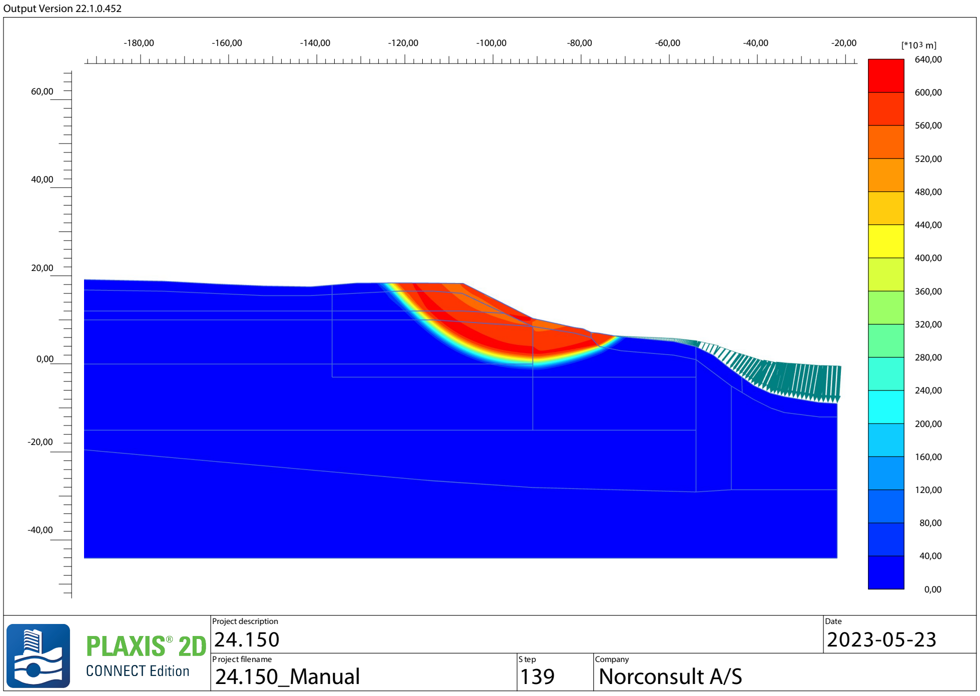


Figure 4.6: Refined manual modelling in Plaxis section 24/150. Safety factor=0.97

Because the Plaxis calculation fails before the safety phase is calculated, there is no accurate safety factor presented in the output. In this project, an estimation of the real safety factor is done based on the phi-c reduction that is done in the Plaxis safety calculation. By increasing the undrained shear strength in the clays and the friction angle in the drained materials, the calculation in Plaxis can successfully go through all phases and reach a safety factor > 1. The percentage difference between the reference and increased undrained shear strength for an arbitrary material is calculated and then multiplied with the safety factor calculated with increased parameters, see an example in equations 4.1 and 4.2. This results in an estimation of the real safety factor at failure. It is concluded that for section 24/150, an increase of 20% of the undrained shear strength and friction angle results in a safety factor of 1.17. If then this safety factor is decreased based on the explanation above, the real safety factor for the section can be obtained as 0.97, which was the same for both original and refined analyses. An important note is that when increasing the cohesion and friction angle, no changes are made to the stiffness even though it can be related to the strength parameters. The actual value of the stiffness is not of importance in the safety calculation.

$$\frac{\text{Original cohesion for Le1}}{\text{Increased cohesion for Le1}} = \frac{23.5}{28.2} = 0.833 \tag{4.1}$$

$$\text{Real safety factor} = \text{Increased safety factor} \cdot 0.833 \rightarrow 1.17 \cdot 0.833 = 0.97 \tag{4.2}$$

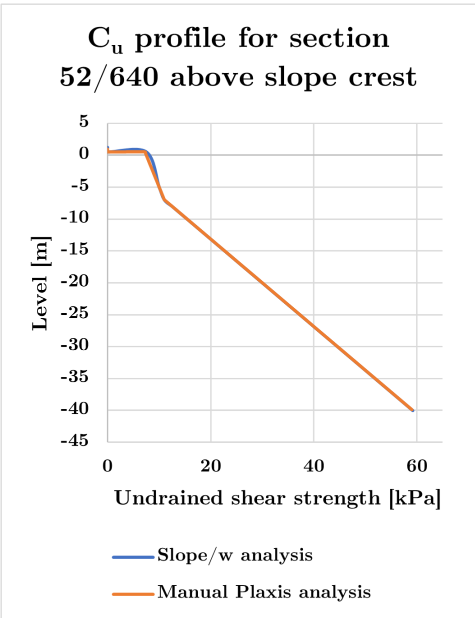
4.4 Validation of Manual Plaxis Analysis

Table 4.1 shows the difference in the generated safety factors for the two sections from the original Slope/w analysis conducted in GÄU to the manual Plaxis analysis. It can be seen that for section 52/640, the safety factor decreases in the Plaxis analysis while it is slightly higher for section 24/150.

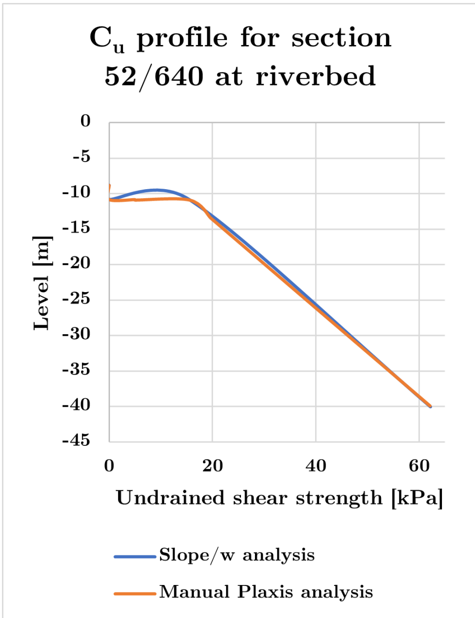
Table 4.1: Safety factors for section 52/640 and 24/150 from Slope/w and Plaxis.

Analysis type	SF for 52/640	SF for 24/150
Slope/w analysis in GÄU	1.24	0.92
Updated Slope/w analysis	1.28	0.92
Manual Plaxis analysis	1.18	0.97
Manual refined Plaxis analysis	1.17	0.97

The undrained shear strength profile from the Slope/w analyses and the manual Plaxis analyses were derived to see if the same soil behavior can be seen. Figure 4.7 shows the profiles taken from above the slope crest, at x=-101 m, and at the river bed at x=-53 m. The profiles are almost identical. Figure 4.8 shows the corresponding profiles for section 24/150 at x=-113 m and x=-70m. The assumption of constant cohesion in the riverbed can be seen to affect the undrained strength profile for the first three meters, with a slight difference.



(a)



(b)

Figure 4.7: Cu-profile for section 52/640 a) above the slope crest (x=-101 m) and b) at the riverbed (x=-53 m).

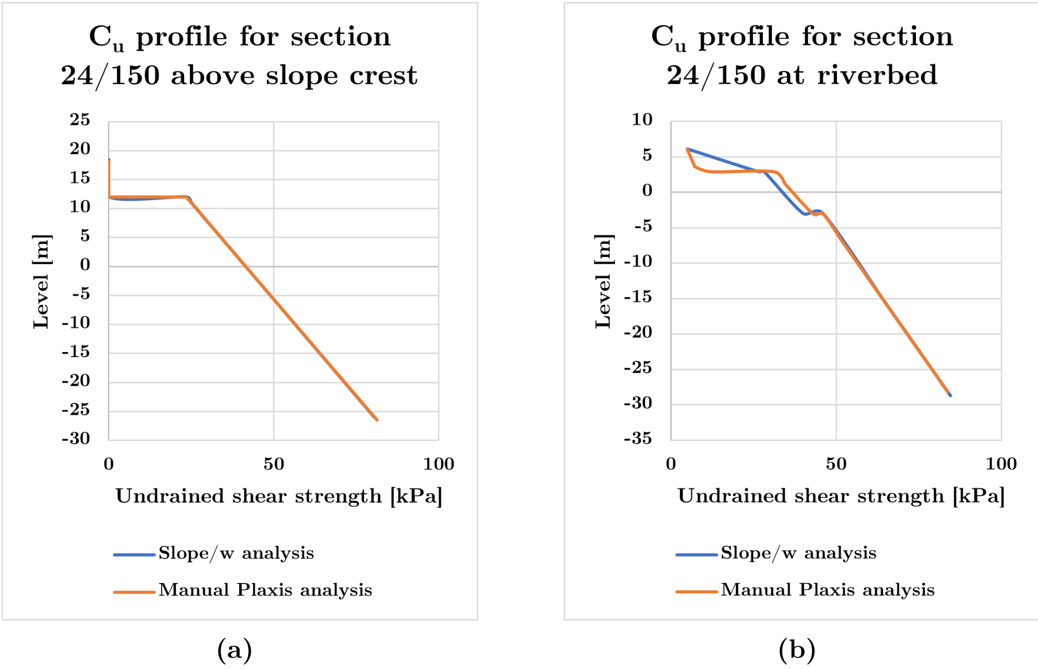


Figure 4.8: Cu-profile for section 24/150 a) above the slope crest (x=-113 m) and b) at the riverbed (x=-70 m).

4.5 Automation of Plaxis Analysis

To complete the aim of this project, an automation of the same calculations conducted manually in Plaxis above was developed. This was done by gather further information of topography- and bathymatry of the surrounding areas of the two main sections. However, this new data is not the same as the one in GÄU and the topography will differ a bit in the geometries for the automated calculations. The automation spans from an extraction of DXF files from AutoCAD models of the areas around the two sections, to the calculation of safety factors. This section will explain the process of the automation and explain how the code connected to Plaxis work. The full scripts for the two main sections can be found in appendix H and I.

4.5.1 Geometry

Geometries for each subsection are defined as AutoCAD DXF files. With topography and batymetry, provided by SGI, two separate 3D models for the areas around each main section could be derived from which each DXF file could be extracted. The 3D models span over approximately 1 km up- and downstream from each main section, and subsections were taken every 200 m. This resulted in 8 subsections for main section 52/640 and 12 subsections for main section 24/150, see figures 4.9 and 4.10. The location of the main sections are marked as bold and this is at the same locations as for the previous performed manual analyses. Because of the change in topography and batymetry along the river, the subsection geometry varies even though the soil stratigraphy is assumed to be the same as the main section.

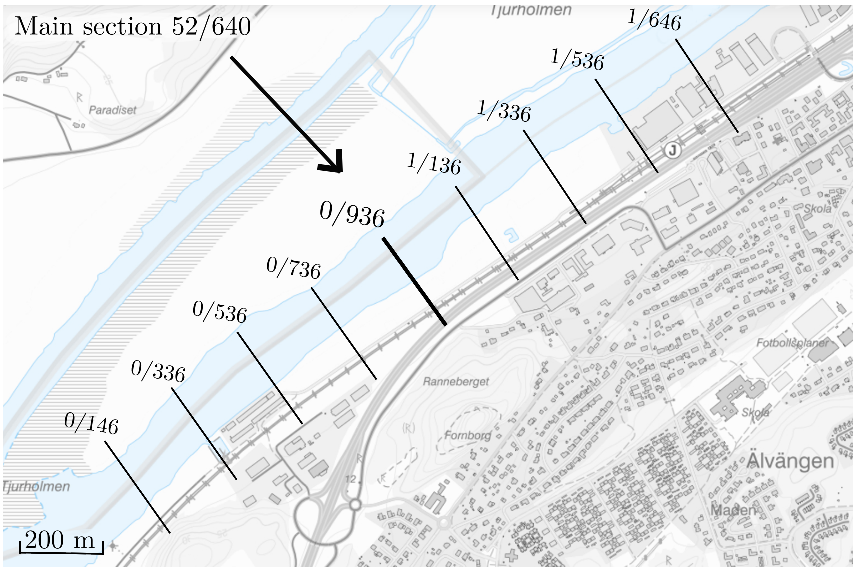


Figure 4.9: Subsections for section 52/640 where the location of the main section is marked in bold, which is the same as the one in GÄU.

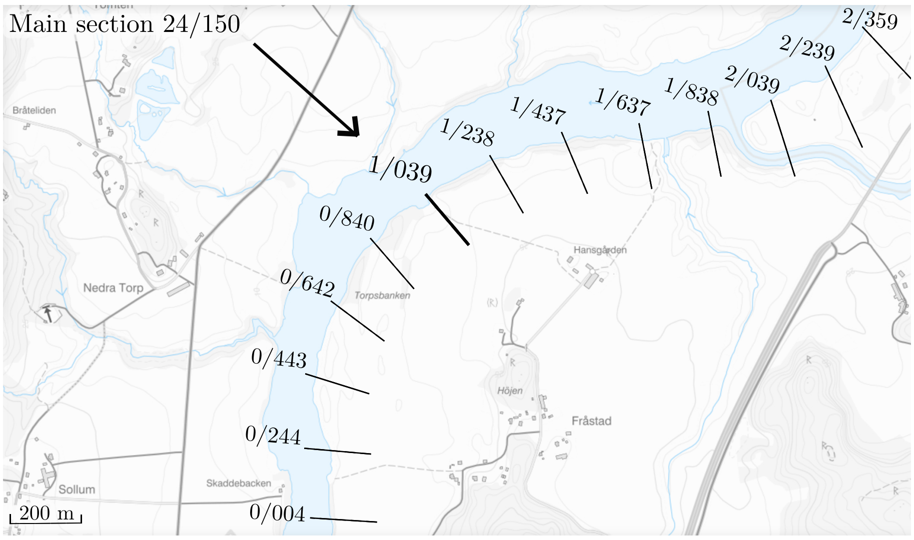


Figure 4.10: Subsections for section 24/150 where the location of the main section is marked in bold, which is the same as the one in GÄU.

The soil layer geometry for the two main sections, 0/936 and 1/039, is created in AutoCAD using the same x and y coordinates from the SGI-provided Slope/w files. In each subsection, the soil layers are defined as AutoCAD regions. Regions are defined from polylines in AutoCAD and it is important that each soil layer's polyline is a complete unit for the further steps of the automation. It is also of high importance that the polylines are connected to each other at every point between all soil layers, or else there will be problems with the Plaxis calculation. However, the polylines that are used to create regions in AutoCAD must be deleted once the region has been created. This is because polylines are used to define the line loads for section 52/640 and the water level for section 24/150, and only these polylines can be in the DXF file. This can be observed in figure 4.11 and 4.12. An important note is that the order in which the regions are created is crucial to consider for the further steps of automation. It is also important that this order is the same for all subsections. The water level for all subsection to section 52/640 is defined from the same CSV file as explained in section 4.5.2.

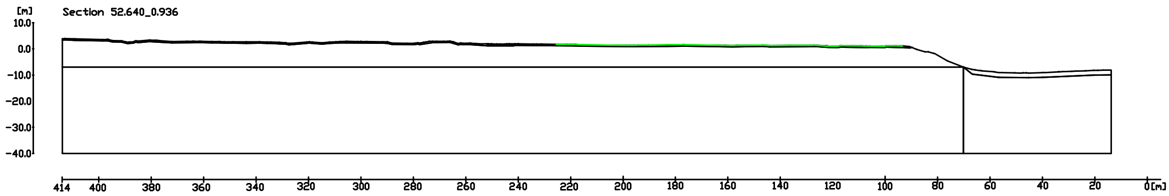


Figure 4.11: Regions and polyline in main 52/640 section. Regions marked in black and polyline for line loads marked in green.

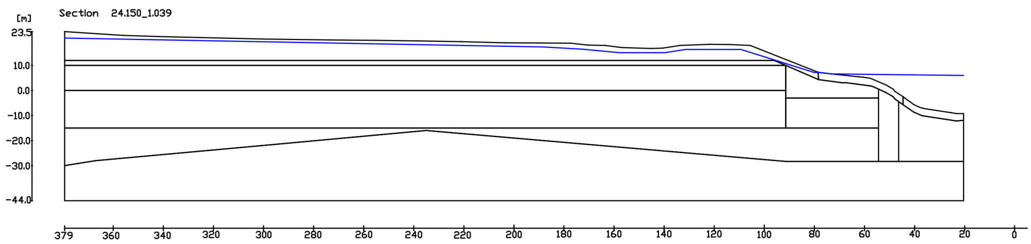


Figure 4.12: Regions and polyline in the main 24/150 section. Regions marked in black and polyline for waterlevel marked in blue.

The DXF files for each subsection can be found in appendix J and K as figures of the regions and polylines. As noted before, it is the topography and batymetry that is the changed parameter between the subsections, and figure 4.13 and 4.14 shows how the slope changes over the inspected area for each main section.

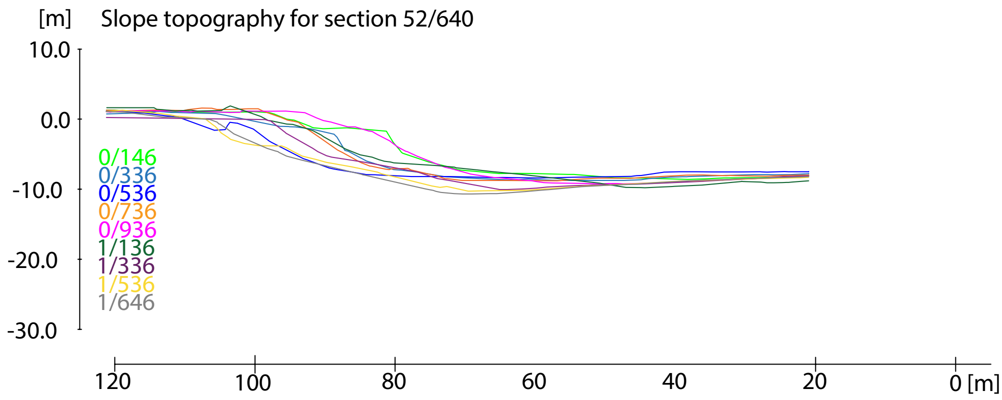


Figure 4.13: Variations in topography at the slope for section 52/640.

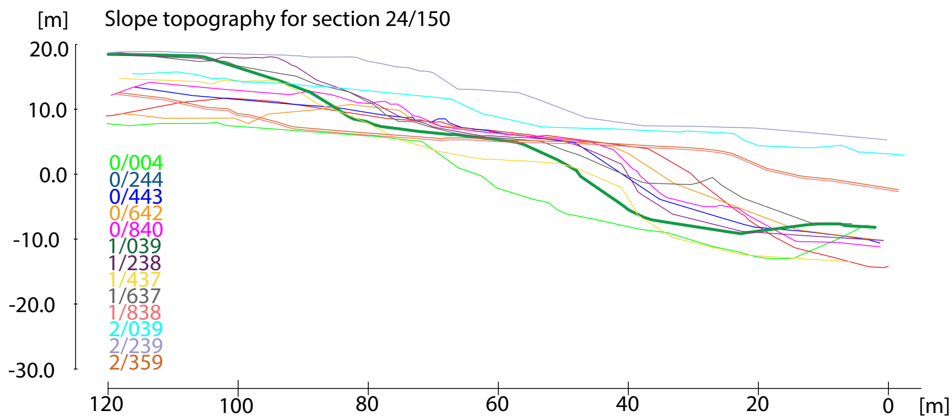


Figure 4.14: Variations in topography at the slope for section 24/150.

4.5.2 Python Code

The automation of the Plaxis input and calculation is made in a Python script created in VS code. In order for the script to command Plaxis, it must be connected to Plaxis via an API. Fung Tsang's (2022) tutorial on how to connect VS code to Plaxis was used as a base for the script. In addition to this script, the Plaxis python environment must be activated in VS code by selecting this as the Python interpreter. To be able to communicate through Python with Plaxis, a special library for the Plaxis commands needs to be installed, this is called plxscripting. Also, it is important to open the folder that where the script is saved in the VS code explorer. This is with favour the same folder where other important files, such as DXF- and CSV files for the automation are saved. Once the Plaxis environment is connected to the Python code, all commands can be done from the code. In total two scripts are created, one for section 52/640 and one for section 24/150 with respective subsections, found in appendices H and I. The script loops over the different subsections DXF files and subsequently saves the results for each calculation. The codes for each main section are in general the same but were made separate because there are some differences explained below. Figure 4.15 shows the outline of the codes. This is followed by a more detailed description.

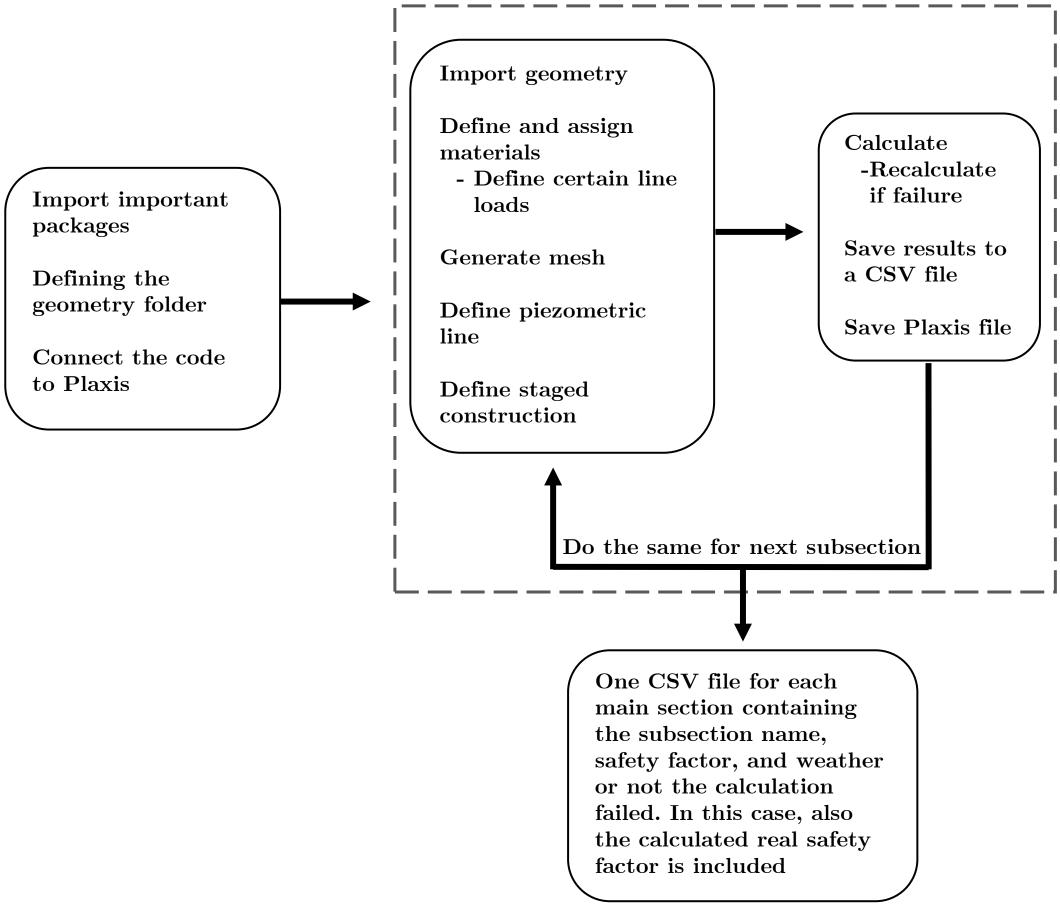


Figure 4.15: Schematic overview of the Python codes.

Import Geometry

The geometry creation is the first step of the Plaxis analysis. This is done by importing regions from each subsection's DXF file. When importing the geometry, soil polygons are created in the order that the AutoCAD regions were created. This means that the first polygon generatedin Plaxis is also the first region created in AutoCAD. As noted before, this is important for the further steps of the automation.

Define and Assign Materials

When the geometry has been defined, the material properties are read from a CSV file. The properties are the same as in the manual Plaxis modelling, see appendix C and D. The code reads the CSV file and creates the materials, and assigns them to the corresponding soil polygon. It is at this step it is important to have noted the order in which the AutoCAD regions, and hence Plaxis soil polygons, were created. The code matches the index of the soil polygon to the corresponding index in the material properties CSV file. Therefore it is important that the order of the materials in the CSV file is the same as the order of the regions.

Define Line Loads
For some of the subsections to main section 52/640, line loads from a nearby industry area and a railway need to be defined. The code is built in a way that only the DXF files with the presence of polylines is analysed with line loads. The extent of the industry area was measured on a map of the area to see which of the subsections should be calculated with line loads. The line loads are defined by the code in Plaxis from the polylines in the DXF file. The position of the industry load is assumed to be 2 m from the slope crest and is extended ca 130 m. Loads from the railway is 2 m wide at the embankment. This whole code block is not included in the script for the 24/150 subsections because no line loads are present.

Generate Mesh
When all structures in terms of soil polygons and certain line loads have been created, a very fine mesh is generated, an element size of 0.03. No refinement is done at the slope in the codes. Meshing for all subsections can be found in appendix L and M.

Define Piezometric Line
The location of the piezometric line is done in two different ways depending on the main section. For section 52/640 it was observed that the topography is not changed significantly over the investigated area, and therefore the piezometric line is assumed to be located at the same levels for all subsections. In this case, the waterlevel is defined in Plaxis by importing a CSV file containing the coordinates for the global waterlevel. However, in the subsections to section 24/150, the topography and batymetry was found to have large variations, and using the same waterlevel for the whole area would not be realistic. Instead, a polyline was defined in each DXF file from which the waterlevel is defined. The assessment of where the waterlevels should be located is not done from observed values, instead they are only based on what seems reasonable for each subsection. Before the safety calculations was performed, the pore water pressure pressure distribution was inspected. In appendix L and M the pore water pressure for each section is presented, this shows that every section has correct hydrostatic pore water distribution.

Define Staged Construction
The final step before the calculation is to define the different phases for the calculation. All soil polygons are activated from the initial phase. As already performed in the manual Plaxis models, gravity loading is set as loading type for the initial stress generation. The phases for each main section are the same as in the manual Plaxis model with the exception that for the subsections to main section 52/640 with no line loads, the third phase is skipped because no loads need to be activated. In these cases, the phase structure is the same as for all subsections to main section 24/150.

Calculate and Save Results
The calculation is performed and the reached safety factor for each subsection is saved in a CSV file. There are two CSV files, one for each main section. The subsection's name and calculated safety factor, with either original or increased values of undrained shear strength and friction angle, are saved. If the first calculation with original parameters fails due to "Soil body seems to collapse", i.e. if the calculation result in Plaxis for one of the phases is a 2, the code has a function to recalculate

with increased values of undrained shear strength and friction angle. Depending on the chosen increase factor, the code then decreases the reached safety factor in the same way as described in section 4.3.2. The real safety factor for the subsection is then saved in a new column in the CSV files. In the cases where a subsection from section 52/640 has no line loads, there is a column that has the text "No load".

4.5.3 Automated Calculation of Section 52/640

Firstly, in order to validate that the developed codes generates numerical models that behave in the same way as the manual Plaxis analysis, the main sections automated results are inspected. The failure mechanism for the main section 0/936 can be seen in figure 4.16. It can be seen that it is located at the same place as in the manual analysis, see figure 4.4. Table 4.2 contains the safety factors from the different analyses performed of the main section. It can be seen that the results varies with +3.2% respectively -9.7% from the original calculation in Slope/w in GÄU. The automated Plaxis analysis results in a safety factor of 1.14. The manual models in Plaxis were refined 6 times at the slope, and therefore the same refinement was done on the automated Plaxis analysis of the main sections as well. The main section 0/936 resulted in a lower safety factor of 1.12 when refined, as seen in table 4.2.

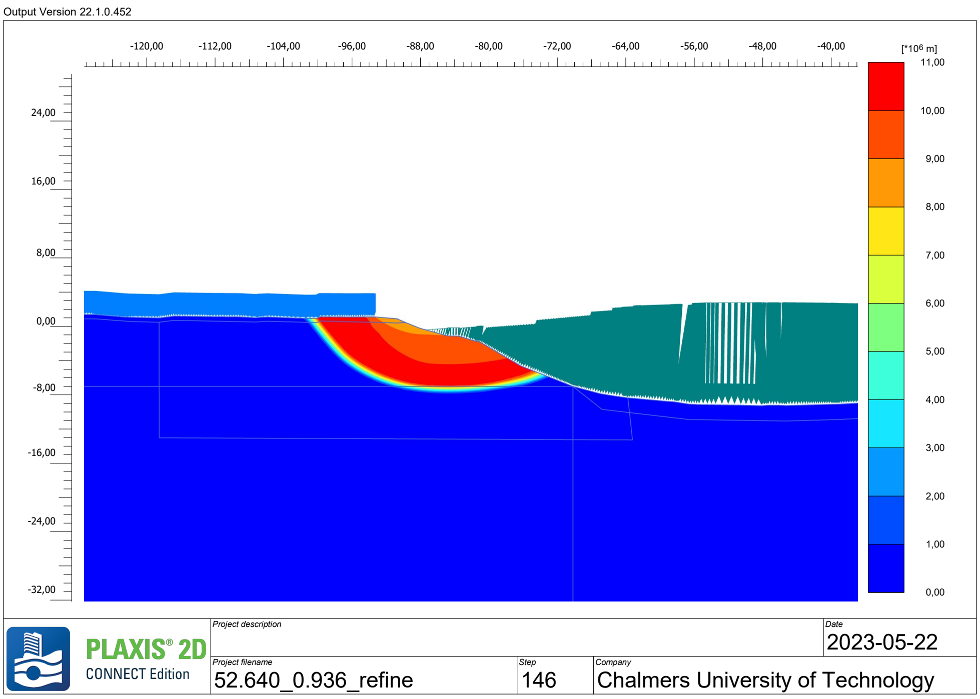


Figure 4.16: Total displacement for main section 0/936 in the refined automated analysis. Safety factor=1.12.

Table 4.2: Safety factor difference from Slope/w to Plaxis for section 52/640.

Analysis type	**SF for 52/640**	**Percentage diff. from GÄU SF**
Slope/w analysis in GÄU	1.24	-
Updated Slope/w analysis	1.28	+3.2%
Manual Plaxis analysis	1.18	-4.9%
Manual refined Plaxis analysis	1.17	-5.6%
Automated Plaxis analysis	1.14	-8.1%
Automated refined Plaxis analysis	1.12	-9.7%

Figure 4.17 show how the safety factor for the different analyses convergence, which implies that the calculations are accurate. One important aspect, that might affect the result of the safety factor is that the topography for the automated analysis are not the same as the topography in the previous manual analyses in sections 4.1.1 and 4.3.1. The topography difference can be seen in figure 4.18 where the slope inclination is steeper for the automated analysis. This is because the topography used previously in GÄU is not the same as the one provided by SGI for the automated calculation. It can be noted that the topography differs 20 m horizontally.

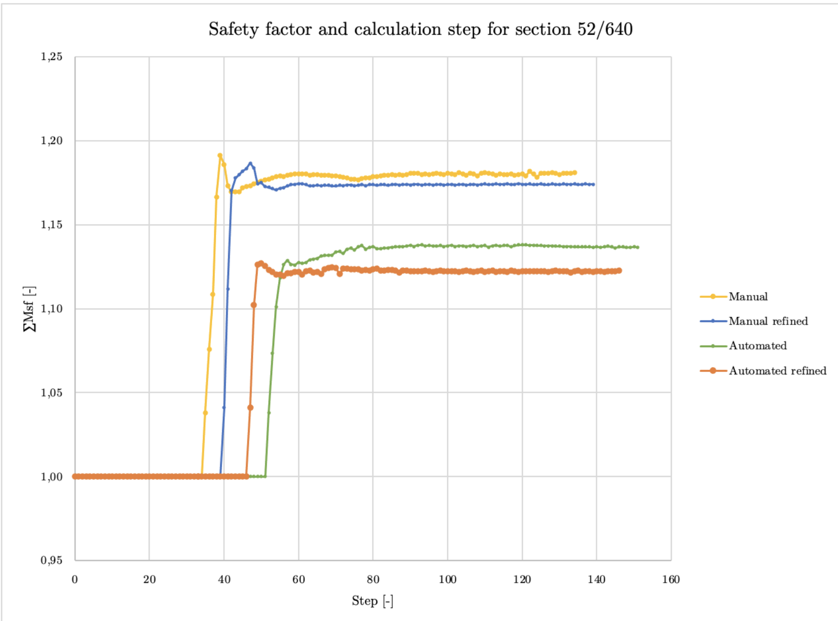


Figure 4.17: Safety factor and calculation step for manual- and automated Plaxis analyses.

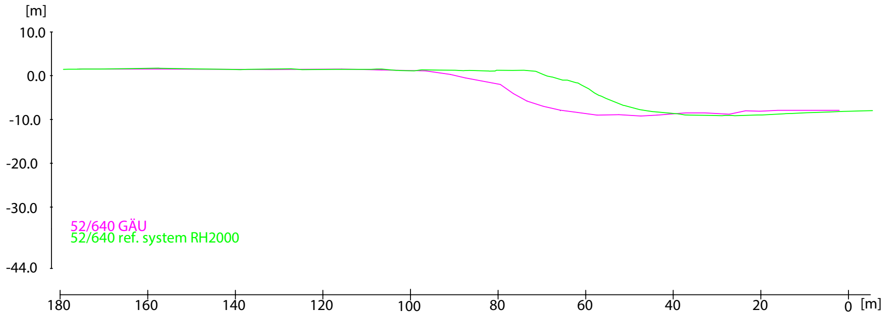


Figure 4.18: Topography difference between the automated Plaxis analysis (ref system RH 2000) and the topography from GÄU

In figure 4.19, the safety factors for each subsection is presented. It can be concluded from the figure that the safety factors converges, which again implies that the safety calculation is accurate. The resulting CSV file from the automation of Plaxis safety calculation for main section 52/640 is presented in table 4.3. As can be seen, only one subsection fails with original values of cohesion and friction angle, as a 2 can be found on Phase 2 for subsection 0/736. What this means was explained in section 4.5.2. In the Python code for section 52/640, the increasing factor was set to 10%. For some of the subsections, the railway line load caused problems in the safety calculation. Instead of the expected soil body collapse in the slope at the shoreline, the displacements and strains at the railway embankment were to high. In these cases, the railway line load was removed from the DXF file, as seen in some of the figures in appendix J. Appendix L includes critical slip surfaces in term of total displacement and deviatoric strain for all subsections.

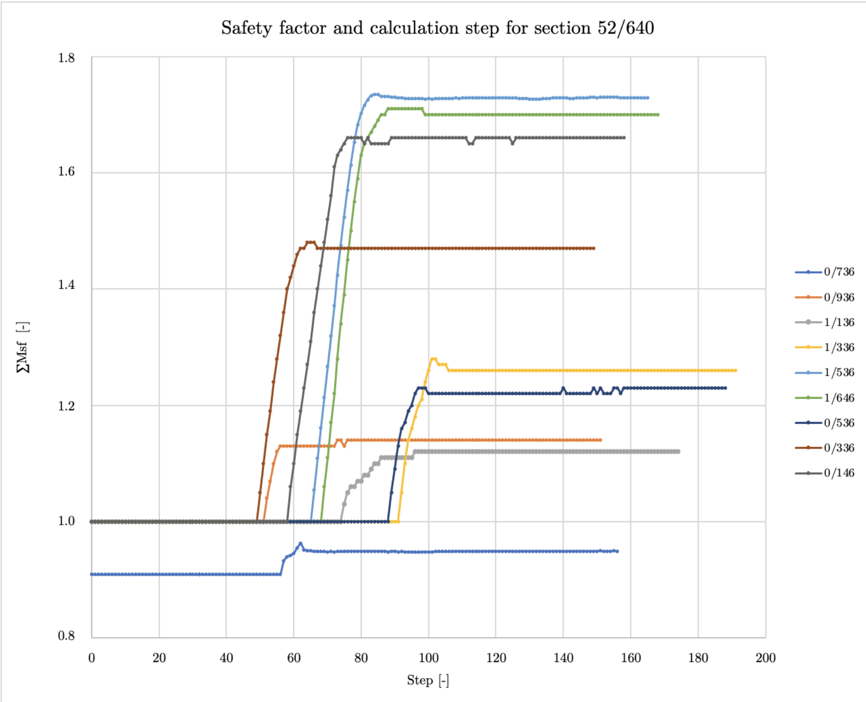


Figure 4.19: Safety factor and calculation step for all subsections for section 52/640.

Table 4.3: Safety factors and calculation results of staged construction in Plaxis for section 52/640. Main section is marked in bold.

Section	SF	InitialPhase	Phase 1	Phase 2	Phase 3	Real SF
0/146	1.66	1	1	1	No load	
0/336	1.47	1	1	1	No load	
0/536	1.23	1	1	1	1	
0/736	1.04	1	1	2	0	0.95
0/936	**1.14**	**1**	**1**	**1**	**1**	
1/136	1.12	1	1	1	1	
1/336	1.26	1	1	1	1	
1/536	1.73	1	1	1	No load	
1/646	1.70	1	1	1	No load	

One of the objectives in this project was to inspect how the safety factor might vary within an area that is subjected to one analysis in GÄU. Changes in topography for the subsections, and more specifically the variance in slope inclination, can have a affect on the safety factor. The correlation of slope inclination and safety factor for section 52/640 can be seen in figure 4.20. It can be observed that a steeper inclination results in a lower safety factor and vice versa.

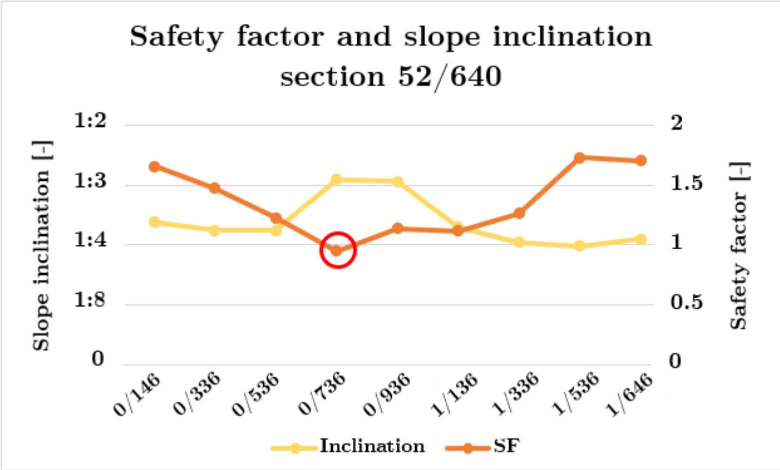


Figure 4.20: Safety factor and slope inclination for section 52/640. Subsections with 10% increased cohesion and friction angle is marked in red.

4.5.4 Automated Calculation of Section 24/150

Because there were two separate codes developed in this project, one for each main section, it is important to also validate the code for main section 24/150. When calculating the main section with the automated method, it resulted in soil collapse without increased values of phi and cohesion. The code had an increase of 20% of these parameters and when recalculating the section, the automated Plaxis analysis generates a safety factor of 1.12 for the main section 1/039. When the real safety factor is calculated as explained in section 4.3.2, the result is 0.93. The refined analysis obtains the same results of safety factor, from 0.934 to 0.931 in the refined analysis. It can be seen in figure 4.21 that the slip surface is located in the same area as for the manual Plaxis analysis, see figure 4.6. Compared to section 52/640, the percentage difference of safety factor from the Slope/w analysis in GÄU to the automated Plaxis analysis, both original and refined, only have a negligible difference of +0.5%, see table 4.4.

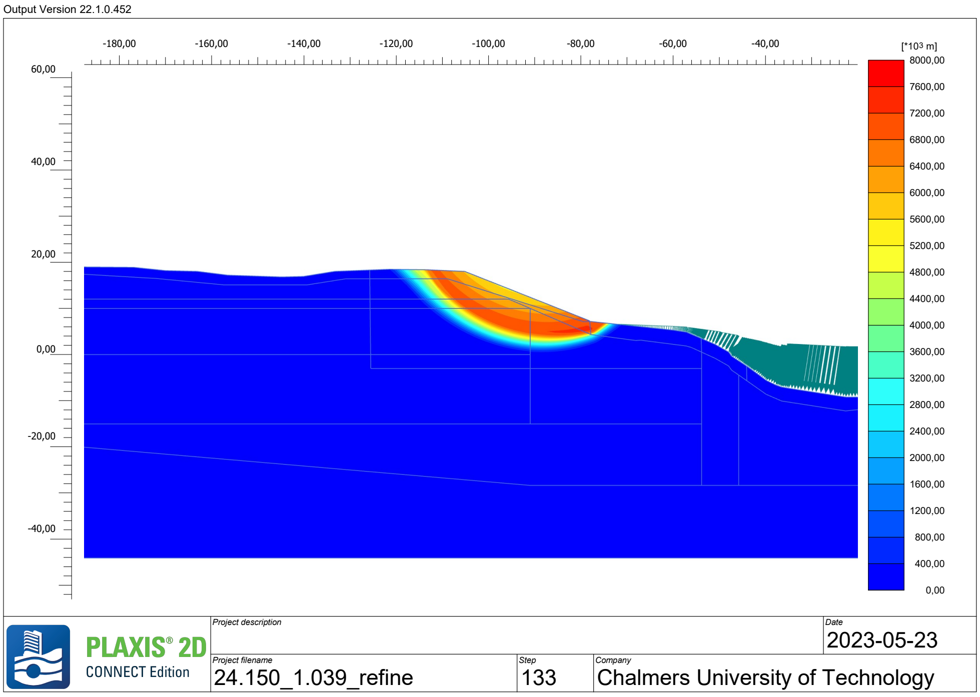


Figure 4.21: Total displacement at safety face for subsection 1/039. Safety factor=0.93.

Table 4.4: Safety factor difference from Slope/w to Plaxis for section 24/150.

Analysis type	**SF for 24/150**	**Percentage diff. from GÄU SF**
Slope/w analysis in GÄU	0.92	-
Updated Slope/w analysis	0.92	0.0%
Manual Plaxis analysis	0.97	+0.5%
Manual refined Plaxis analysis	0.97	+0.5%
Automated Plaxis analysis	0.93	+0.1%
Automated refined Plaxis analysis	0.93	+0.1%

In figure 4.22 the difference in topography between the automated and manual Plaxis analysis are presented. It can be seen that the two are similar which are reflected in the results of safety factors.

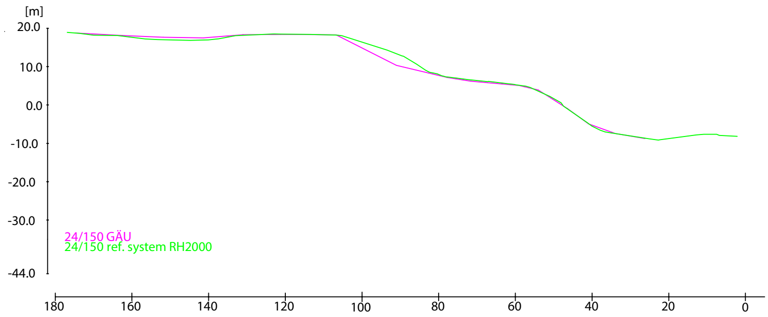


Figure 4.22: Topography difference between the automated Plaxis analysis and the topography from GÄU.

The resulting CSV file from the automation of Plaxis safety calculation for the subsections to section 24/150 is presented as a table in table 4.5. As can be seen, 4 subsections fails with resulting real safety factors < 1. The code recalculates these sections with increased values for friction angle and cohesion with 20%. This resulted in new values of safety factors, > 1, which could be back-calculated to the real safety factors presented in the last column of the table. For some of the sections, for example, 2/039 and 2/239, unexpected slip surfaces firstly occurred. These slip surfaces happened to appear at small slopes approximately 800 m from the shoreline. It is reasonable that Plaxis calculated slip surfaces here because it is the location of Slumpån, mentioned in section 4.1.2. These two sections were cropped, because it is the factor of safety in the slope towards Göta River that is of interest in this project. Furthermore it was a problem in some subsections that the topography far away from the shoreline was the location of the critical slip surface. In these cases, the topography was at the location of the irrelevant critical slip, an example can be seen for subsection 1/838 in the difference from the DXF file in appendix K. Appendix M includes critical slip surfaces in term of total displacement and deviatoric strain. It can be seen that the size of the slip surfaces varies both in depth and width, compared to the main section.

Table 4.5: Safety factor difference from Slope/w to Plaxis for section 24/150. Main section is marked in bold.

Section	SF	InitialPhase	Phase 1	Phase 2	Real SF
0/004	1.36	1	1	1	
0/244	1.43	1	1	1	
0/443	1.50	1	1	1	
0/642	1.76	1	1	1	
0/840	1.48	1	1	1	
1/039	**1.12**	**2**	**0**	**0**	**0.93**
1/238	1.02	2	0	0	0.85
1/437	1.02	2	0	0	0.85
1/637	1.15	2	0	0	0.96
1/838	2.28	1	1	1	
2/039	2.43	1	1	1	
2/239	1.56	1	1	1	
2/359	2.03	1	1	1	

The change in safety factor depending on the change in slope inclination, as presented for section 52/640, are also derived for this section. The correlation of slope inclination and safety factor for section 24/150 can be seen in figure 4.23. It can also for this section be observed that a steeper inclination results in a lower safety factor and vice versa.

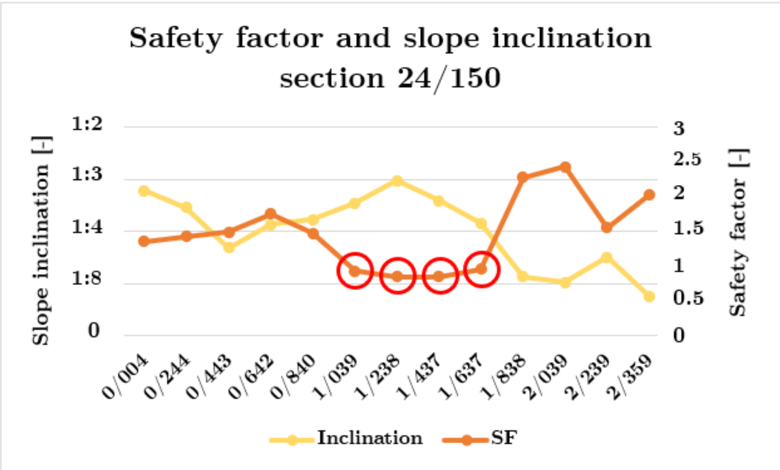


Figure 4.23: Safety factor and slope inclination for section 24/150. Subsections with 20% increased cohesion and friction angle is marked in red.

Chapter 5 – Discussion

This section will discuss the results in relation to the aims and objectives of this project. The discussion begins with a comparison of the theory and reached results for the manual Slope/w and Plaxis analyses, which lays the ground for the further discussion of the automated Plaxis results. A first important note is that despite this project's focus on reality-based slope stability investigations in GÄU, the aim was never to imitate reality. This project's main purpose was to develop and test a Python code that can be used to automate slope stability analysis in Plaxis, and the GÄU investigation is just used to compare the results with. Hence, the simplifications and assumptions that have been made throughout the analyses are not making the results less accurate for the purpose.

5.1 Limit Equilibrium Methods vs. Finite Element Methods for Slope Stability Analysis

A fundamental part of this project was to understand the differences and similarities between limit equilibrium- and finite element methods for slope stability analysis. The major difference is the search for the critical slip surface and the calculation of the safety factor. Limit equilibrium methods, such as Slope/w, tries different positions of a circular surface that assumes that the shear strength is fully mobilised along the whole slip, where the most critical slip surface corresponds to the lowest safety factor. This is in contrast to finite element methods for slope stability in Plaxis, that calculates a global safety factor by reducing the friction angle and cohesion until failure, after which the safety factor is calculated through the relationship of how much the parameters are reduced from the initial state until failure. The advantage of finding the most critical slip surface in Plaxis compared to Slope/w is that the entry and exit, or grid and radius, for the slip surface, cannot be predefined by the user. Instead, the program calculates the most critical one for the whole section. Even if this can be fortunate for cases where it is not obvious where the critical slip will appear, this can also be problematic when critical slip surfaces are found at the wrong locations instead of an expected one. This problem was encountered for some of the analyses in this project, where slips were found at small slopes far from the Göta River shoreline. When these irrelevant slopes were found, the subsection in question were cut shorter, have some modification in the topography, or be calculated without certain line loads. If Plaxis would have offered the opportunity to see several possible slip surfaces, and not only the critical, these modifications to the models would not have to be done. For future research, it would therefore be interesting to test the Plaxis Limit equilibrium converter tool mentioned previously in this report. This would also enable the user to see the stress-strain relationships in Slope/w analyses, which is a functionality that's missing in Slope/w today. The stress-strain relationship in Plaxis results in more realistic stress situations in the soil, where deformations and/or strains along the whole slip surface can be established. Furthermore it has been shown in the theory that this relationship also would generate more accurate safety factors, but this is nothing that can be concluded from this project.

Even if the results of this project propose that Plaxis can be used as an optional software in slope stability analysis in addition to or instead of Slope/w, there is a major drawback in the program that it doesn't provide a clear solution for performing combined analysis. While combined analysis is a requirement in Swedish standards, there is no definite and clear directive of performing slope stability analyses around the world. Slope/w is feasible to use in combined analyses because it is predefined in the software. In Plaxis, the best practice to perform a combined analysis is to carefully define the geometry so that the boundary between drained- and undrained governance is correct. This was also discussed by SGI in the slope stability calculation guideline, but was also highlighted as a complicated modelling. The possibility of conducting a combined analysis in Plaxis was not thoroughly investigated in this project.

When comparing the two softwares one should have in mind that the main purposes of Slope/w and Plaxis are not the same. Slope/w is a slope stability software based on limit equilibrium methods, originating from hand calculations of simple problems, while Plaxis adopts comprehensive finite element methods to analyse complex problems that cannot be understood without computational help. Traditionally in Sweden, Slope/w is used to calculate safety factors and determine slope stability. Plaxis also holds the ability to investigate the stability of slopes but can also be used to investigate the soil response to stresses in the form of for example deformations and pore water pressure, and can handle complex reinforcement structures. As SGI stated in the guideline for slope stability calculations, numerical analysis such as Plaxis is more suitable for complex cases. Future scenarios of increased erosion and changed pore water pressure conditions due to climate change can make geotechnical modelling more challenging, and more complex cases in slope stability modelling might appear. In this scenario, Plaxis can become more relevant to use for slope stability analysis which also supports this project's investigations.

5.1.1 Soil Models and Parameters

In Slope/w, the material models are based upon the Mohr-Coulomb theory whereas Plaxis offers several different soil models, with different complexity, based on various computational theories. This means that in Plaxis, not only the Mohr-Coulomb theory is offered for the definition of material properties, and the user must understand how to use the different soil models in order to generate realistic stresses and strains. This indirectly means that the user must be aware of each soil model's principles and what impact a specific parameter has on the result. This is also important in Slope/w but because the material models are more intuitive, there is less room for major errors. For this project, only the Mohr-Coulomb soil model (and Linear-elastic for the added bedrock in section 24/150) was used in Plaxis because the principles of a safety calculation, phi-c reduction, only come down to Mohr-Coulomb principles. However, Plaxis requires more input data for the materials to be valid, like elasticity modulus, which does not affect the safety factor, but must be inserted in order to run a calculation. The fact that the user must insert some- and can insert additional soil properties, the material definition can be more complicated than necessary for some calculations. The user must be aware of which parameters are of interest for the specific calculation, which in contrast is more evident in Slope/w.

The fact that Slope/w offers a wide selection of modified Mohr-Coulomb-based material models becomes advantageous in slope stability analyses, specifically for natural slopes such as those at the Göta River. For materials at the slope with increased cohesion with depth, the S=f(depth) material model in Slope/w is a great practice. This material model is created to account for the varied elevation of the top of the soil layer in the slope for the definition of the increased cohesion. As the elevation of the top of the layer changes, the elevation from which the increased cohesion starts subsequently changes as well. When performing the analyses in Plaxis this is not possible in the same intuitive way, and therefore an assumption that the average value of cohesion is a good enough approximation to use for these materials was made. No immediate influence of this assumption can be seen in the results, but this assumption of constant cohesion can lead to deeper slip surfaces. Most probably the layer of the riverbed in section 24/150 where this assumption was made is too thin to see this behaviour. in addition to this, the riverbed in section 52/640, the Undrained(phi=0) material model was used in GÄU, with constant cohesion, which indicates that the assumption made for section 24/150 in this project is reasonable. Except for the assumption required to model the riverbed in Plaxis, not many parameters differ between the Slope/w analyses and Plaxis analyses. Some other assumptions that was done, without affecting the safety calculation, was that the unsaturated unit weight from the Slpoe/w analyses was used as both unsaturated and saturated unit weight in Plaxis but also that the cohesion in the drained materials was set to 0 kPa because this is what is done in Slope/w even if the material models doesn't contain this parameter.

5.2 Safety Factor Difference for the Main Sections

Following the differences between Slope/w and Plaxis discussed above, it was expected to find differences also in the out-coming safety factors. The safety factor difference was observed not only between the softwares, but also between modelling options in each software. The theory that Slope/w generally calculates higher safety factors than Plaxis was seen in the analyses of section 52/640, where the difference from GÄU to the refined automated analysis was approximately 10%. Furthermore, it was also noted that the optimized slip surface option in Slope/w gave a lower safety factor than using a perfectly circular slip surface, which was also expected according to the theory. Refinement of the mesh at the slope in the Plaxis analyses also leads to lower safety factors than in the unrefined versions. It is explained that the difference of 10% of safety factors between the GÄU and automated Plaxis analysis was due to the 20 m horizontal topography difference between the automated analysis and GÄU. This difference is not reasonable as the elevation measurement is done in the same location, and this implies that either one of the measurements, or both, are incorrect. As long as this difference is accounted for in the evaluation, the automated method results can still be compared to the manual results. The safety factor obtained in the manual Plaxis analysis of section 24/150 was higher than the safety factor obtained in the Slope/w analyses. However, the automated Plaxis analyses resulted in safety factors just 0.5% larger than in GÄU. The percentage difference of safety factors for this section is notably lower than for section 52/640. This would be explained by the fact that the topography and slope inclination difference from GÄU to the automated analysis for section 24/150 is negligible. With this in mind, the results of section 24/150 can confirm that Plaxis can be used for slope stability analyses, and that the Python code can also be used to model sections in Plaxis and get appropriate results. It is important to note that when comparing the safety factors generated in the analyses in this project, with the safety factors obtained in GÄU, this is not done with the assumption that the GÄU safety factor is accurate. However, for the purpose of this project, it was convenient to have a reference point from an approved Swedish analysis to compare the results to. Though the analyses in GÄU are approved it can be debated whether or not Slope/w is the best representation of the real slope stability. The results in GÄU for section 24/150 suggests a safety factor < 1, which would indicate a failure, but with reality in mind, instability is not the case in this area of Göta River. This would indicate faulty input data rather than incorrect calculations in Slope/w. However, these possible errors are not discussed further in this project, and the GÄU analyses are only used as an appropriate reference point. Moreover it should be noted that this is a relevant discussion also for the safety factors obtained in Plaxis. The focus in this project are not if the results are realistic or not, but instead on the comparison between the methods. The comparison could as well have been made between the automated Plaxis analysis and the updated Slope/w analysis as the updated analysis is more alike the Swedish standards today. However, some simplifications are done to the updated models and therefore the comparison is made with the original GÄU analyses. In general, both Slope/w analyses are similar and therefore both would be appropriate to compare the automated results with. Generally in this project, it could be observed that Plaxis generated lower safety factors than Slope/w, suggesting that maybe Slope/w offers the upper bound solution, and Plaxis the lower bound solution, to the actual stability of a slope.

5.3 Automation of Plaxis Analysis

The automation of slope stability analysis in Plaxis is the main purpose of this project with the objective that this can be used as a way to investigate future scenarios and more efficiently analyse several sections at once. This section will discuss the limitations in the codes, variance in safety factor as well as the applicability of the automated method.

5.3.1 Limitations in the Codes

It is important to note that the developed scripts that are used in the automation of Plaxis analyses in this project are not universal. The scripts are developed with respect to the two chosen main sections and will need adjustment to fit another slope section. As for now, there is no general way for the script to understand the order that the soil polygons are made in and that needs to be defined by the user itself. That the code is not general lies within the limitations of this project because the main focus is on geotechnical engineering and the evaluation of how an automated method can be used for slope stability calculations. Although the scrips cannot be applied to any arbitrary case, they work immaculately for the two chosen main sections. This means that the codes are generated so that changes can be made to the DXF- and CSV files and can in that way be used to test the subsections in future scenarios of changed erosion conditions and pore water pressures etc. The purpose of this project was never to make a generic code, only to make it validated for the specific cases. There are several shortcomings in the code but due to lack of coding knowledge and time, this was not investigated further.

Another aspect of the automation is that it is important to note the fact that Plaxis can only read DXF- and CSV files in a certain way. The code requires the DXF files to be generated in a certain way in order for Plaxis to import soil polygons and line loads/waterlines correctly. Instead of manually modelling the geometries, materials, etc. in Plaxis, the focus shifts to the development of the DXF- and CSV files. As explained before, the DXF files cannot contain any polylines other than certain line loads and waterline, and regions must be made in a certain order. The material order in the CSV files must also be in the same order as the polygons are created in Plaxis. A great future development of this project would therefore be to generate a code that is not as sensitive to uniform data templates, such as DXF- and CSV files formation.

5.3.2 Safety Factor Difference for the Subsections

One of the objectives to this project was to investigate if a variance of safety factors could be observed for an area that in GÄU is subjected to the calculation of only one section. For both main sections, a slight change in safety factors could be seen with the change of topography and slope inclination along to subsections. It was observed that the steeper slope inclination, the lower safety factor, which is an expected outcome. For section 52/640, where the GÄU calculation resulted in a safety factor of 1.24 (later 1.12 in the refined automated Plaxis analysis, with the noted difference in topography from GÄU to this project), one subsection was calculated to fail when inspecting the results of the automation. This can be referred back to what was noted in the geotchnical PM for this section, which stated that the area around the Älvängen industry area was known to have low stability conditions prior to GÄU.

Throughout this project it has been noted that the resulting safety factor in Plaxis is sensitive to the change of topography. It has also been observed that the refinement of mesh at the slope has influenced the safety factor to become somewhat lower, for example in the refinement of the automated Plaxis analysis for the main section 52/640 where the safety factor changed from 1.14 to 1.12 with the refinement.

5.3.3 Applicability of the Automated Method

The Python codes developed for the automation of Plaxis analysis has previously been confirmed for this specific project. However, the application of the automated method in general is important to discuss. This project has, as noted before, only focused on the undrained analysis of slopes because this is the only feasible analysis to conduct in Plaxis. This limits the ability to claim that the developed automated method in Plaxis can be used in favour of manual Slope/w analysis because the Swedish guidelines require that a combined analysis should be conducted as well. Looking above this limitation, the developed automated method can be used to simplify the investigation of the impact of changed parameters and conditions on the slope stability: How does changed topography due to erosion, and increased pore water pressure impact the slope stability? It is a method to easily scale up, and investigate how changes in different parameters impact the slope stability for several sections at once. In this project, there were two main sections with corresponding subsections that had a spacing of 200 m, but the number of analysed sections could be increased if one wanted to look for a broader view in some aspects.

One important aspect to have in mind is that this method was not developed to decrease the work amount for the geotechnical engineer, but to ease it. When the automated calculations have been conducted the engineer still needs to analyse the results and make adjustments if needed. For example, the code in this project has no block that makes refinement of the slope, and if this is needed, the engineer still needs to investigate this manually in those specific cases. The developed automatic method is not a tool for the engineer to "only press play" and then present the result, the importance of great knowledge within geotechnology is still necessary. Just as the previous research could conclude, the use of Python coding to automate geotechnical modelling is not done to reduce the need for geotechnical engineers. Instead, an automation, of at least some parts, of slope stability analysis can make their work more effective and give more time to analyse the results. The Göta River investigation that was studied in the literature study gave the impression that large parts of the investigation are done in a repetitive way. These parts of the analysis doesn't require much knowledge from the geotechnical engineer. Even if this is a great way to learn the investigated section, it is a task that easily can be automated and leave room for a more thorough investigation of the results. For example, make a sensitivity analysis, test different erosion- and pore water conditions etc. Overall, the use of an automatic approach in slope stability analyses can only make the work more effective and the use of coding will be a natural part of all engineering branches in the future.

5.4 Future Research

Considering the limitations to apply the automated method on slope stability analysis in Sweden because only undrained analysis was investigated in this project, it would be interesting to study the possibility of conducting combined analysis in Plaxis as an extension to this project. There is no soil model or precise way of performing a combined analysis today. However, SGI has highlighted the possibility if the geometry is precisely defined. It would therefore be interesting to investigate this and from that develop a Python code that both calculates undrained and drained behaviour for the section and then combine those analyses, as a conventional combined analysis.

It was also mentioned in this project that Bentley have developed a Plaxis Limit equilibrium converter tool that creates an extension of Plaxis and Slope/w analyses. This tool was not further investigated in this project, but if it would make the connection between limit equilibrium- and finite element methods more feasible, a great combination of the advantages of both methods can be obtained.

As already mentioned, the codes developed in this project are not universal and cannot be applied on any type of case without adjustments. To investigate the possibility of making the codes more generic would therefore be interesting to be able to broad the application of the automated method. A more comprehensive code could also be used to automate calculations for modelling of geoconstructions or settlement calculations, where the engineer could be able to easily test different solutions on one section at once. Another aspect that makes the development of the code important is that the requirement on the DXF- and CSV files in this project is very strict. A possible future research is therefore to investigate machine learning in combination with geotechnical investigations. A machine learning software could be developed that reads borehole information and instead of importing geometry into Plaxis through DXF files, soil layers can be created from the boreholes. Using machine learning like this would enable to only insert borehole information, and the part of knowing exactly which order each soil polygon was modelled in AutoCAD , which is the case in this project, can be skipped. However, all these improvements to the code is a more suitable study for a programming engineer rather than a geotechnical engineer. Nonetheless, the programmer does not know which functions related to geotechnology are needed in the code, so a cooperation between a programmer and geotechnical engineers is necessary.

Chapter 6 – Conclusion

In conclusion, this project has focused on comparing the results obtained from manual slope stability analysis using Slope/w and Plaxis with the automated Plaxis analysis. The aim of the project was not to replicate reality but to develop and test a Python code for automating slope stability analysis in Plaxis. The simplifications and assumptions made in the analysis do not compromise the accuracy of the results for the intended purpose.

A fundamental difference between Slope/w and Plaxis lies in how they determine the critical slip surface and calculate the safety factor. Limit equilibrium methods assume fully mobilized shear strength along a circular slip surface, while Plaxis calculates a global safety factor by reducing friction angle and cohesion until failure. Plaxis offers the advantage of determining the most critical slip surface automatically, but it can also result in finding irrelevant slip surfaces. Further research could explore tools like the Plaxis Limit equilibrium converter to address this limitation. While Slope/w is commonly used in Sweden for slope stability analysis, Plaxis offers more comprehensive capabilities, including analyzing complex cases and investigating soil response to stresses and deformations. The selection of soil models and parameters differs between the two software, with Plaxis providing more options and complexities. Slope/w's intuitive material models, such as the S=f(depth) model, prove advantageous for natural slopes like those along the Göta River. Plaxis requires more input data and understanding of different soil models, making material definition potentially more complicated.

The comparison of safety factors between Slope/w and Plaxis revealed differences not only between the softwares but also among modelling options within each software. Generally, Slope/w calculated higher safety factors than Plaxis, suggesting that Slope/w may provide the upper bound solution while Plaxis offers the lower bound solution to slope stability. However, the safety factors obtained from the analyses in this project are not assumed to be accurate representations of reality but rather serve as a reference point for comparison. The automated Plaxis analysis demonstrated slight variations in safety factors among subsections within an area represented by a single section in GÄU. Steeper slope inclinations resulted in lower safety factors, which aligns with expectations. It is important to note that the safety factors obtained from the automated analysis should be interpreted with caution due to the assumptions and simplifications made.

The automation of Plaxis analysis was a key objective of this project, aiming to enable efficient analysis of multiple sections and investigation of future scenarios. The developed scripts are specific to the chosen main sections and require adjustments for other slope sections. The codes work effectively for the selected sections but are not universally applicable. They depend on specific formatting of DXF- and CSV files for Plaxis import, which may limit their flexibility. Future development could focus on making the code less sensitive to file formation.

In summary, the automated Plaxis analysis code developed in this project provides a useful tool for slope stability analysis, but it has limitations and requires customisation for different sections. Plaxis offers advantages over Slope/w in handling complex cases and capturing soil response, while Slope/w remains practical for combined analyses and intuitive material modelling. The comparison of safety factors suggests that Slope/w may provide higher safety factors than Plaxis. Overall, the project contributes to the understanding of slope stability analysis methods and highlights areas for further research and improvement. From this project it can be concluded that Plaxis can be controlled through Python code, and the possibilities this entails are endless.

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Appendix A – Stiffness Modulus for Undrained Materials

The elasticity modulus under undrained conditions can be determined with the equations below (Karlsson & Moritz, 2014). Factor 500 is for low plasticity clay, 250 for high plasticity clay and muddy clay, and 150 for mud. The undrained B drainage type in Plaxis uses E'_{50}, but because the stiffness doesn't influence the safety calculation, E_{50} is used instead.

$$E_{50} = 500 \cdot c_u \qquad E_{50} = 250 \cdot c_u \qquad E_{50} = 150 \cdot c_u$$

Appendix B – Stiffness Modulus for Drained Materials

Characteristic values of frictional angles for different materials (Karlsson & Moritz, 2016):

Material/Jordart	Friktionsvinkel °	
	Löst lagrad[2]	Fast lagrad[1, 2]
Förstärkningslagermaterial	-	45
Makadamballast	-	42
Underballast	-	45
Grovkrossad sprängsten	-	45
Sorterad sprängsten	-	45
Sprängsten	-	45
Grovkornig mineraljord	30	37
Grus	30	37
Grusig morän	38	45
Sand	28	35
Sandig morän	35	42
Silt	26	33
Siltig morän	33	40
[1]Fyllningsmaterial som packats enligt AMA 13 kan förutsättas vara fast lagrad. [2]Lagringstäthet kan beskrivas med resultat från fältundersökningar enligt Figur 5.2-9 i TR Geo 13.		

Characteristic values of stiffness modulus for different materials (Karlsson & Moritz, 2016):

Material/Jordart	Elasticitetsmodul, MPa	
	Löst lagrad[2]	Fast lagrad[1, 2]
Förstärkningslagermaterial	-	50
Makadamballast	-	50
Underballast	-	50
Krossad sprängsten	-	50
Sorterad sprängsten	-	50
Sprängsten	-	50
Grovkornig mineraljord	10	30
Grus	10	40
Grusig morän	10	40
Sand	5	20
Sandig morän	5	20
Silt	2	10
Siltig morän	2	10
[1]Fyllningsmaterial som packats enligt AMA 13 kan förutsättas vara fast lagrad. [2]Lagringstäthet kan beskrivas med resultat från fältundersökningar enligt Figur 5.2-9 i TR Geo 13.		

Appendix C – Material Properties Section 52/640

Slope/w input values for section 52/640

Soil type	**Le1**	**Le2**	**Le Älv**	**Gyttja**	**Fyllning**	**Bank-fyllning**
Material model	S= f(datum)	S= f(datum)	S= f(datum)	Undrained (Phi=0)	Mohr-Coulomb	Mohr-Coulomb
Unit weight $[kN/m^3]$	15	15	15	14	20	20
Unsaturated unit weight $[kN/m^3]$	-	-	-	-	18	18
c $[kPa]$	7	11	11	5	-	-
c_{inc} $[kPa/m]$	0.5	1.46	1.6	-	-	-
Elevation $[m]$	1	-7	-8	-	-	-
$\phi\prime$ [°]	-	-	-	-	35	37

Plaxis input values for section 52/640

Soil type	**Le1**	**Le2**	**Le Älv**	**Gyttja**	**Fyllning**	**Bank-fyllning**
Material model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Drainage type	Undrained B	Undrained B	Undrained B	Undrained B	Drained	Drained
Unsaturated unit weight $[kN/m^3]$	15	15	15	14	18	18
Saturated unit weight $[kN/m^3]$	15	15	15	14	20	20
c $[kPa]$	7	11	11	5	-	-
c_{inc} $[kPa/m]$	0.5	1.46	1.6	-	-	-
E' $[kPa]$	3500	5500	5500	750	20 000	35 000
E'_{inc} $[kPa/m]$	250	730	800	-	-	-
Elevation $[m]$	1	-7	-8	-	-	-
ϕ' [°]	-	-	-	-	35	37

Appendix D – Material Properties Section 24/150

Slope/w input values for section 24/150

Soil type	**Si**	**Cl1**	**Cl2**	**Cl3**	**Cl4**	**Cl5**	**ClGÄ1**	**ClGÄ2**	**ClGÄ3**
Material model	Mohr-Coulomb	S= f(datum)	S= f(depth)	S= f(datum)	S= f(datum)	S= f(datum)	S= f(depth)	S= f(datum)	S= f(datum)
Unit weight $[kN/m^3]$	18	16.6	17.4	16.5	17	17.4	15	16.5	16.5
c $[kPa]$	0	23.5	26.5	19	19	22	5	25	28
c_{inc} $[kPa/m]$	-	1.5	1.5	1.5	1.5	2	6.7	1.6	1.8
Elevation $[m]$	-	12	-	15	15	6	-	1	-5
ϕ' [°]	28	-	-	-	-	-	-	-	-

Plaxis input values for section 24/150

Soil type	**Si**	**Le1**	**Le2**	**Le3**	**Le4**	**Le5**	**Le Älv1**	**Le Älv2**	**Le Älv3**
Material model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Drainage type	Drained	Undrained B	Undrained B	Undrained B	Undrained B	Undrained B	Undrained B	Undrained B	Undrained B
Unsaturated unit weight $[kN/m^3]$	18	16.6	17.4	16.5	17	17.4	15	16.5	16.5
Saturated unit weight $[kN/m^3]$	18	16.6	17.4	16.5	17	17.4	15	16.5	16.5
c $[kPa]$	0	23.5	26.5	19	19	22	12.55	25	28
c_{inc} $[kPa/m]$	0	1.5	1.5	1.5	1.5	2	0	1.6	1.8
E' $[kPa]$	6000	11 750	13 250	9500	9500	11 000	2500	12 500	14 000
E'_{inc} $[kPa/m]$	-	750	750	750	750	1000	3350	800	900
Elevation $[m]$		12	10	15	15	9/7.5	-	0/4/1	-5
ϕ' [°]	28	0	0	0	0	0	0	0	0
c *** 20%**	-	28.2	29.15	20.9	20.9	24.2	5.5	27.5	30.8
c_{inc} *** 20%**	-	1.8	1.65	1.65	1.65	2.2	7.37	1.76	1.98
ϕ' *** 20%** [°]	30.32	-	-	-	-	-	-	-	-

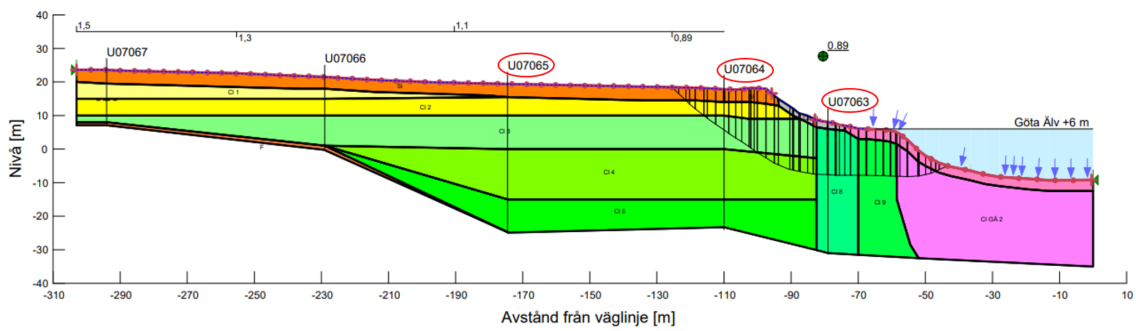
Appendix E – Pore Water Pressure Section 24/150

Pore water pressure measured from boreholes in section 23/910, used for section 24/150:

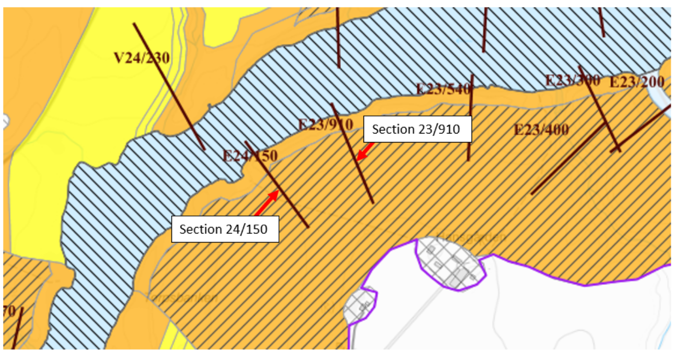
Tabell 54 Uppmätta maxvärden på portrycket i sektionen E23/910

U07063		U07064		U07065	
Djup (m)	Maxvärde (kPa)	Djup (m)	Maxvärde (kPa)	Djup (m)	Maxvärde (kPa)
3	28	4	21	4	30
8	68	8	52	8	63
15	143	15	101	30	218
30	295	30	223		

Location of boreholes (marked in red) in section 23/910:

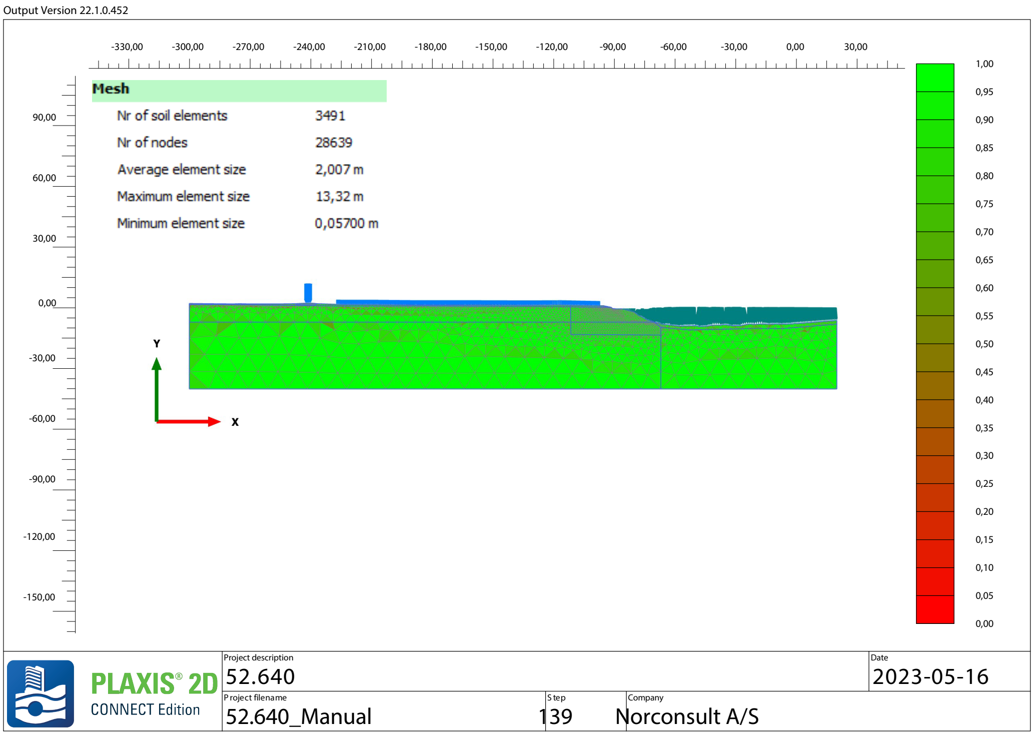


Location of section 23/910 in relation to section 24/150, 240 m apart:

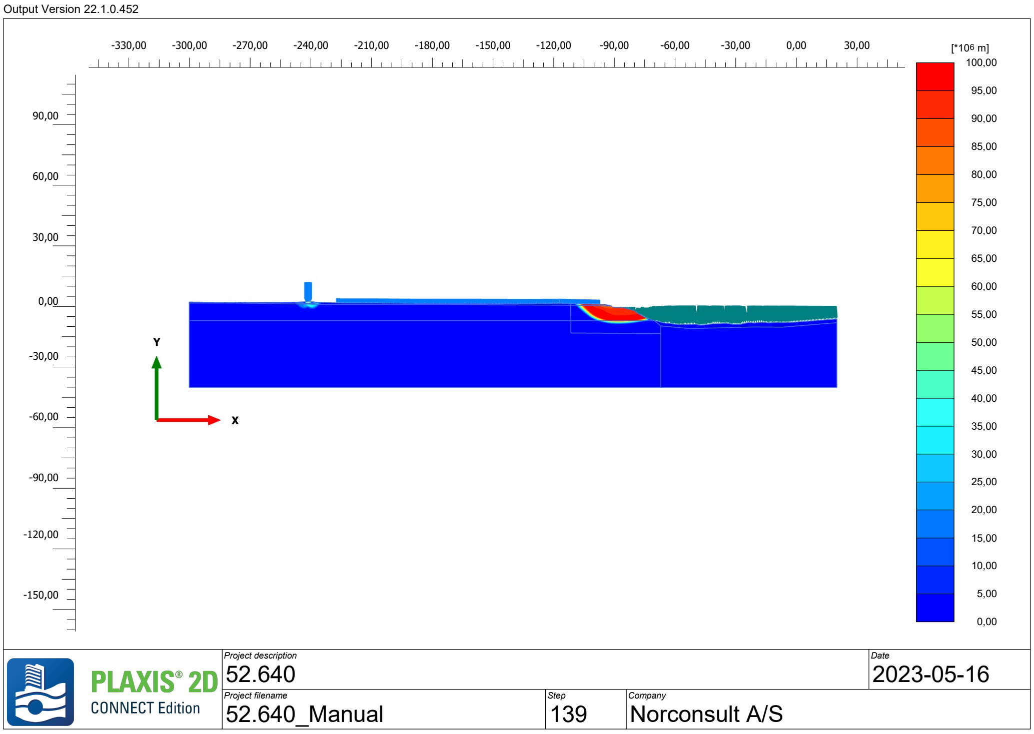


Appendix F – Manual Plaxis Analysis Section 52/640

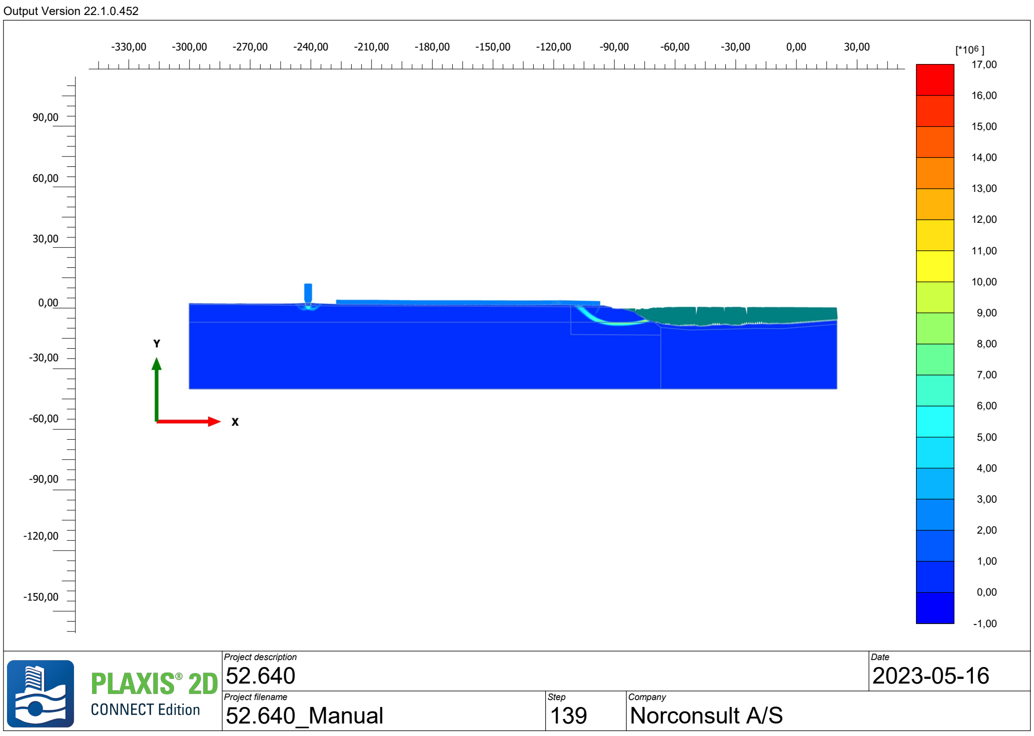
Mesh quality:



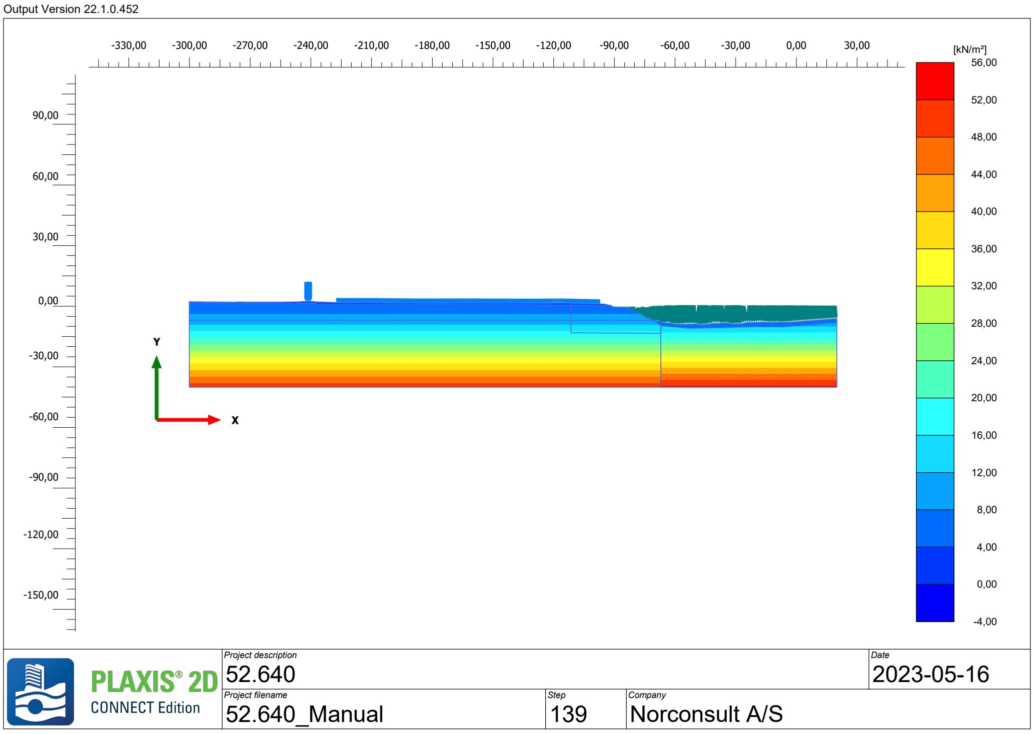
Total displacement:



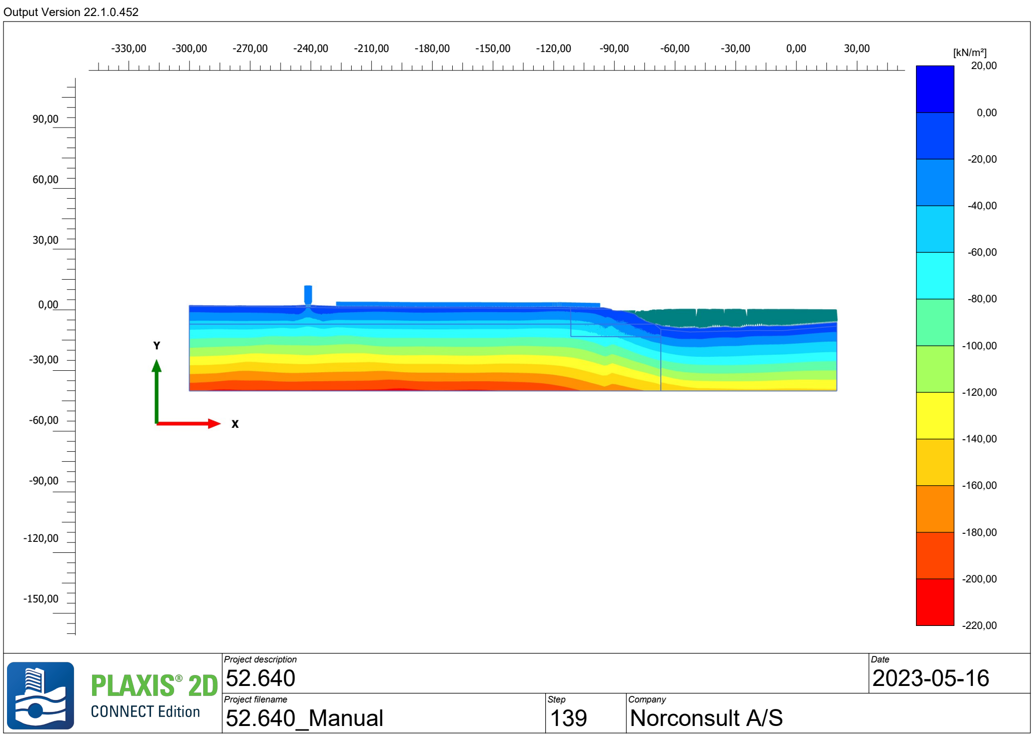
Deviatoric strain:



Cohesion:

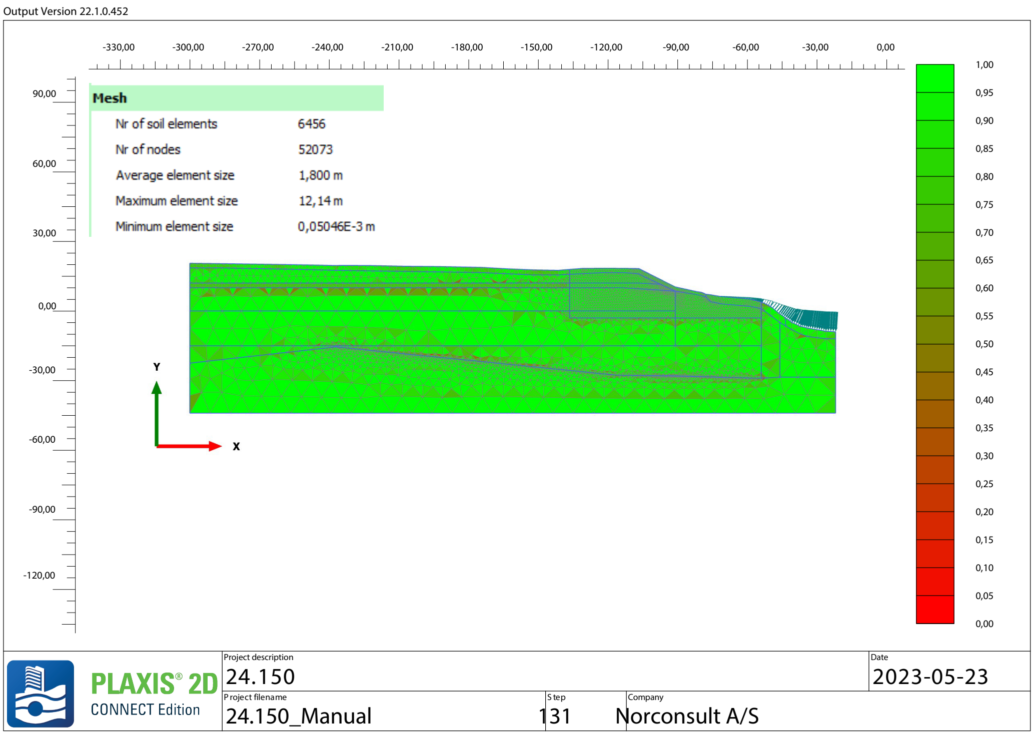


Vertical effective stress:

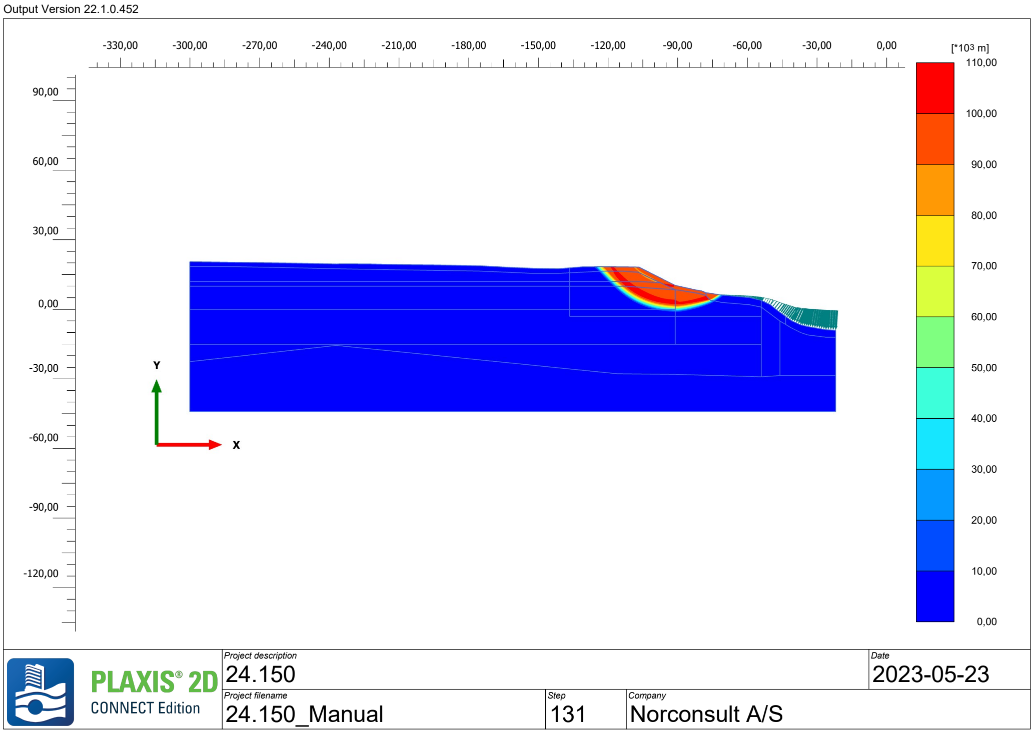


Appendix G – Manual Plaxis Analysis Section 24.150

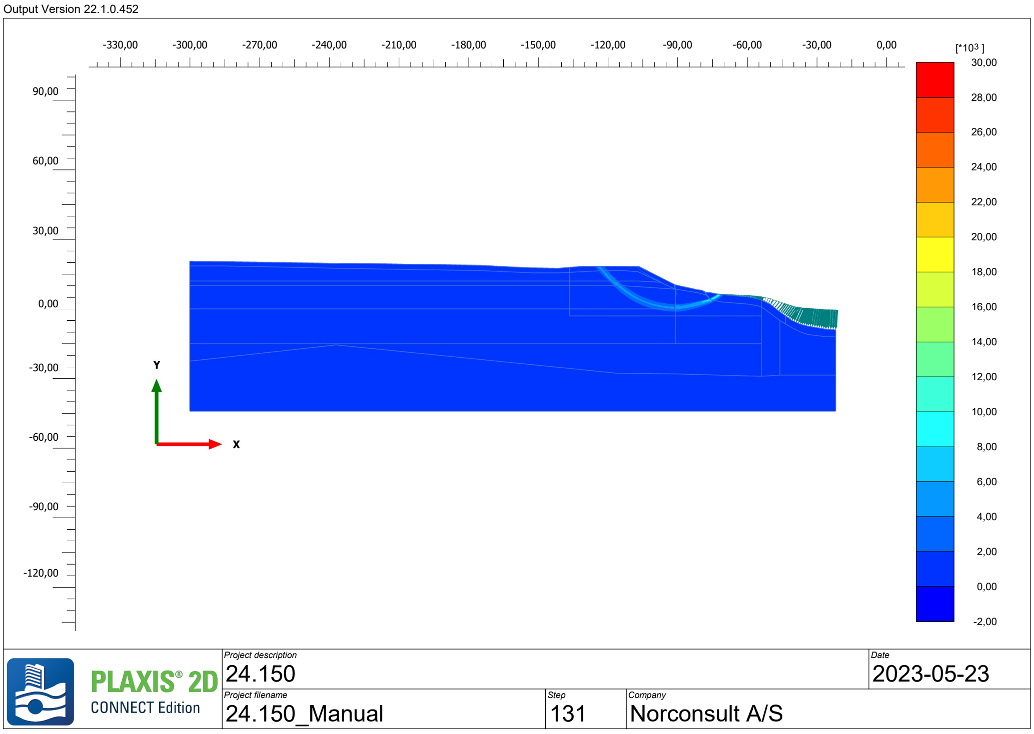
Mesh:



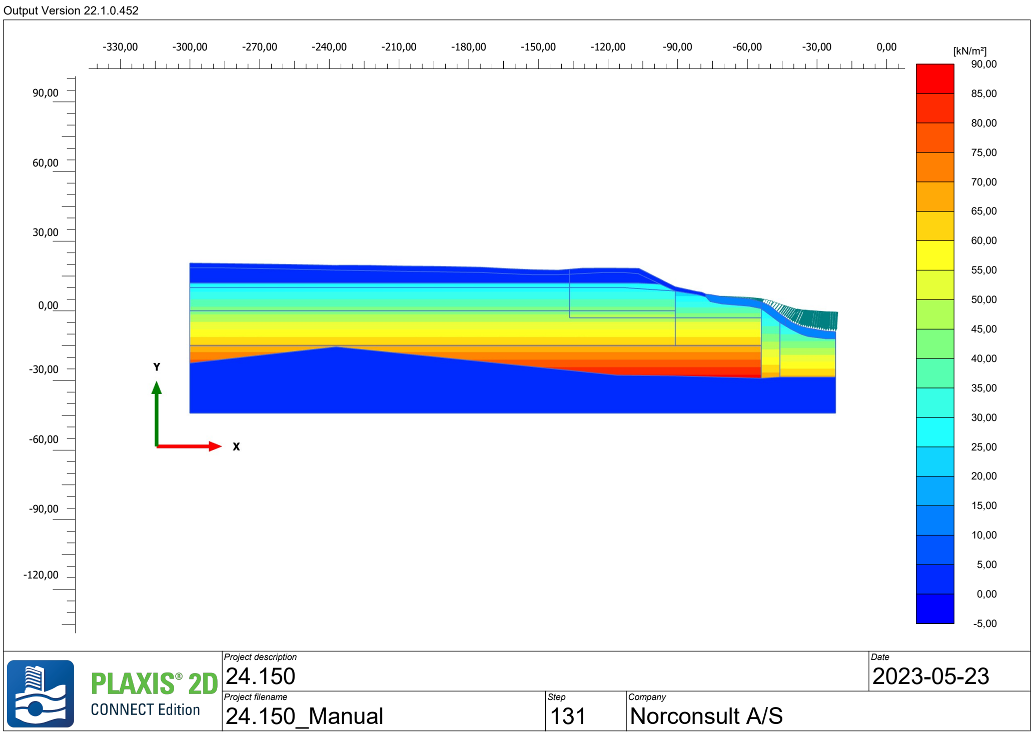
Total displacements:



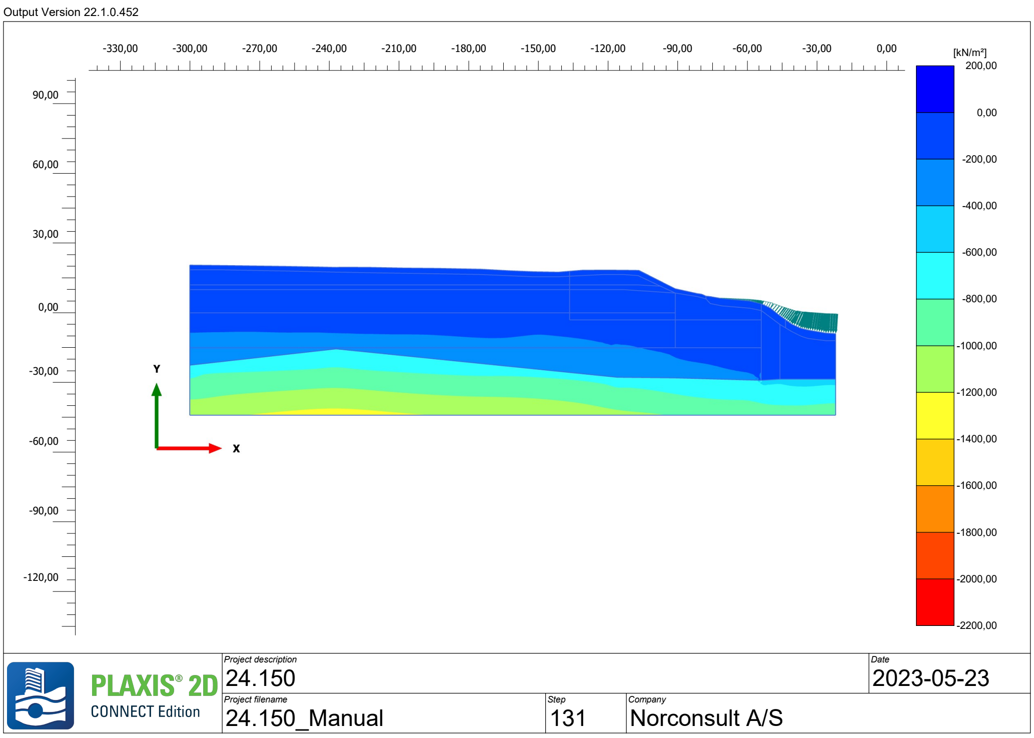
Deviatoric strain:



Cohesion:



Vertical effective stress:



Appendix H – Python Code Section 52/640

Python code section 52/640

Import required packages:

In [ ]:
```
from plxscripting.easy import *
import subprocess, time
import pandas as pd
import ezdxf
import ast
import openpyxl
import os
import win32gui
import win32con
import numpy as np
import xlrd
```

Define folder path and connect the code to Plaxis:

In [ ]:
```
folder_path = r'your_full_folder_path'
#Extract files with .dxf only
file_names = [f for f in os.listdir(folder_path) if f.endswith('.dxf')]

#For-loop that loops over each DXF file
for file_name in file_names:
 file_path = os.path.join(folder_path, file_name)
 dxf_filename = os.path.splitext(os.path.basename(file_path))[0]
 PLAXIS_PATH = r'C:\Program Files\Bentley\Geotechnical\PLAXIS 2D CONNECT Edition V22\
 PORT_i = 10000
 PORT_o = 10001
 PASSWORD = 'SxDBR<TYKRAX834~'
 subprocess.Popen([PLAXIS_PATH, f'--AppServerPassword={PASSWORD}', f'--AppServerPort={
 time.sleep(5)
 s_i, g_i = new_server('localhost', PORT_i, password=PASSWORD)
 s_o, g_o = new_server('localhost', PORT_o, password=PASSWORD)
 s_i.new()
```

Import geometry:

In [ ]:
```
 g_i.gotostructures()
 #Import polylines and regions
 g_i.import_("lines|polygons", file_path, 1, 1, 0, 0)
```

Create materials and assign to corresponding soil layer:

In [ ]:
```
 material = pd.read_csv(".\\SoilProperties_52640.csv", sep=";")

 for i in range(len(material)):
     name = material.iloc[i,1]
     soilmodel = material.iloc[i,2]
     drainagetype = material.iloc[i,3]
     gammaUnsat= material.iloc[i,4]
     gammaSat= material.iloc[i,5]
```

```
    ERef=material.iloc[i,6]
    EInc = material.iloc[i,7]
    verticalref = material.iloc[i,8]
    cref=material.iloc[i,9]
    cinc = material.iloc[i,10]
    phi = material.iloc[i,11]

    if drainagetype == "Drained":
        material1 = g_i.soilmat()
        material1.setproperties(
            "Identification",name,
            "SoilModel",soilmodel,
            "DrainageType", drainagetype,
            "gammaUnsat", gammaUnsat,
            "gammaSat", gammaSat,
            "Eref",ERef,
            "Phi", phi
    )

    if drainagetype == "Undrained B":
        material1 = g_i.soilmat()
        material1.setproperties(
            "Identification",name,
            "SoilModel",soilmodel,
            "DrainageType", drainagetype,
            "gammaUnsat", gammaUnsat,
            "gammaSat", gammaSat,
            "Eref",ERef,
            "EInc",EInc,
            "verticalRef",verticalref,
            "cref", cref,
            "cInc",cinc,
    )

soilmat=[mat for mat in g_i.Materials[:] if mat.TypeName.value == 'SoilMat']
#Define this list from the order of the regions generation in AutoCAD
soil_map = {0: 'Le1', 1: 'Le2', 2: 'LeÄlv', 3: 'Gyttja', 4: 'Fyllning',
            5: 'BankFyllning'}

#Assign materials to corresponding soil layer
for j in range(len(soil_map)):
    for i in range(len(soilmat)):
       if soil_map[j] == soilmat[i].Name:
            g_i.Soils[j].setmaterial(soilmat[i])
```

Define lineloads from AutoCAD polylines:

In [ ]:
```
doc = ezdxf.readfile(file_path)
msp = doc.modelspace()

has_lwpolyline = False #Check if the dxf-file has polylines
for ent in doc.entitydb.values():
    if ent.dxftype() == 'LWPOLYLINE':
        has_lwpolyline = True
        break

if has_lwpolyline: #If polylines: define lineloads
    Lineloads = []
    for e in msp.query('LWPOLYLINE'):
```

```
        layer_name = e.dxfattribs()['layer']
        pts = []
        for lwpoint in e.lwpoints:
            x = round(lwpoint[0], 2)
            y = round(lwpoint[1], 2)
            pts.append(f'({x}, {y})')
        Lineload_str = ', '.join(pts)
        Lineloads.append(f'polygon {Lineload_str}')

    Lineloads_str = '\n'.join(Lineloads)
    Lineloads_list = Lineloads_str.split('polygon')
    Lineloads_list.pop(0)

    Lineloads_data = []
    for i, Lineload_str in enumerate(Lineloads_list):
        coords = Lineload_str.strip().split(' ')
        coords_str = ' '.join(coords)
        Lineloads_data.append((i+1, coords_str))
    df = pd.DataFrame(Lineloads_data, columns=['Lineloads','Coordinates'])

    df_coordinates = df['Coordinates'].copy()

    x_list = []
    y_list = []

    for e in msp.query("LWPOLYLINE"):
        vertices = list(e.vertices())
        for vertex in vertices:
            x_list.append(vertex[0])
            y_list.append(vertex[1])

    BankLoad_place = df_coordinates.iloc[0]
    BankLoad_place_list = ast.literal_eval(BankLoad_place)
    BankLoad_len = len(BankLoad_place_list)

    for i in range(len(BankLoad_place_list)-1):
        start_idx = i
        end_idx = start_idx + 1
        BankLoad_coords = [(x_list[start_idx], y_list[start_idx]), (x_list[end_idx],
        BankLoad = g_i.lineload(*BankLoad_coords, "q_start",44)[-1]

    Industry_place = df_coordinates.iloc[1]
    Industry_place_list = ast.literal_eval(Industry_place)
    Industry_len = len(Industry_place_list)+BankLoad_len

    for i in range(len(Industry_place_list)-1):
        start_idx = i + BankLoad_len
        end_idx = start_idx + 1
        if end_idx == len(x_list):
            end_idx = 0
        Industry_coords = [(x_list[start_idx], y_list[start_idx]), (x_list[end_idx],
        Industry = g_i.lineload(*Industry_coords,"q_start",10)[-1]
```

Generate mesh:

In [ ]:

```
g_i.gotomesh()
g_i.mesh(0.03) #Very fine mesh
```

Define piezometric line from a CSV file:

In [ ]:
```
waterlevel=pd.read_csv(".\\waterlevel52640.csv", sep=";")
x = list(waterlevel['x'])
y = list(waterlevel['y'])
points = [(x[i], y[i]) for i in range(len(x))]
g_i.waterlevel(*points)
```

Define staged construction:

In [ ]:
```
g_i.gotostages()
g_i.activate(g_i.Polygons[:],g_i.InitialPhase) #Activate polygons
g_i.InitialPhase.DeformCalcType = "Gravity Loading"

#If there are lineloads: an extra phase for activating lineloads
if has_lwpolyline:
    g_i.phase(g_i.InitialPhase) #Phase 1
    g_i.phase(g_i.Phase_1) #Phase 2
    g_i.activate(g_i.LineLoads, g_i.Phase_2)
    g_i.phase(g_i.Phase_2) #Phase 3
    g_i.Phase_3.DeformCalcType = "Safety"
    Phases = [g_i.InitialPhase, g_i.Phase_1, g_i.Phase_2, g_i.Phase_3]

#If there are no lineloads: skip the extra phase
else:
    g_i.phase(g_i.InitialPhase) #Phase 1
    g_i.phase(g_i.Phase_1) #Phase 2
    g_i.Phase_2.DeformCalcType = "Safety"
    Phases = [g_i.InitialPhase, g_i.Phase_1, g_i.Phase_2]
```

Calculate and save results to a CSV file:

In [ ]:
```
g_i.calculate()

InitialPhase = g_i.InitialPhase.CalculationResult
Phase_1 = g_i.Phase_1.CalculationResult
Phase_2 = g_i.Phase_2.CalculationResult

if has_lwpolyline: #If lineloads
    Phase_3 = g_i.Phase_3.CalculationResult
    CalculationResult_before = [InitialPhase, Phase_1, Phase_2, Phase_3]
    df_before = pd.DataFrame({'InitialPhase': [InitialPhase],
                              'Phase_1': [Phase_1],
                              'Phase_2': [Phase_2],
                              'Phase_3': [Phase_3]})
else: #If no lineloads
    CalculationResult_before = [InitialPhase,Phase_1,Phase_2]
    df_before = pd.DataFrame({'InitialPhase': [InitialPhase],
                              'Phase_1': [Phase_1],
                              'Phase_2': [Phase_2],
                              'Phase_3': 'No load'})

#Create CSV file with calculation result (0, 1 or 2)
df_before.to_csv('CalculationResult.csv', index=False)

#Increase cohesion and friction ange if calculation fails (2=Failed calculation)
```

```
if 2 in [e.value for e in CalculationResult_before]:
        Inc = 0.1 #Choose the factor of which the parameters should be increased
        if mat.DrainageType.value == 2:
           mat.setproperties("sURef", mat.sURef.value * (1+Inc))
           mat.setproperties("sUInc", mat.sUInc.value * (1+Inc))
        if mat.DrainageType.value == 0:
           mat.setproperties('phi', mat.phi.value * (1+Inc))

    for phase in Phases:
        phase.ShouldCalculate = True
        g_i.calculate()

#Get reached safety factor
if has_lwpolyline:
    SF = g_i.Phase_3.Reached.SumMsf
else:
    SF = g_i.Phase_2.Reached.SumMsf

df_CR = pd.read_csv('CalculationResult.csv')
df_SF = pd.DataFrame({'Plaxis_File_Name': [dxf_filename],'SF': [SF]})
SF_merged = pd.concat([df_SF, df_CR], axis=1)
SF_merged.to_csv('SafetyFactor.csv', index=False)

SF_csv = pd.read_csv('SafetyFactor.csv')
#Create a new column for the "real safety factor" if recalculation
SF_csv['Real_SF'] = np.nan

for i, row in SF_csv.iterrows():
    #Calculate the "real safety factor" if recalculation
    if row['Plaxis_File_Name'] == dxf_filenames and 2 in df_CR.values.flatten():
        #Find the increased cohesion for a arbitrary material (in this case Le1)
        for mat in g_i.Materials[:]:
               if mat.Identification.value == "Le1":
                   c_inc = mat.sURef.value
        c_ref = material.iloc[0,9]
        c_change = c_ref/c_inc
        SF_real = row[1]*c_change
        SF_csv.at[i, 'Real_SF'] = SF_real

#Save the final CSV file with safety factors
if not os.path.exists('SafetyFactorUpdated.csv'):
    SF_csv.to_csv('SafetyFactorUpdated.csv', index=False)
else:
    existing_df = pd.read_csv('SafetyFactorUpdated.csv')
    updated_df = existing_df.append(SF_csv, ignore_index=True)
    updated_df.to_csv('SafetyFactorUpdated.csv', index=False)

SF = pd.read_csv('SafetyFactorUpdated.csv')

#Save Plaxis file
plaxis_file_path = os.path.join("your_full_plaxis_file_path", dxf_filename + ".p2dx")
g_i.save(plaxis_file_path)

#Press ok when Plaxis error box shows up before reading a new DXF file
plaxis_window_handle = win32gui.FindWindow(None, "Plaxis")
win32gui.PostMessage(plaxis_window_handle, win32con.WM_KEYDOWN, win32con.VK_RETURN, 0
win32gui.PostMessage(plaxis_window_handle, win32con.WM_KEYUP, win32con.VK_RETURN, 0)
```

Appendix I – Python Code Section 24/150

Python code section 24/150

Import required packages:

In [ ]:

```
from plxscripting.easy import *
import subprocess, time
import pandas as pd
import ezdxf
import ast
import os
import win32gui
import win32con
import numpy as np
import math
```

Define folder path and connect the code to Plaxis:

In [ ]:

```
folder_path = r'your_full_folder_path'
#Extract files with .dxf only
file_names = [f for f in os.listdir(folder_path) if f.endswith('.dxf')]

#For-loop that loops over each DXF file
for file_name in file_names:
 file_path = os.path.join(folder_path, file_name)
 dxf_filenames = os.path.splitext(os.path.basename(file_path))[0]
 PLAXIS_PATH = r'C:\Program Files\Bentley\Geotechnical\PLAXIS 2D CONNECT Edition V22\
 PORT_i = 10000
 PORT_o = 10001
 PASSWORD = 'SxDBR<TYKRAX834~'
 subprocess.Popen([PLAXIS_PATH, f'--AppServerPassword={PASSWORD}', f'--AppServerPort={
 time.sleep(5)
 s_i, g_i = new_server('localhost', PORT_i, password=PASSWORD)
 s_o, g_o = new_server('localhost', PORT_o, password=PASSWORD)
 s_i.new()
```

Import geometry:

In [ ]:

```
 g_i.gotostructures()
 #Import polylines and regions
 g_i.import_("lines|polygons", file_path, 1, 1, 0, 0)
```

Create materials and assign to corresponding soil layer:

In [ ]:

```
 material = pd.read_csv('SoilProperties24.150.csv', sep=';')

 for i in range(len(material)):
     name = material.iloc[i,1]
     soilmodel = material.iloc[i,2]
     drainagetype = material.iloc[i,3]
     gammaUnsat= material.iloc[i,4]
     gammaSat= material.iloc[i,5]
     ERef=material.iloc[i,6]
```

```
    EInc = material.iloc[i,7]
    verticalref = material.iloc[i,8]
    cref=material.iloc[i,9]
    cinc = material.iloc[i,10]
    phi = material.iloc[i,11]

    if drainagetype == "Drained":
        material1 = g_i.soilmat()
        material1.setproperties(
            "Identification",name,
            "SoilModel",soilmodel,
            "DrainageType", drainagetype,
            "gammaUnsat", gammaUnsat,
            "gammaSat", gammaSat,
            "Eref",ERef,
            "Phi", phi
    )

    if drainagetype == "Undrained B":
        material1 = g_i.soilmat()
        material1.setproperties(
            "Identification",name,
            "SoilModel",soilmodel,
            "DrainageType", drainagetype,
            "gammaUnsat", gammaUnsat,
            "gammaSat", gammaSat,
            "Eref",ERef,
            "EInc",EInc,
            "verticalRef",verticalref,
            "cref", cref,
            "cInc",cinc,
    )
    if drainagetype == "Non-porous":
        material1 = g_i.soilmat()
        material1.setproperties(
            "Identification",name,
            "SoilModel",soilmodel,
            "DrainageType", drainagetype,
            "gammaUnsat", gammaUnsat,
            "Eref",ERef
    )

soilmat=[mat for mat in g_i.Materials[:] if mat.TypeName.value == 'SoilMat']

#Define these lists from the order of the regions generation in AutoCAD
soil_map = [
   {0: 'Si', 1: 'Cl1', 2: 'Cl2', 3: 'Cl3', 4: 'Cl4', 5: 'Cl3', 6: 'Cl5',
    7: 'ClGä1', 8: 'ClGä2', 9: 'ClGä3', 10: 'Rock'},
   {0: 'Si', 1: 'Cl1', 2: 'Cl2', 3: 'Cl3', 4: 'Cl4', 5: 'Cl3', 6: 'Cl5',
    7: 'ClGä1', 8: 'ClGä1_nedre', 9: 'ClGä2', 10: 'ClGä3', 11: 'Rock'},
   {0: 'Si', 1: 'Cl1', 2: 'Cl2', 3: 'Cl3', 4: 'Cl4', 5: 'Cl3', 6: 'Cl5',
    7: 'ClGä1', 8: 'ClGä1_nedre', 9: 'ClGä2', 10: 'ClGä3', 11: 'Rock', 12: 'Si'},
   {0: 'Si', 1: 'Cl1', 2: 'Cl2', 3: 'Cl3', 4: 'Cl4', 5: 'Cl3', 6: 'Cl5',
    7: 'ClGä1', 8: 'ClGä1_nedre', 9: 'ClGä2', 10: 'ClGä3', 11: 'Rock',
    12: 'Si', 13: 'Cl1'},]

#Count the number of soil polygons in Plaxis and use the right soil_map
if len(g_i.Soils) == 11:
    soil_map = soil_map[0]
elif len(g_i.Soils) == 12:
```

```
    soil_map = soil_map[1]
elif len(g_i.Soils) == 13:
    soil_map = soil_map[2]
elif len(g_i.Soils) == 14:
    soil_map = soil_map[3]

#Assign materials to corresponding soil layer
for j in range(len(soil_map)):
    for i in range(len(soilmat)):
        if soil_map[j] == soilmat[i].Name:
              g_i.Soils[j].setmaterial(soilmat[i])
```

Generate mesh:

In [ ]:
```
g_i.gotomesh()
g_i.mesh(0.05) #Very fine mesh
```

Define piezometric line from AutoCAD polyline:

In [ ]:
```
g_i.gotoflow()
doc = ezdxf.readfile(file_path)
msp = doc.modelspace()

waterlevel = []
for e in msp.query('LWPOLYLINE'):
    layer_name = e.dxfattribs()['layer']
    pts = []
    for lwpoint in e.lwpoints:
        x = round(lwpoint[0], 2)
        y = round(lwpoint[1], 2)
        pts.append(f'({x}, {y})')
    waterlevel_str = ', '.join(pts)
    waterlevel.append(f'polygon {waterlevel_str}')

waterlevel_str = '\n'.join(waterlevel)
waterlevel_list = waterlevel_str.split('polygon')
waterlevel_list.pop(0)

waterlevel_data = []
for i, waterlevel_str in enumerate(waterlevel_list):
    coords = waterlevel_str.strip().split(' ')
    coords_str = ' '.join(coords)
    waterlevel_data.append((i+1, coords_str))
df = pd.DataFrame(waterlevel_data, columns=['Waterlevel','Coordinates'])

df_coordinates = df['Coordinates'].copy()

x_list = []
y_list = []

for e in msp.query("LWPOLYLINE"):
   vertices = list(e.vertices())
   for vertex in vertices:
       x_list.append(vertex[0])
       y_list.append(vertex[1])

waterlevel_place = df_coordinates.iloc[0]
waterlevel_place_list = ast.literal_eval(waterlevel_place)
```

```
waterlevel_len = len(waterlevel_place_list)

points = [(x_list[i], y_list[i]) for i in range(waterlevel_len)]
g_i.waterlevel(*points)
```

Define staged construction:

In [ ]:

```
g_i.gotostages()
g_i.activate(g_i.Polygons[:],g_i.InitialPhase) #Activate polygons
g_i.InitialPhase.DeformCalcType = "Gravity Loading"
g_i.phase(g_i.InitialPhase) #Phase 1
g_i.phase(g_i.Phase_1) #Phase 2
g_i.Phase_2.DeformCalcType = "Safety"
Phases = [g_i.InitialPhase, g_i.Phase_1, g_i.Phase_2]
```

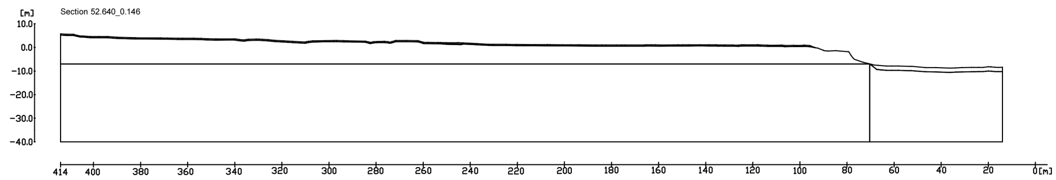
Calculate and save results to a CSV file:

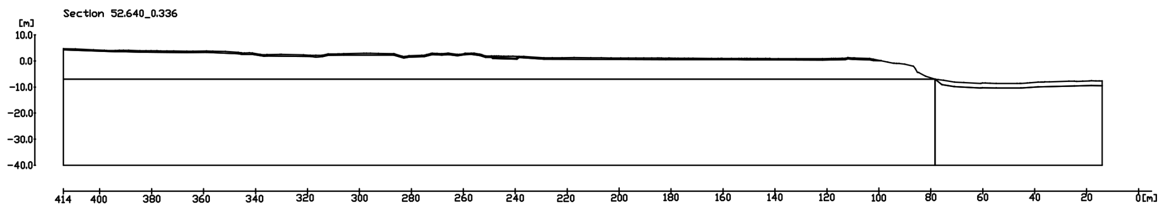
In [ ]:

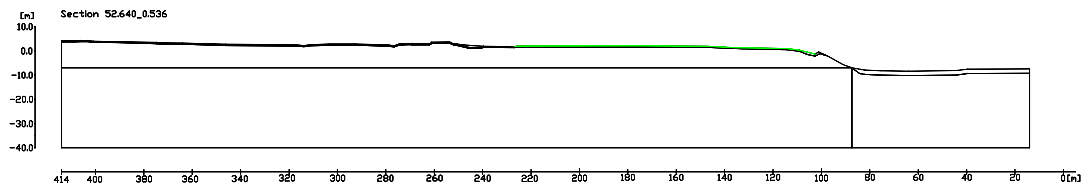
```
g_i.calculate()

InitialPhase = g_i.InitialPhase.CalculationResult
Phase_1 = g_i.Phase_1.CalculationResult
Phase_2 = g_i.Phase_2.CalculationResult
CalculationResult_before = [InitialPhase, Phase_1, Phase_2]
df_before = pd.DataFrame({'InitialPhase': [InitialPhase],
                          'Phase_1': [Phase_1],
                          'Phase_2': [Phase_2]})

#Create CSV file with calculation result (0, 1 or 2)
df_before.to_csv('CalculationResult.csv', index=False)

#Increase cohesion and friction ange if calculation fails (2=Failed calculation)
if 2 in [e.value for e in CalculationResult_before]:
    for mat in g_i.Materials[:]:
        Inc = 0.1 #Choose the factor of which the parameters should be increased
        if mat.DrainageType.value == 2:
           mat.setproperties("sURef", mat.sURef.value * (1+Inc))
           mat.setproperties("sUInc", mat.sUInc.value * (1+Inc))
        if mat.DrainageType.value == 0:
           phi_inc = math.tan(math.radians(mat.phi.value)) * (1 + Inc)
           mat.setproperties('phi', math.degrees(math.atan(phi_inc)))

    for phase in Phases:
        phase.ShouldCalculate = True
        g_i.calculate()

#Get reached safety factor
SF = g_i.Phase_2.Reached.SumMsf
df_CR = pd.read_csv('CalculationResult.csv')
df_SF = pd.DataFrame({'Plaxis_File_Name': [dxf_filenames],'SF': [SF]})
SF_merged = pd.concat([df_SF, df_CR], axis=1)
SF_merged.to_csv('SafetyFactor.csv', index=False)

SF_csv = pd.read_csv('SafetyFactor.csv')
#Create a new column for the "real safety factor" if recalculation
SF_csv['Real_SF'] = np.nan

for i, row in SF_csv.iterrows():
    #Calculate the "real safety factor" if recalculation
```

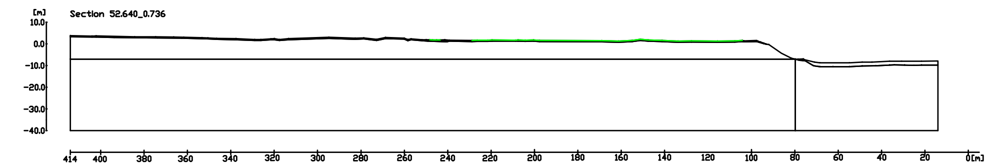
```
    if row['Plaxis_File_Name'] == dxf_filenames and 2 in df_CR.values.flatten():
        for mat in g_i.Materials[:]:
        #Find the increased cohesion for a arbitrary material (in this case Cl1)
               if mat.Identification.value == "Cl1":
                   c_inc = mat.sURef.value
        c_ref = material.iloc[1,9]
        c_change = c_ref/c_inc
        SF_real = row[1]*c_change
        SF_csv.at[i, 'Real_SF'] = SF_real

#Save the final CSV file with safety factors
if not os.path.exists('SafetyFactorUpdated.csv'):
    SF_csv.to_csv('SafetyFactorUpdated.csv', index=False)
else:
    existing_df = pd.read_csv('SafetyFactorUpdated.csv')
    updated_df = existing_df.append(SF_csv, ignore_index=True)
    updated_df.to_csv('SafetyFactorUpdated.csv', index=False)

SF = pd.read_csv('SafetyFactorUpdated.csv')

#Save Plaxis file
plaxis_file_path = os.path.join("your_full_plaxis_file_path", dxf_filenames + ".p2dx'
g_i.save(plaxis_file_path)

#Press ok when Plaxis error box shows up before reading a new DXF file
plaxis_window_handle = win32gui.FindWindow(None, "Plaxis")
win32gui.PostMessage(plaxis_window_handle, win32con.WM_KEYDOWN, win32con.VK_RETURN, 0
win32gui.PostMessage(plaxis_window_handle, win32con.WM_KEYUP, win32con.VK_RETURN, 0)
```

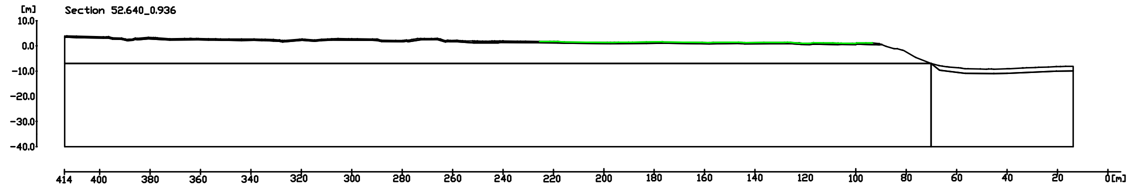
Appendix J – DXF Files Section 52/640

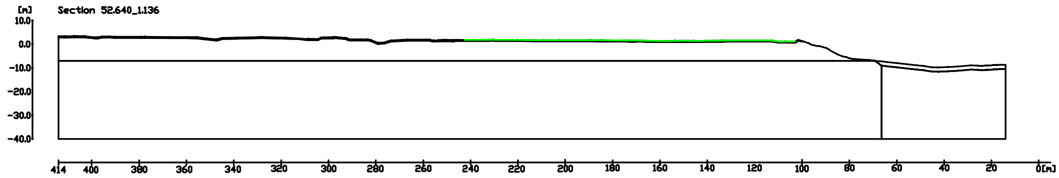


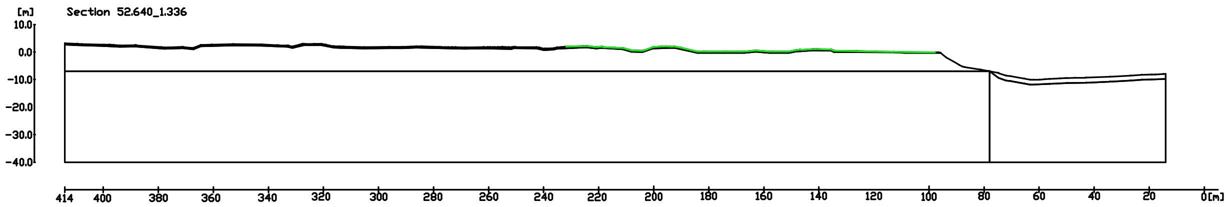


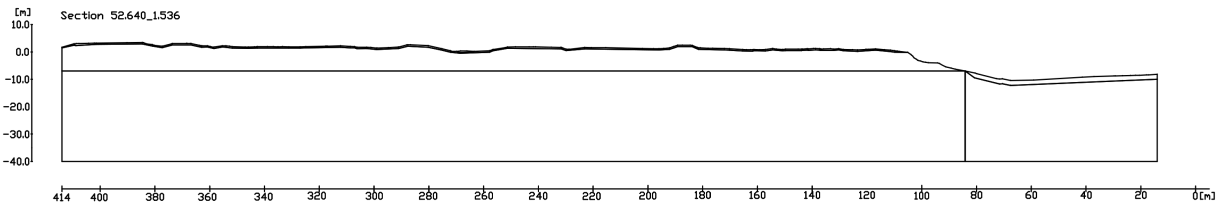


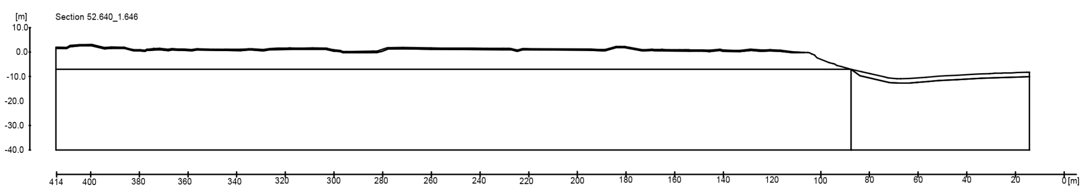



[m]
Section 52.640_0.936
10.0
0.0
-10.0
-20.0
-30.0
-40.0
414 400 380 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0[m]

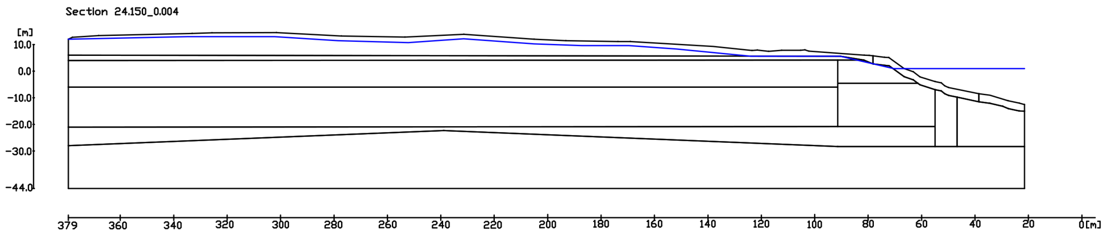

[m]
Section 52.640_1.136
10.0
0.0
-10.0
-20.0
-30.0
-40.0
414 400 380 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0[m]

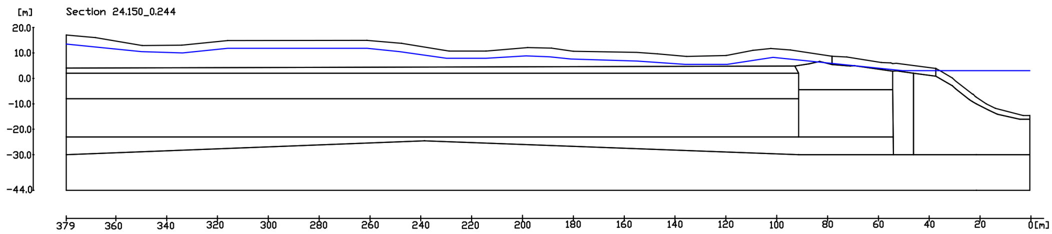

[m]
Section 52.640_1.336
10.0
0.0
-10.0
-20.0
-30.0
-40.0
414 400 380 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0[m]

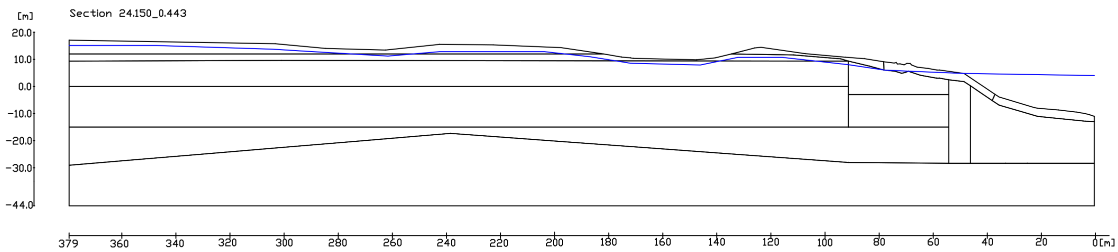

[m]
Section 52.640_1.536
10.0
0.0
-10.0
-20.0
-30.0
-40.0
414 400 380 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0[m]

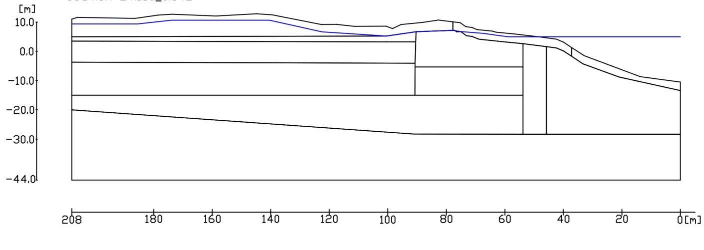

[m]
Section 52.640_1.646
10.0
0.0
-10.0
-20.0
-30.0
-40.0
414 400 380 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0[m]

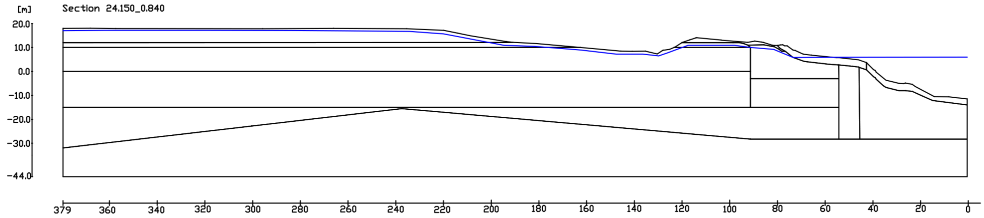
Appendix K – DXF Files Section 24/150

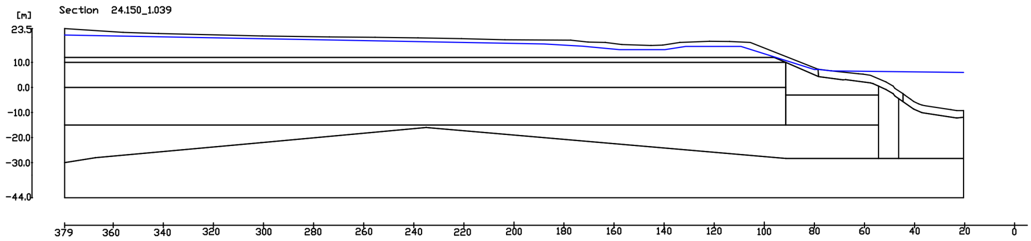


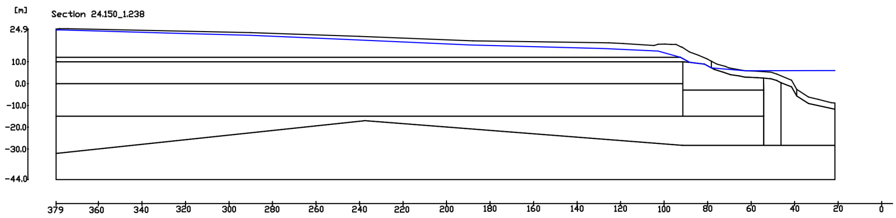


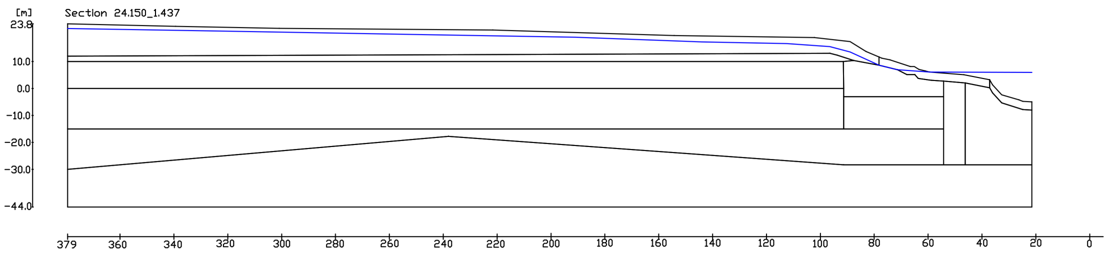


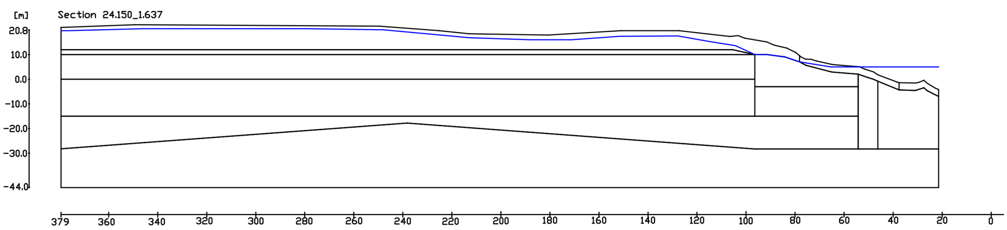


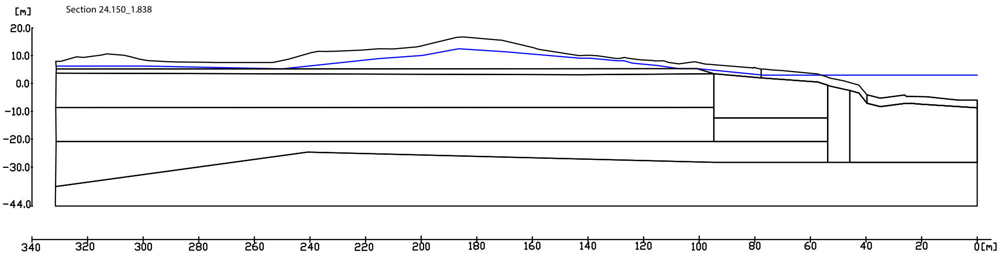

[m]
Section 24.150_0.840
20.0
10.0
0.0
-10.0
-20.0
-30.0
-44.0
379 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0

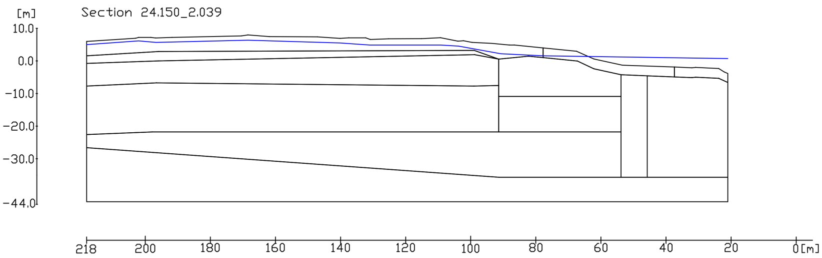

[m]
Section 24.150_1.039
23.5
10.0
0.0
-10.0
-20.0
-30.0
-44.0
379 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0

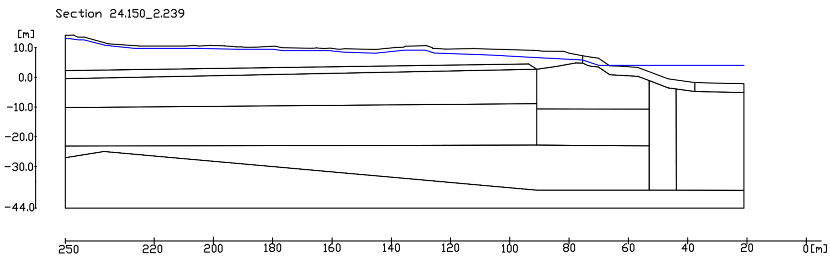

[m]
Section 24.150_1.238
24.9
10.0
0.0
-10.0
-20.0
-30.0
-44.0
379 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0

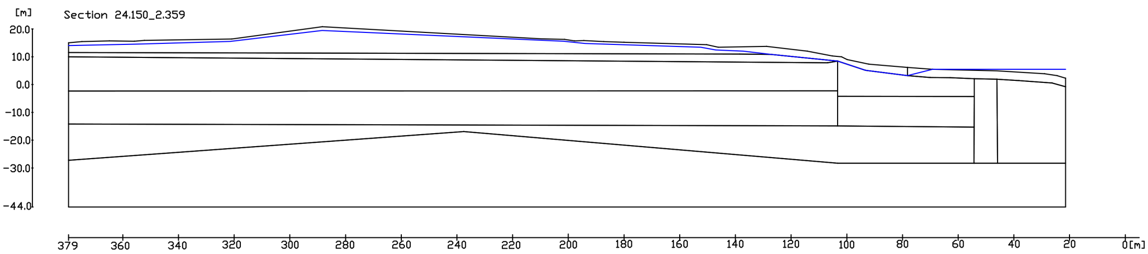

[m]
Section 24.150_1.437
23.8
10.0
0.0
-10.0
-20.0
-30.0
-44.0
379 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0


[m]
Section 24.150_1.637
20.8
10.0
0.0
-10.0
-20.0
-30.0
-44.0
379 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0

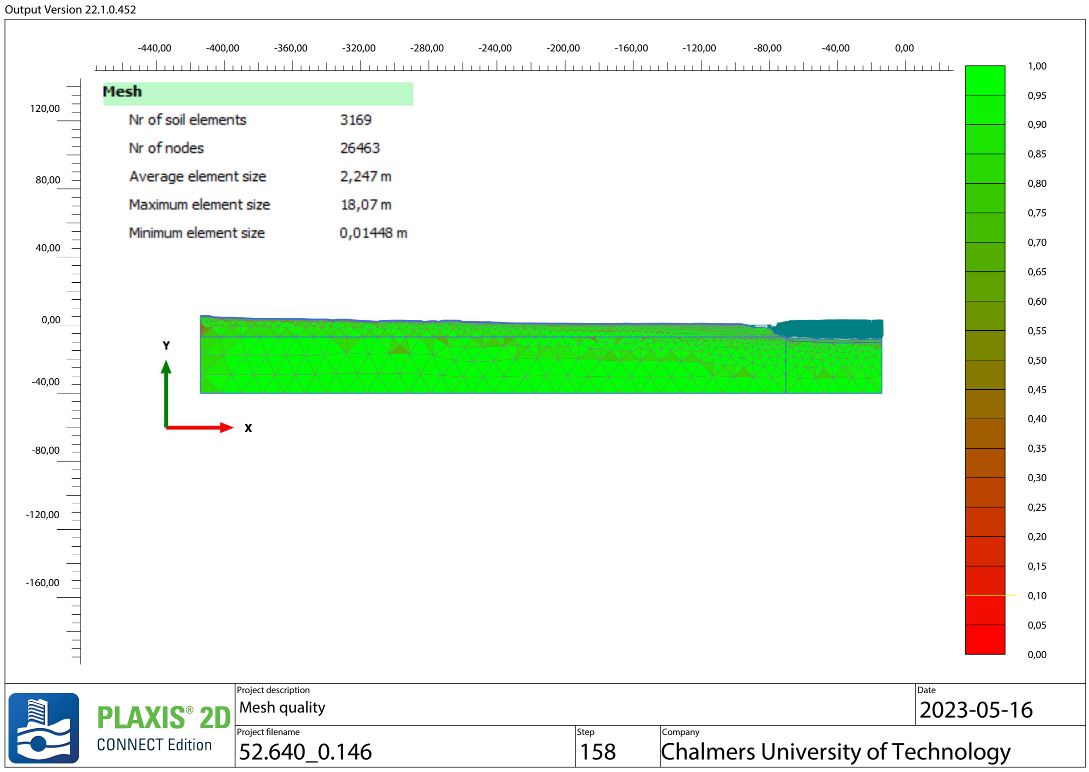

Section 24.150_1.838
[m]
20.0
10.0
0.0
-10.0
-20.0
-30.0
-44.0
340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0[m]


Section 24.150_2.039
[m]
10.0
0.0
-10.0
-20.0
-30.0
-44.0
218 200 180 160 140 120 100 80 60 40 20 0[m]

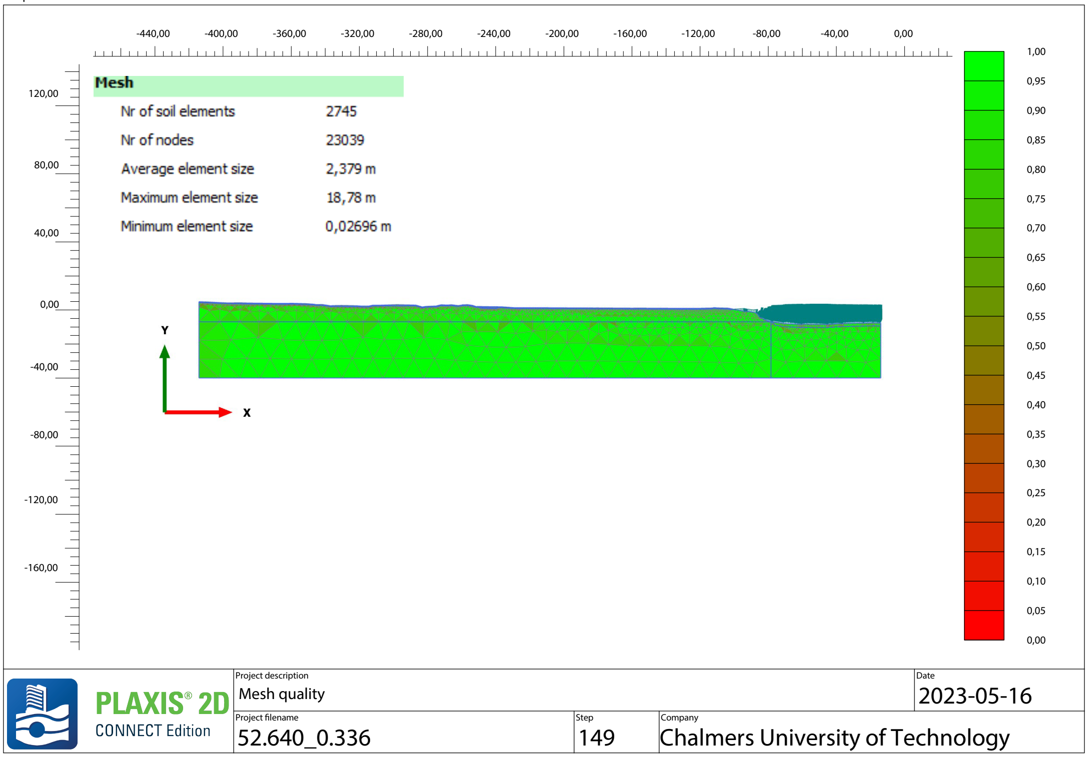

Section 24.150_2.239
[m]
10.0
0.0
-10.0
-20.0
-30.0
-44.0
250 220 200 180 160 140 120 100 80 60 40 20 0[m]


Section 24.150_2.359
[m]
20.0
10.0
0.0
-10.0
-20.0
-30.0
-44.0
379 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0[m]

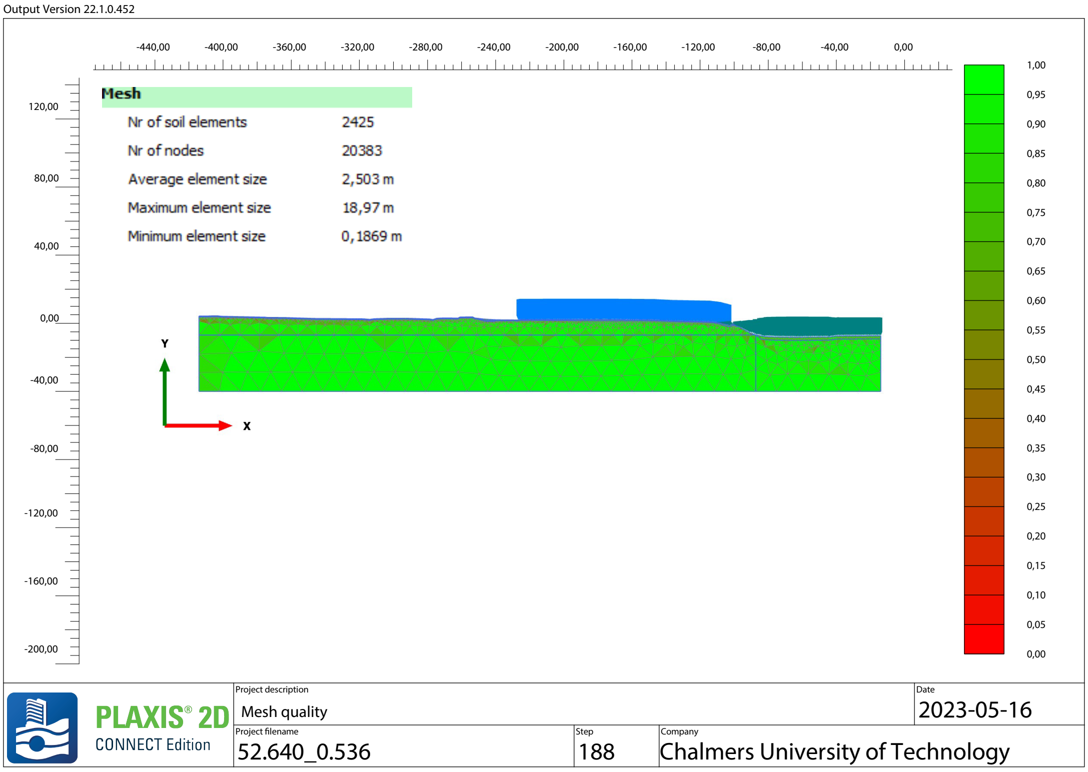
Appendix L – Automated Plaxis Analysis 52/640

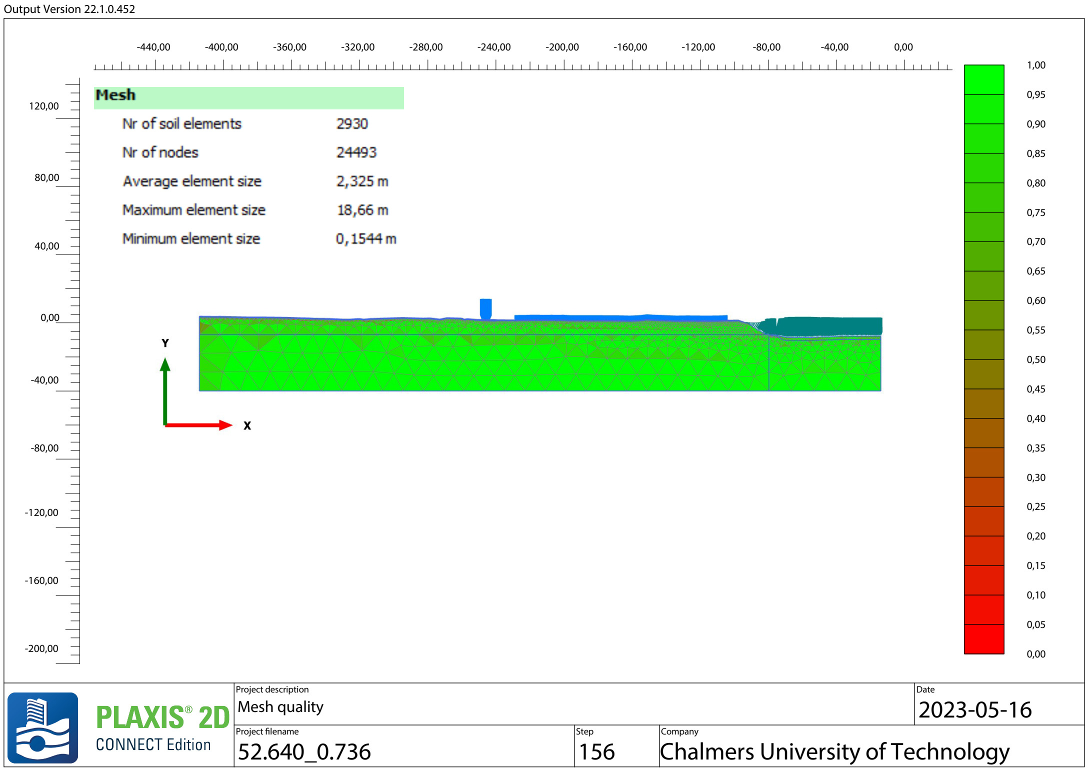


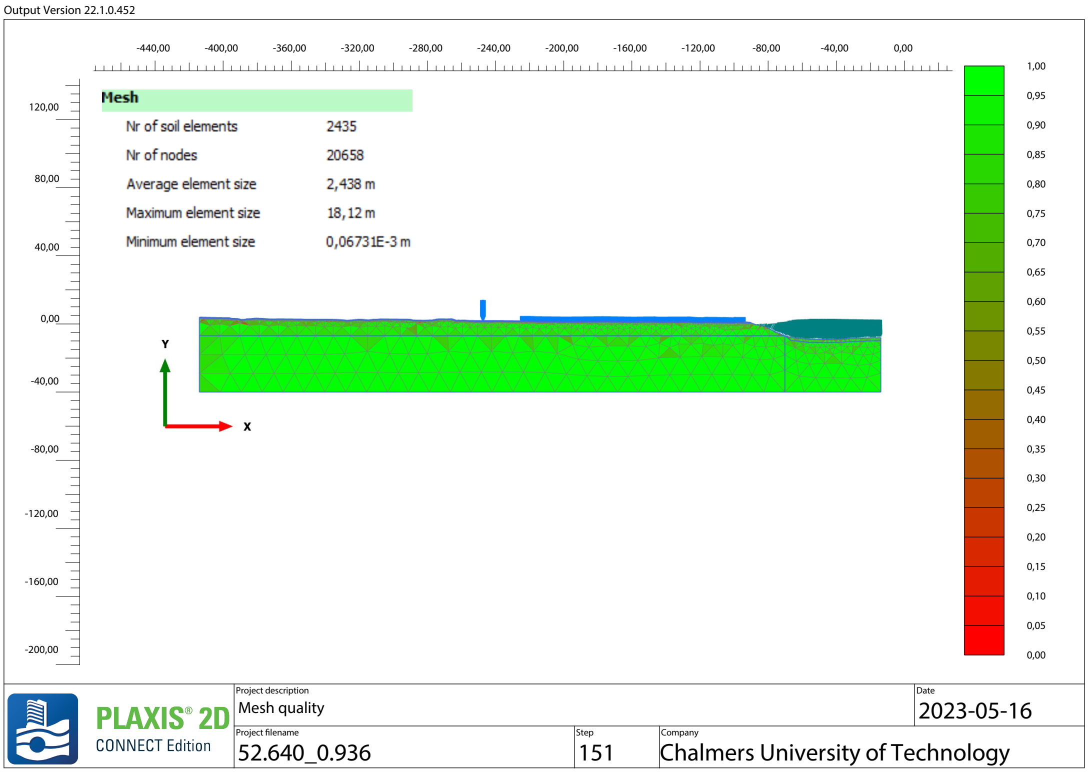
Output Version 22.1.0.452



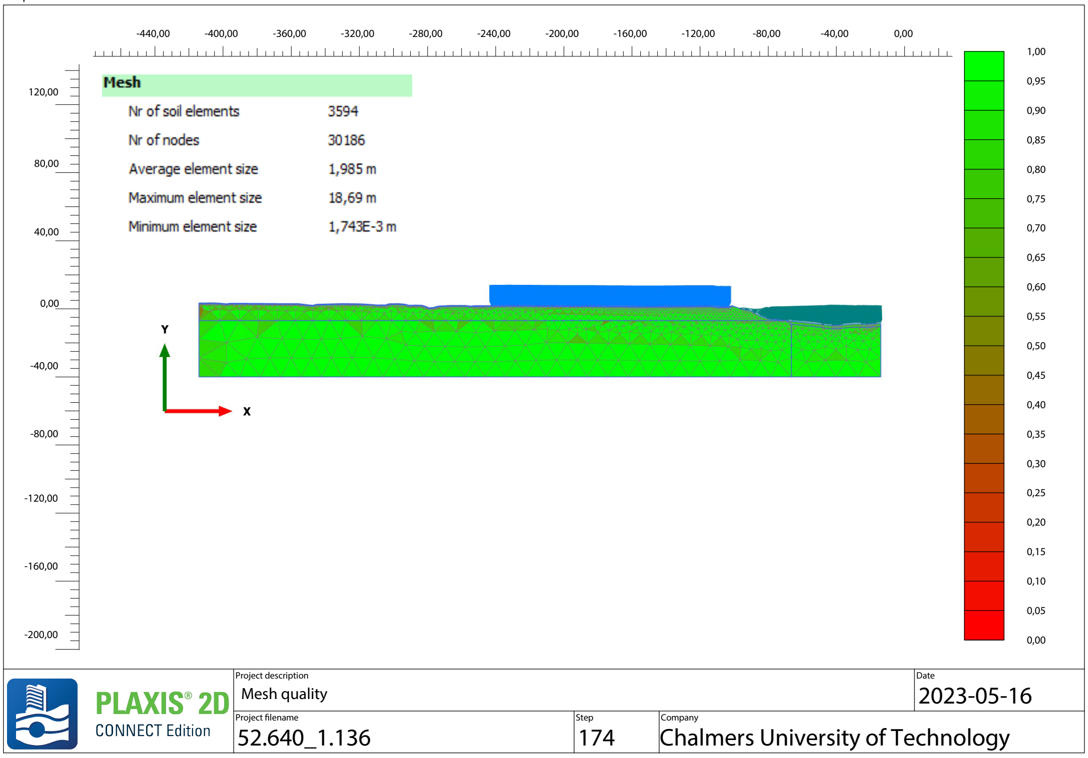
Output Version 22.1.0.452



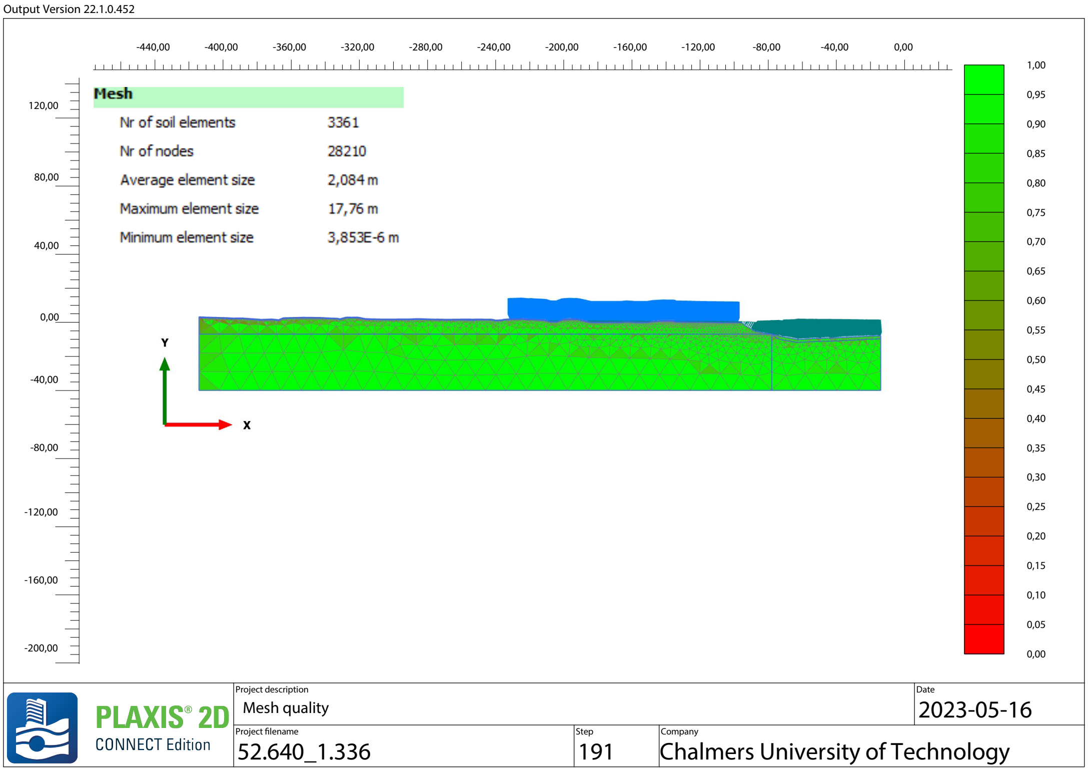

Output Version 22.1.0.452
Mesh
Nr of soil elements 2930
Nr of nodes 24493
Average element size 2,325 m
Maximum element size 18,66 m
Minimum element size 0,1544 m
Project description
Mesh quality
Project filename
52.640_0.736
Step
156
Company
Chalmers University of Technology
Date
2023-05-16
PLAXIS® 2D
CONNECT Edition

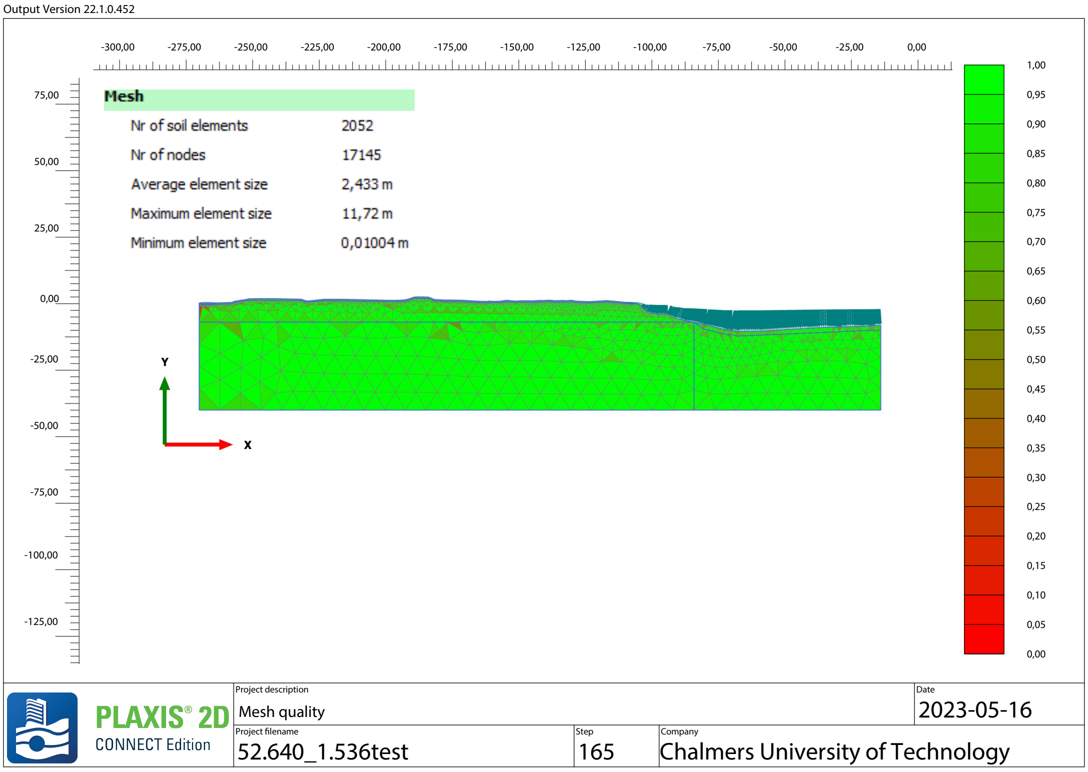

Output Version 22.1.0.452
Mesh
Nr of soil elements 2435
Nr of nodes 20658
Average element size 2,438 m
Maximum element size 18,12 m
Minimum element size 0,06731E-3 m
Project description
Mesh quality
Project filename
52.640_0.936
Step
151
Company
Chalmers University of Technology
Date
2023-05-16
PLAXIS® 2D
CONNECT Edition

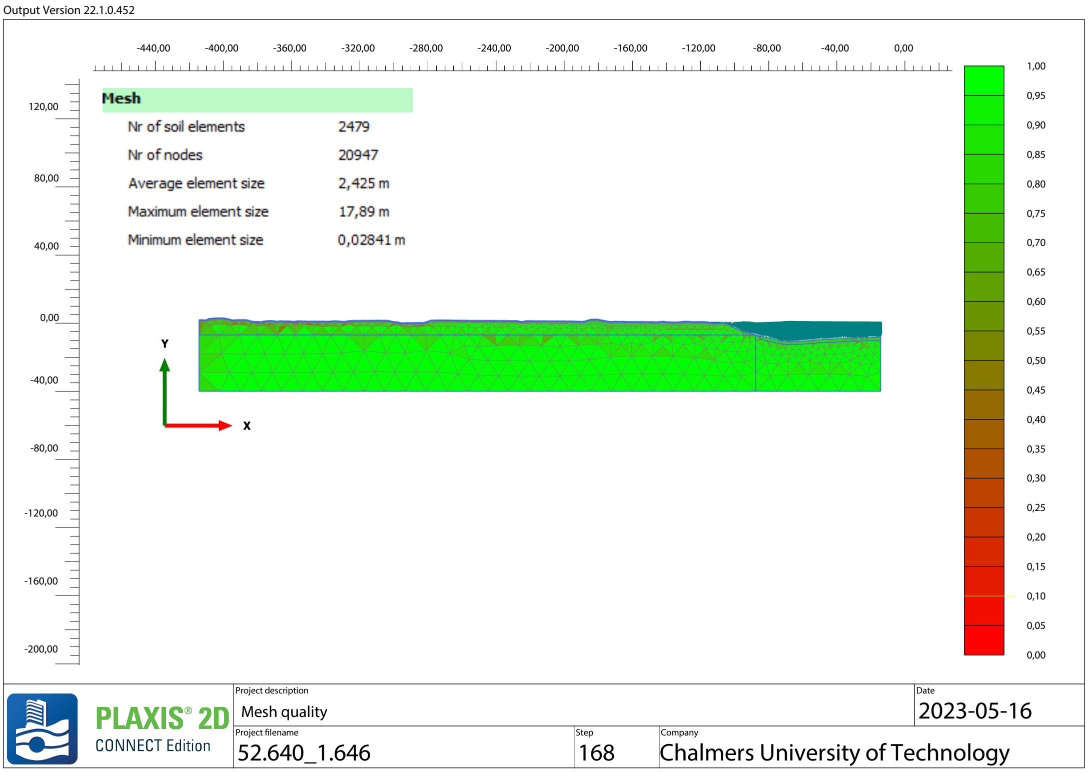
Output Version 22.1.0.452



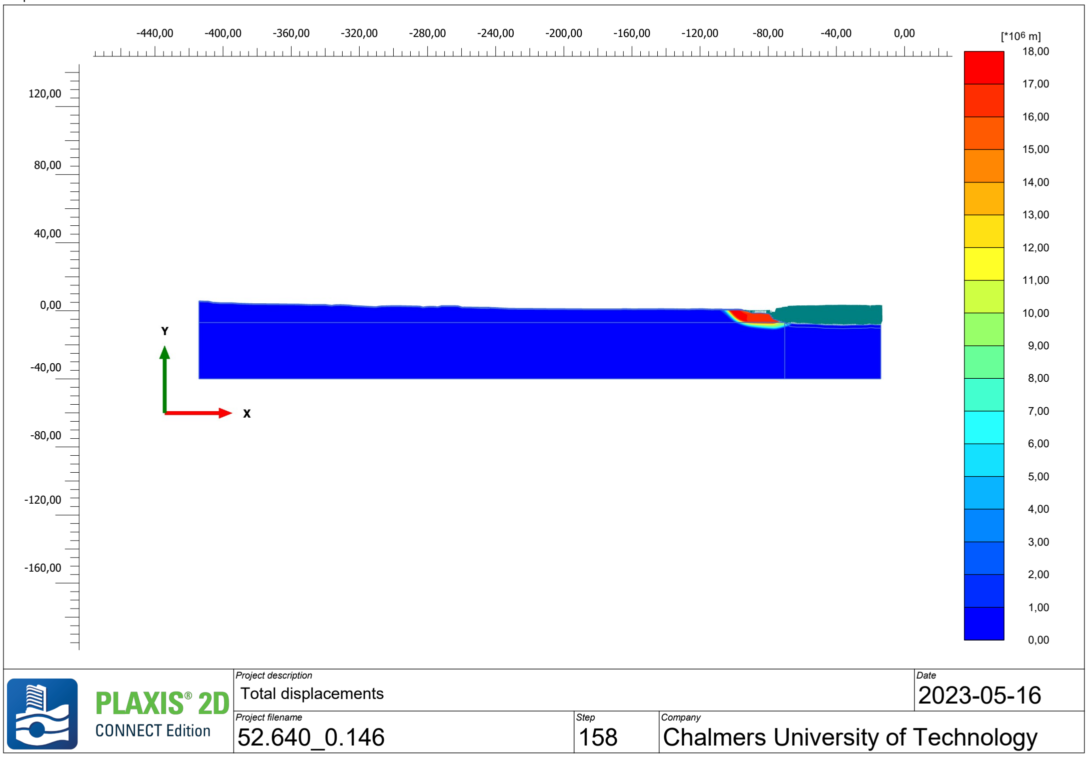
Output Version 22.1.0.452



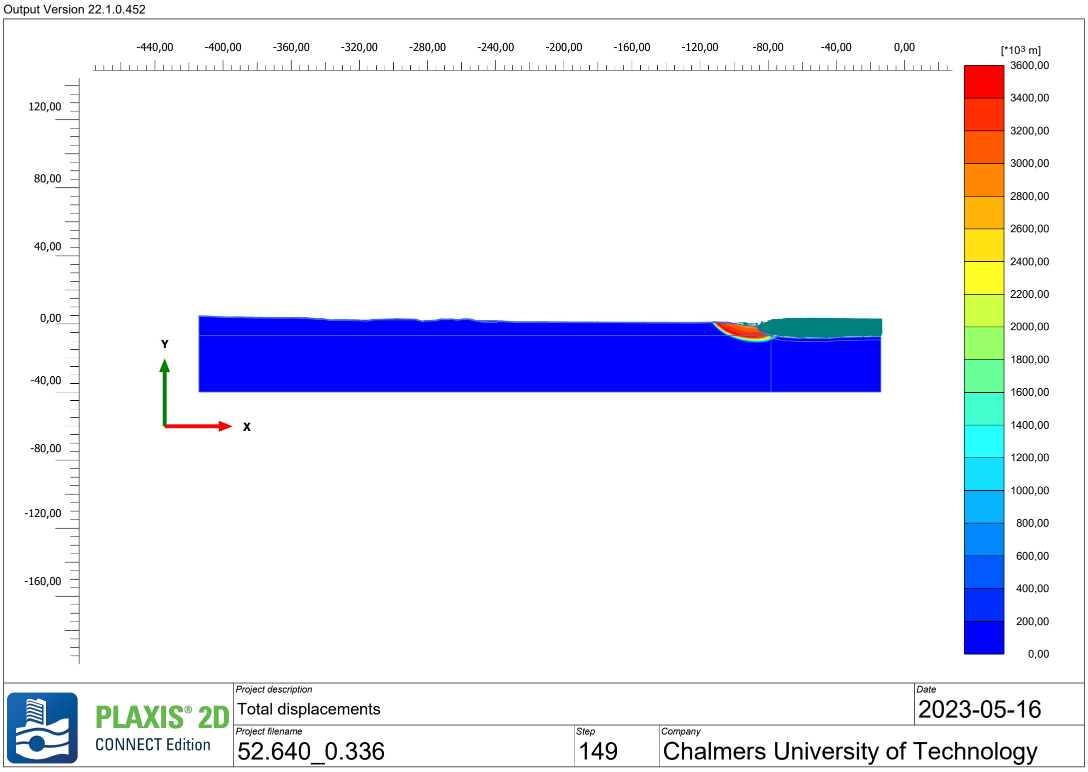

Output Version 22.1.0.452
Mesh
Nr of soil elements 2052
Nr of nodes 17145
Average element size 2,433 m
Maximum element size 11,72 m
Minimum element size 0,01004 m
Y
X
PLAXIS 2D
CONNECT Edition
Project description
Mesh quality
Date
2023-05-16
Project filename
52.640_1.536test
Step
165
Company
Chalmers University of Technology


Output Version 22.1.0.452
Mesh
Nr of soil elements 2479
Nr of nodes 20947
Average element size 2,425 m
Maximum element size 17,89 m
Minimum element size 0,02841 m
Y
X
PLAXIS 2D
CONNECT Edition
Project description
Mesh quality
Date
2023-05-16
Project filename
52.640_1.646
Step
168
Company
Chalmers University of Technology

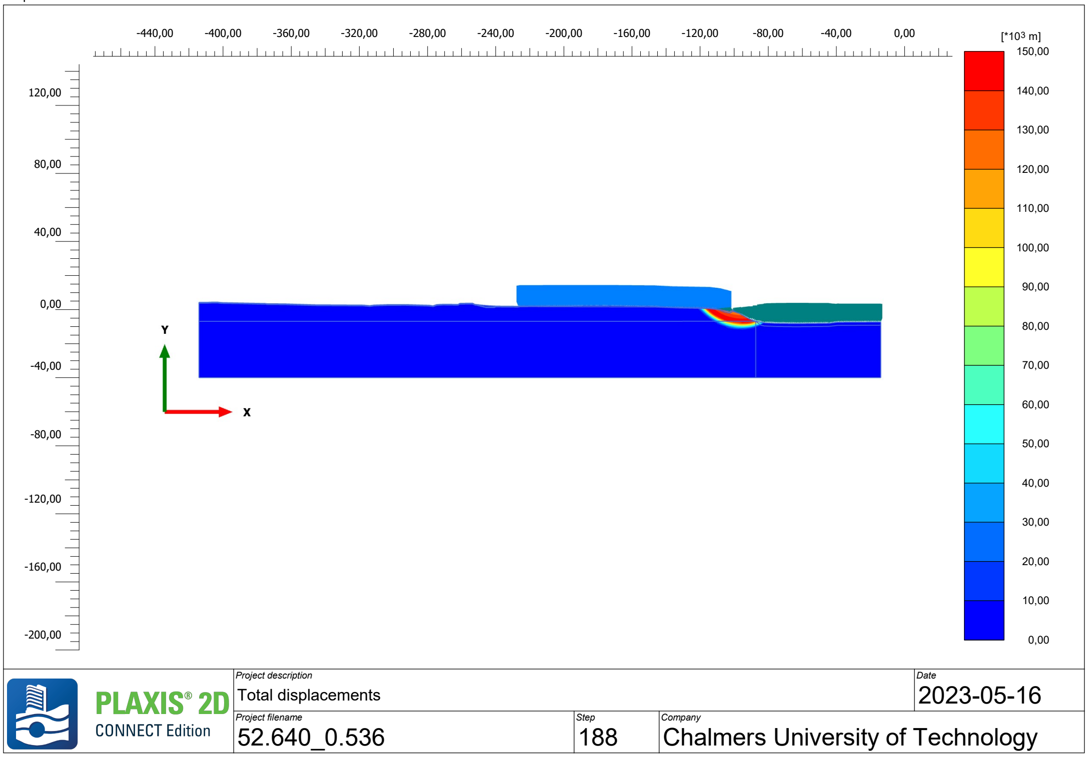
Output Version 22.1.0.452



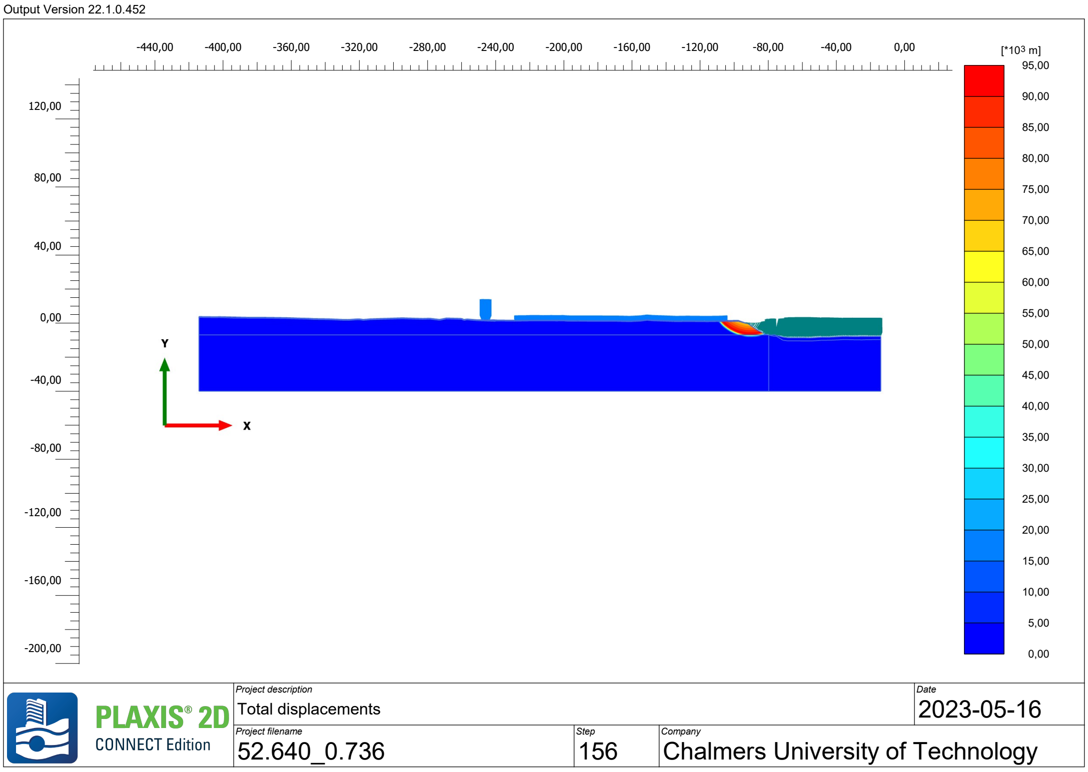
Output Version 22.1.0.452



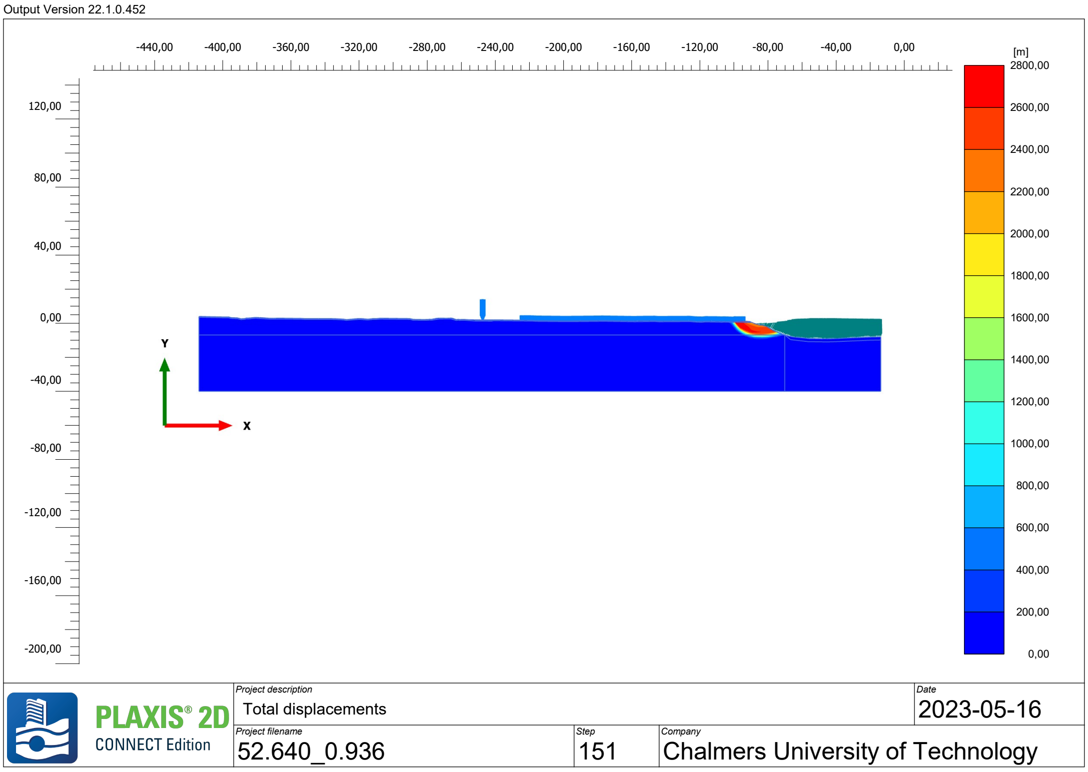
Output Version 22.1.0.452



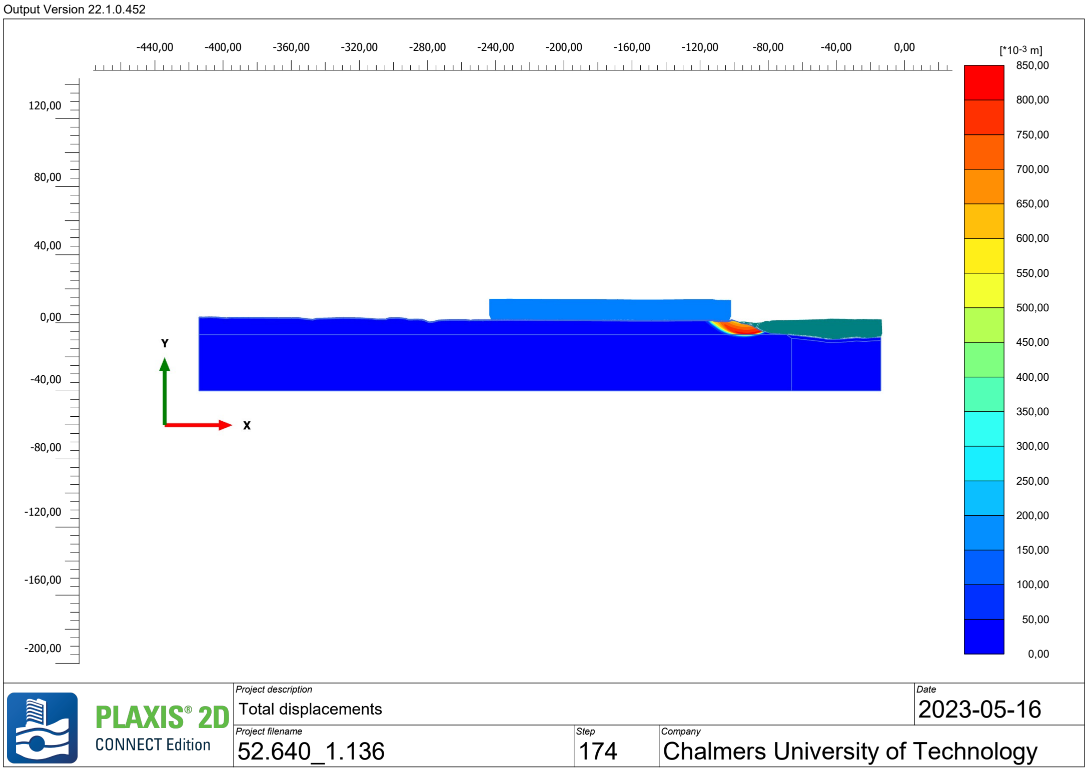
Output Version 22.1.0.452



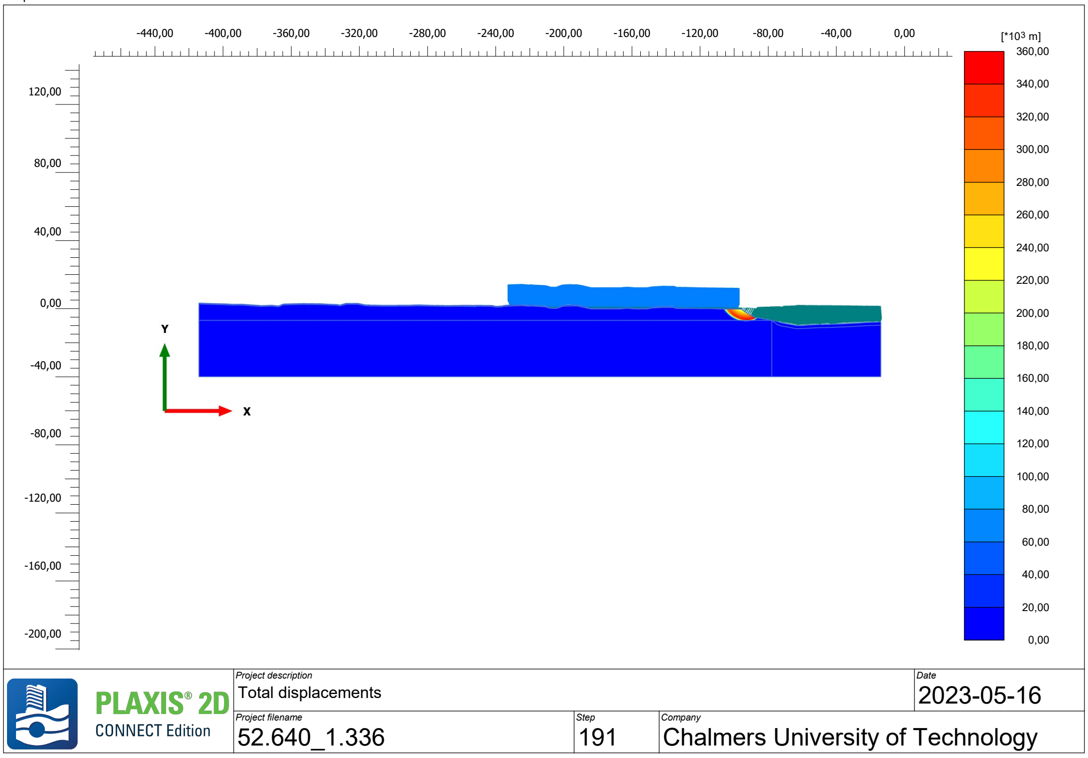
Output Version 22.1.0.452



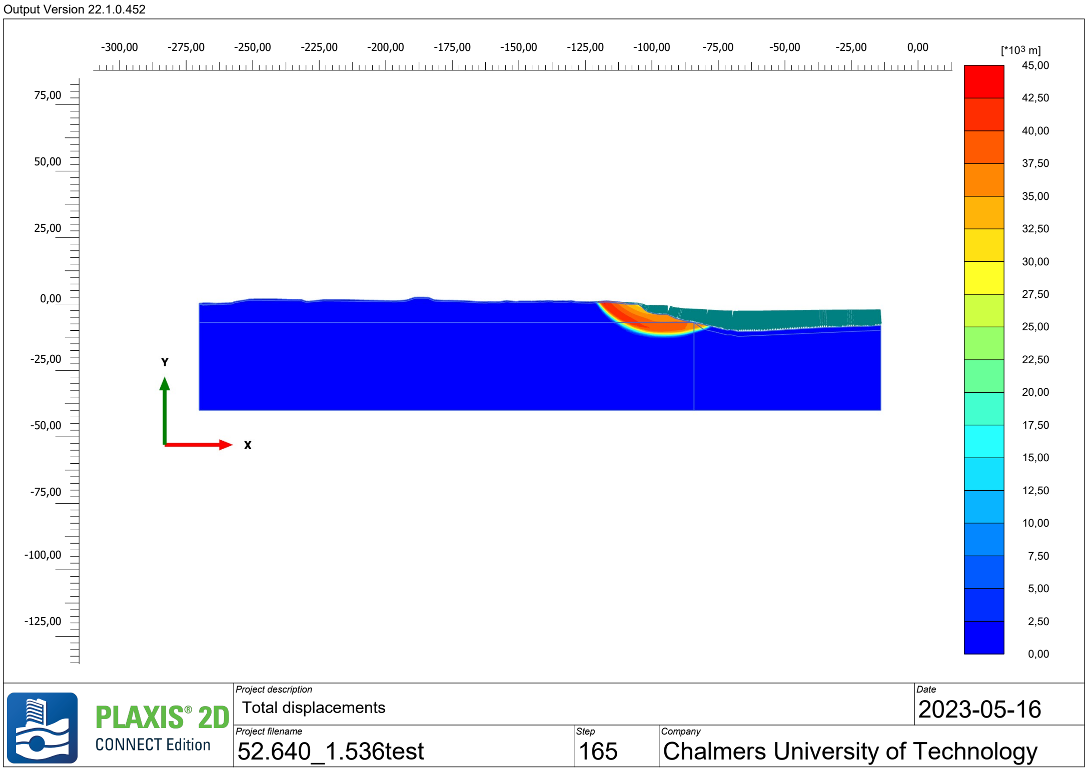
Output Version 22.1.0.452

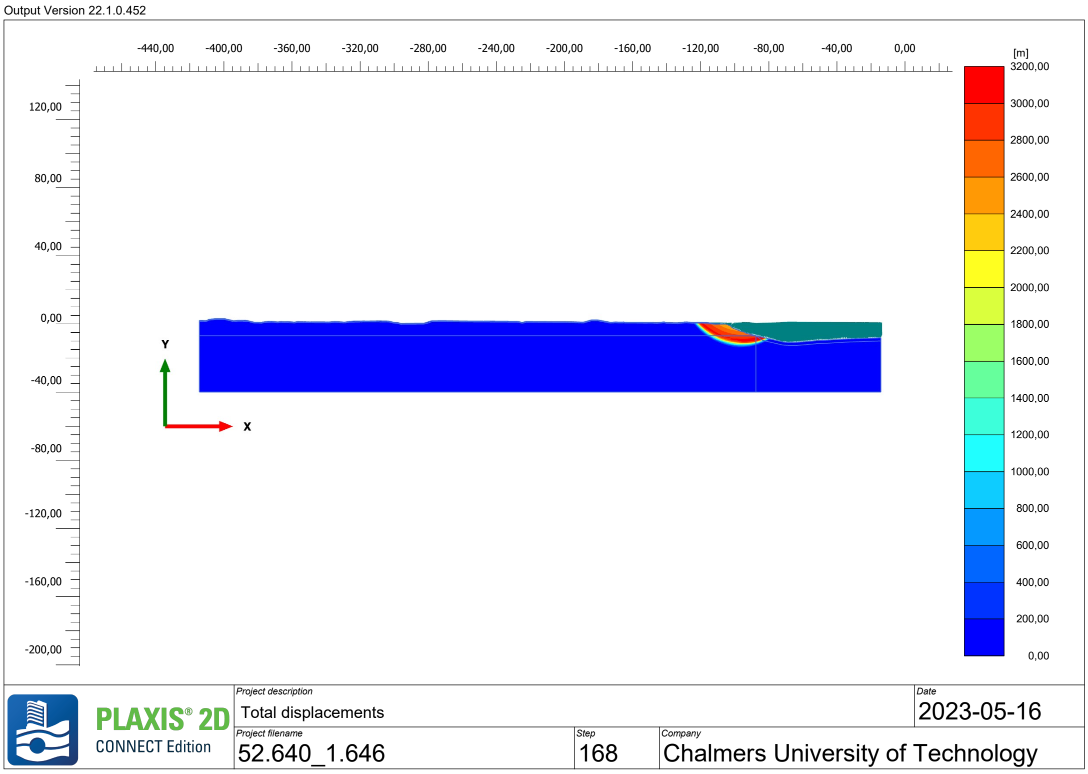


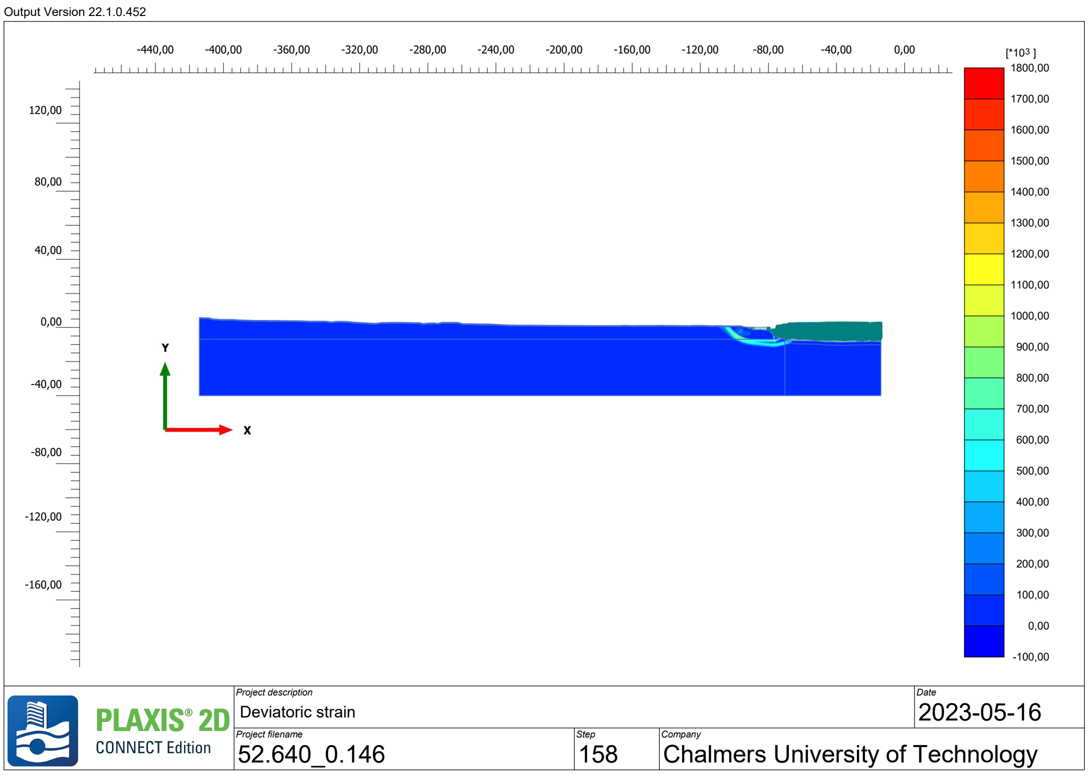
Output Version 22.1.0.452

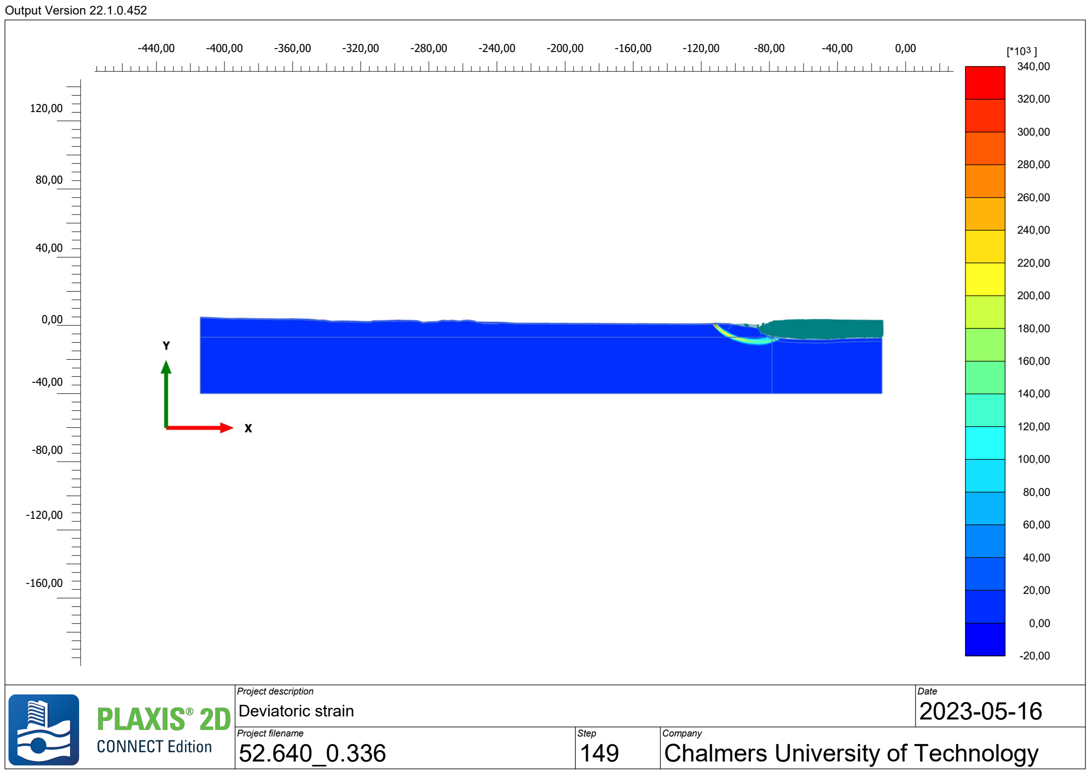


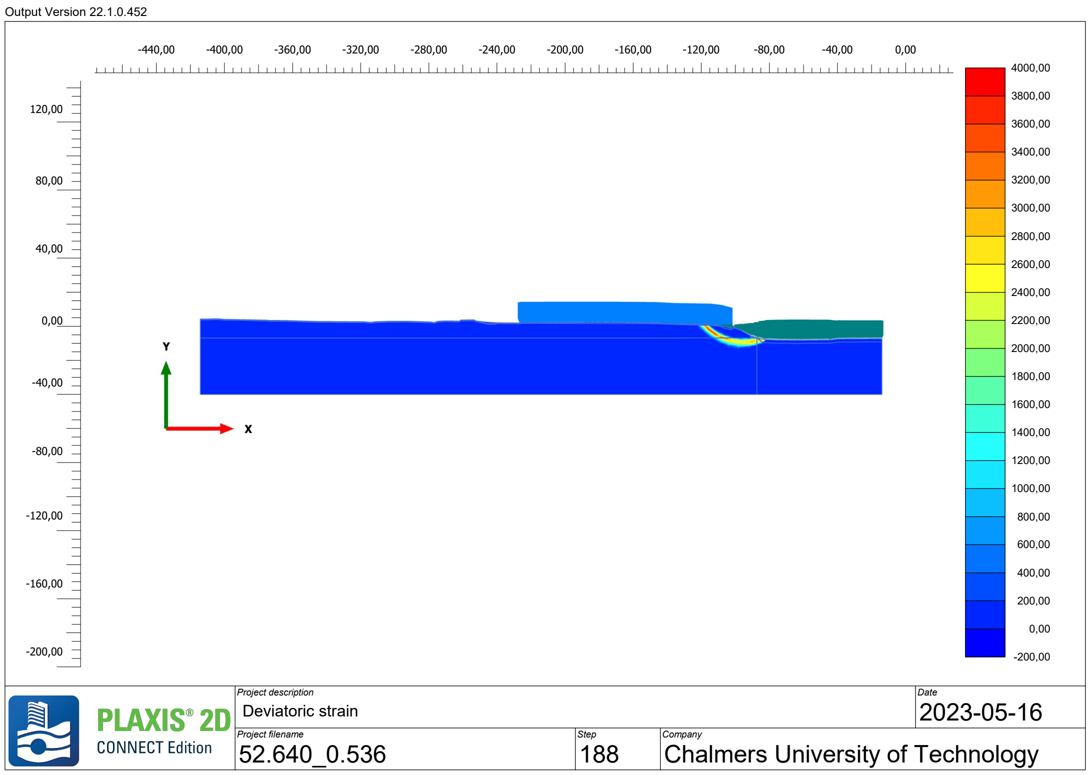
Output Version 22.1.0.452



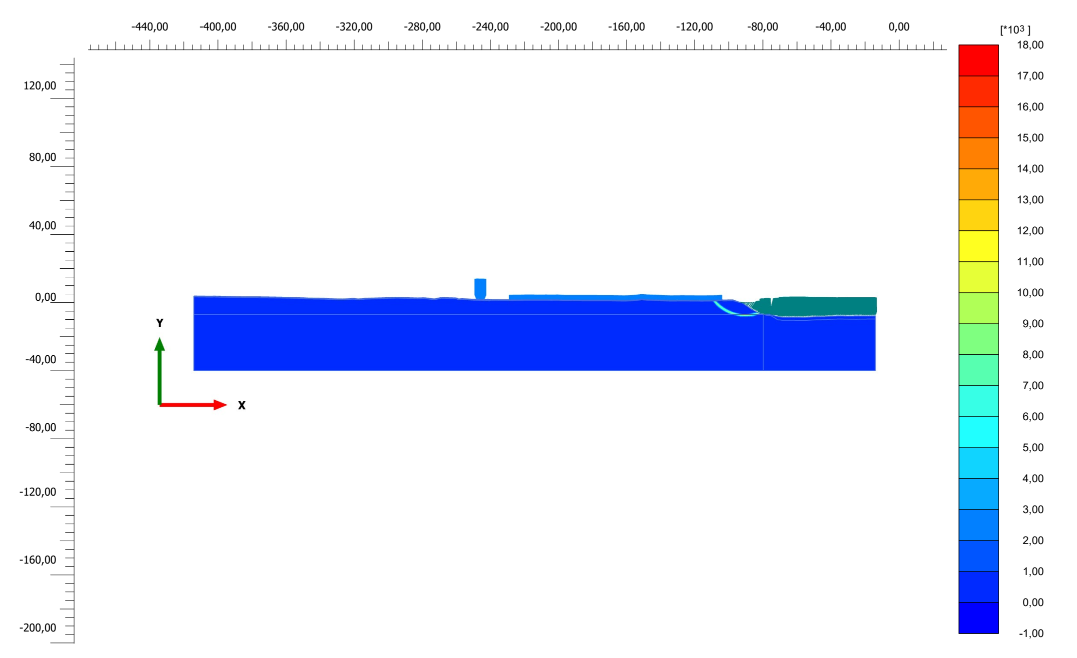

Output Version 22.1.0.452
-440,00 -400,00 -360,00 -320,00 -280,00 -240,00 -200,00 -160,00 -120,00 -80,00 -40,00 0,00
120,00 80,00 40,00 0,00 -40,00 -80,00 -120,00 -160,00 -200,00
Y
X
[m]
3200,00 3000,00 2800,00 2600,00 2400,00 2200,00 2000,00 1800,00 1600,00 1400,00 1200,00 1000,00 800,00 600,00 400,00 200,00 0,00
PLAXIS® 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-16
Project filename
52.640_1.646
Step
168
Company
Chalmers University of Technology


Output Version 22.1.0.452
-440,00 -400,00 -360,00 -320,00 -280,00 -240,00 -200,00 -160,00 -120,00 -80,00 -40,00 0,00
120,00 80,00 40,00 0,00 -40,00 -80,00 -120,00 -160,00
Y
X
[*10³]
1800,00 1700,00 1600,00 1500,00 1400,00 1300,00 1200,00 1100,00 1000,00 900,00 800,00 700,00 600,00 500,00 400,00 300,00 200,00 100,00 0,00 -100,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
52.640_0.146
Step
158
Company
Chalmers University of Technology


Output Version 22.1.0.452
-440,00 -400,00 -360,00 -320,00 -280,00 -240,00 -200,00 -160,00 -120,00 -80,00 -40,00 0,00
120,00 80,00 40,00 0,00 -40,00 -80,00 -120,00 -160,00
Y
X
[*10³]
340,00 320,00 300,00 280,00 260,00 240,00 220,00 200,00 180,00 160,00 140,00 120,00 100,00 80,00 60,00 40,00 20,00 0,00 -20,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
52.640_0.336
Step
149
Company
Chalmers University of Technology

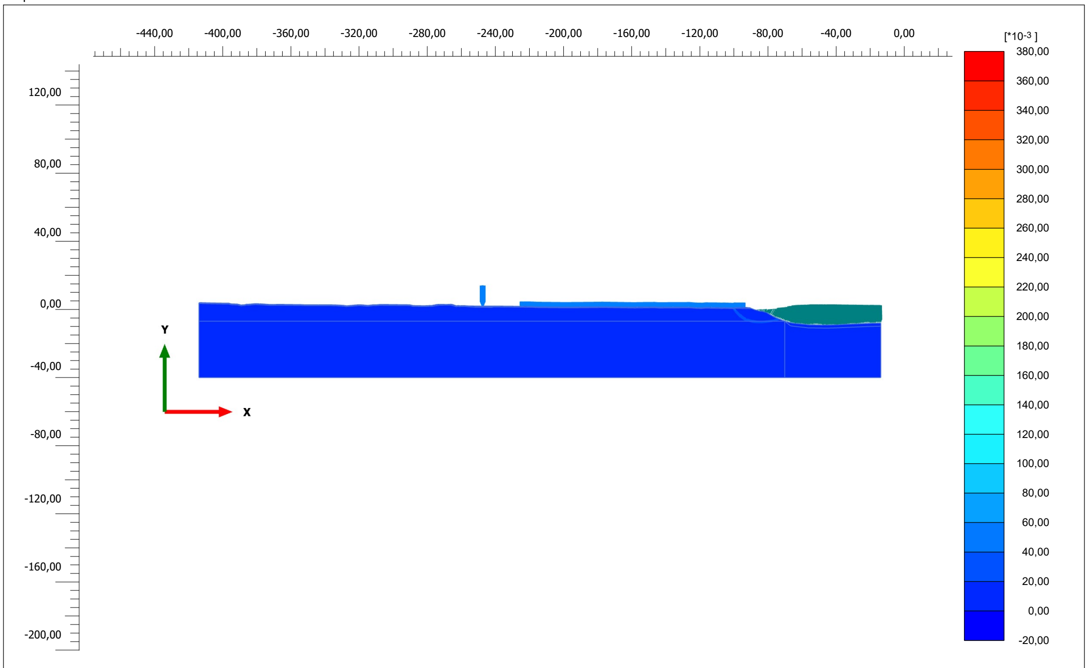

Output Version 22.1.0.452
-440,00 -400,00 -360,00 -320,00 -280,00 -240,00 -200,00 -160,00 -120,00 -80,00 -40,00 0,00
120,00 80,00 40,00 0,00 -40,00 -80,00 -120,00 -160,00 -200,00
Y
X
4000,00 3800,00 3600,00 3400,00 3200,00 3000,00 2800,00 2600,00 2400,00 2200,00 2000,00 1800,00 1600,00 1400,00 1200,00 1000,00 800,00 600,00 400,00 200,00 0,00 -200,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
52.640_0.536
Step
188
Company
Chalmers University of Technology

Output Version 22.1.0.452



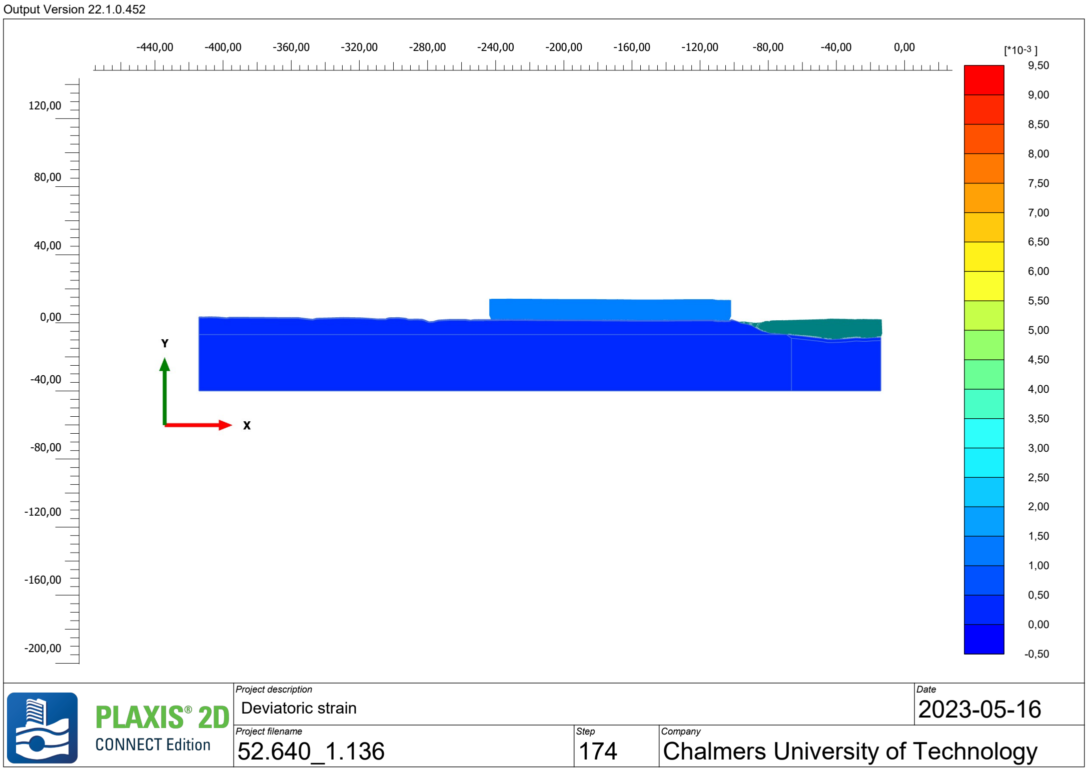
PLAXIS® 2D CONNECT Edition	Project description: Deviatoric strain		Date: 2023-05-16
	Project filename: 52.640_0.736	Step: 156	Company: Chalmers University of Technology

Output Version 22.1.0.452

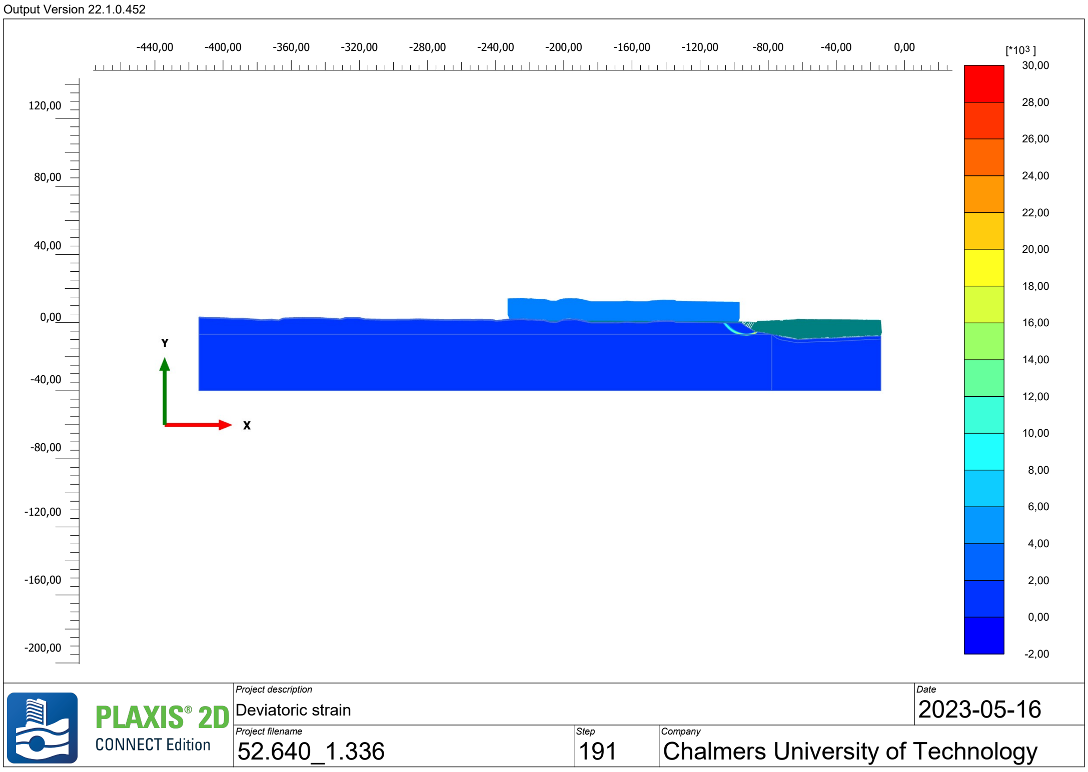


PLAXIS® 2D CONNECT Edition	Project description: Deviatoric strain		Date: 2023-05-16
	Project filename: 52.640_0.936	Step: 151	Company: Chalmers University of Technology

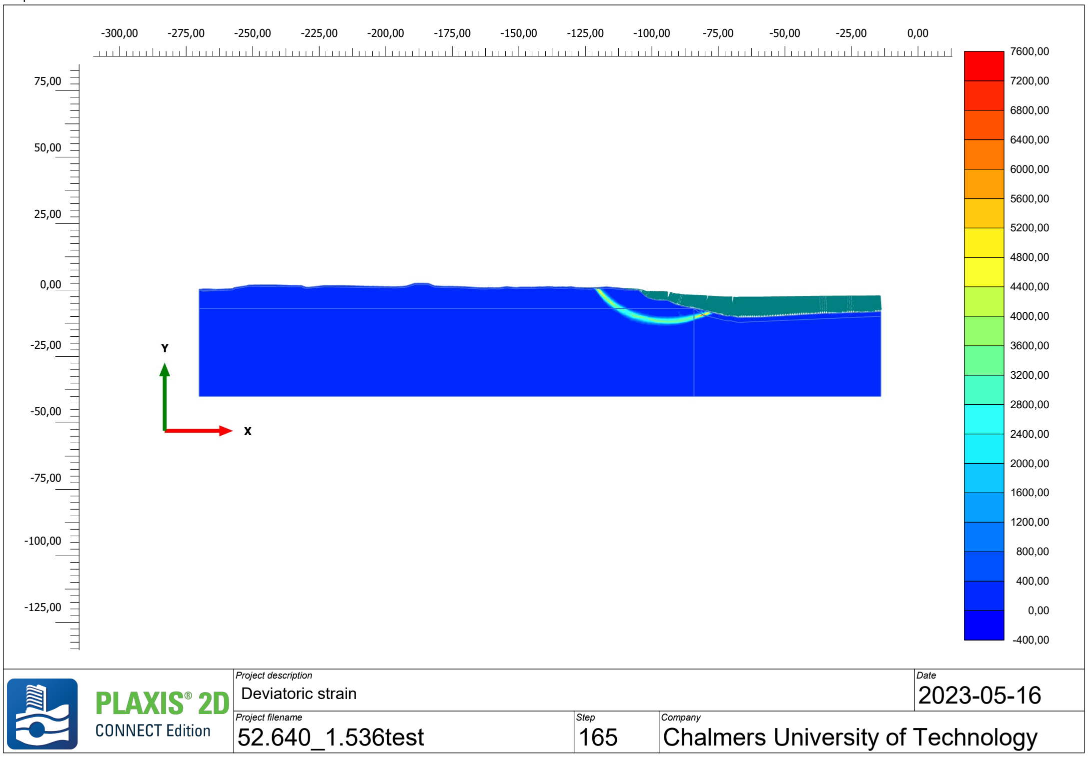
Output Version 22.1.0.452



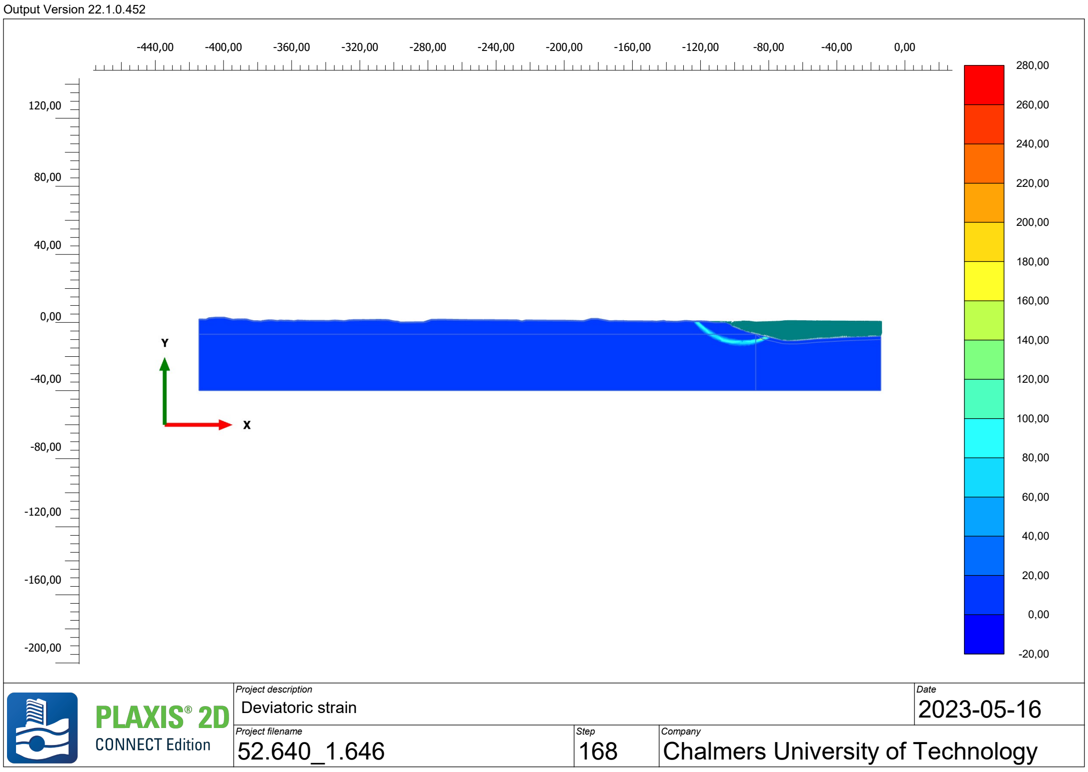
Output Version 22.1.0.452

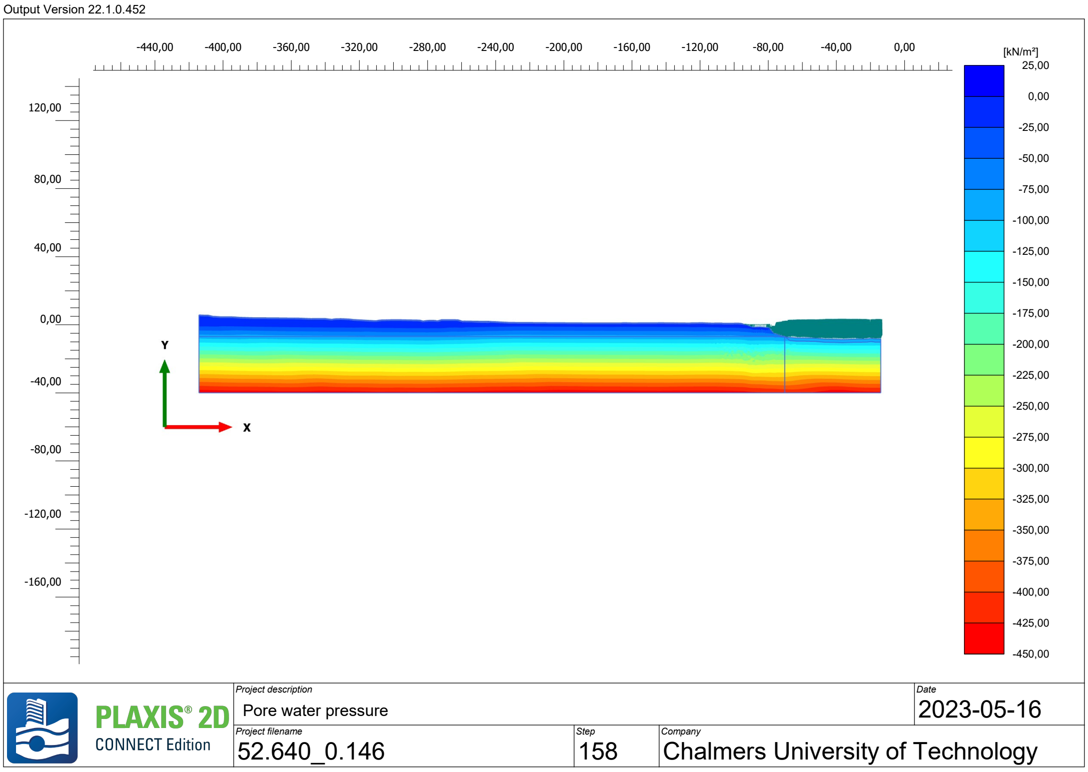


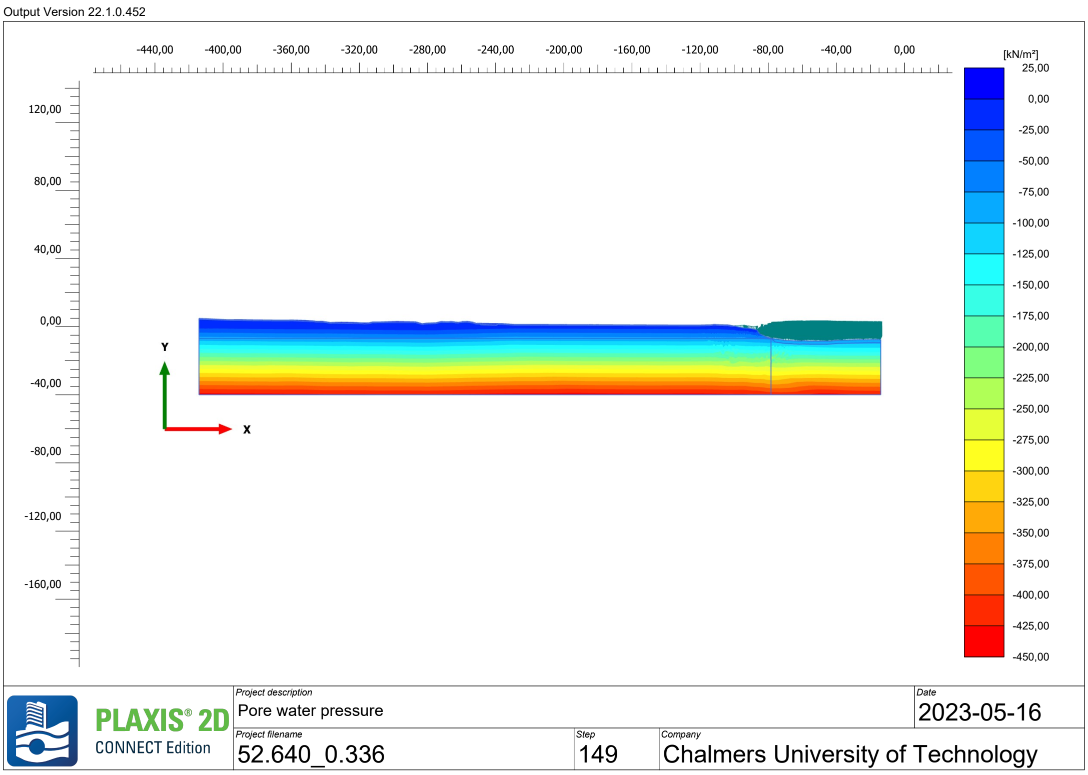
Output Version 22.1.0.452



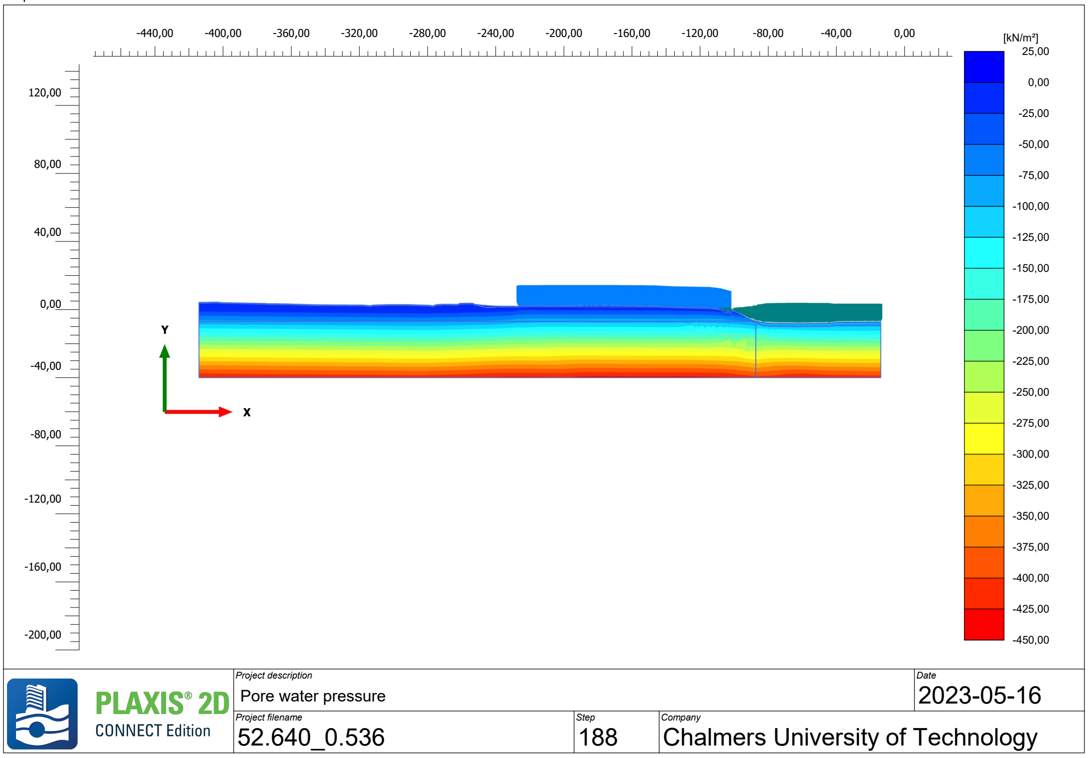
Output Version 22.1.0.452



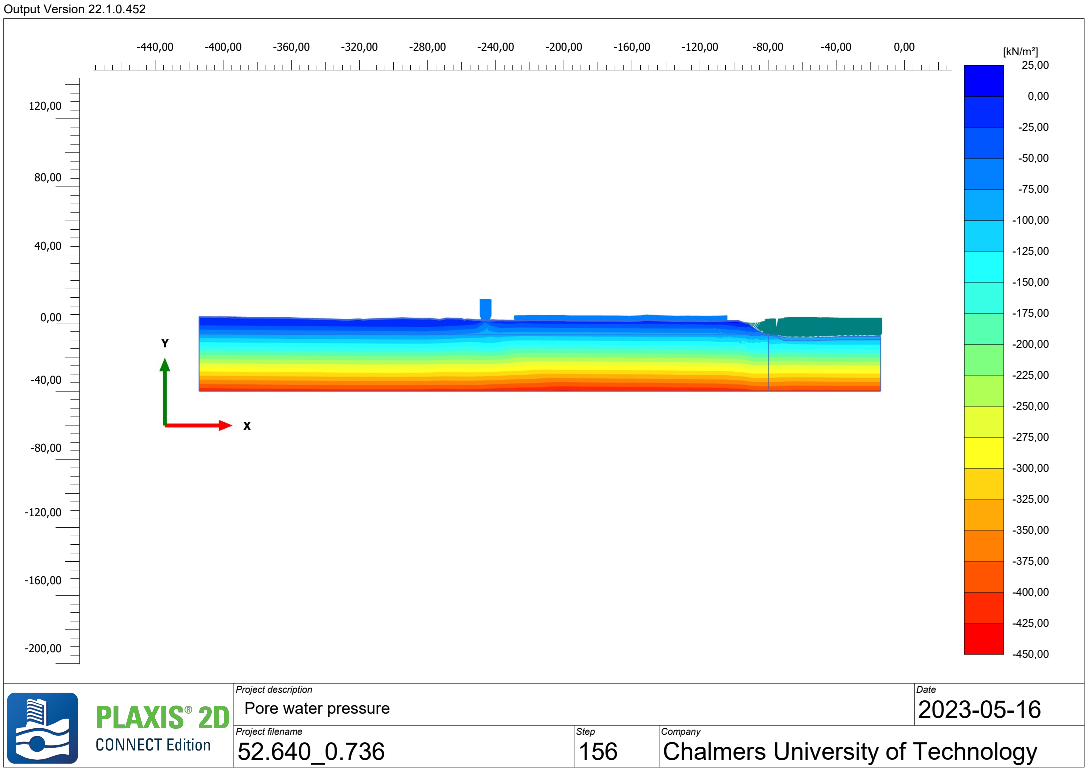

Output Version 22.1.0.452
-440,00
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[kN/m²]
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
-150,00
-175,00
-200,00
-225,00
-250,00
-275,00
-300,00
-325,00
-350,00
-375,00
-400,00
-425,00
-450,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
52.640_0.146
Step
158
Company
Chalmers University of Technology

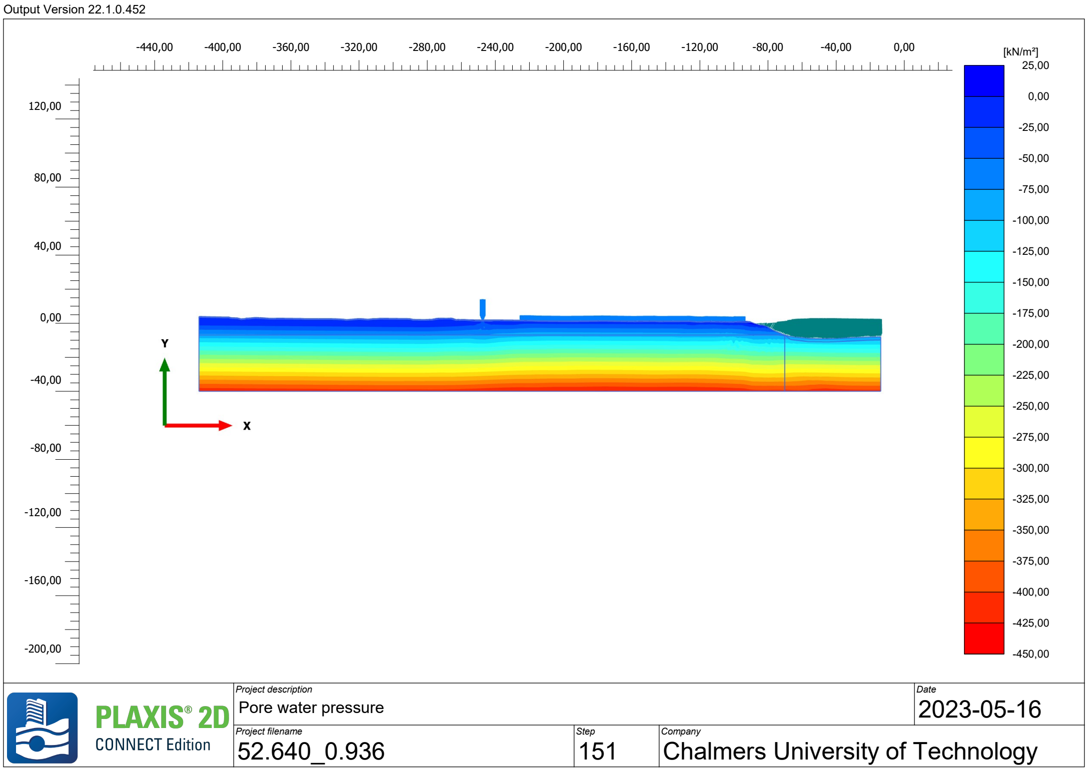

Output Version 22.1.0.452
-440,00
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[kN/m²]
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
-150,00
-175,00
-200,00
-225,00
-250,00
-275,00
-300,00
-325,00
-350,00
-375,00
-400,00
-425,00
-450,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
52.640_0.336
Step
149
Company
Chalmers University of Technology

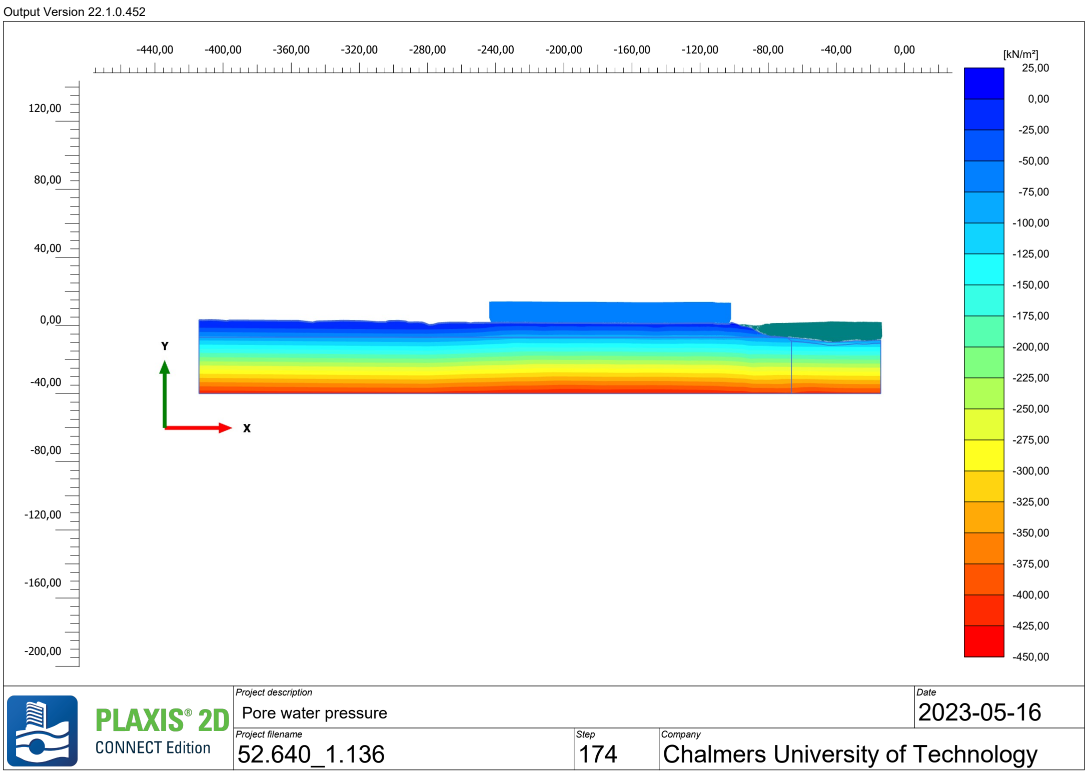
Output Version 22.1.0.452

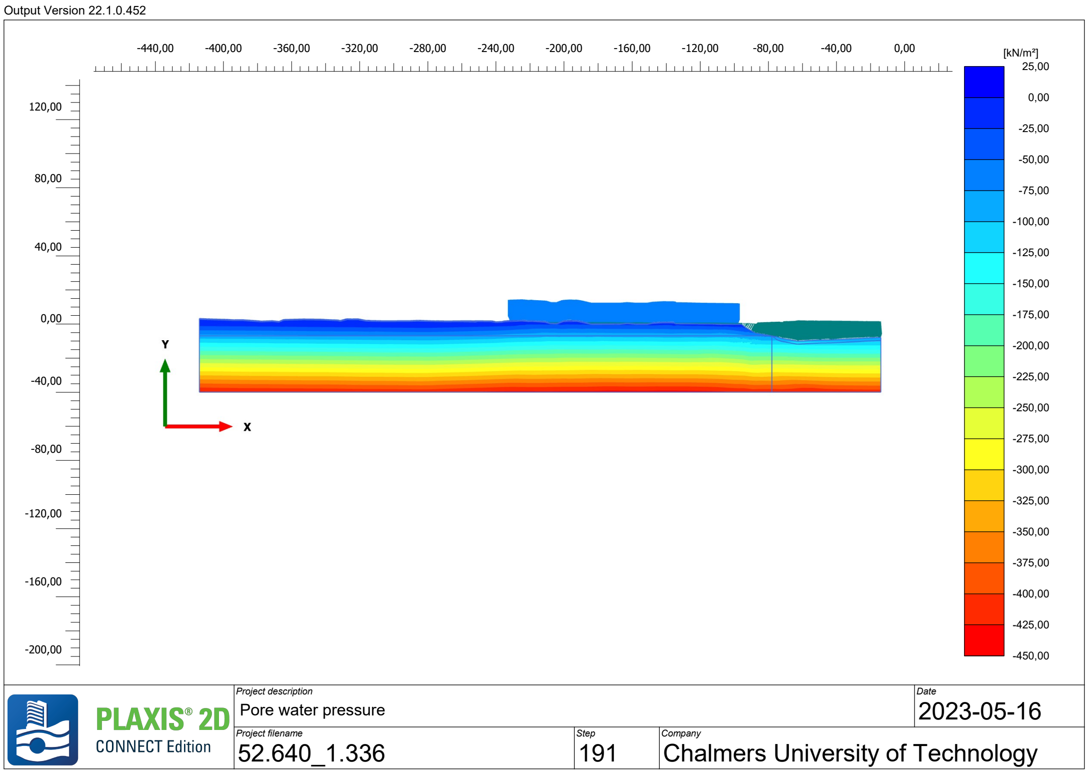


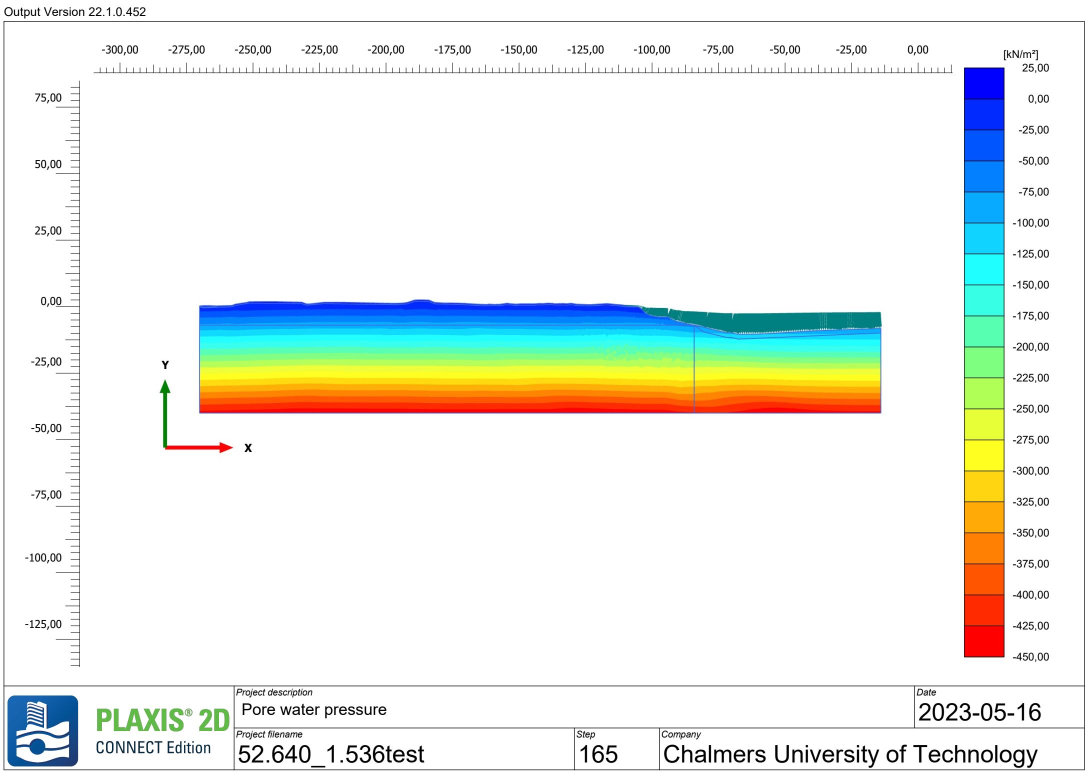
Output Version 22.1.0.452

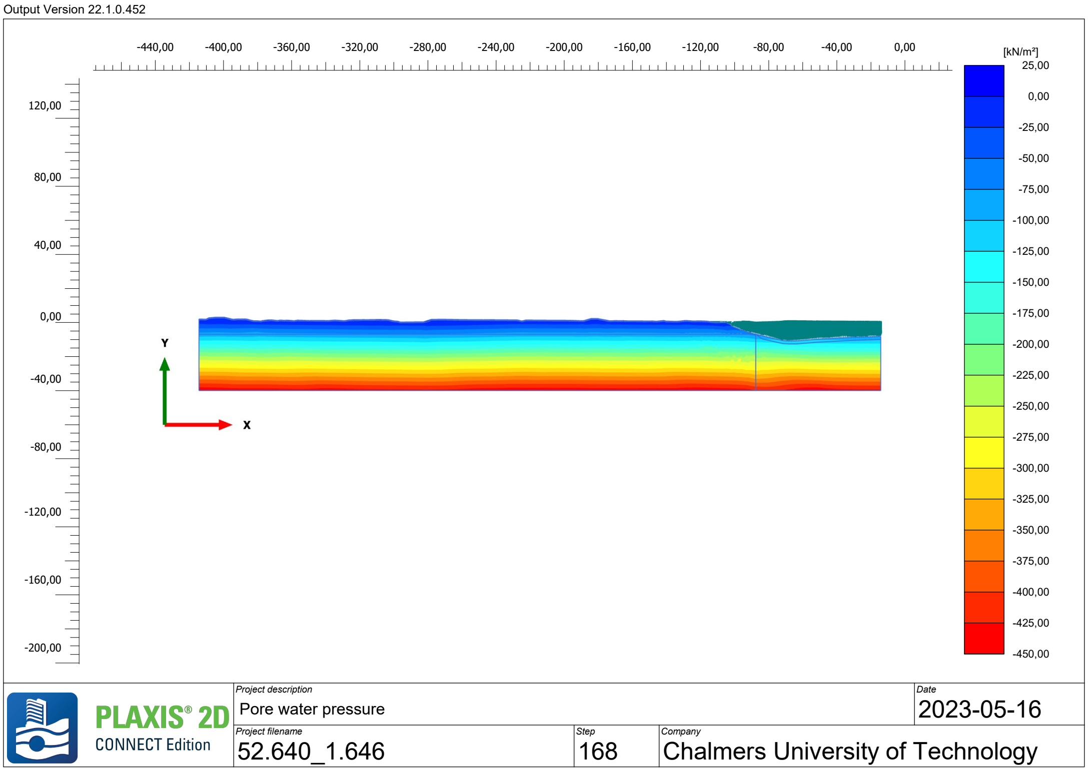



Output Version 22.1.0.452
-440,00 -400,00 -360,00 -320,00 -280,00 -240,00 -200,00 -160,00 -120,00 -80,00 -40,00 0,00
120,00 80,00 40,00 0,00 -40,00 -80,00 -120,00 -160,00 -200,00
Y
X
[kN/m²]
25,00 0,00 -25,00 -50,00 -75,00 -100,00 -125,00 -150,00 -175,00 -200,00 -225,00 -250,00 -275,00 -300,00 -325,00 -350,00 -375,00 -400,00 -425,00 -450,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
52.640_0.936
Step
151
Company
Chalmers University of Technology

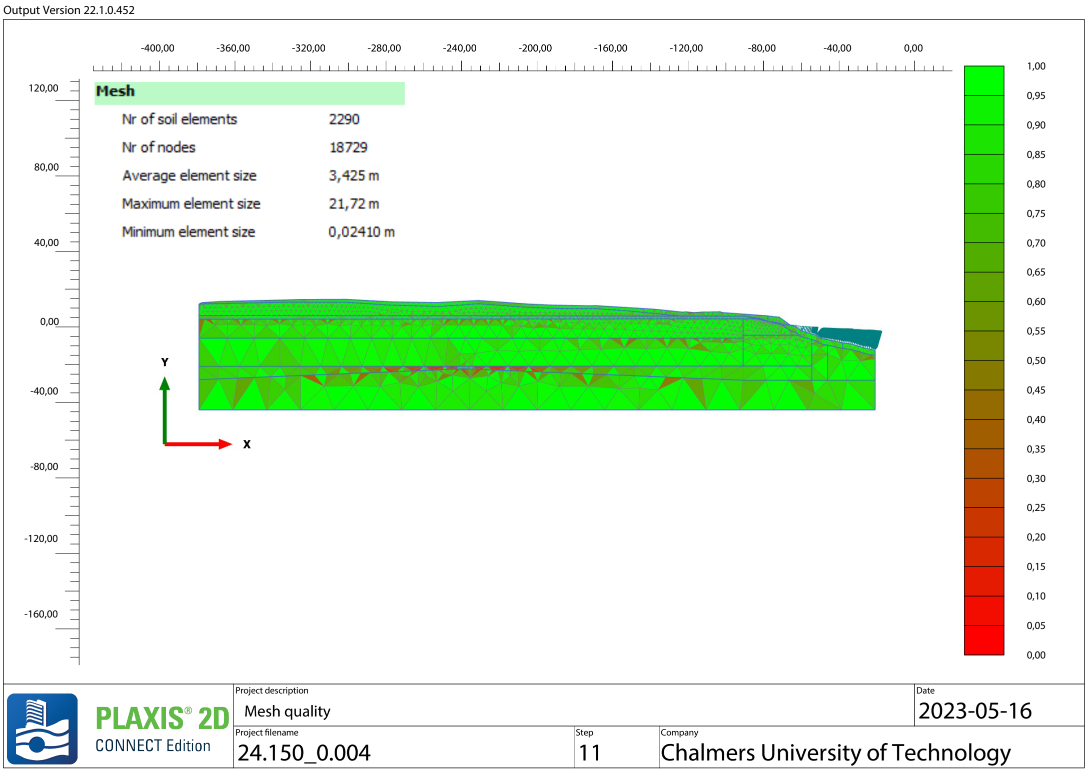

Output Version 22.1.0.452
-440,00 -400,00 -360,00 -320,00 -280,00 -240,00 -200,00 -160,00 -120,00 -80,00 -40,00 0,00
120,00 80,00 40,00 0,00 -40,00 -80,00 -120,00 -160,00 -200,00
Y
X
[kN/m²]
25,00 0,00 -25,00 -50,00 -75,00 -100,00 -125,00 -150,00 -175,00 -200,00 -225,00 -250,00 -275,00 -300,00 -325,00 -350,00 -375,00 -400,00 -425,00 -450,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
52.640_1.136
Step
174
Company
Chalmers University of Technology

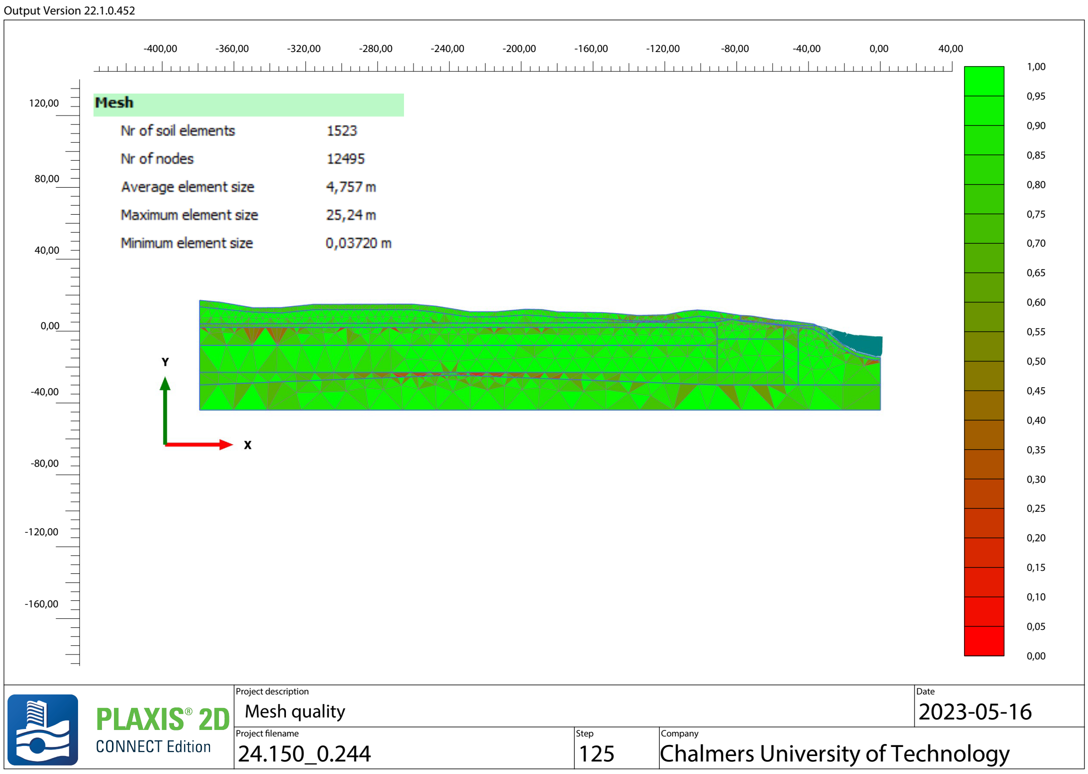

Output Version 22.1.0.452
-440,00
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
-200,00
Y
X
[kN/m²]
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
-150,00
-175,00
-200,00
-225,00
-250,00
-275,00
-300,00
-325,00
-350,00
-375,00
-400,00
-425,00
-450,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
52.640_1.336
Step
191
Company
Chalmers University of Technology

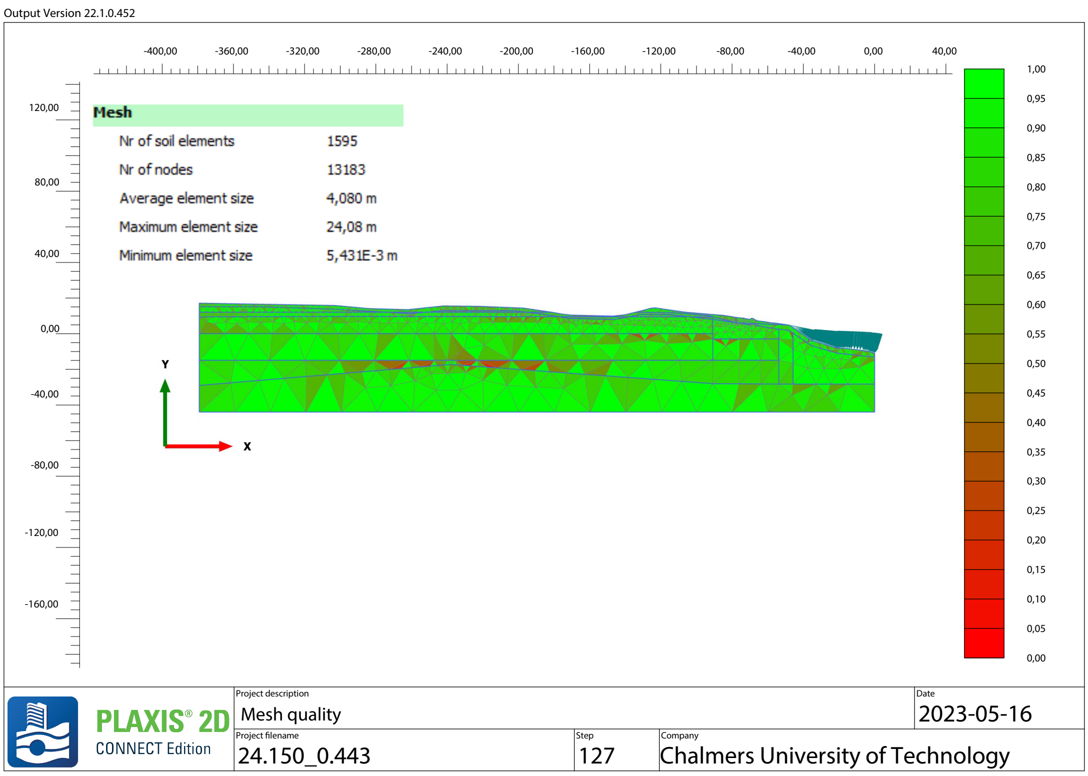

Output Version 22.1.0.452
-300,00
-275,00
-250,00
-225,00
-200,00
-175,00
-150,00
-125,00
-100,00
-75,00
-50,00
-25,00
0,00
75,00
50,00
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
Y
X
[kN/m²]
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
-150,00
-175,00
-200,00
-225,00
-250,00
-275,00
-300,00
-325,00
-350,00
-375,00
-400,00
-425,00
-450,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
52.640_1.536test
Step
165
Company
Chalmers University of Technology

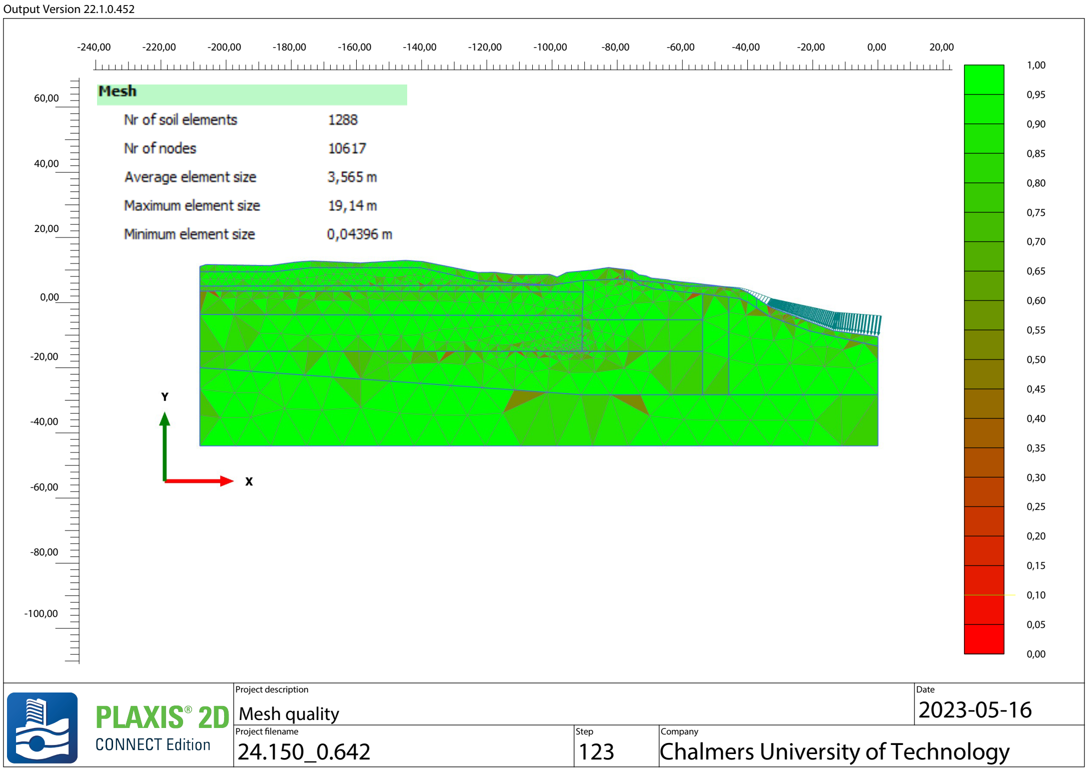

Output Version 22.1.0.452
-440,00
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
-200,00
Y
X
[kN/m²]
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
-150,00
-175,00
-200,00
-225,00
-250,00
-275,00
-300,00
-325,00
-350,00
-375,00
-400,00
-425,00
-450,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
52.640_1.646
Step
168
Company
Chalmers University of Technology

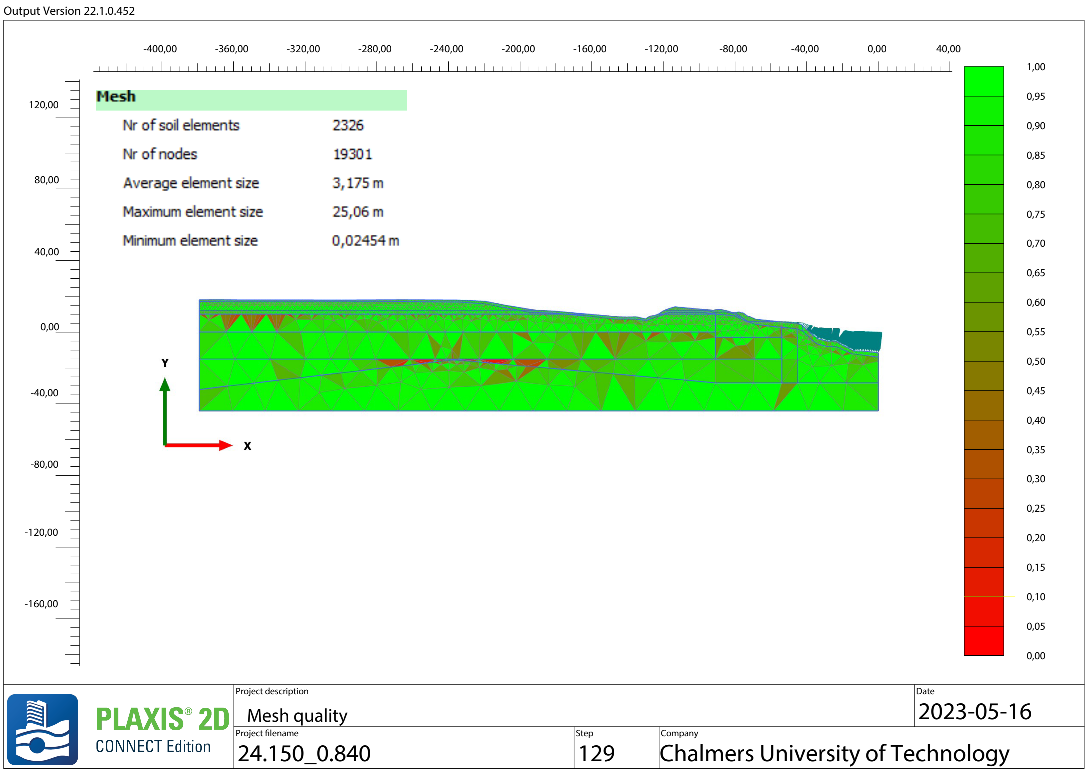
Appendix M – Automated Plaxis Analysis Section 24/150

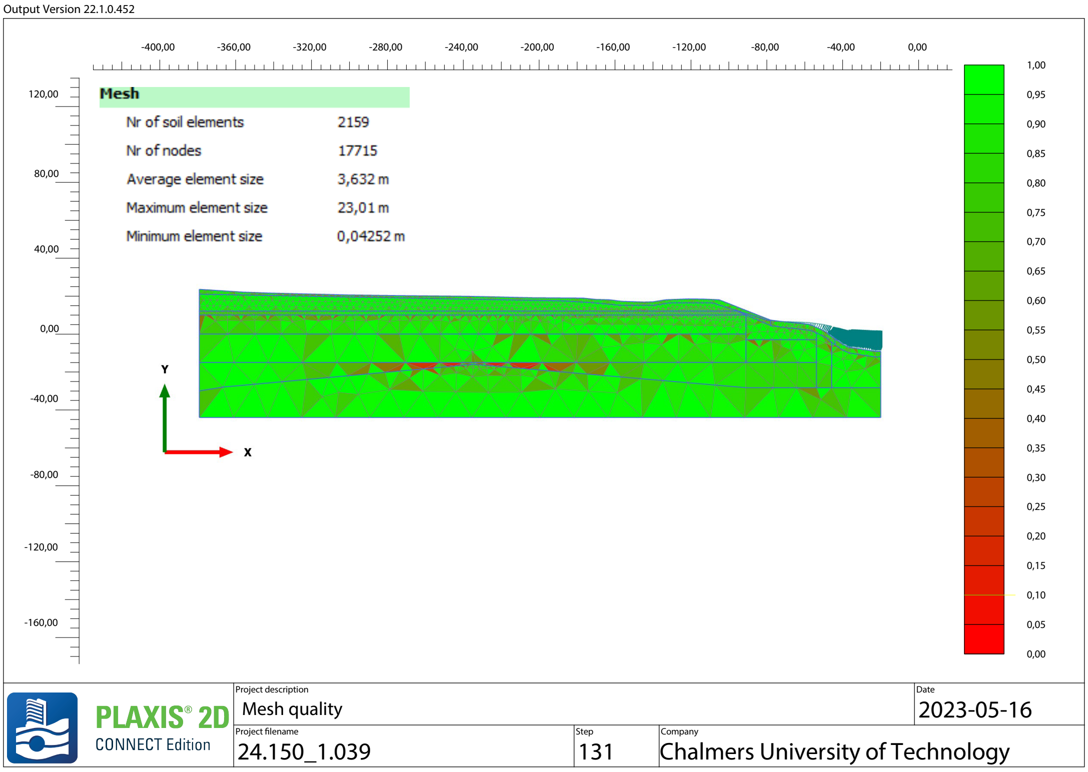


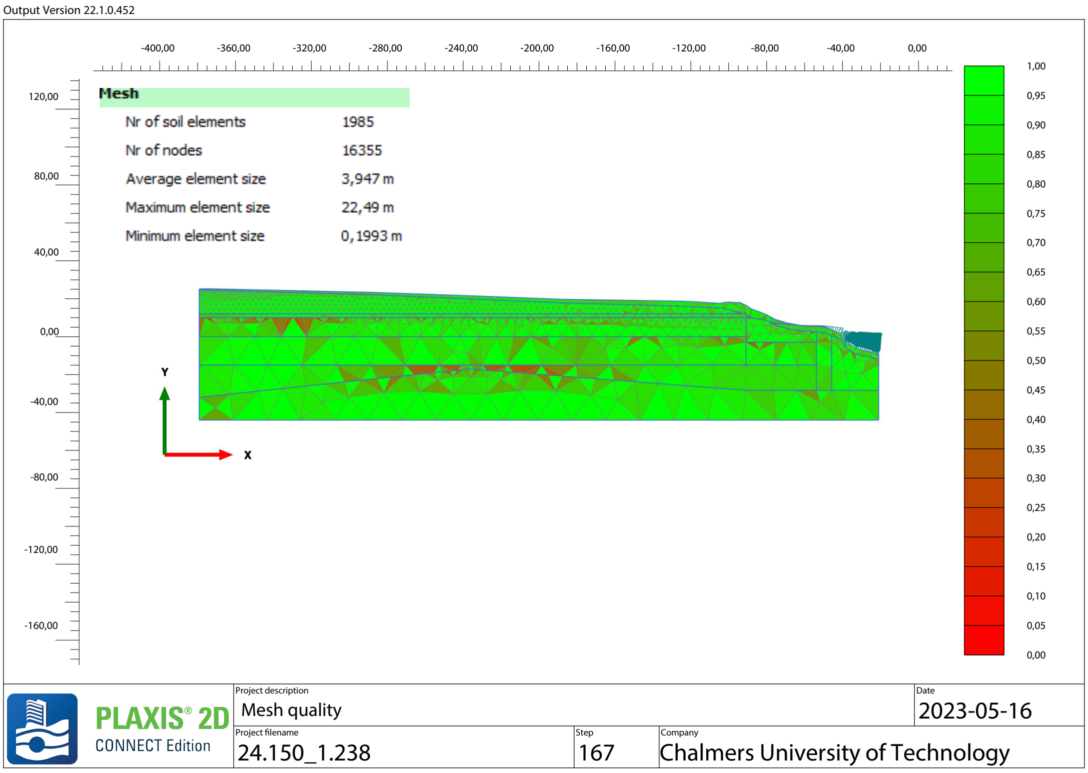

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
40,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Mesh
Nr of soil elements 1523
Nr of nodes 12495
Average element size 4,757 m
Maximum element size 25,24 m
Minimum element size 0,03720 m
Y
X
1,00
0,95
0,90
0,85
0,80
0,75
0,70
0,65
0,60
0,55
0,50
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Date
2023-05-16
Project filename
24.150_0.244
Step
125
Company
Chalmers University of Technology

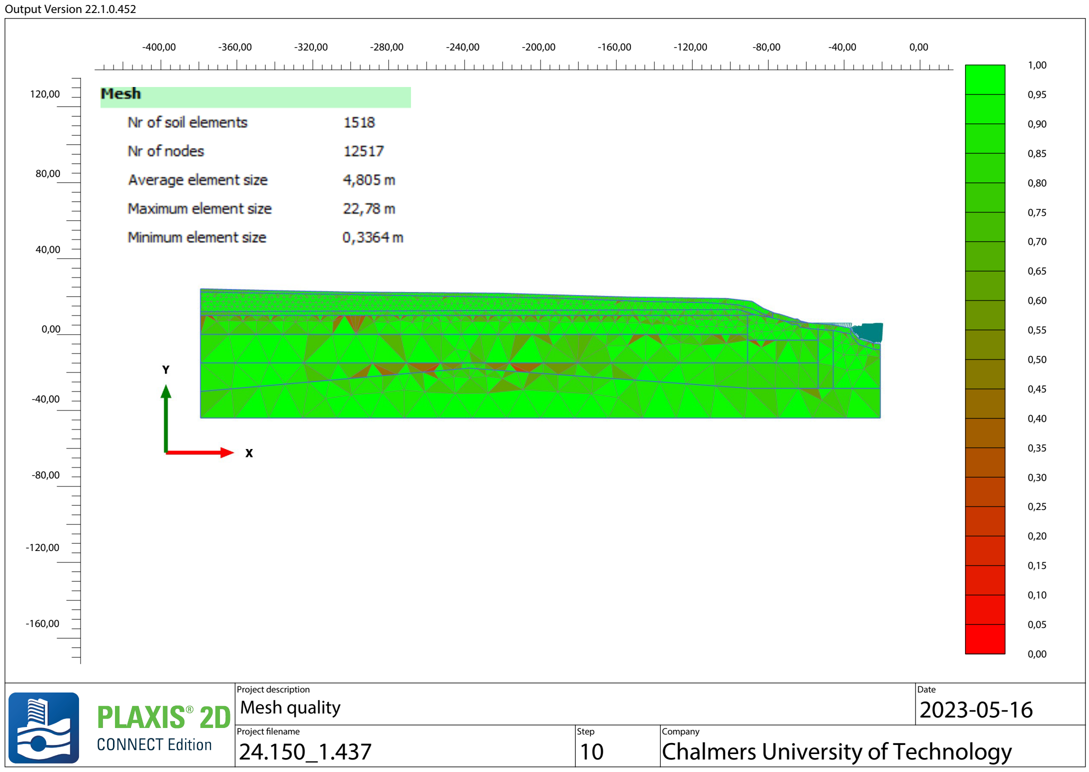

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
40,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Mesh
Nr of soil elements 1595
Nr of nodes 13183
Average element size 4,080 m
Maximum element size 24,08 m
Minimum element size 5,431E-3 m
Y
X
1,00
0,95
0,90
0,85
0,80
0,75
0,70
0,65
0,60
0,55
0,50
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Date
2023-05-16
Project filename
24.150_0.443
Step
127
Company
Chalmers University of Technology

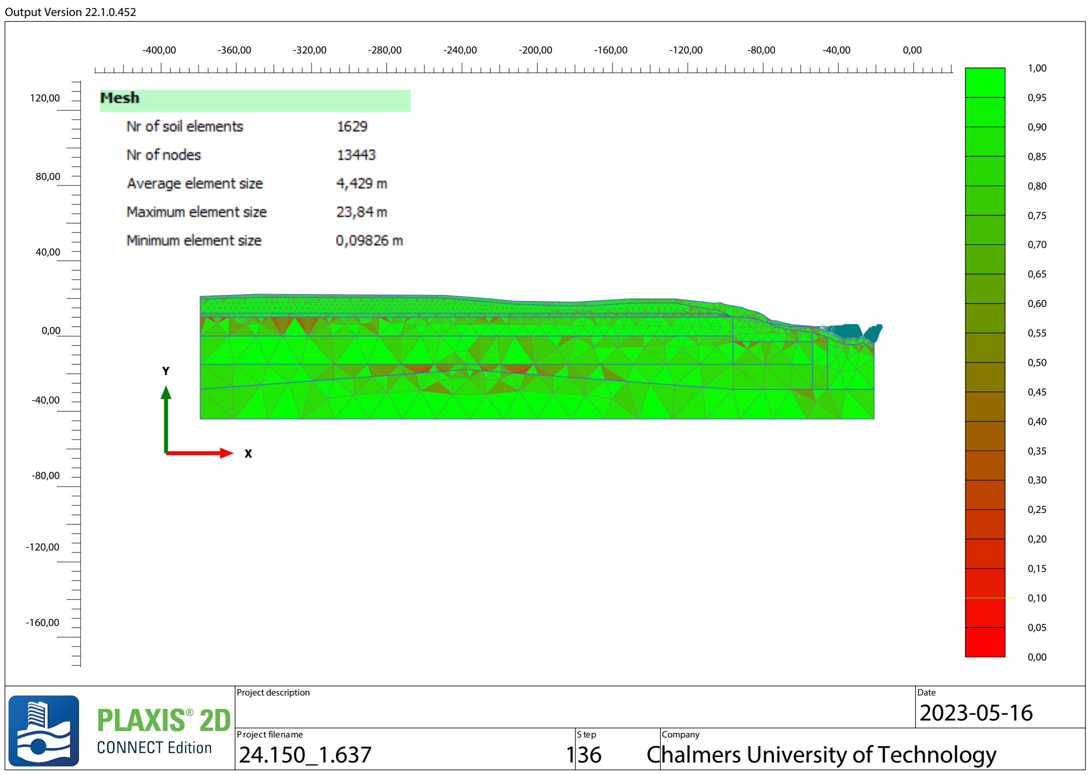

Output Version 22.1.0.452
Mesh
Nr of soil elements 1288
Nr of nodes 10617
Average element size 3,565 m
Maximum element size 19,14 m
Minimum element size 0,04396 m
Y
X
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Project filename
24.150_0.642
Step
123
Company
Chalmers University of Technology
Date
2023-05-16

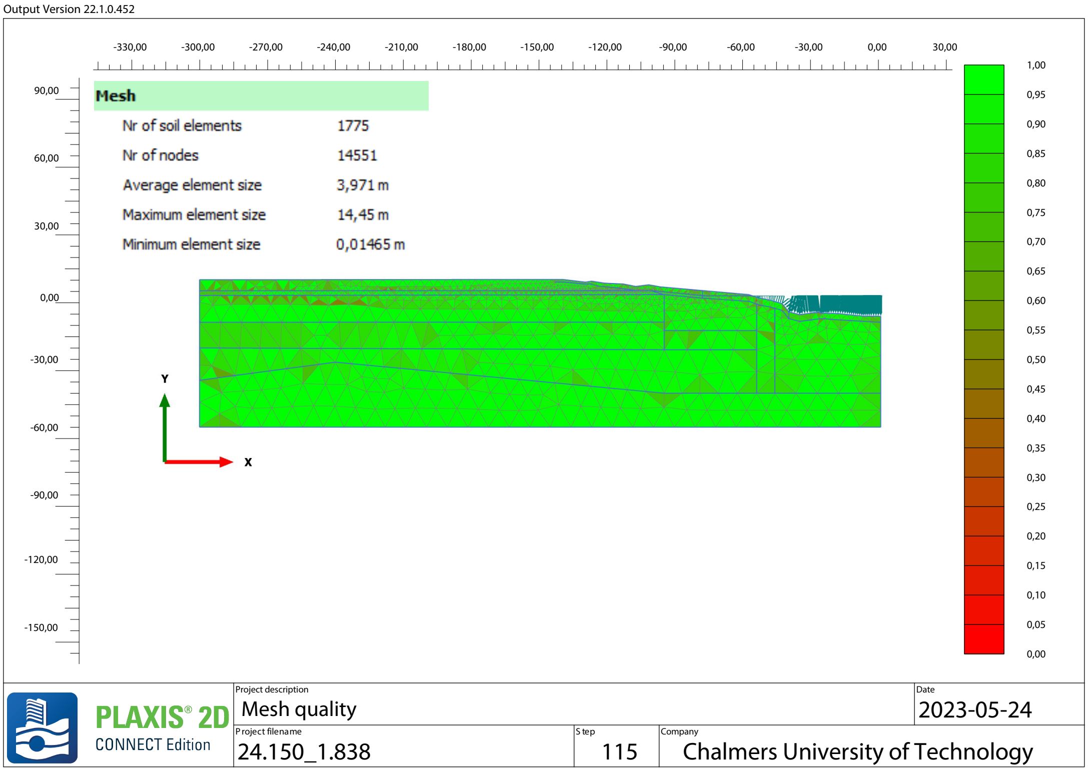

Output Version 22.1.0.452
Mesh
Nr of soil elements 2326
Nr of nodes 19301
Average element size 3,175 m
Maximum element size 25,06 m
Minimum element size 0,02454 m
Y
X
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Project filename
24.150_0.840
Step
129
Company
Chalmers University of Technology
Date
2023-05-16

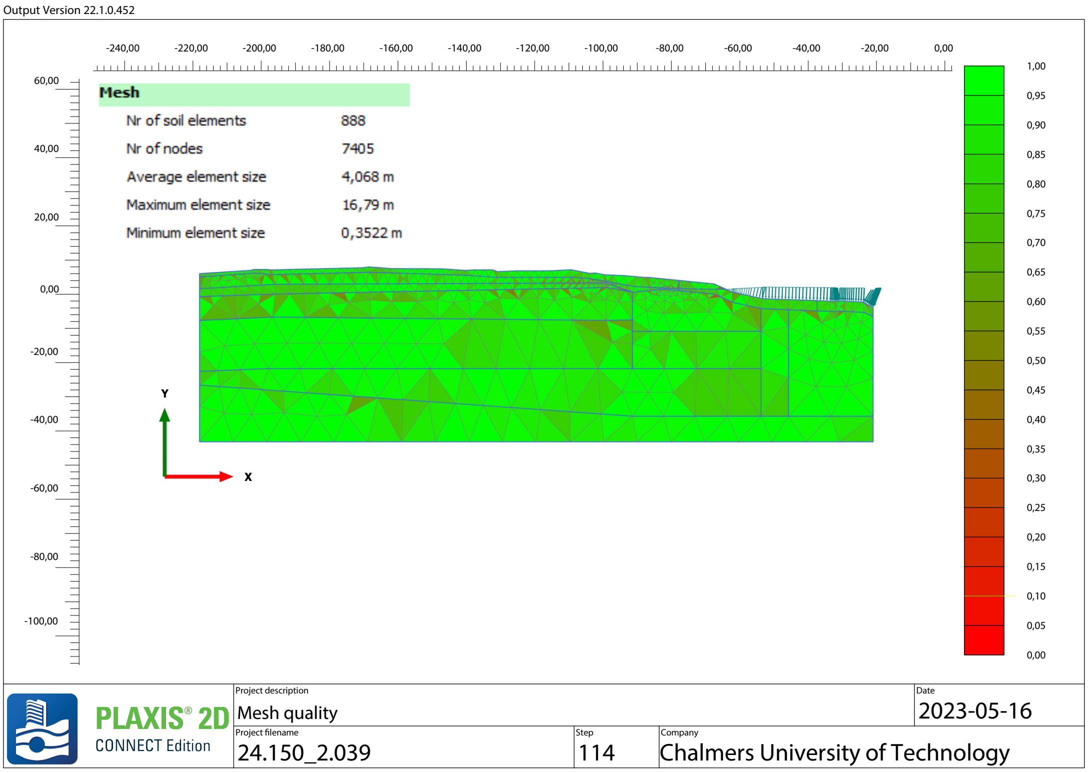

Output Version 22.1.0.452
Mesh
Nr of soil elements 2159
Nr of nodes 17715
Average element size 3,632 m
Maximum element size 23,01 m
Minimum element size 0,04252 m
Y
X
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Project filename
24.150_1.039
Step
131
Company
Chalmers University of Technology
Date
2023-05-16

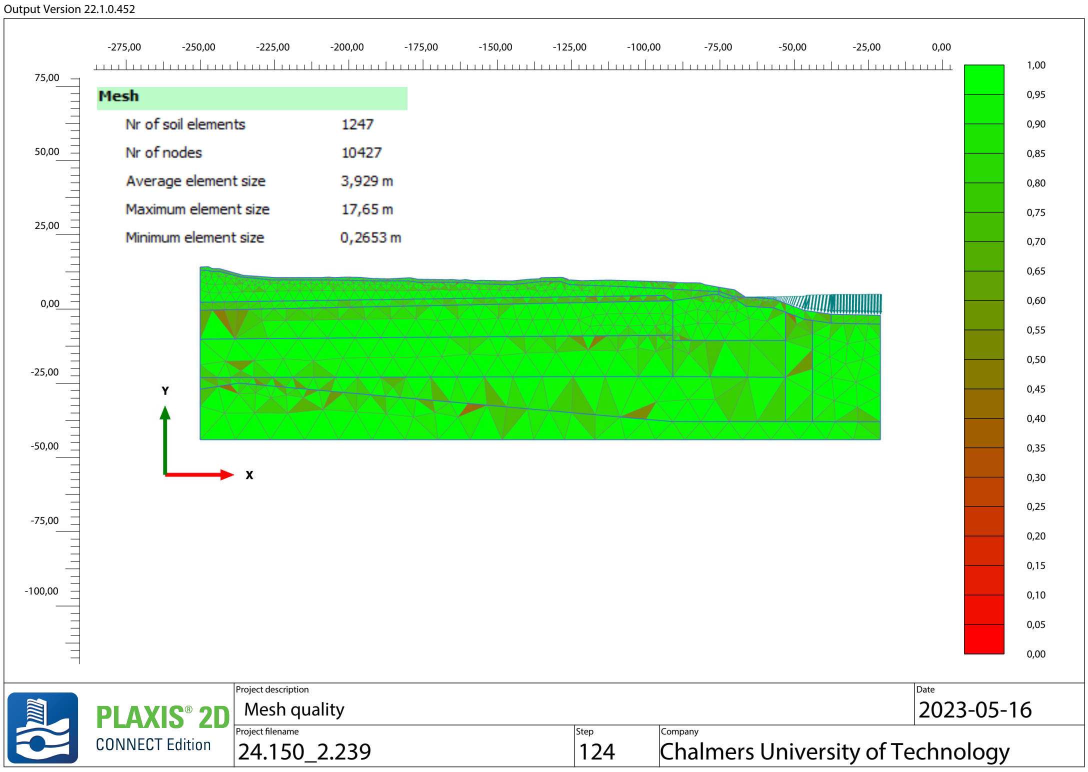

Output Version 22.1.0.452
Mesh
Nr of soil elements 1985
Nr of nodes 16355
Average element size 3,947 m
Maximum element size 22,49 m
Minimum element size 0,1993 m
Y
X
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Project filename
24.150_1.238
Step
167
Company
Chalmers University of Technology
Date
2023-05-16

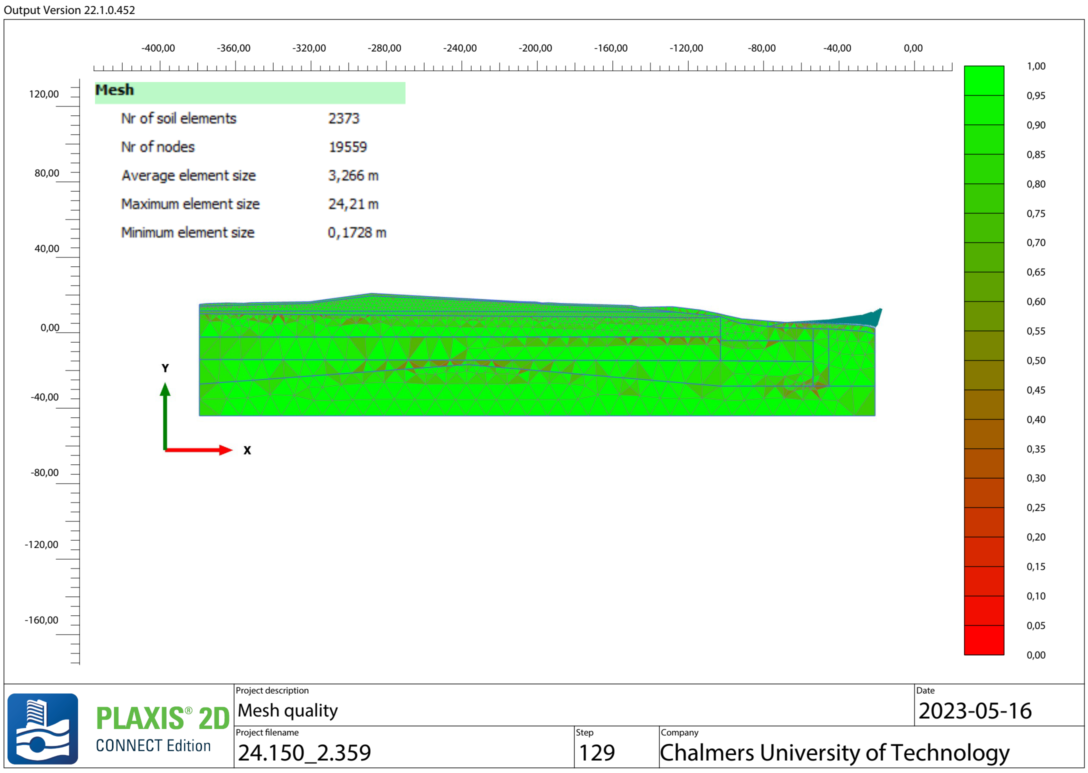

Output Version 22.1.0.452
Mesh
Nr of soil elements 1518
Nr of nodes 12517
Average element size 4,805 m
Maximum element size 22,78 m
Minimum element size 0,3364 m
Y
X
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Date
2023-05-16
Project filename
24.150_1.437
Step
10
Company
Chalmers University of Technology

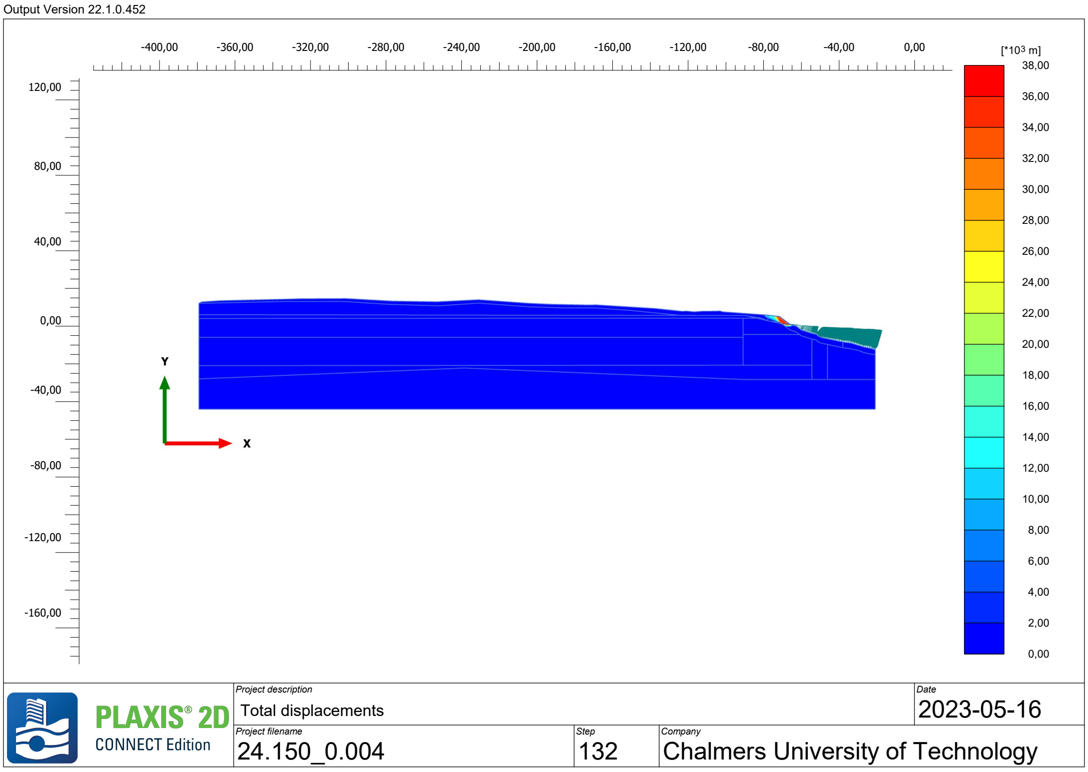

Output Version 22.1.0.452
Mesh
Nr of soil elements 1629
Nr of nodes 13443
Average element size 4,429 m
Maximum element size 23,84 m
Minimum element size 0,09826 m
Y
X
PLAXIS® 2D
CONNECT Edition
Project description
Date
2023-05-16
Project filename
24.150_1.637
Step
136
Company
Chalmers University of Technology

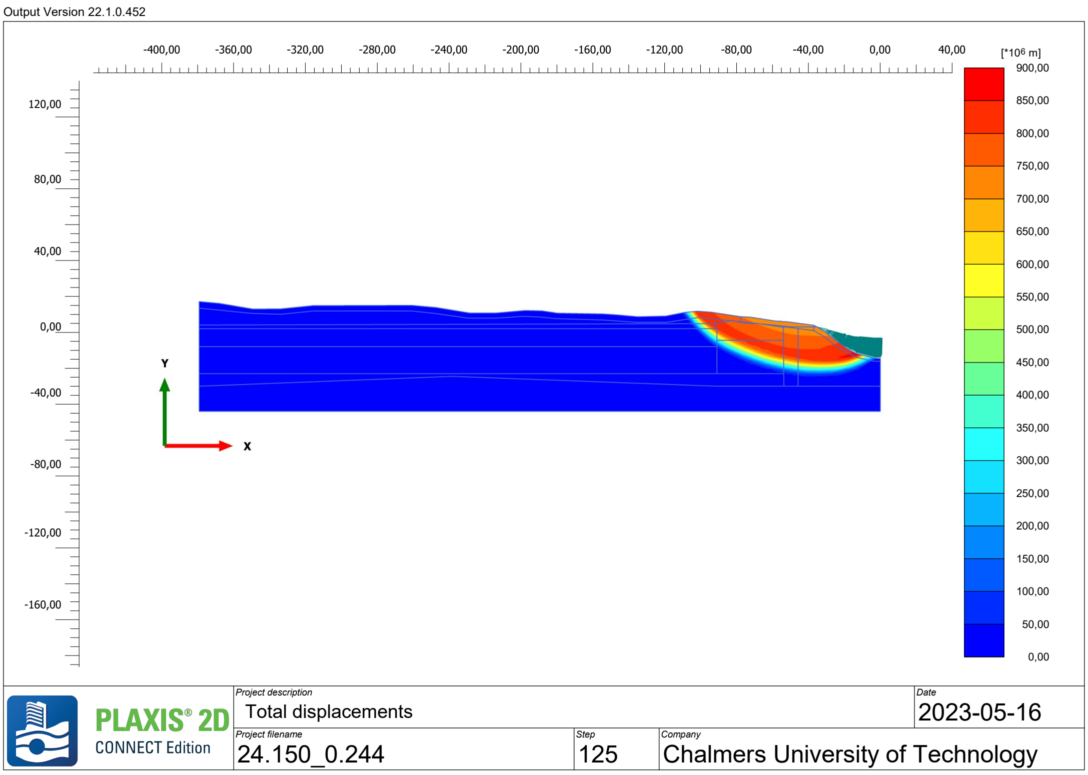

Output Version 22.1.0.452
Mesh
Nr of soil elements 1775
Nr of nodes 14551
Average element size 3,971 m
Maximum element size 14,45 m
Minimum element size 0,01465 m
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Date
2023-05-24
Project filename
24.150_1.838
Step
115
Company
Chalmers University of Technology

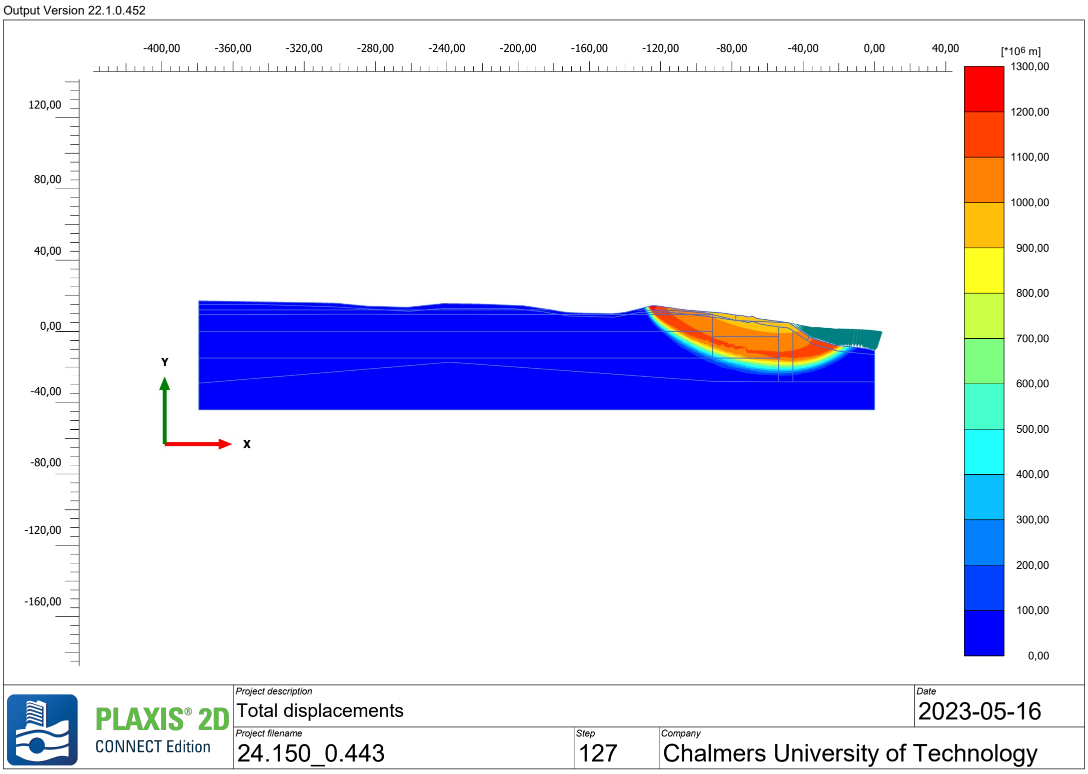

Output Version 22.1.0.452
Mesh
Nr of soil elements 888
Nr of nodes 7405
Average element size 4,068 m
Maximum element size 16,79 m
Minimum element size 0,3522 m
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Date
2023-05-16
Project filename
24.150_2.039
Step
114
Company
Chalmers University of Technology

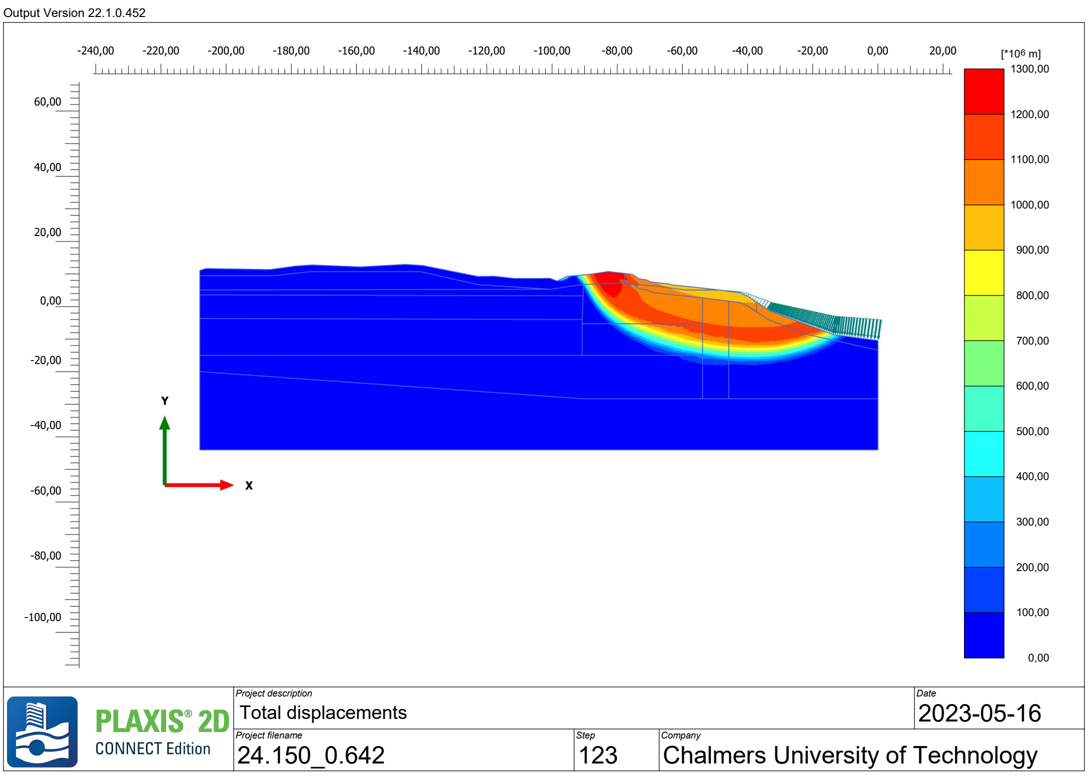

Output Version 22.1.0.452
Mesh
Nr of soil elements 1247
Nr of nodes 10427
Average element size 3,929 m
Maximum element size 17,65 m
Minimum element size 0,2653 m
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Project filename
24.150_2.239
Step
124
Company
Chalmers University of Technology
Date
2023-05-16


Output Version 22.1.0.452
Mesh
Nr of soil elements 2373
Nr of nodes 19559
Average element size 3,266 m
Maximum element size 24,21 m
Minimum element size 0,1728 m
PLAXIS® 2D
CONNECT Edition
Project description
Mesh quality
Project filename
24.150_2.359
Step
129
Company
Chalmers University of Technology
Date
2023-05-16


Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10³ m]
38,00
36,00
34,00
32,00
30,00
28,00
26,00
24,00
22,00
20,00
18,00
16,00
14,00
12,00
10,00
8,00
6,00
4,00
2,00
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-16
Project filename
24.150_0.004
Step
132
Company
Chalmers University of Technology


Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
40,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10⁶ m]
900,00
850,00
800,00
750,00
700,00
650,00
600,00
550,00
500,00
450,00
400,00
350,00
300,00
250,00
200,00
150,00
100,00
50,00
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-16
Project filename
24.150_0.244
Step
125
Company
Chalmers University of Technology


Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
40,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
[*10⁶ m]
1300,00
1200,00
1100,00
1000,00
900,00
800,00
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
Y
X
PLAXIS 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-16
Project filename
24.150_0.443
Step
127
Company
Chalmers University of Technology


Output Version 22.1.0.452
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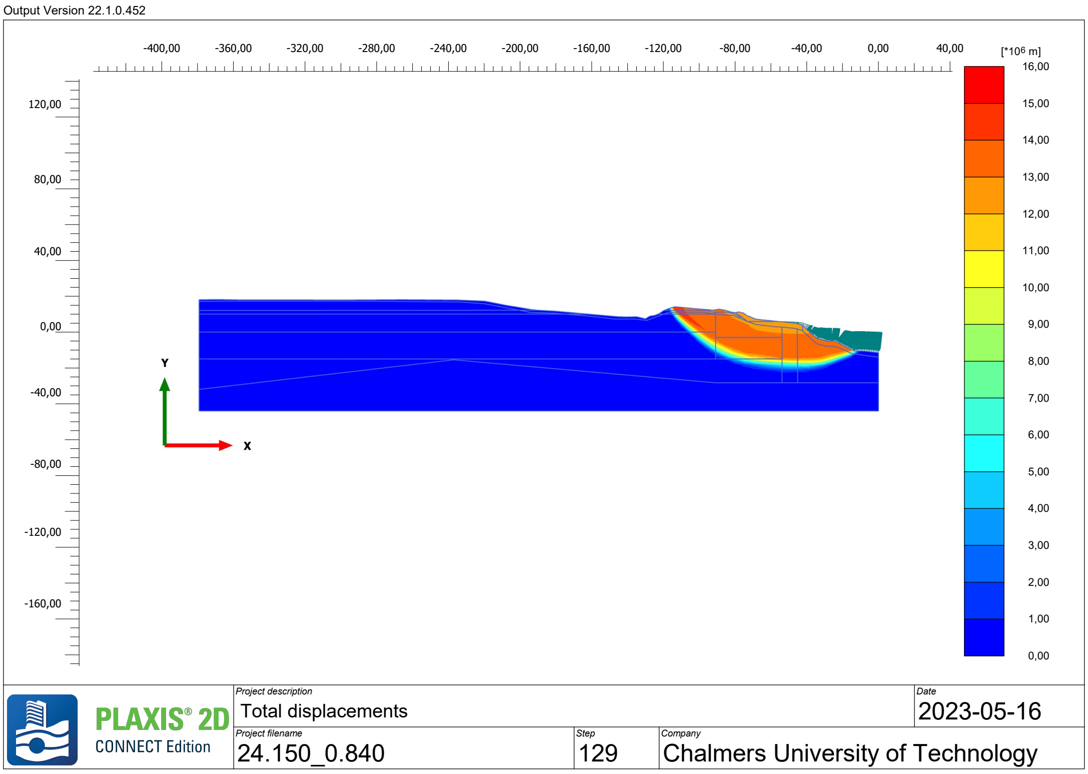
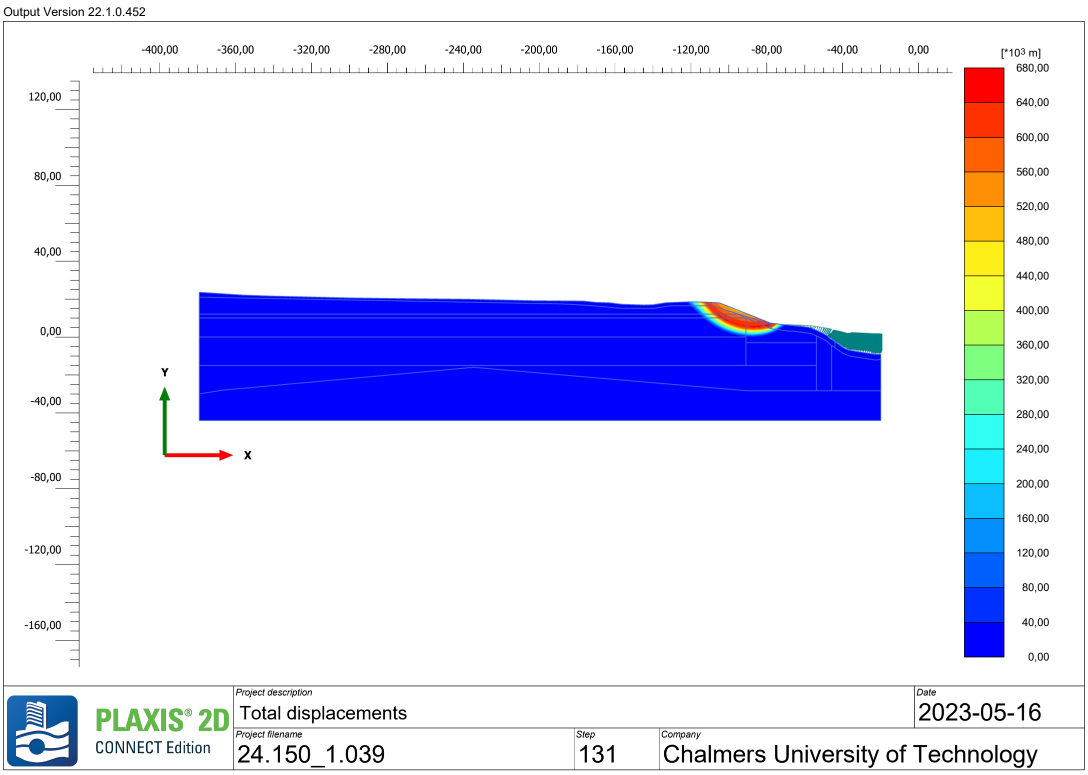
-220,00
-200,00
-180,00
-160,00
-140,00
-120,00
-100,00
-80,00
-60,00
-40,00
-20,00
0,00
20,00
60,00
40,00
20,00
0,00
-20,00
-40,00
-60,00
-80,00
-100,00
[*10⁶ m]
1300,00
1200,00
1100,00
1000,00
900,00
800,00
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
Y
X
PLAXIS 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-16
Project filename
24.150_0.642
Step
123
Company
Chalmers University of Technology


Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
40,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10⁶ m]
16,00
15,00
14,00
13,00
12,00
11,00
10,00
9,00
8,00
7,00
6,00
5,00
4,00
3,00
2,00
1,00
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-16
Project filename
24.150_0.840
Step
129
Company
Chalmers University of Technology


Output Version 22.1.0.452
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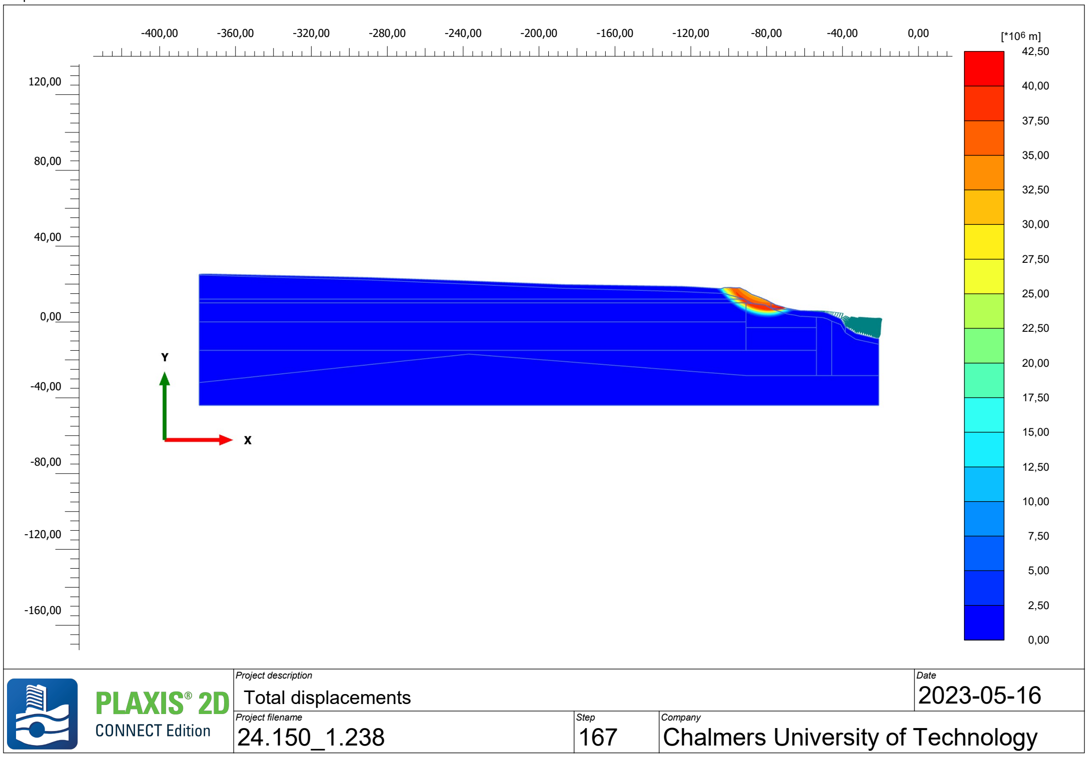
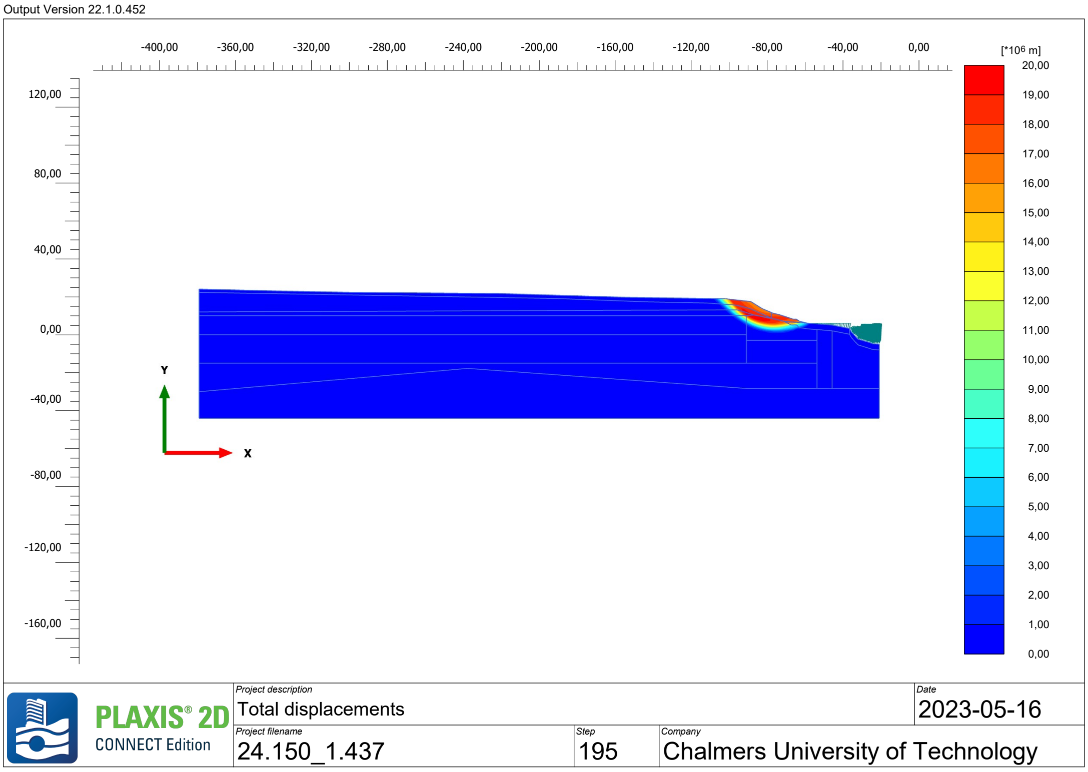
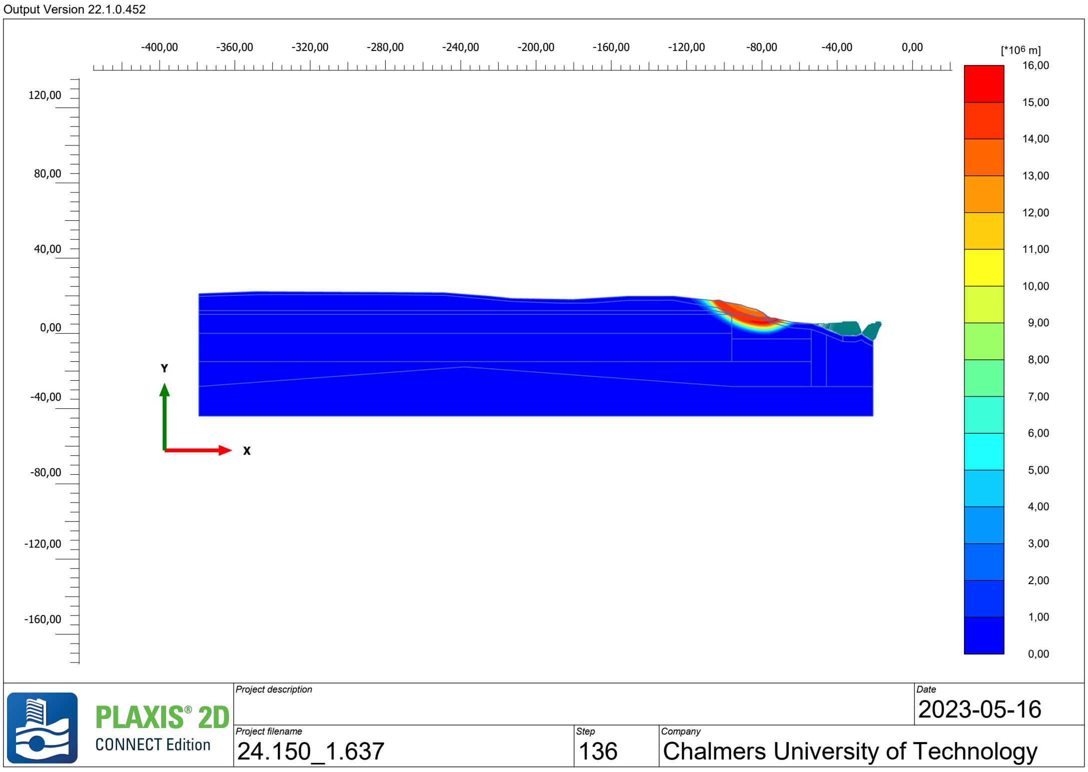
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10³ m]
680,00
640,00
600,00
560,00
520,00
480,00
440,00
400,00
360,00
320,00
280,00
240,00
200,00
160,00
120,00
80,00
40,00
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-16
Project filename
24.150_1.039
Step
131
Company
Chalmers University of Technology

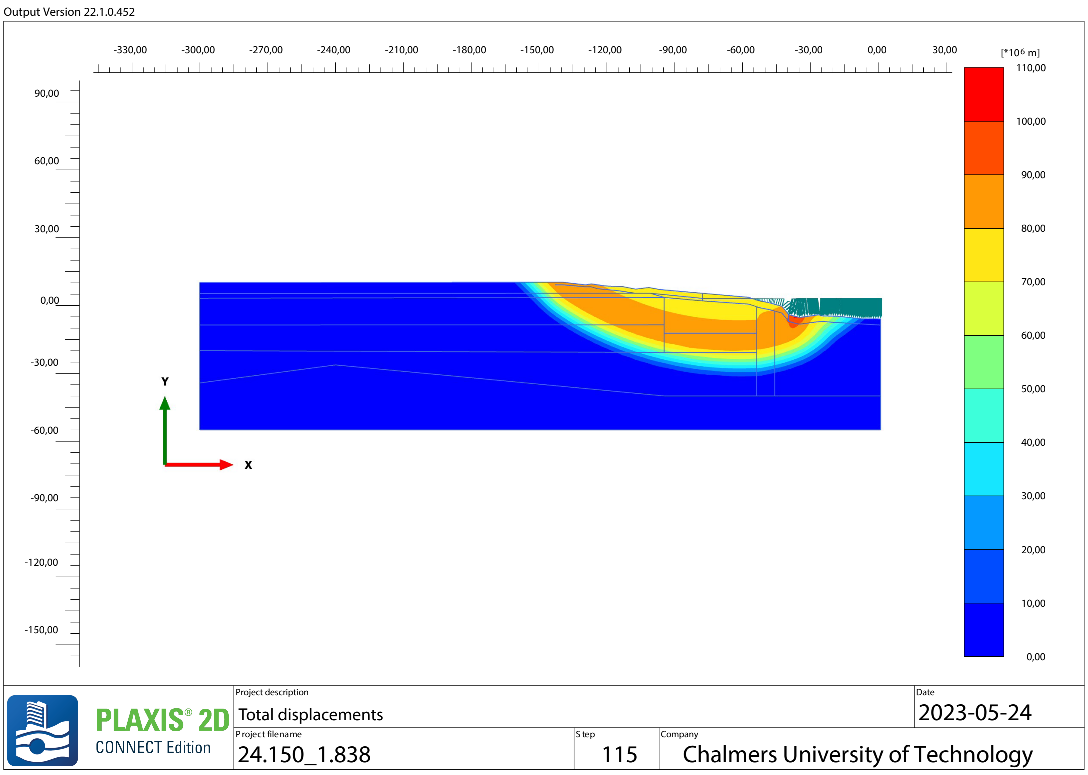
Output Version 22.1.0.452



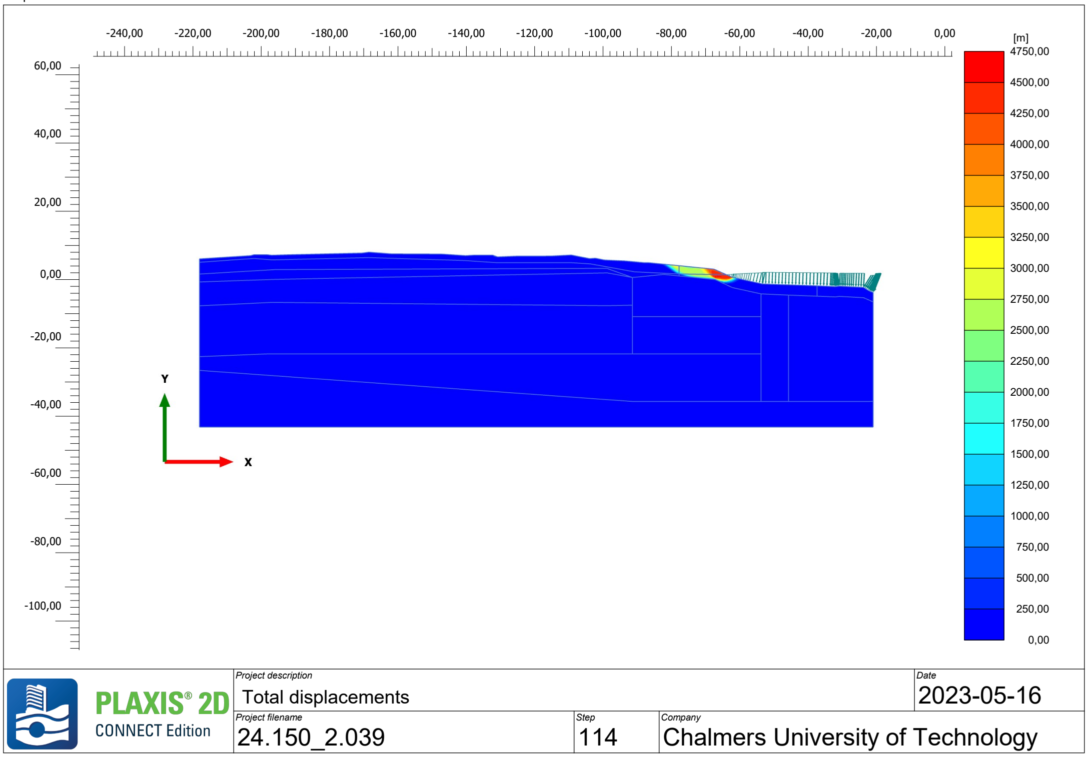
Output Version 22.1.0.452



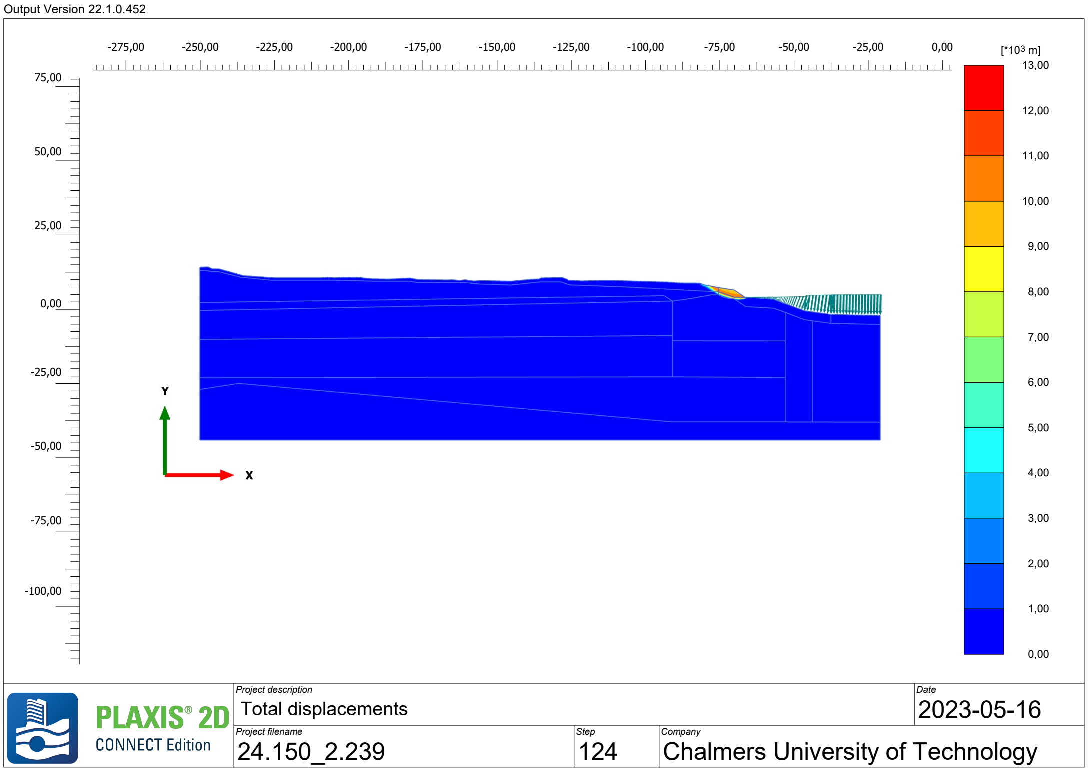

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10⁶ m]
16,00
15,00
14,00
13,00
12,00
11,00
10,00
9,00
8,00
7,00
6,00
5,00
4,00
3,00
2,00
1,00
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Date
2023-05-16
Project filename
24.150_1.637
Step
136
Company
Chalmers University of Technology


Output Version 22.1.0.452
-330,00
-300,00
-270,00
-240,00
-210,00
-180,00
-150,00
-120,00
-90,00
-60,00
-30,00
0,00
30,00
90,00
60,00
30,00
0,00
-30,00
-60,00
-90,00
-120,00
-150,00
Y
X
[*10⁶ m]
110,00
100,00
90,00
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
PLAXIS® 2D
CONNECT Edition
Project description
Total displacements
Date
2023-05-24
Project filename
24.150_1.838
Step
115
Company
Chalmers University of Technology

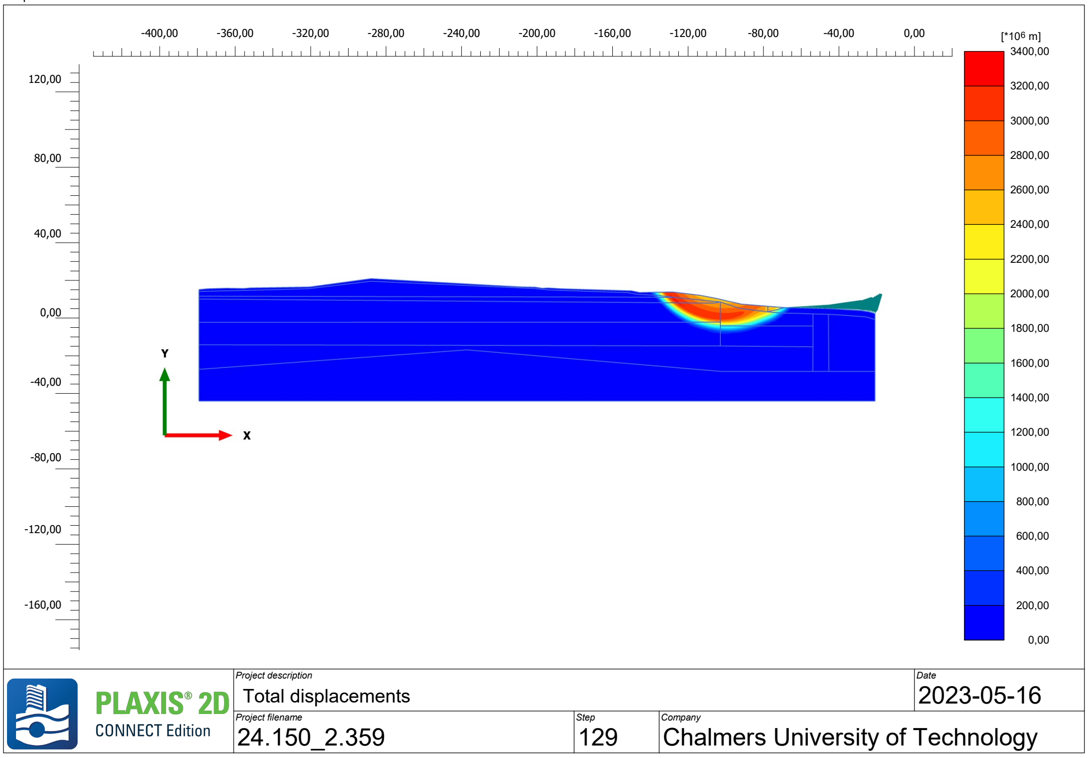
Output Version 22.1.0.452



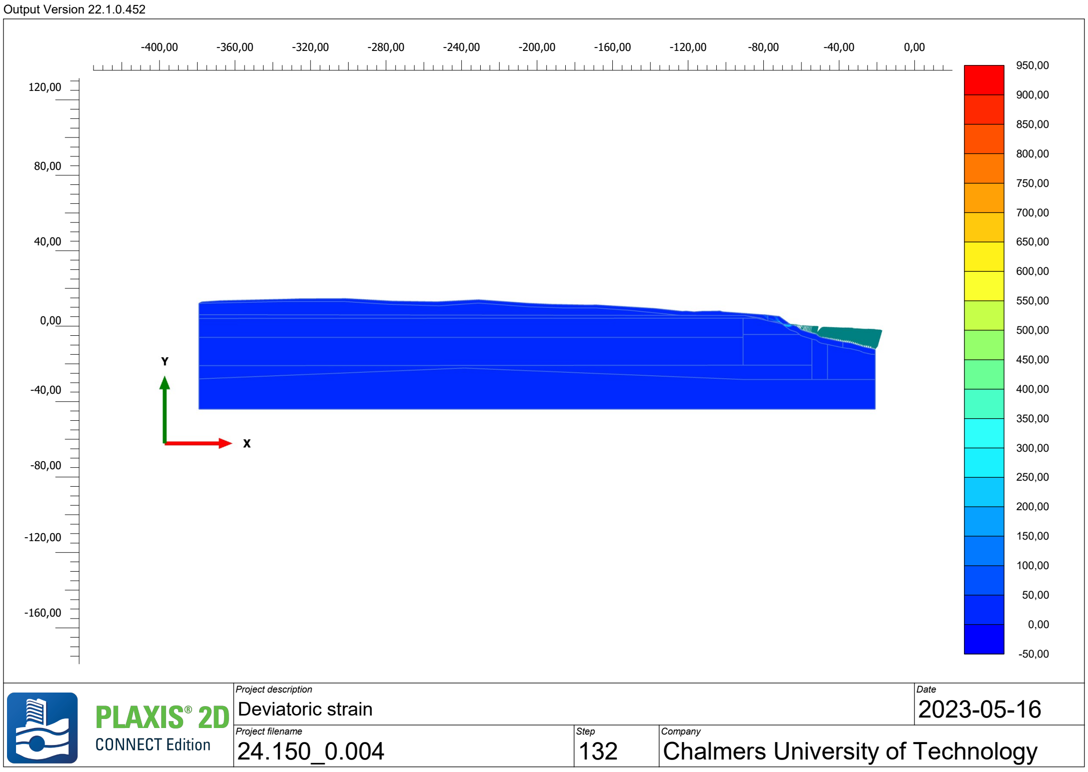
Output Version 22.1.0.452

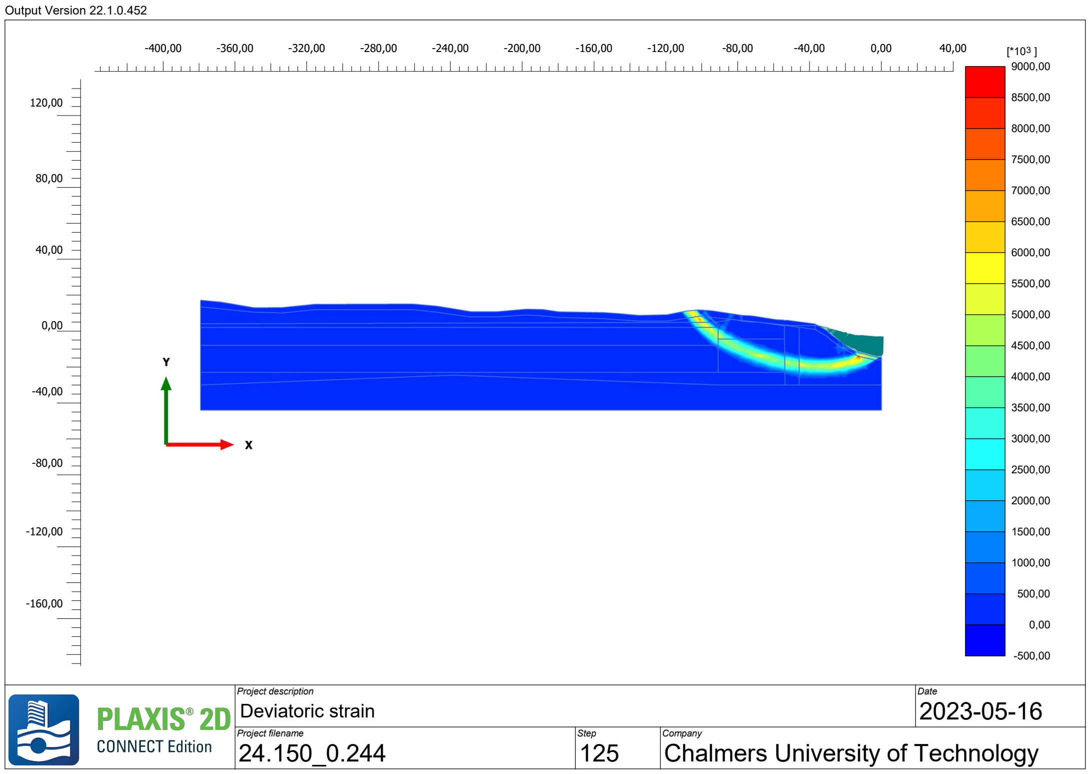


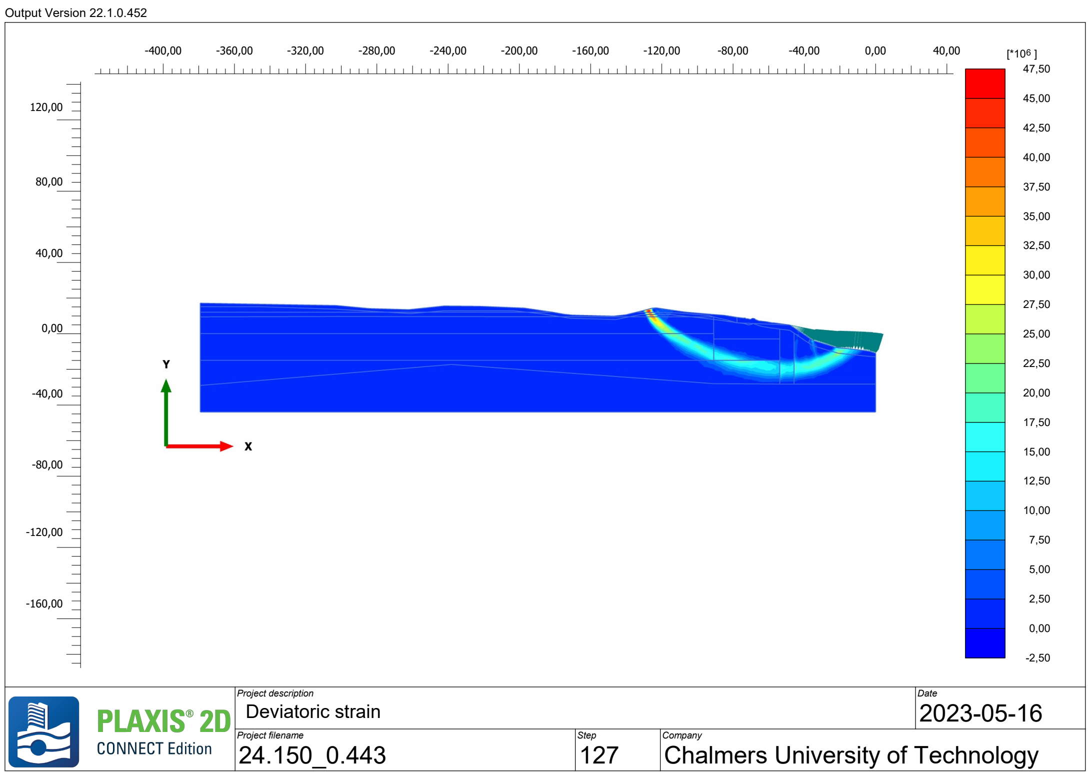
Output Version 22.1.0.452

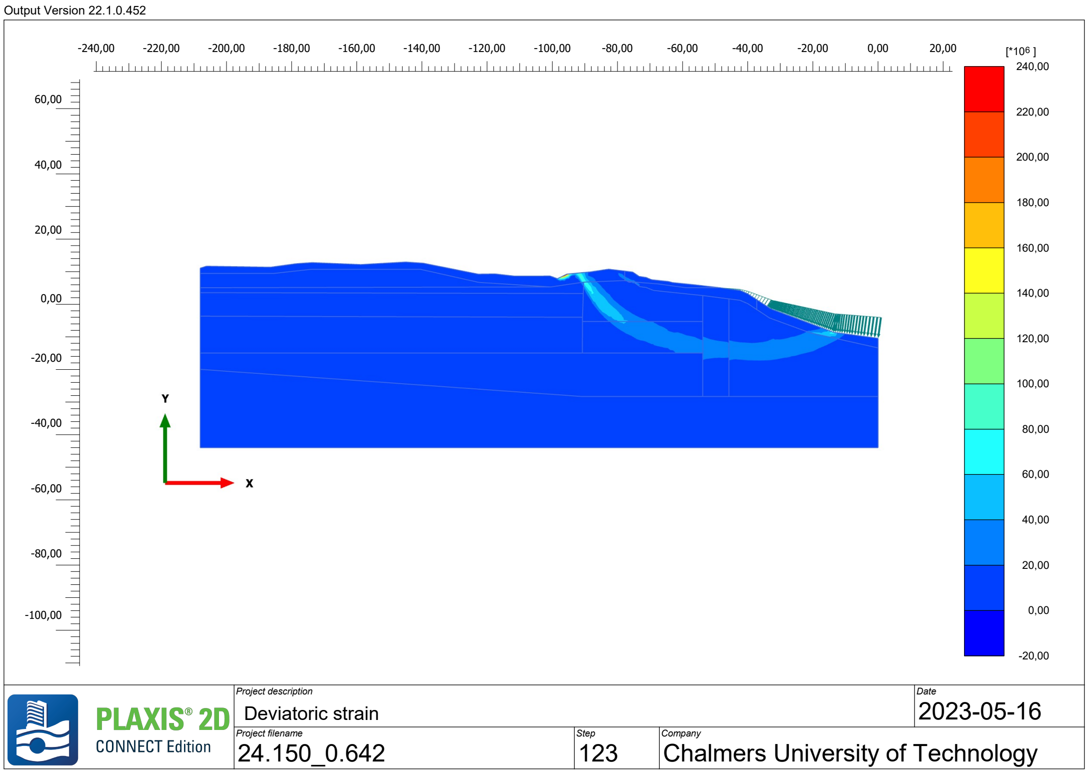


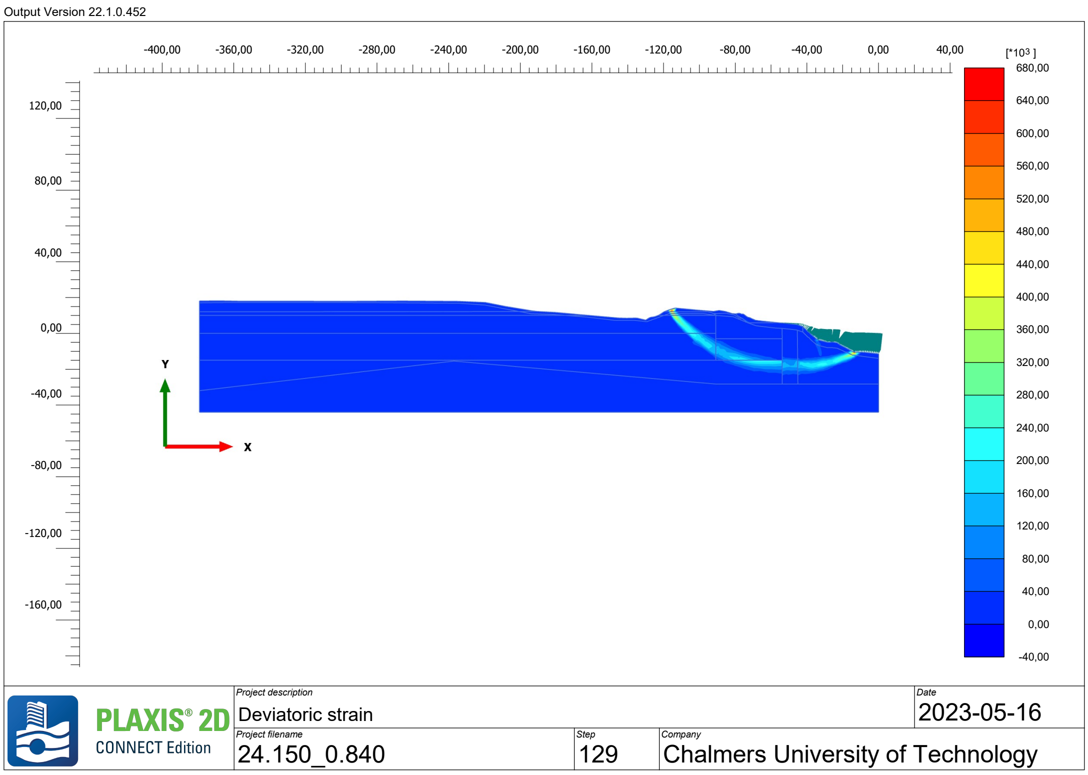
Output Version 22.1.0.452



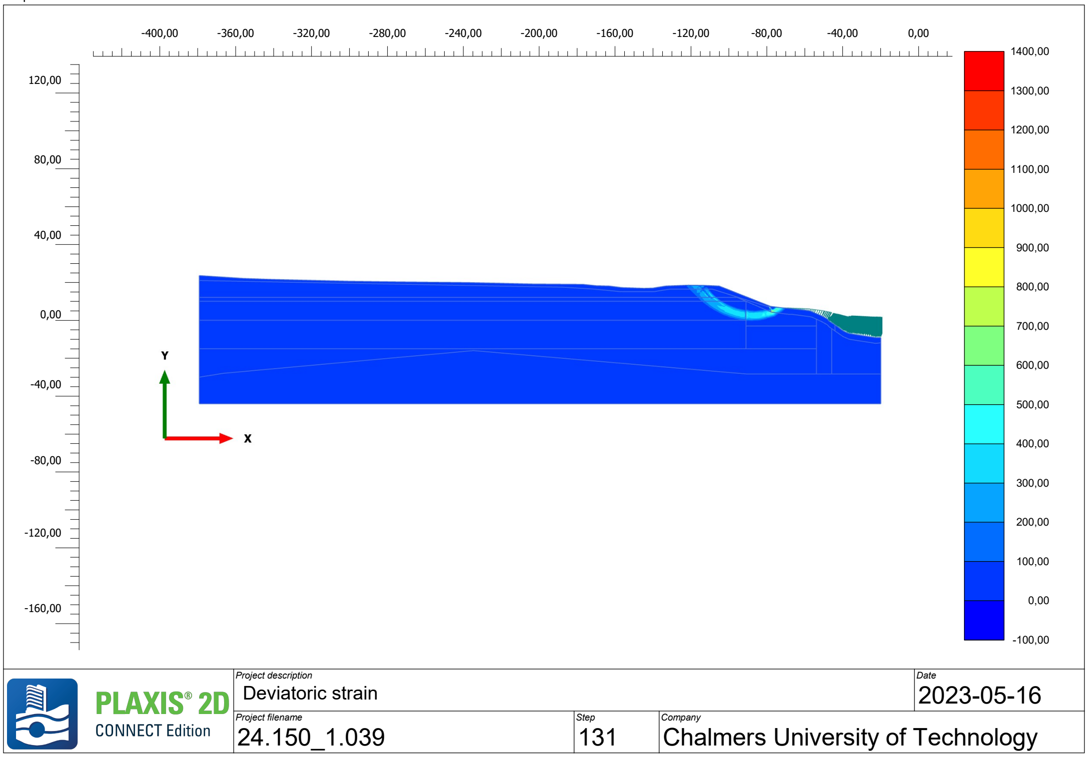

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
40,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10³]
9000,00
8500,00
8000,00
7500,00
7000,00
6500,00
6000,00
5500,00
5000,00
4500,00
4000,00
3500,00
3000,00
2500,00
2000,00
1500,00
1000,00
500,00
0,00
-500,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
24.150_0.244
Step
125
Company
Chalmers University of Technology


Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
40,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10⁶]
47,50
45,00
42,50
40,00
37,50
35,00
32,50
30,00
27,50
25,00
22,50
20,00
17,50
15,00
12,50
10,00
7,50
5,00
2,50
0,00
-2,50
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
24.150_0.443
Step
127
Company
Chalmers University of Technology

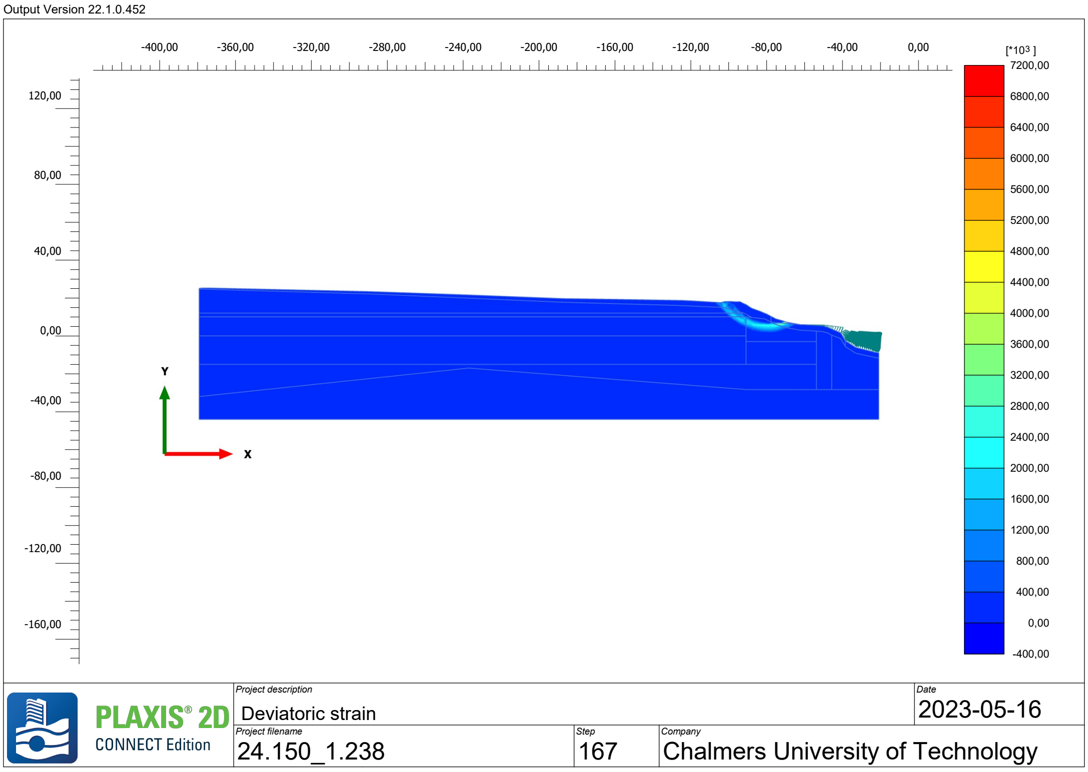

Output Version 22.1.0.452
-240,00 -220,00 -200,00 -180,00 -160,00 -140,00 -120,00 -100,00 -80,00 -60,00 -40,00 -20,00 0,00 20,00
60,00 40,00 20,00 0,00 -20,00 -40,00 -60,00 -80,00 -100,00
Y
X
[*10⁶]
240,00 220,00 200,00 180,00 160,00 140,00 120,00 100,00 80,00 60,00 40,00 20,00 0,00 -20,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
24.150_0.642
Step
123
Company
Chalmers University of Technology

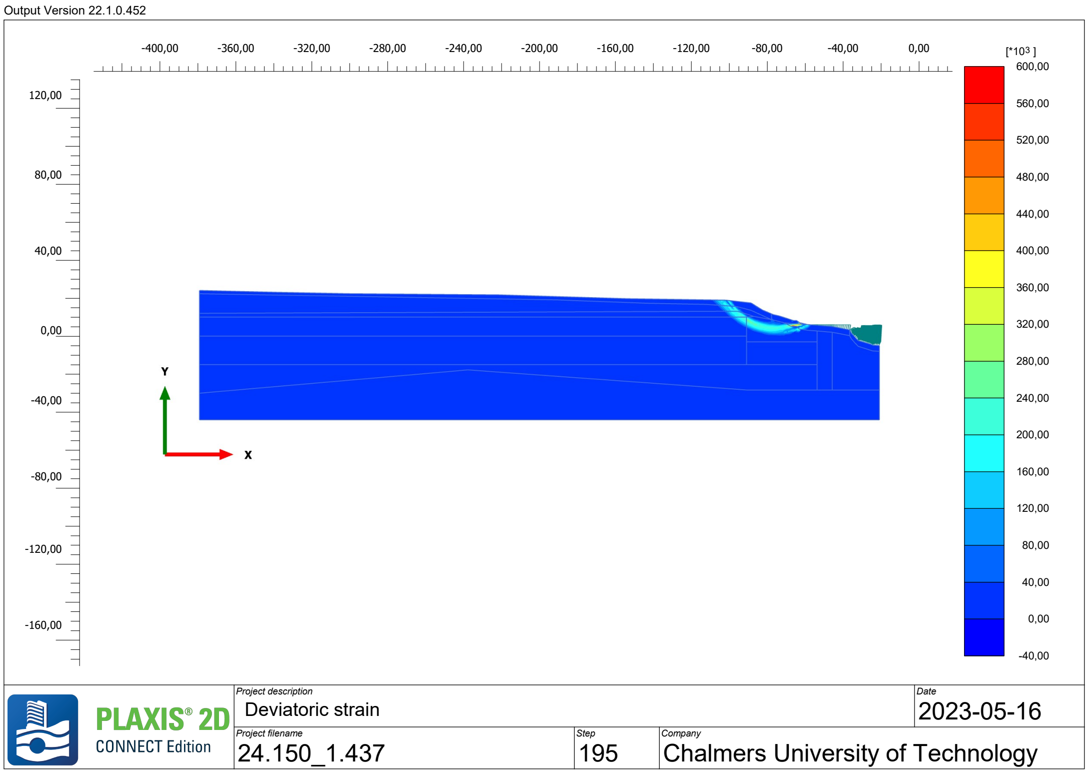

Output Version 22.1.0.452
-400,00 -360,00 -320,00 -280,00 -240,00 -200,00 -160,00 -120,00 -80,00 -40,00 0,00 40,00
120,00 80,00 40,00 0,00 -40,00 -80,00 -120,00 -160,00
Y
X
[*10³]
680,00 640,00 600,00 560,00 520,00 480,00 440,00 400,00 360,00 320,00 280,00 240,00 200,00 160,00 120,00 80,00 40,00 0,00 -40,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
24.150_0.840
Step
129
Company
Chalmers University of Technology

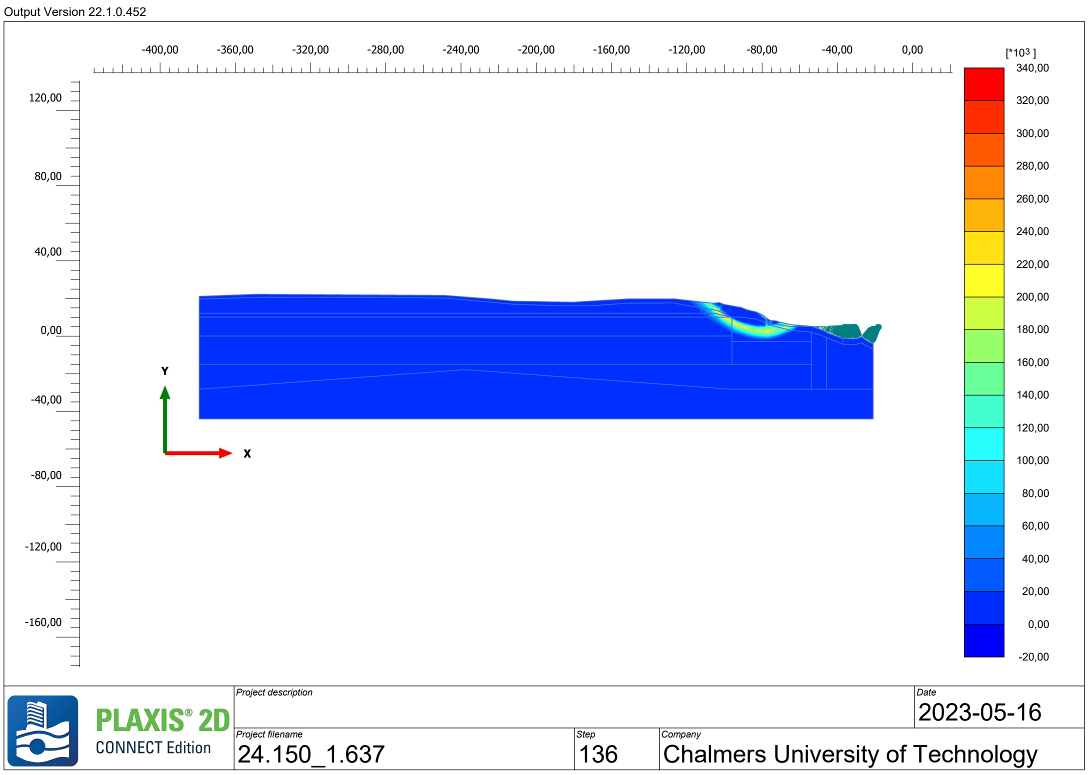
Output Version 22.1.0.452



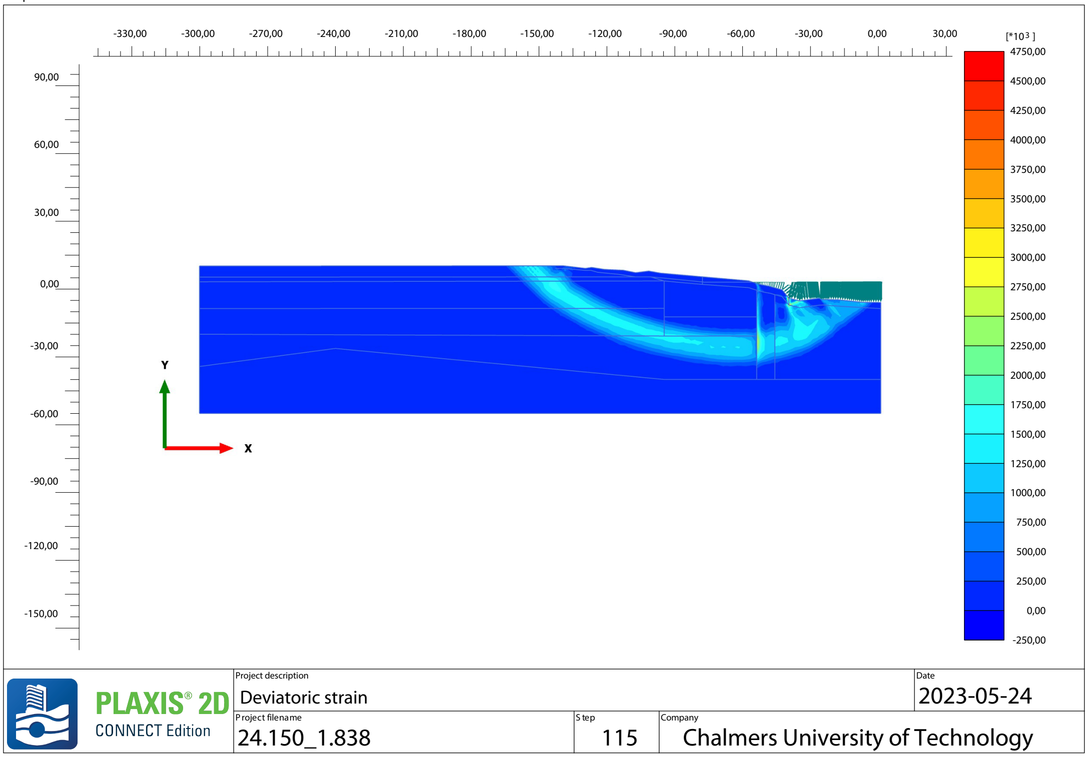
Output Version 22.1.0.452



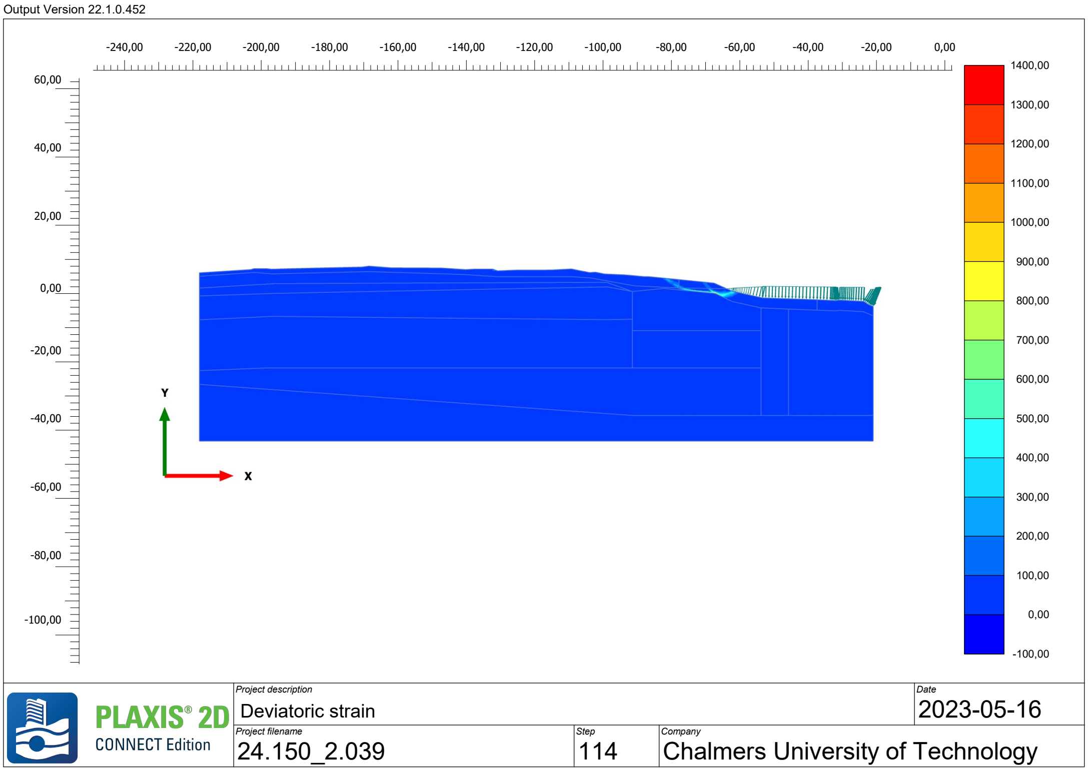

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10³]
600,00
560,00
520,00
480,00
440,00
400,00
360,00
320,00
280,00
240,00
200,00
160,00
120,00
80,00
40,00
0,00
-40,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
24.150_1.437
Step
195
Company
Chalmers University of Technology

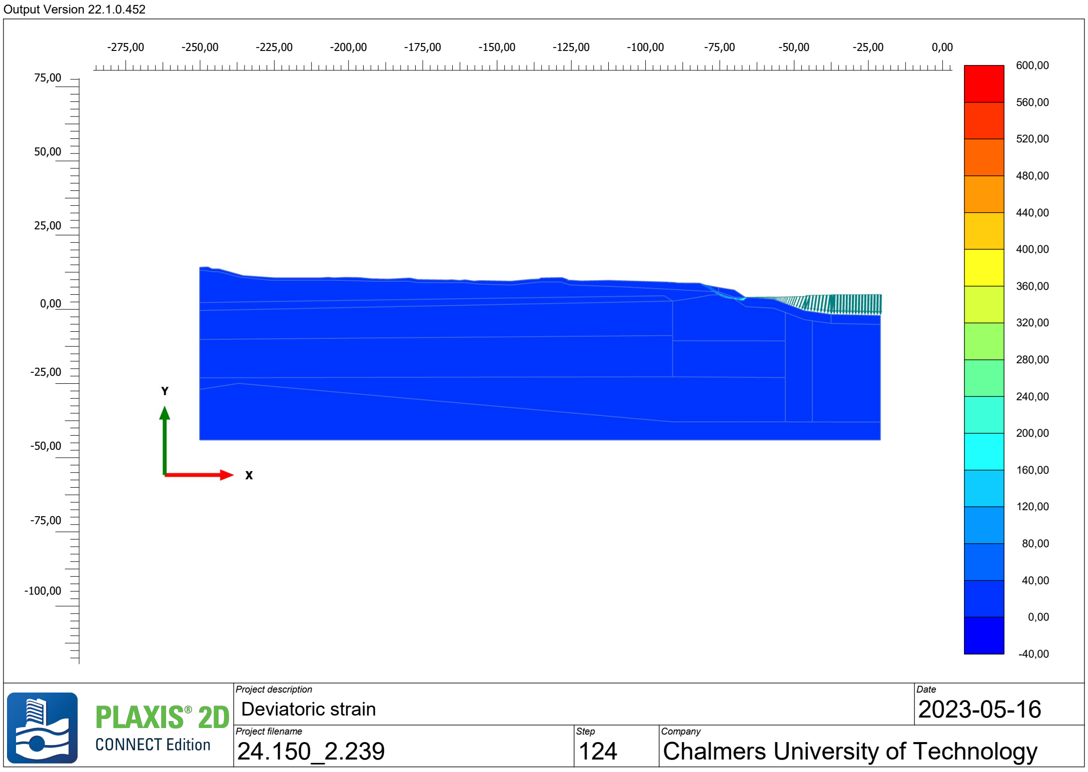

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10³]
340,00
320,00
300,00
280,00
260,00
240,00
220,00
200,00
180,00
160,00
140,00
120,00
100,00
80,00
60,00
40,00
20,00
0,00
-20,00
PLAXIS® 2D
CONNECT Edition
Project description
Date
2023-05-16
Project filename
24.150_1.637
Step
136
Company
Chalmers University of Technology

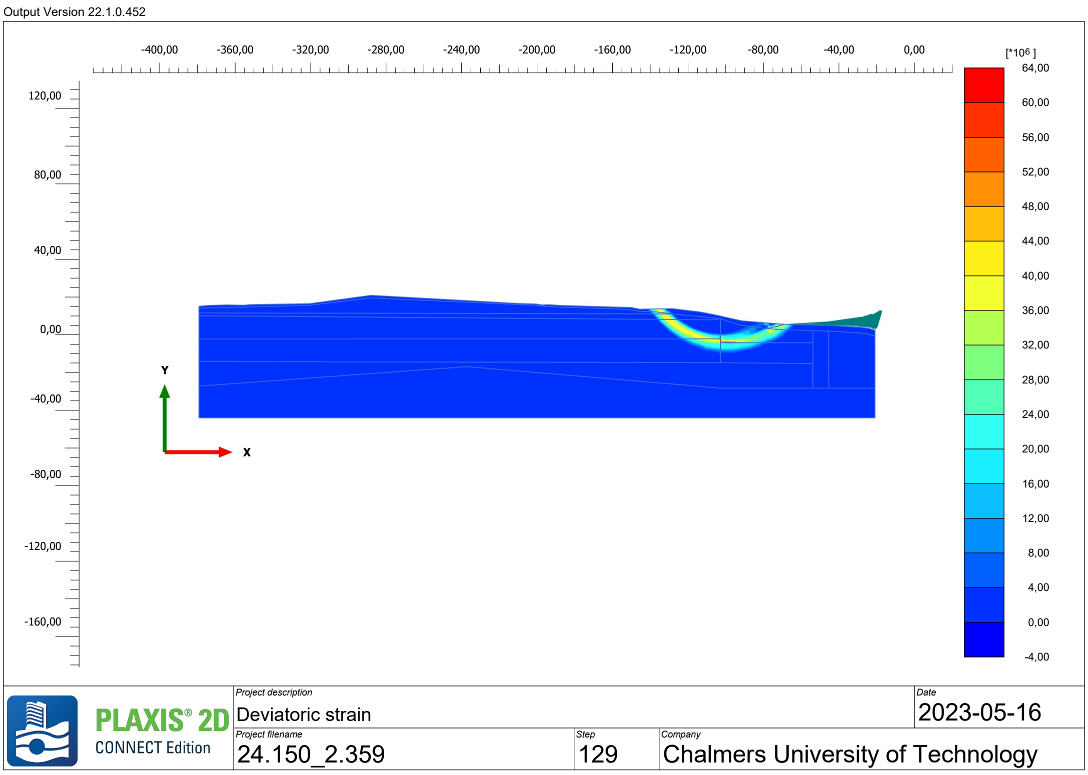
Output Version 22.1.0.452



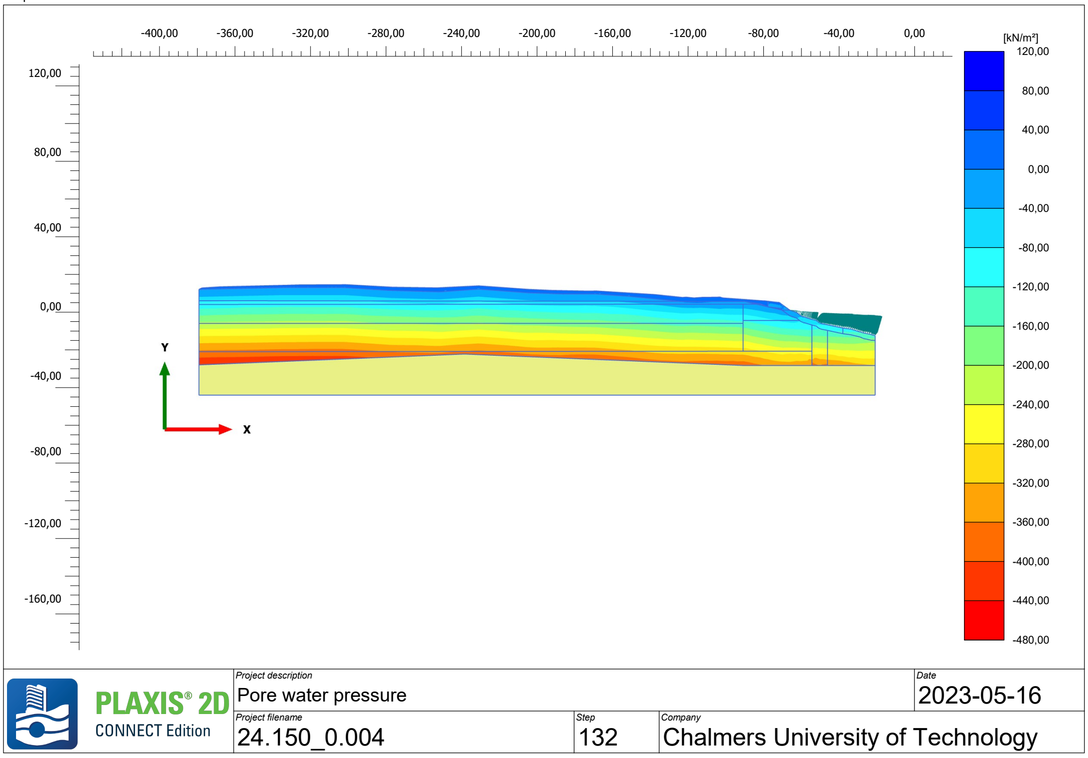
Output Version 22.1.0.452



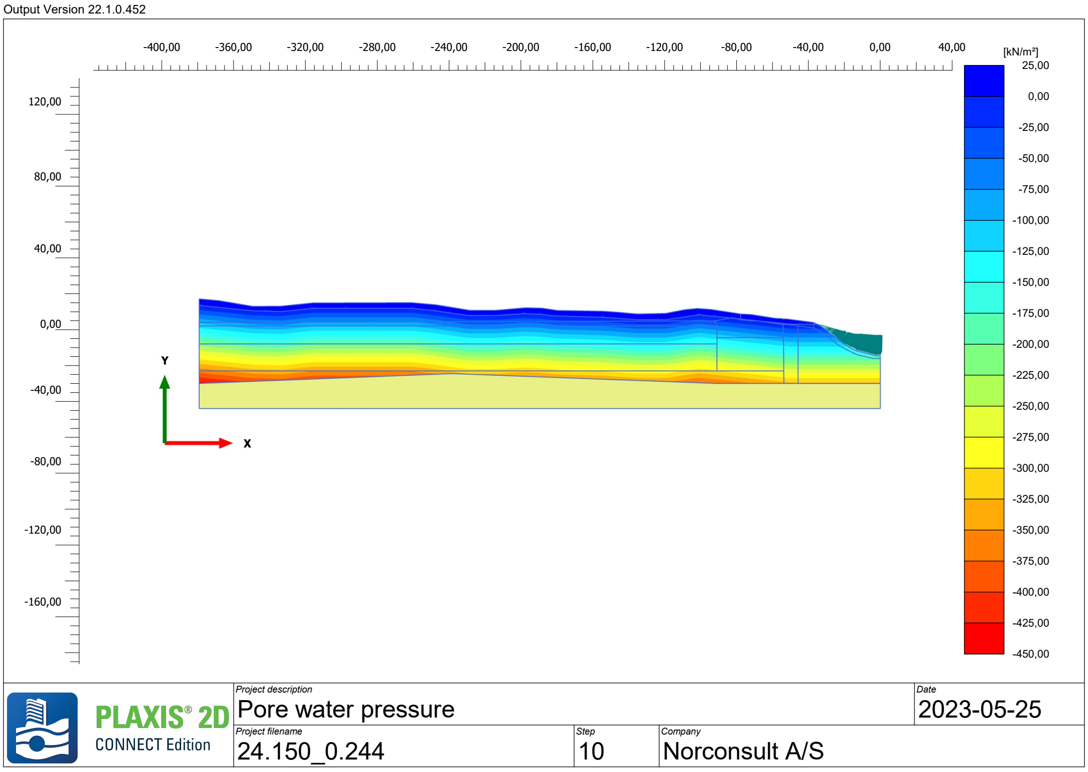

Output Version 22.1.0.452
-275,00
-250,00
-225,00
-200,00
-175,00
-150,00
-125,00
-100,00
-75,00
-50,00
-25,00
0,00
75,00
50,00
25,00
0,00
-25,00
-50,00
-75,00
-100,00
Y
X
600,00
560,00
520,00
480,00
440,00
400,00
360,00
320,00
280,00
240,00
200,00
160,00
120,00
80,00
40,00
0,00
-40,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
24.150_2.239
Step
124
Company
Chalmers University of Technology


Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[*10⁶]
64,00
60,00
56,00
52,00
48,00
44,00
40,00
36,00
32,00
28,00
24,00
20,00
16,00
12,00
8,00
4,00
0,00
-4,00
PLAXIS® 2D
CONNECT Edition
Project description
Deviatoric strain
Date
2023-05-16
Project filename
24.150_2.359
Step
129
Company
Chalmers University of Technology

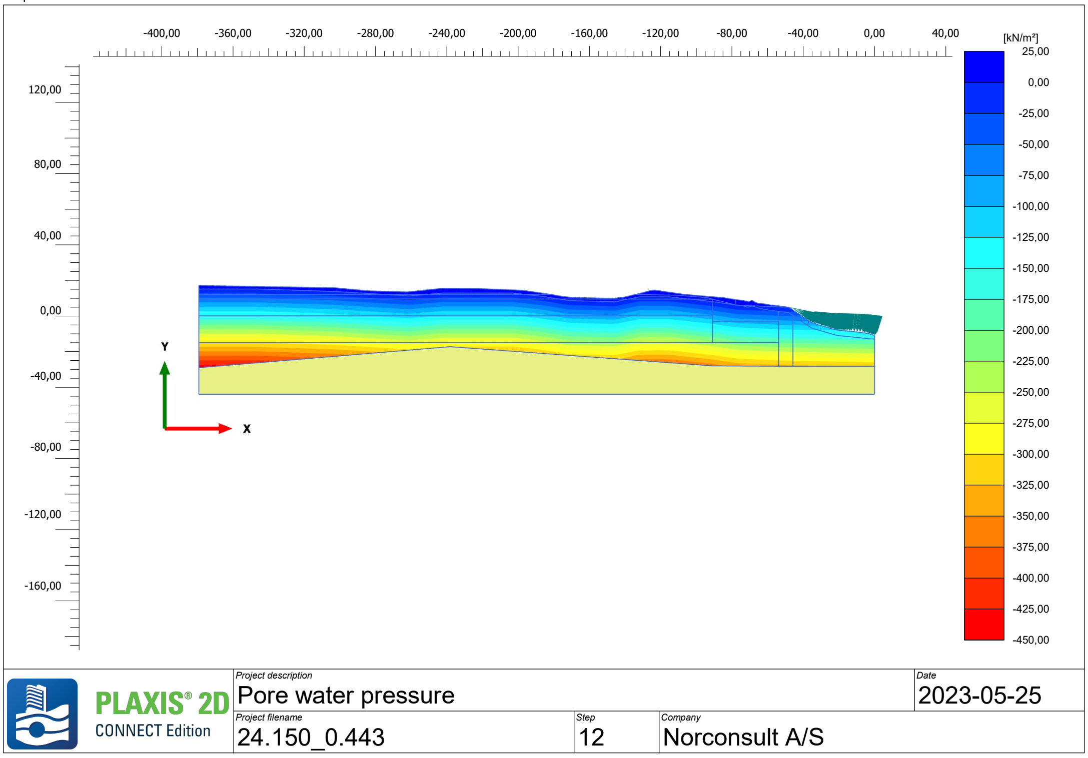
Output Version 22.1.0.452



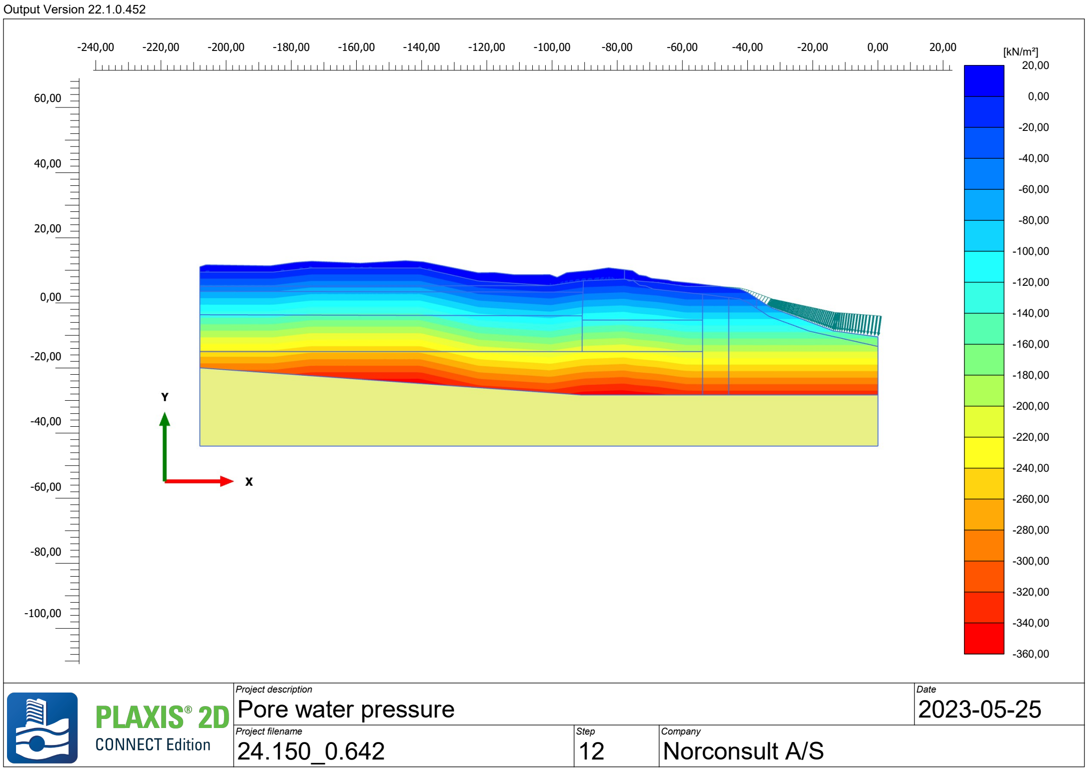
Output Version 22.1.0.452



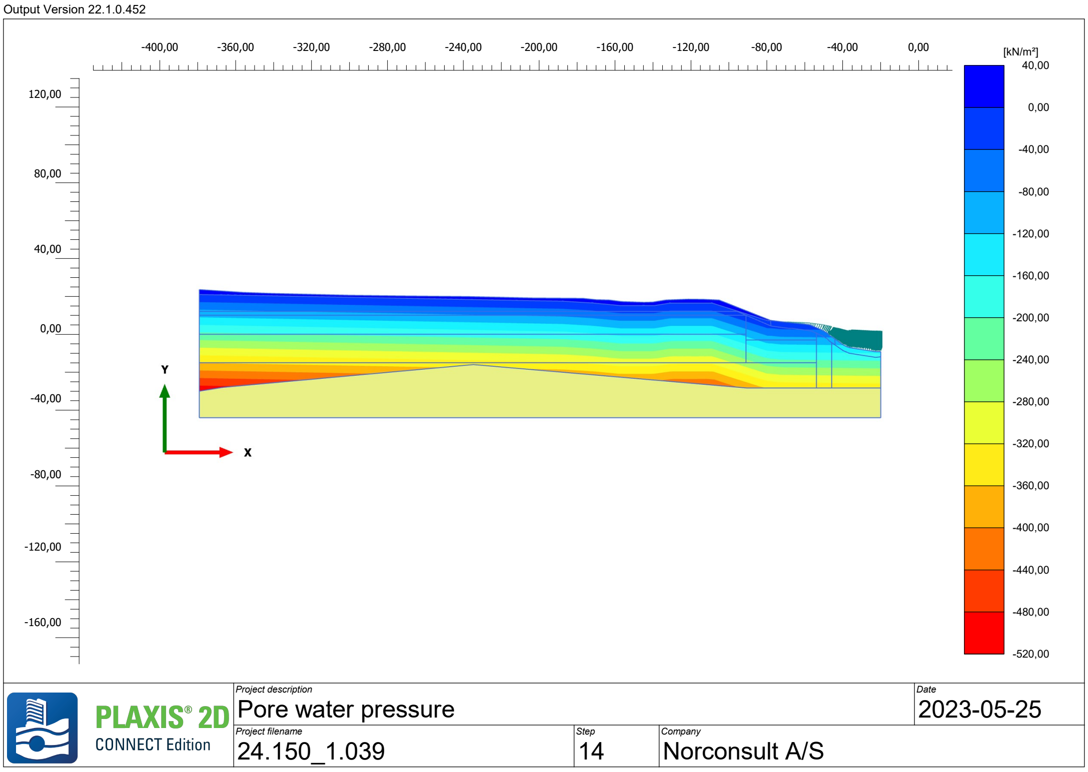
Output Version 22.1.0.452



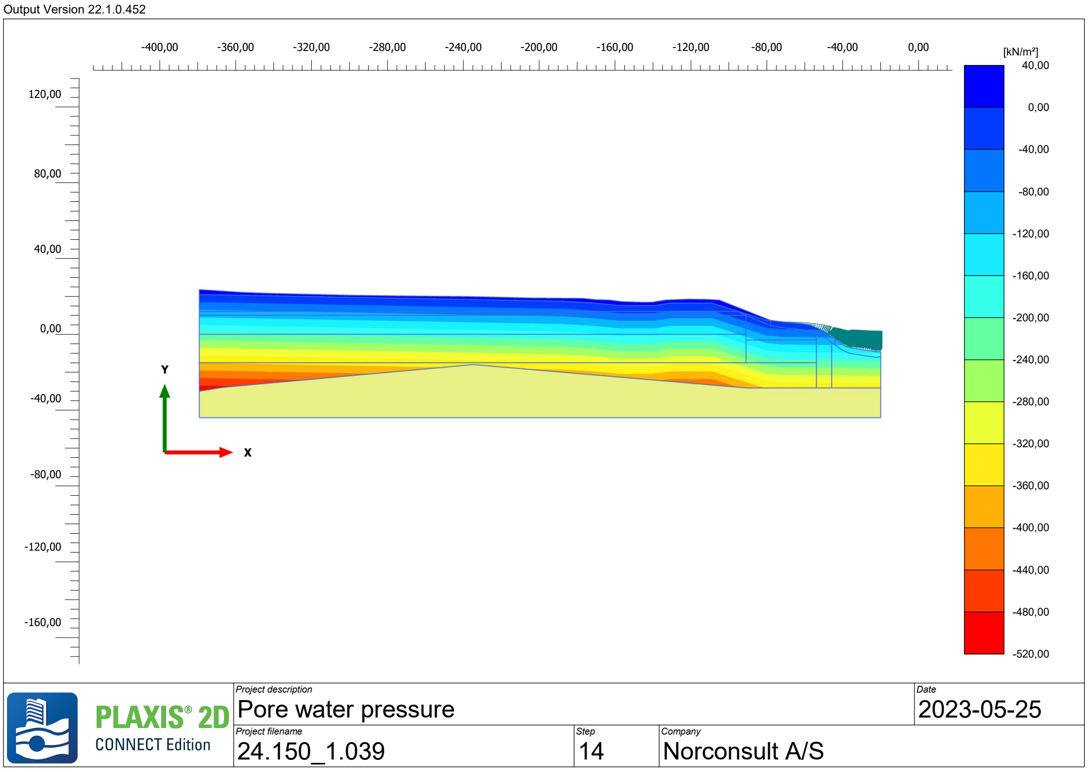
Output Version 22.1.0.452

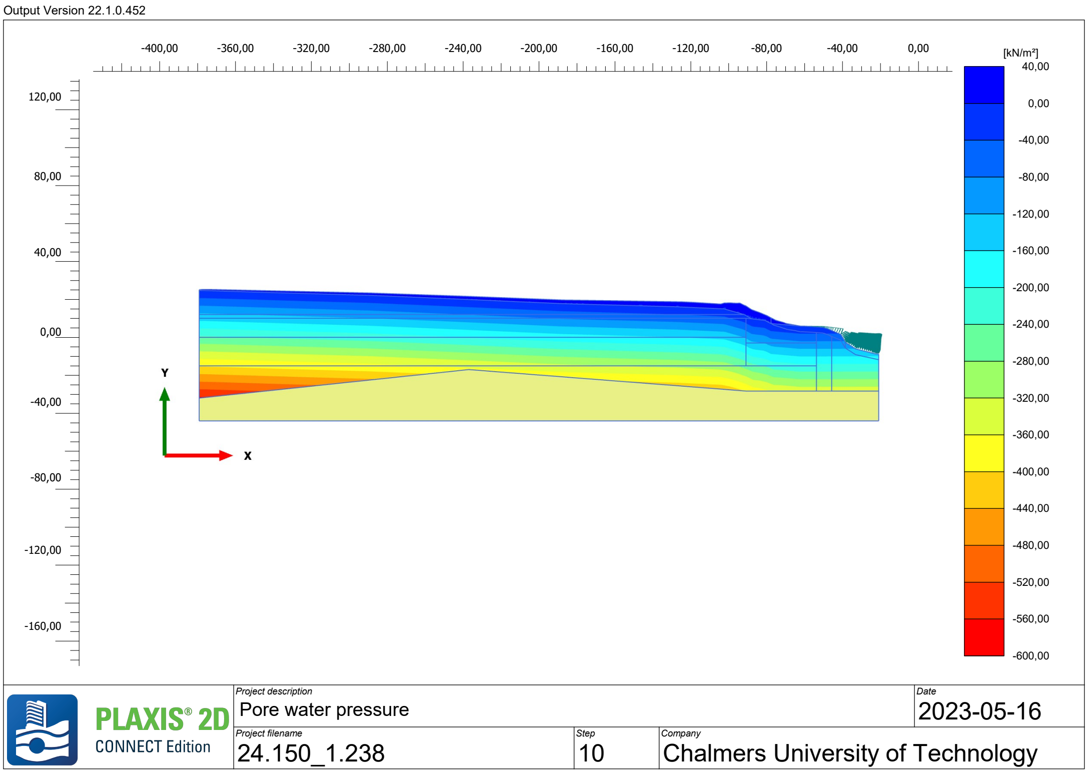


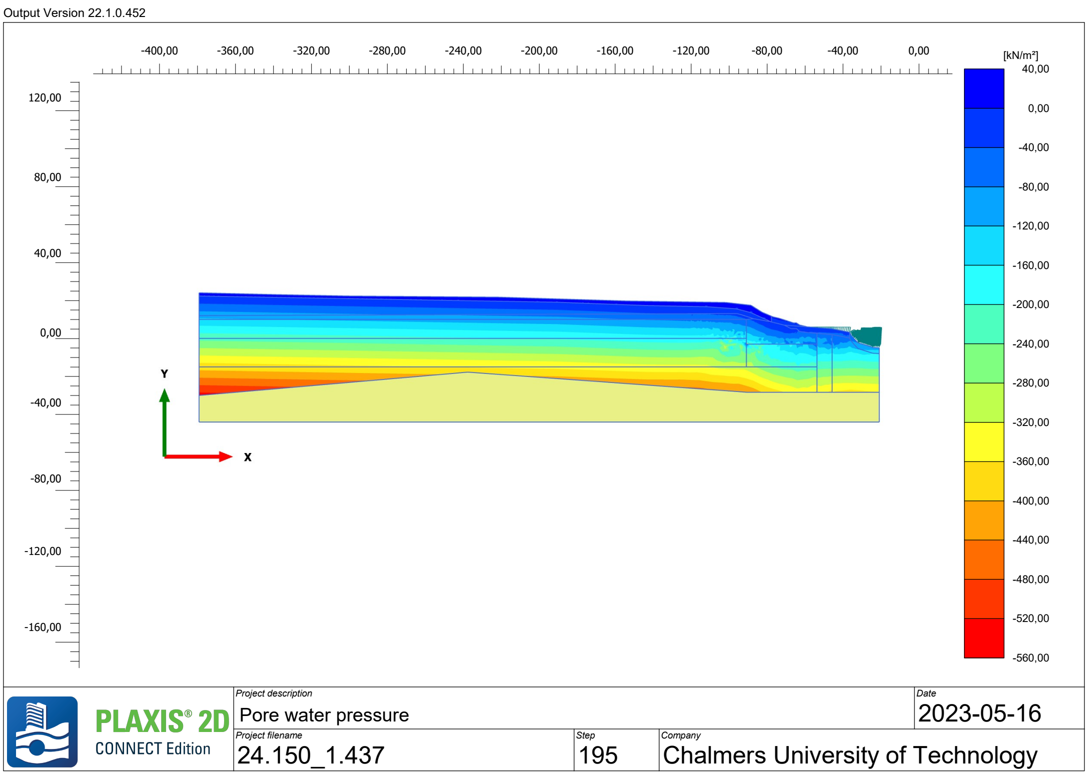
Output Version 22.1.0.452



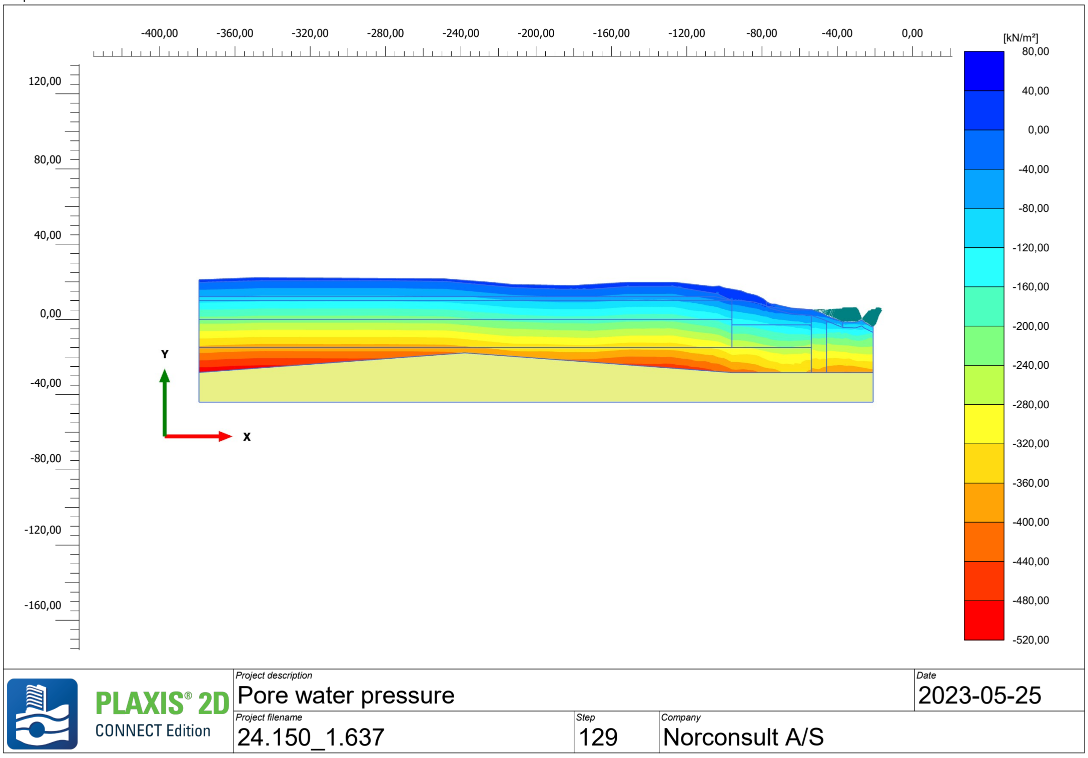
Output Version 22.1.0.452



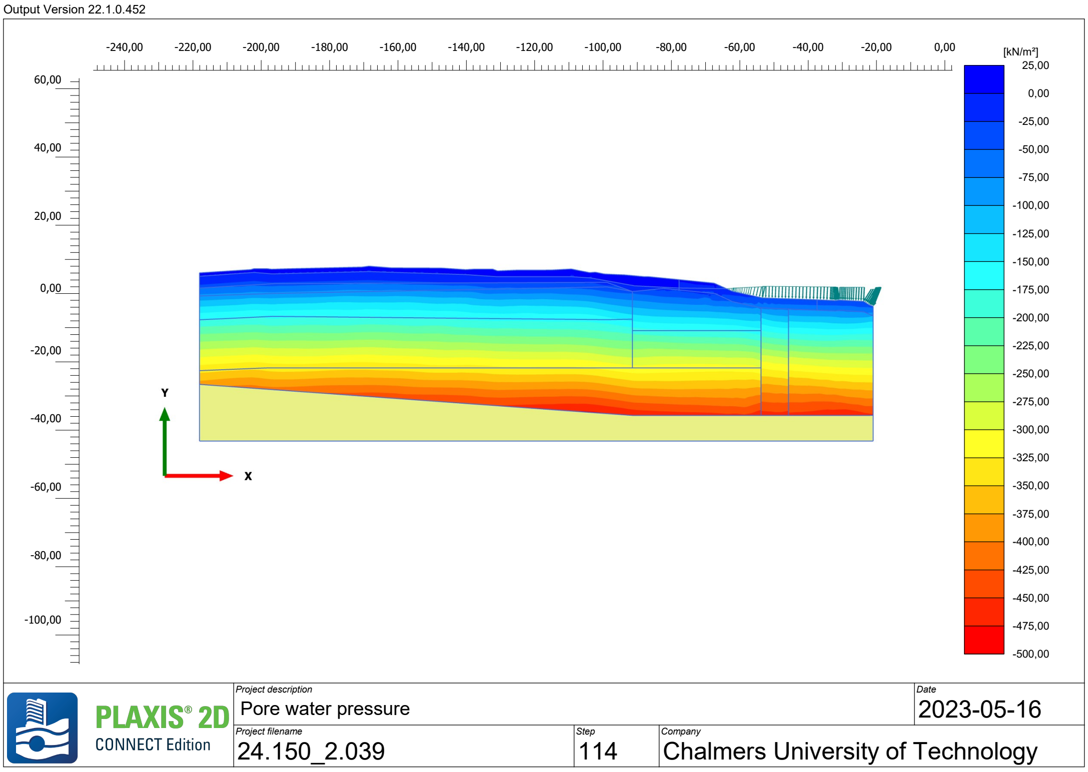

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[kN/m²]
40,00
0,00
-40,00
-80,00
-120,00
-160,00
-200,00
-240,00
-280,00
-320,00
-360,00
-400,00
-440,00
-480,00
-520,00
-560,00
-600,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
24.150_1.238
Step
10
Company
Chalmers University of Technology

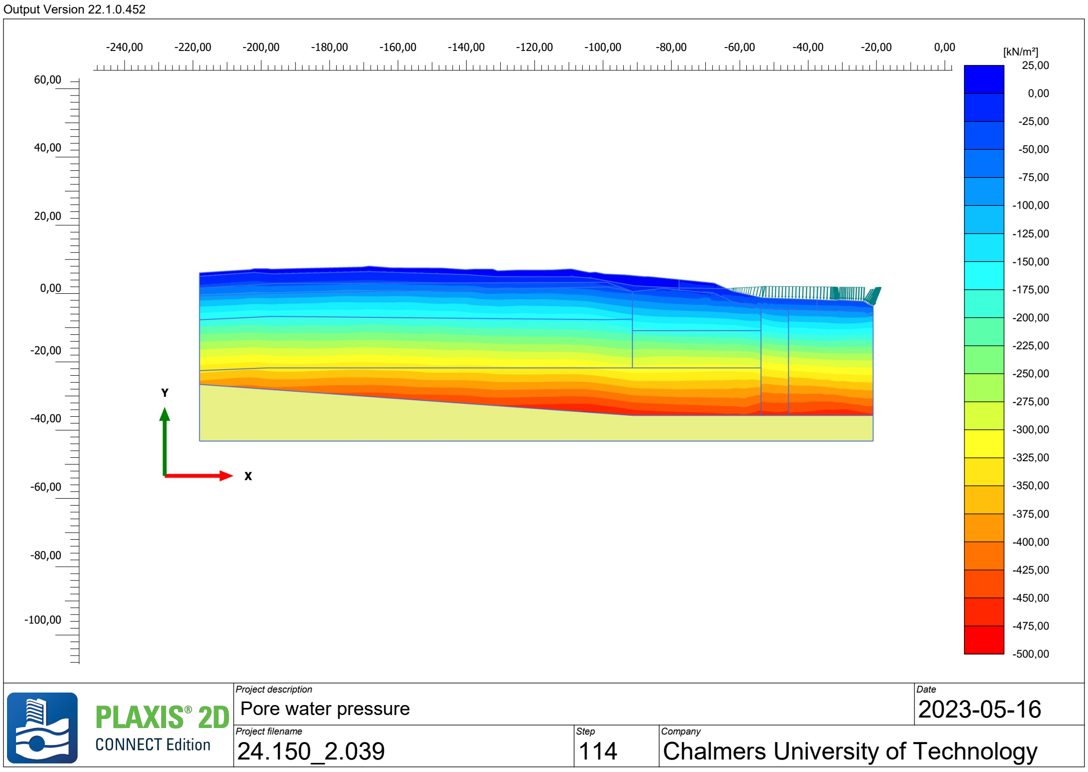

Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[kN/m²]
40,00
0,00
-40,00
-80,00
-120,00
-160,00
-200,00
-240,00
-280,00
-320,00
-360,00
-400,00
-440,00
-480,00
-520,00
-560,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
24.150_1.437
Step
195
Company
Chalmers University of Technology

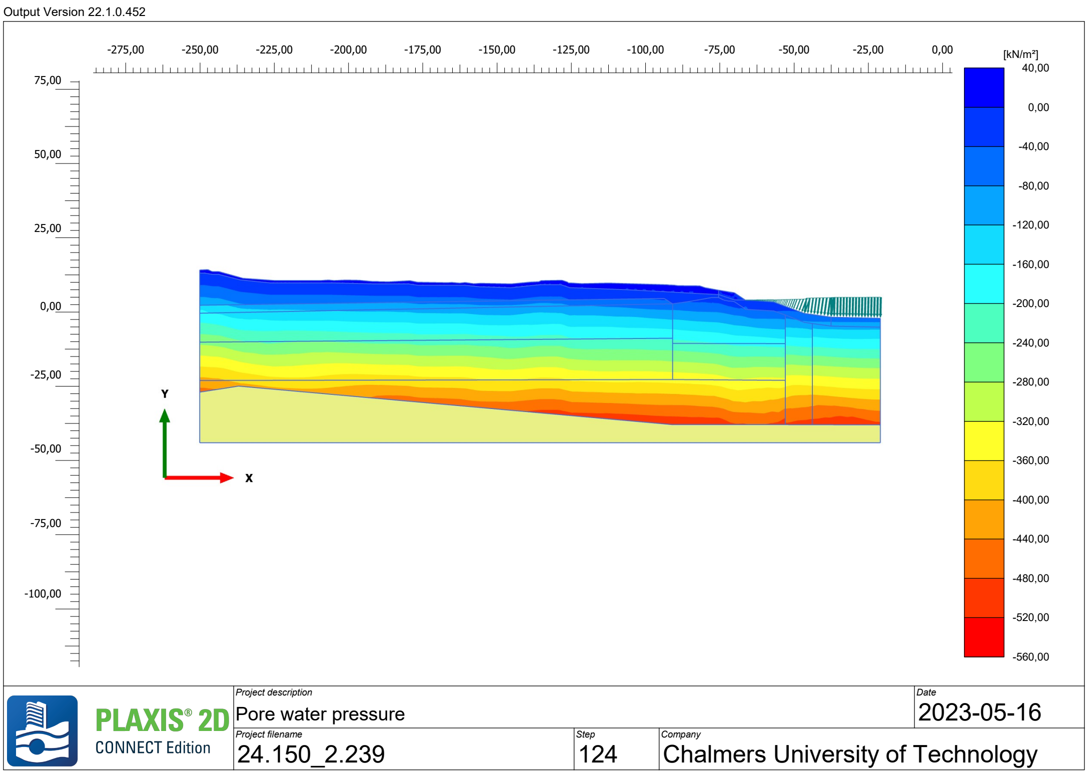
Output Version 22.1.0.452

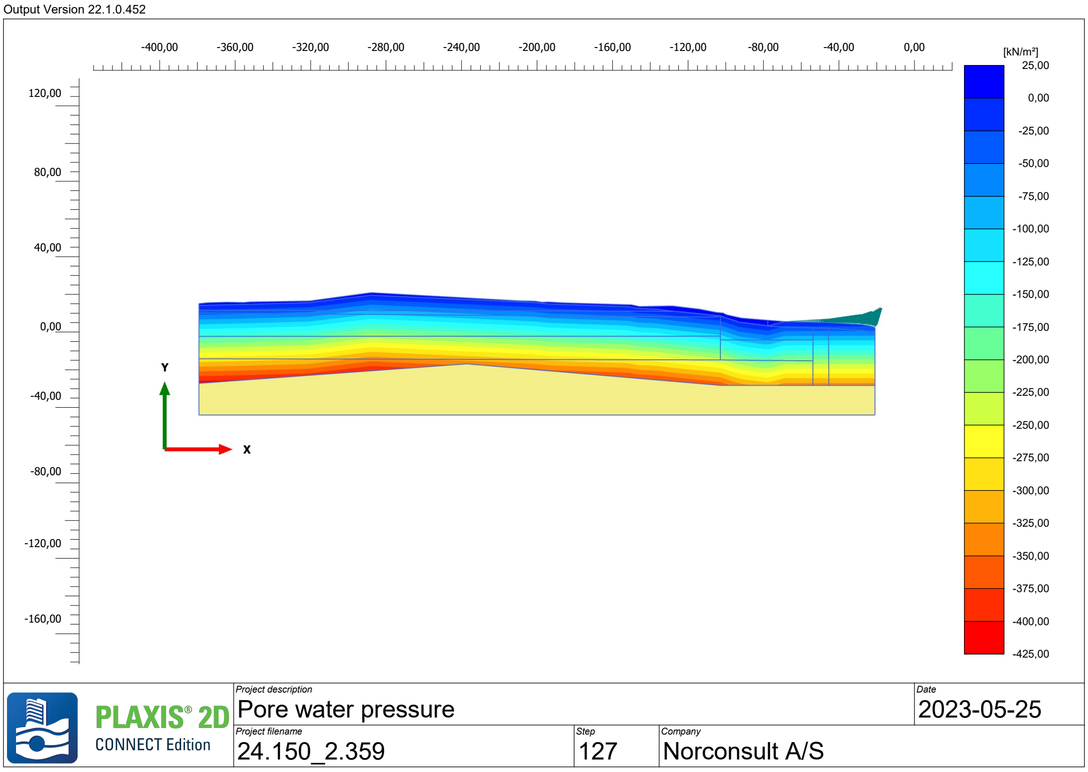


Output Version 22.1.0.452




Output Version 22.1.0.452
-240,00
-220,00
-200,00
-180,00
-160,00
-140,00
-120,00
-100,00
-80,00
-60,00
-40,00
-20,00
0,00
60,00
40,00
20,00
0,00
-20,00
-40,00
-60,00
-80,00
-100,00
Y
X
[kN/m²]
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
-150,00
-175,00
-200,00
-225,00
-250,00
-275,00
-300,00
-325,00
-350,00
-375,00
-400,00
-425,00
-450,00
-475,00
-500,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
24.150_2.039
Step
114
Company
Chalmers University of Technology


Output Version 22.1.0.452
-275,00
-250,00
-225,00
-200,00
-175,00
-150,00
-125,00
-100,00
-75,00
-50,00
-25,00
0,00
75,00
50,00
25,00
0,00
-25,00
-50,00
-75,00
-100,00
Y
X
[kN/m²]
40,00
0,00
-40,00
-80,00
-120,00
-160,00
-200,00
-240,00
-280,00
-320,00
-360,00
-400,00
-440,00
-480,00
-520,00
-560,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-16
Project filename
24.150_2.239
Step
124
Company
Chalmers University of Technology


Output Version 22.1.0.452
-400,00
-360,00
-320,00
-280,00
-240,00
-200,00
-160,00
-120,00
-80,00
-40,00
0,00
120,00
80,00
40,00
0,00
-40,00
-80,00
-120,00
-160,00
Y
X
[kN/m²]
25,00
0,00
-25,00
-50,00
-75,00
-100,00
-125,00
-150,00
-175,00
-200,00
-225,00
-250,00
-275,00
-300,00
-325,00
-350,00
-375,00
-400,00
-425,00
PLAXIS® 2D
CONNECT Edition
Project description
Pore water pressure
Date
2023-05-25
Project filename
24.150_2.359
Step
127
Company
Norconsult A/S

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