Rock Wedge Stability Assessment

A Comparative Analysis of Limit Equilibrium and Discrete Element Methods

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This report is the result of the work I have performed during my master thesis study, which is the final part of my Civil Engineering studies at Luleå University of Technology.

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SUMMARY

This thesis work focused on the common issue of rock wedge stability in underground excavations. Since the wedge stability influences the support design, it is important to use a wedge stability analysis method that can capture factors like excavation geometry, joint parameters and properties, rock mass properties, rock cover, and stress field as accurately as possible.

The Limit Equilibrium Method (LEM) and Discrete Element Method (DEM) are two methods that can be used when analysing rock wedge stability. Using the software UnWedge (LEM) and 3DEC (DEM), the objectives of this thesis work was to:

- Study how excavation geometry, joint geometry, stress field, rock cover and rock mass quality can be considered by the different methods.
- Study how the choice of analysis method affects the wedge stability and support design.
- Study how support can be simulated using the chosen software.
- Compile recommendations for the use of the different methods for rock wedge stability analysis and support design.

Nine different analysis cases were defined with the aim of capturing wedge stability analysis parameters representable for both the civil engineering and mining sector. The cases should also include properties and parameters of different complexity and detail. The cases combined different excavation geometries, joint parameters and properties, rock mass properties, rock covers and stress fields. UnWedge and 3DEC were used to model these cases and analyse the obtained factors of safety. The software was also used to simulate support and determine the required amount of support.

Modelling of the cases showed that UnWedge had limitations in creating intersecting tunnels accurately, while 3DEC allowed for more accurate modelling of the intersecting tunnels. UnWedge generated wedges assuming joint ubiquity with infinite joint length by default, with the option of scaling the wedges by limiting the joint length. Probabilistic analysis in UnWedge was performed with statistical variation of joint orientations and sizes but joint density could not be considered. A full DFN analysis considering statistical variation of joint orientations, size and spacing was only possible in 3DEC.

Using 3DEC with analysis of stress redistribution gave a more comprehensive understanding of how the rock mass quality effected the results and identified failure mechanisms other than wedge failure. Comparing results directly between the methods was challenging, for example due to the differences in joint network generation and the support installation process.

Based on the conducted study, the following conclusions could be drawn:

- UnWedge and 3DEC with no redistribution of stresses require similar input data and gives similar factors of safety for a single rock wedge in the tunnel roof. The benefits of 3DEC are that full 3D geometries and full DFN can be investigated.
• *UnWedge* and *3DEC* with no redistribution of stresses does not take the rock mass quality into consideration.

• The only method studied with the ability to capture rock mass failure mechanisms in addition to wedge failure is *3DEC* where consideration is taken to the redistribution of stresses as well as material yielding using a plastic material model.

• Assuming infinite joint lengths can severely overestimate the wedge volumes, which, in turn, can lead to an excessive amount of support being used.

• Shotcrete has a greater contribution to the wedge factor of safety in *UnWedge* compared to *3DEC*. However, the only assumed failure mode of the shotcrete in *UnWedge* is direct shear, which may be misleading when using results for actual support design.

The following recommendations were given:

• For situations where the excavation geometry cannot be assumed as two-dimensional with constant cross-section, the Discrete Element Method should be used when analysing wedge stability.

• If stress-induced rock mass failure is expected, the Discrete Element Method with consideration of the redistribution of stresses should be used to capture both wedge failure as well as stress-induced failure mechanisms.

• If information about the joint lengths is available, it should be used in the analysis. In any case, engineering judgment needs to be applied when studying the results, in particular if excessively large wedges are formed.

• It is vital to understand how the software determines support force and use engineering judgement to determine whether the obtained quantity is sufficient, or overly conservative.
SAMMANFATTNING

Detta examensarbete har fokuserat på kilstabilitet vilket är ett vanligt stabilitetsproblem i tunnlar. Eftersom kilstabiliteten påverkar den erforderliga förstärkningsmängden är det viktigt att använda en kilanalysmetod som kan ta hänsyn till faktorer som tunnelgeometri, sprickparametrar och -egenskaper, bergmassans egenskaper, bergtäckning och spänningsfält på ett så korrekt sätt som möjligt.

Jämviktsanalys och Diskreta Element Metoden (DEM) är två metoder som kan användas för att analysera kilstabilitet. Genom att använda programvarorna UnWedge (jämviktsanalys) och 3DEC (DEM) var målet med detta examensarbete att:

• Studera hur tunnelgeometri, sprickparametrar och -egenskaper, bergmassans egenskaper, bergtäckning och spänningsfält kan tillämpas i de olika metoderna.

• Studera hur valet av analysmetod påverkar kilstabiliteten och förstärkningsdesign.

• Studera hur förstärkning kan simuleras med programvarorna.

• Sammanställa rekommendationer för användningen av olika metoderna för analys av kilstabilitet och förstärkningsdesign.


Modelleringen av de olika fallen visade att UnWedge hade begränsningar när det gällde att skapa korsande tunnlar på ett korrekt sätt, medan 3DEC gav en mer korrekt representation av geometrin. UnWedge genererade kilar genom att som standard anta obegränsad spricklängd och att sprickorna kunde vara överallt i bergmassan. Alternativet att begränsa kilstorleken genom att begränsa spricklängden fanns. Sannolikhetsanalys genomfördes i UnWedge genom att lägga till variation i sprickorientering och -längd, men sprickavstånd kunde inte inkluderas i analysen. En fullständig DFN-analys med sprickavstånd samt variation i sprickorientering och spricklängd var endast möjlig i 3DEC.

Användning av 3DEC med spänningsomfördelning analyserad gav den mest detaljerade och korrekta bilden över hur bergmassans kvalitet påverkade resultat och identifierade brottmekanismer utöver strukturstyrda brott. Att jämföra resultat direkt mellan metoderna var utmanande, till exempel på grund av skillnaderna i genereringen av sprickor och installation av förstärkning.

Baserat på studien kunde följande slutsatser dras:

• UnWedge och 3DEC utan spänningsomfördelning tar hänsyn till liknande indata och ger liknande säkerhetsfaktorer för en enskild kil i tunneltaket. Fördelen med 3DEC är att fullständiga 3D-geometrier och DFN kan undersökas.
• *UnWedge* och *3DEC* utan spänningsomfördelning tar inte hänsyn till bergmassans kvalitet.

• Den enda studerade metoden med förmåga att fånga brottmekanismer utöver strukturstyrda brott är *3DEC* där hänsyn tas till spänningsomfördelning samt plasticing i bergmassan (vid användande av plastisk materialmodell).

• Att anta oändliga spricklängder kan leda till att kilvolymen kraftigt överskattas, vilket i sin tur kan leda till att den erhållna mängden förstärkning blir överdrivet konservativ.

• Sprutbetong har en större bidragande effekt till kilens säkerhetsfaktor i *UnWedge* jämfört med *3DEC*. Den enda brottmod i sprutbetong som tas hänsyn till i *UnWedge* är dock direkt skjuvning, vilket kan vara vilseledande vid tillämpning på praktisk förstärkningsdesign.

Följande rekommendationer gavs:

• Om tunnelgeometrin inte kan antas vara långsträckt och med konstant tvärsnitt bör Diskreta Element Metoden användas vid kilstabilitetsanalys.

• Om spänningsinducerat brott förväntas bör Diskreta Element Metoden med spänningsomfördelning användas för att fånga både strukturstyrda och spänningsinducerade brott.

• Om information angående spricklängder finns tillgänglig bör den användas i analysen. I alla fall bör en ingenjörsmedvetig bedömning tillämpas, speciellt om orimligt stora kilar bildas.

• Det är viktigt att förstå hur programvaran bestämmer förstärkningskraften och använda ingenjörsmedvetig bedömning för att avgöra om den erhållna mängden förstärkning är erforderlig eller överdrivet konservativ.
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ABBREVIATIONS

**LEM** Limit Equilibrium Method

**DEM** Discrete Element Method

**DFN** Discrete Fracture Network

**FS** Factor of Safety
1 INTRODUCTION

1.1 Background

Wedge stability is a common concern in underground rock excavations. A wedge in an underground excavation is formed from at least three intersecting joint planes together with the free face created by the excavation. Depending on its location on the excavation perimeter as well as the rock mass and joint conditions, the wedge can fall, slide, or remain stable.

Analysis of rock wedge stability is important as input to determining the required amount of support in underground rock excavations. To avoid excessive or insufficient use of support and thus get a balance between safety and cost when designing support for mining and rock projects, it is important to use a wedge stability analysis method that represents the excavation geometry, rock mass properties, and rock mass behaviour as realistically as possible.

When assessing rock wedge stability, the Limit Equilibrium Method (LEM) is a commonly used approach. This method assumes the rock mass to be composed of rigid blocks and does not consider the deformability of the rock, redistribution of stresses, the actual lengths of joints, or the presence of multiple joints with the same orientation. An example of a software that uses LEM to determine wedge stability is *UnWedge* developed by Rocscience (2019).

Another method that can be used for rock wedge stability assessment is the Discrete Element Method (DEM). The Discrete Element Method can consider several excavations including intersecting tunnels, deformability of the rock mass, different joint properties and material models, and redistribution of stresses. An example of a software based on DEM is *3DEC* developed by Itasca (2023a).

Due to the differences in approaches and required assumptions of the methods, it is of interest to compare these methods with respect to how they assess rock wedge stability and how that affects the determined wedge stability and associated support design.

1.2 Purpose, aim and objectives

The purpose of this thesis work was to compare the Limit Equilibrium Method (LEM) and Discrete Element Method (DEM) with respect to rock wedge stability analysis and support design. The work was divided into two parts with the following aims:

Part 1: Investigation of how the methods can accommodate different excavation geometries, rock coverage, stress fields, joint geometries, rock mass qualities, and support designs when performing rock wedge stability analysis.

Part 2: Investigation of how the choice of method and input parameters affects the wedge stability and support design.

*UnWedge* and *3DEC* were used to perform comparative wedge stability analyses with the objective to:

- Study how excavation geometry, joint geometry, stress field, rock cover and rock mass quality can be considered by the different methods.
• Study how the choice of analysis method affects the wedge stability and support design.

• Study how support can be simulated using the chosen software.

• Compile recommendations for the use of the different methods for rock wedge stability analysis and support design.

1.3 Limitations

The analyses were limited to study roof wedges formed in underground rock excavations and were performed using two different software, UnWedge, version 5.014, by Rocscience (2019) and 3DEC, version 9.00.164 (pre-release), by Itasca (2023a). The UnWedge analyses included both deterministic and probabilistic analyses. Furthermore, two different analysis methods were used in 3DEC, one not considering the redistribution of stresses in the rock mass and one considering the excavation-induced stress redistribution.

The analyses focused on investigating the effect of:

• Rock cover
• Stress field
• Joint geometry
• Rock mass quality
• Excavation geometry

Analysis cases were developed and used for comparing the different software and approaches with the focus on investigating (i) how the software could consider the different aspects of wedge stability analysis listed above and (ii) how the choice of software affects wedge stability and support design.

Modelling parameters were based on two projects, Nya Tunnelbanan, an extension of the Stockholm metro, and a study of hydraulic fracturing in the Kiirunavaara mine. Rock mass and joint data based on the following reports for Nya Tunnelbanan:

• Design rapport Station Barkarby (Isaksson Mettävainio et al., 2018)
• The process from pre-investigation to design and excavation in episyenite (Edelbro et al., 2023)

Since DFN parameters were not available for Nya Tunnelbanan, they were instead based on data for the Kiirunavaara mine:

• Effect of hydraulic fracture spacing and injection medium on discontinuity activation (Vatcher et al., 2020)
Due to time limitations, only the analysis method without consideration of the redistribution of stresses was used for the model with DFN parameters in 3DEC.

Support elements used in the analyses were rock bolts and shotcrete. No consideration was given to the hardening process of the shotcrete. The shotcrete was assumed to reach its maximum strength and stiffness immediately after the installation. In the 3DEC analysis the excavation of the tunnel and the installation of the support was made in the same step, meaning that the support was assumed to be installed immediately after the excavation, thus providing maximum load on the rock support. Due to time limitations, the effect of rock support was not studied for the DFN cases.
2 ROCK WEDGE STABILITY ANALYSIS

2.1 Introduction

Different methods can be used when performing a wedge stability analysis, for example analytical methods, Limit Equilibrium Methods, and Discrete Element Methods. The methods are different regarding the underlying assumptions as well as the adaptation of different parameters. This chapter describes the theory behind the different methods.

2.2 Wedge analysis methods

2.2.1 Analytical methods

A general description of analytical methods is provided in Brown (1987). Analytical methods are methods in which the problem is divided into simple elements and traceable equations are used. Solutions to analytical methods are given in closed or pseudo-closed forms, which means that the equation gives an exact answer with a finite number of standard operations. In this thesis, the term analytical method refers to a method that is not numerical.

The simplest analytical method for rock wedges is the identification of potential wedges by spherical projection of the major joint sets in the rock mass. This method includes a kinematic analysis to determine if wedges can form and if they can fall or slide. For a wedge to form, at least three intersecting joint planes need to exist together with the free face created by the excavation. However, kinematic analysis using spherical projections is limited in that no factor of safety can be determined, nor can the effect of support be considered in the stability assessment.

2.2.2 Limit Equilibrium Method (LEM)

Limit equilibrium analysis is a method simplified from limit theory. Limit theory includes the differential equations of equilibrium, boundary conditions, constitutive equations for the material, and the strain compatibility equations. To get a closed form solution in a limit equilibrium analysis the problem must be simplified with respect to geometry and constitutive model. A failure surface must be also assumed when performing the analysis (Sjöberg, 1999).

Usually, the equilibrium is only satisfied for forces and the simplest form of limit equilibrium analysis describes force equilibrium. A factor of safety can be calculated by dividing the resisting forces with the driving forces, see Equation 2.1:

\[ FS = \frac{\sum \text{Resisting forces}}{\sum \text{Driving forces}} \]  \hspace{1cm} (2.1)

where:

- \( FS \geq 1 \) correspond to stable conditions, and
- \( FS < 1 \) correspond to unstable conditions.

Although a factor of safety of one or above one is considered stable, when designing rock support, Hoek (2023) means that a desirable factor of safety should be 1.3 to 1.5 to include an allowance for errors and poor installation. The lower number may be used for temporary...
excavations such as a drilling drive, and the higher value for permanent excavations such as a highway tunnel.

2.2.2.1 Limit Equilibrium Method in UnWedge

Although LEM can be done analytically, it can also be used in computer software. UnWedge is a software developed by Rocscience that uses the Limit Equilibrium Method to determine the wedge stability (Rocscience, 2019). The calculations are made by determining which forces to include, their magnitude as well as which are driving, and which are resisting. Equation 2.1 is applied to calculate the factor of safety of any formed wedge.

2.2.3 Discrete Element Method (DEM)

A discrete system is a system in which the global behaviour of a problem is analysed by defining correlations between independent elements. The Discrete Element Method is a discontinuum numerical analysis method which divides the model into a finite number of individual units (Jing & Stephansson, 2007). In rock engineering applications these units are blocks separated by fractures like joints and faults. Figure 2.1 shows how the fractured rock mass is converted into blocks and discontinuities for DEM.

![Discrete Element Method](image)

*Figure 2.1 a) The fractured rock mass b) DEM application. After Jing & Stephansson (2007).*

A discontinuum numerical method should be used when the ratio of block size volume to the problem domain volume leads to discontinuous conditions in the rock mass, see Figure 2.2.

![Continuous and discontinuous rock masses](image)

*Figure 2.2 Continuous and discontinuous rock masses (Edelbro, 2003).*

The behaviour of the discontinuous system in DEM is divided into two parts where the first represents the mechanical behaviour of the intact rock mass and the other represents the behaviour of the joints. Existence of interfaces separating the discrete units must first be
recognized by the program. Contacts between these interfaces can be treated differently depending on the numerical method used (Itasca, 2023a).

### 2.2.3.1 Discrete Element Method in 3DEC

A 3D numerical analysis program based on the Discrete Element Method is 3DEC, developed by Itasca (2023a). More specifically it is based on the Distinct Element Method, which is a sub-group to Discrete Element Method. In this thesis no difference will be made between the Distinct and Discrete Element Methods. In Figure 2.3 the basic arrangement and features of 3DEC are presented.

![3DEC features](image)

*Figure 2.3 3DEC features. After Itasca (2023b).*

3DEC uses a time-stepping algorithm to solve motion equations for a block system with an explicit finite difference approach. It applies motion and constitutive equations at each time step, considering both rigid and deformable blocks. Sub-contact force-displacement relations are used to update block positions and sub-contact forces (Itasca, 2023a). The cycle of calculations is illustrated in Figure 2.4.

![3DEC calculation cycle](image)

*Figure 2.4 3DEC calculation cycle (Itasca, 2023a).*
2.3 Applicability of wedge analysis methods

2.3.1 Excavation geometry

When performing a wedge stability analysis, one important aspect to consider is the excavation geometry. In a spherical projection only the strike relative to the excavation is considered. The cross-section geometry is not considered, and the excavation is assumed to be long, which for a tunnel means that it does not curve or have any intersections. Brown (1987) mentions that analytical methods rarely can be applied to geometries found in practical rock engineering.

In UnWedge, which is based on the Limit Equilibrium Method, it is possible to have intersecting tunnels and curves by importing a DXF-file (from CAD). However, the tunnel floor and roof are assumed to be flat, and it is not possible to do a full three-dimensional analysis using LEM. The tunnel is also assumed to have a constant cross-section along its axis (Rocscience, 2023).

In the Discrete Element Method, it is possible to customize the geometry of the excavation and use full 3D. However, when importing complex geometries into 3DEC there is a risk of thin sliver-shaped blocks, which can cause numerical problems. Therefore, the geometry may have to be slightly simplified in certain cases (Itasca, 2023a).

2.3.2 Joints

2.3.2.1 Deterministic and probabilistic analysis

Deterministic and probabilistic analysis are two approaches that can be used when performing wedge stability analysis. In a deterministic analysis, no consideration is made to uncertainties in the input values. Probabilistic analysis deals with the uncertainty and variability of input values by incorporating probability distributions into the analyses.

In this thesis work, both approaches have been applied to the joint orientations. For all other input parameters and properties, a deterministic approach has been applied.

2.3.2.2 Joint geometry

In a spherical projection, only the main joint sets are considered. Their strike and dip are considered, but they are assumed to have an infinite length. Conventional LEM assumes infinite joint length, which can lead to an overestimation of block size. When considering limited joint length in LEM the block volume is reduced but still far from reality (Bagheri, 2011). In deterministic LEM it is also not possible to analyse more than three intersecting joint planes at a time and the surfaces of the joint planes are assumed to be perfectly planar (Rocscience, 2023).

In analytical methods the joint geometry is usually considered by the dip and dip direction of the major joint sets. In some methods the length is considered, e.g., in Yow & Goodman (1987) to calculate the shear stiffness of the joint. In the Discrete Element Method, the following geometry properties are considered: orientation, joint density, spacing, shape (planar or wavy), size, length, aperture, and location (coordinates) (Jing & Stephansson, 2007). Even if all these properties can be considered it is important to note that some are more difficult than others to determine through field measurements like mapping or core logging.
2.3.2.3 Joint properties

When performing a spherical projection analysis, it is possible to take the friction angle of the joints into account by adding a cone representing the joints frictional strength. In Figure 2.5 it is shown how the friction angle is added to the spherical projection. Generally, sliding wedges are considered stable if their dip is less than the frictional angle, i.e., if the intersections of the joint sets are outside of the circle. The stable area is marked in grey in Figure 2.5 and the unstable area is white.

![Spherical projection example with joint friction angle (bold circle). Grey marks the stable area and white marks the unstable area.](image)

When using this method, the only joint property considered is the friction angle. It is, however, a quick way to determine if there are possible wedges and provide a first estimation about their stability.

In LEM the joint properties friction angle, shear and tensile strength can be considered when performing a force equilibrium calculation (Rocscience, 2019). The contacts between the bodies can only be modelled as rigid (Cundall & Hart, 1992).

The Discrete Element Method gives different options to model the constitutive behaviour of the joints e.g., elastic joint model, Mohr-Coulomb joint model, non-linear joint model, and continuously yielding joint model (Itasca 2023a).

2.3.2.4 Discrete Fracture Network

Discrete Fracture Network (DFN) is a computational model that describes the geometrical properties of individual pre-existing fractures in a rock mass in terms of e.g., orientation, size, position, shape, and aperture. The conventional DFN model is based on a probabilistic approach being used on a limited amount of sampling data to generate a more extensive fracture network (Lei et al., 2017). Examples of fracture parameter distributions are shown in Figure 2.6.
The term fractures associated with DFN refers to both small- and large-scale structures (micro-cracks, joints, faults, and shear zones) but will in this thesis work only be applied to joints. Due to the statistical variation added to the joint properties, DFN gives a more realistic joint network compared to only analysing the major joint sets since the joints can have varying orientations and do not have an infinite length. Figure 2.7 shows an example of a joint network in 3DEC.

When using DFN models in 3DEC, a fracture template is created for each joint set. The template contains a set of statistical joint geometry parameters including size distribution, the position distribution, and the orientation distribution (Itasca, 2023a). Examples of distribution laws that can be assigned to the joints are Fisher distribution and Gaussian distribution. The Fisher distribution is a 3D counterpart to the normal distribution and is commonly used to model joint orientations (dip and dip-direction) with a specified spread around the mean value.
Gaussian distribution is also known as normal distribution and is defined by giving a mean value and standard deviation of a parameter (e.g., joint size).

After a fracture template has been created, the joints are generated from the statistical description provided by the template. Before generating, a joint density limit is defined for each joint set. The generation of fractures stops when the limit is reached. Figure 2.8 shows a schematic overview of the DFN workflow. When joints have been generated, they are used to cut the blocks in the model.

2.3.3 Rock mass characteristics and quality

A spherical projection does not consider the rock mass characteristics. According to Yow & Goodman (1987) analytical methods treat the adjustment of boundary stresses as the block moves to failure differently. Some take them into account, and some do not. Generally, if the model does not consider stress changes it will not consider the dilatancy and stiffness of the joints or displacement of the wedge either. This leads to unrealistic shear stress conditions and an overestimation of the wedge stability.

The Limit Equilibrium Method does not take the deformation properties of the rock mass into account since the blocks are assumed to be rigid. Neither does it consider the redistribution of loads in the rock mass. In UnWedge, the only rock mass property considered is the unit weight of the rock mass. Furthermore, UnWedge assumes that the rock mass is of high strength and that no stress-induced rock mass failure occurs (Rocscience, 2023).

In 3DEC, a constitutive model can be defined to describe the behaviour of the rock mass e.g., elastic model, anisotropic model, Mohr-Coulomb model, and strain softening/hardening model. Depending on the constitutive model chosen different rock mass properties are required. These properties are used to describe the behaviour of the rock mass as well as its quality. The rock mass can be modelled as both rigid and deformable blocks (Itasca, 2023a).
2.4 Wedge stability calculations

2.4.1 Wedge stability calculation in UnWedge

When using unwedge, the factor of safety is calculated by Equation 2.2 (Rocscience, 2019).

\[ FS = \max (FS_f, FS_w, FS_s) \]  

(2.2)

where:

- \( FS_f \) is falling factor of safety,
- \( FS_w \) is unsupported factor of safety, and
- \( FS_s \) is supported factor of safety.

The displayed factor of safety is the maximum of the ones listed above and are in general based on three joints creating a tetrahedral wedge together with the free face created by the excavation boundary. Each factor of safety is defined according to Equation 2.3 (Rocscience, 2019).

\[ FS = \frac{\text{resisting forces (e.g., shear or tensile strength, support)}}{\text{driving forces (e.g., weight, seismic load, water pressure)}} \]  

(2.3)

A constant or gravitational stress field can be incorporated into the analysis; however, it can only increase the factor of safety since both unstressed and stressed factors of safety will be calculated and the maximum of the two will be displayed (Rocscience, 2019). To determine the induced stress distribution surrounding the excavation, a complete plane strain boundary element stress analysis is performed. The method is used to analyse the distribution of stresses in a two-dimensional section of a three-dimensional body. Ghazal et al. (2011) describes that this method treats the model as continuous without considering discontinuities. Normal forces on the wedge faces are determined by integrating stresses from the continuous model. These forces are then added to the kinematic analysis.

When performing a probabilistic analysis with varying joint orientations, multiple wedge arrangements are generated, and their respective factors of safety are computed.

2.4.2 Wedge stability calculation in 3DEC

To determine the kinematic factor of safety in 3DEC, the isolated block stability method was used (Itasca, 2023c). The method assesses the stability of a single 3D rigid block positioned at the surface of an underground excavation. The block moves as a rigid body in translation and rotation, interacting with the surrounding rock mass through joint elements. Currently, the 3DEC implementation only consider elastic joints. Before excavation, the block experiences initial stresses applied to all its faces. The approach involves calculating the blocks movement and stress variations on its faces caused by the excavation process, specifically the release of stresses on the excavation faces. A factor of safety is calculated on the block faces (Itasca, 2023c). A conceptual picture of the method is presented in Figure 2.9 where \( F_0 \) and \( M_0 \) are the force and moment resultants acting on a face before excavation. \( U \) is the displacement vector and \( W \) is the rotation vector.
The 3DEC command used to analyse the wedge stability using this method is *block analyze-stability free-face*. To use the command, a block model must be defined and meshed (discretized), and in-situ stresses and joint properties (stiffness, cohesion, and friction angle) must be defined. The tunnel free face also needs to be defined. Blocks with faces touching the tunnel free face are identified and the displacements at every grid point of the block, forces on the faces, and factors of safety per zone face are computed. The volume, and minimum and mean factor of safety value of these blocks are then given (Itasca, 2023a).

To investigate if redistribution of stresses influenced the wedge stability when using the method, it was used both with and without the solve command. When the *model solve* command is applied, the model is run iteratively in time steps (cycles) and, in every cycle new velocities, displacements and forces are updated, see Figure 2.10. The model is cycled until a specified criteria is met, for example a convergence ratio, thus bring the model to an equilibrium state. This will allow stresses to redistribute around the excavation and excavation-induced displacement in the rock mass to develop.
3 METHOD DESCRIPTION

To be able to investigate the differences between *UnWedge* and *3DEC* with respect to wedge stability analysis, nine analysis cases were developed. This chapter describes the different cases as well as the comparison methodology.

3.1 Comparison methodology

Initially, nine different analysis cases that combine different tunnel geometries, rock cover, joint geometries, stress fields and rock mass properties were defined. *UnWedge* and *3DEC* were used to conduct wedge stability analyses using the parameters of the different cases. The *UnWedge* analyses included both deterministic and probabilistic analyses. In *3DEC*, two different approaches were used, one not considering the redistribution of stresses in the rock mass and one considering them.

The way in which the different analysis methods could consider the different input parameters was investigated and their respective wedge stability results for the different cases were analysed. Factor of safety was used as the way of determining the wedge stability since it could be obtained from both the *UnWedge* and *3DEC* analyses.

After the initial wedge stability analysis, support was added to one case that was selected based on the obtained wedge factors of safety. An initial support design was developed based on the excavation width and rock mass classification and was then incorporated into the models while investigating the support elements and design options available when using the different software. The degree of utilization of the support was investigated by evaluating the wedge factor of safety in *UnWedge* and the bolt factor of safety in *3DEC*. If the support was extensive or insufficient, a different support design was tested. This process was continued until the amount of support was sufficient to obtain a factor of safety of at least 1.5 for the wedges in *UnWedge*. The acceptance criterion with a factor of safety of 1.5 was chosen since it is commonly used for permanent excavations such as a railway tunnel (Hoek, 2023). In *3DEC* the acceptance criterion was that the axial force of the bold should not exceed its strength.

3.2 Development of cases

The analysis cases were developed with the aim of capturing wedge stability analysis input parameters representable for both the civil engineering and mining sector. Furthermore, the cases should represent parameters and properties of different complexity and detail. Variation in stress field, rock cover, rock mass quality, excavation geometry, and joint geometry were chosen as the input parameters for this study.

A tunnel was chosen as the studied excavation type since it is common in both the civil engineering and mining sector. Two different types of geometries were chosen, single tunnel and intersecting tunnels. These geometries are both common and require different degrees of complexity in the analysis. The intersecting tunnels were set to intersect at a 90° angle to simplify the geometry creation in the models.

Three joint sets as well as DFN generated joints were chosen based on their different complexities and accuracy. In some projects, the only joint orientation geometries obtained from joint mapping are the major joint sets. For a DFN model a more detailed and more
representative, statistical description of the joint distribution and spacing is obtained, but additional input data describing the stochastic distribution of parameters are required.

Three different cases of rock cover and corresponding stress fields were chosen to incorporate tunnels in both the civil engineering and mining sector. A rock cover of half the tunnel width was chosen to represent a shallow civil engineering tunnel, a tunnel depth of 100 meters was chosen to represent a deeply located civil tunnel (or a shallow mining drift) and a depth of 1000 meters was chosen to represent mining drifts at large depth.

In total, nine analyses were performed:

- Variation in tunnel geometry
  - Single tunnel
  - Tunnel intersection
- Variation in joint geometry
  - 3 joint sets
  - DFN generated joints
- Variation in stress field and tunnel depth
  - Gravitational stress field, shallow tunnel, rock cover ½ of tunnel width
  - Regional stress field, deep tunnel, 100 meters of rock cover
  - Regional stress field, very deep tunnel, 1000 meters of rock cover
- Variation in rock mass quality
  - Strength according to low values
  - Strength according to typical values

A summary of the different cases is presented in Table 3.1. The first six cases are base cases where the effect of tunnel depth and rock mass quality will be investigated. Each case and input data determined is further described in the next chapter.

Table 3.1 Description of the input parameters used for the different analysis cases.

<table>
<thead>
<tr>
<th>Rock cover</th>
<th>Stress field</th>
<th>Joint geometry</th>
<th>Rock mass quality</th>
<th>Tunnel geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>½ of tunnel width</td>
<td>100 meters</td>
<td>1000 meters</td>
<td>Gravitational</td>
<td>Regional</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
<td>S</td>
<td>E</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>9</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
4 MODEL DESCRIPTION

4.1 Tunnel geometries

Using Råd tunnelbyggande (Trafikverket, 2016), a cross-section geometry was chosen based on the type-section for a single railway tunnel, straight track. The geometry was then simplified with a horizontal floor and symmetric cross-section. In Figure 4.1 a sketch of the cross-section with its dimensions is shown.

Two different tunnel geometries were then defined, one single tunnel and one intersection. The length of the single tunnel as well as the length and width of the intersection was set to 70 meters to minimize boundary effects and replicate two-dimensional conditions at the centre of the tunnel, see Figure 4.2 and Figure 4.3. The strike of the single tunnel is assumed 0° relative to the north and the tunnels of the intersection strike 0° and 90° respectively.

Figure 4.1 Cross-section dimensions.

Figure 4.2 Length, single tunnel (top view).
4.2 Joint geometries

Two different cases of joint geometry were defined, one with three joint sets and one using DFN parameters.

4.2.1 Three joint sets

The orientation of the three joint sets were initially based on Isaksson Mettävainio et al. (2018). The dip and dip direction were then modified to create a wedge in the tunnel roof, see Table 4.1 and Figure 4.4 below.

Table 4.1 Orientations of joint sets.

<table>
<thead>
<tr>
<th>Joint set</th>
<th>Dip [°]</th>
<th>Dip direction [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55</td>
<td>270</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>060</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>110</td>
</tr>
</tbody>
</table>
4.2.2 DFN parameters

DFN parameters were based on hydraulic fracturing tests in the Kiirunavaara mine (Vatcher et al., 2020). The mean joint set orientations were set to be the same as for the three joint sets. All DFN parameters, including joint orientation, size and spacing are presented in Table 4.2.

Table 4.2 DFN parameters, based on Vatcher et al. (2020).

<table>
<thead>
<tr>
<th>Joint set</th>
<th>Property</th>
<th>Distribution</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Position</td>
<td>Uniform</td>
<td>Generated in model domain</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>Fisher</td>
<td>Dip = 55°, dip-dir = 270°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K = 200</td>
</tr>
<tr>
<td></td>
<td>Discontinuity size (radius)</td>
<td>Gauss</td>
<td>Mean = 10 m</td>
</tr>
<tr>
<td></td>
<td>Discontinuity spacing</td>
<td>-</td>
<td>Std-dev = 5 m</td>
</tr>
<tr>
<td>2</td>
<td>Position</td>
<td>Uniform</td>
<td>Generated in model domain</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>Fisher</td>
<td>Dip = 40°, dip-dir = 060</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K = 200</td>
</tr>
<tr>
<td></td>
<td>Discontinuity size (radius)</td>
<td>Gauss</td>
<td>Mean = 15 m</td>
</tr>
<tr>
<td></td>
<td>Discontinuity spacing</td>
<td>-</td>
<td>Std-dev = 10 m</td>
</tr>
<tr>
<td>3</td>
<td>Position</td>
<td>Uniform</td>
<td>Generated in model domain</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>Fisher</td>
<td>Dip = 60°, dip-dir = 110</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K = 200</td>
</tr>
<tr>
<td></td>
<td>Discontinuity size (radius)</td>
<td>Gauss</td>
<td>Mean = 15 m</td>
</tr>
<tr>
<td></td>
<td>Discontinuity spacing</td>
<td>-</td>
<td>Std-dev = 10 m</td>
</tr>
</tbody>
</table>
4.3 Initial stress field

4.3.1 Gravitational stress field

The initial gravitational stress field was assumed based on a case for the lowest possible stresses. It was calculated using Poisson’s ratio and assuming that no tectonic stresses act on the rock mass. The initial vertical and horizontal stress were calculated using Equation 4.1 and 4.2.

\[ \sigma_v = \rho g z \]  
\[ \sigma_h = \sigma_H = \sigma_v \frac{\nu}{(1-\nu)} \]  

where:
- \( \rho \) is density [kg/m\(^3\)],
- \( g \) is gravitational constant 10 m/s\(^2\),
- \( z \) is the depth [m],
- \( \sigma_h \) is the minimum horizontal stress [MPa],
- \( \sigma_H \) is the maximum horizontal stress [MPa], and
- \( \sigma_v \) is the vertical stress [MPa].

4.3.2 Regional stress field

The initial regional stress field was assumed based on evaluation and interpretation of initial rock stresses in Stockholm and Gothenburg (Edelbro et al., 2022). The stress field for Stockholm was used since the rock mass and joint properties from the project *Nya Tunnelbanan*, an extension of the Stockholm metro, were used (explained further in 4.4). Type values for in-situ regional stresses were calculated using Equation 4.3-4.5 (Edelbro et al., 2022).

\[ \sigma_h = 3.2 + 0.035z \]  
\[ \sigma_H = 3.6 + 0.080z \]  
\[ \sigma_v = \rho g z \]  

Since the purpose of the thesis work was to investigate wedge stability, the direction of the major horizontal stress was set parallel to the tunnel axis for the single tunnel. This led to lowest possible compressive stresses around the tunnel perimeter and thereby the lowest possible confinement of the rock wedges. The stress field was assumed constant at the excavation depth (100 and 1000 meters, respectively) for the deep and very deep tunnels.
4.4 Rock mass and joint properties

The Mohr-Coulomb constitutive model was used for both the rock mass and the joints. Data for the rock mass and joint properties were based on the project *Nya Tunnelbanan*. Two different sets of values were used for the rock mass and joint sets, typical, and low values. Typical values for the rock mass as well as typical and low values for the joint sets were based on Isaksson Mettävainio et al. (2018) and the low values for the rock mass strength were based on Edelbro et al. (2023). The rock mass and joint properties are presented in Table 4.3 and Table 4.4.

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical value</th>
<th>Low value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>RMR</em>&lt;sub&gt;base&lt;/sub&gt;</td>
<td>77</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Young's modulus, <em>E</em></td>
<td>52</td>
<td>5.4</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson's ratio, <em>v</em></td>
<td>0.31</td>
<td>0.34</td>
<td>-</td>
</tr>
<tr>
<td>Cohesion, <em>c</em></td>
<td>4.2</td>
<td>0.6</td>
<td>MPa</td>
</tr>
<tr>
<td>Dilation angle, <em>ψ</em></td>
<td>7</td>
<td>2</td>
<td>°</td>
</tr>
<tr>
<td>Friction angle, <em>ϕ</em></td>
<td>57</td>
<td>47</td>
<td>°</td>
</tr>
<tr>
<td>Tensile strength, <em>σ</em>&lt;sub&gt;t&lt;/sub&gt;</td>
<td>1.0</td>
<td>0.08</td>
<td>MPa</td>
</tr>
<tr>
<td>Density, <em>ρ</em></td>
<td>2650</td>
<td>2430</td>
<td>kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Compressive Strength, <em>JCS</em></td>
<td>59</td>
<td>-</td>
</tr>
<tr>
<td>Joint Roughness Coefficient, <em>JRC</em></td>
<td>9.0</td>
<td>-</td>
</tr>
<tr>
<td>Friction angle, <em>ϕ</em>&lt;sub&gt;j&lt;/sub&gt;</td>
<td>31.5</td>
<td>°</td>
</tr>
<tr>
<td>Cohesion, <em>c</em>&lt;sub&gt;j&lt;/sub&gt;</td>
<td>0.16</td>
<td>MPa</td>
</tr>
<tr>
<td>Joint normal stiffness, <em>k</em>&lt;sub&gt;n&lt;/sub&gt;</td>
<td>837</td>
<td>GPa/m</td>
</tr>
<tr>
<td>Joint shear stiffness, <em>k</em>&lt;sub&gt;s&lt;/sub&gt;</td>
<td>320</td>
<td>GPa/m</td>
</tr>
</tbody>
</table>

4.5 Rock support

An initial support design was developed using the *Design report for Station Barkarby* (Isaksson Mettävainio et al., 2018). The support design is based on the rock mass quality and tunnel width:

- *RMR*<sub>base</sub> = 77 (typical value), tunnel width = 7.5 m
  - Selective bolting
  - Shotcrete in roof, abutment, and walls with 40 mm thickness

Material properties for the bolts and shotcrete were also based on Isaksson Mettävainio et al. (2018). They are presented in Table 4.5 and Table 4.6.
Table 4.5 Bolt material properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, $D$</td>
<td>0.025</td>
<td>m</td>
</tr>
<tr>
<td>Cross-section area, $A$</td>
<td>4.91E-04</td>
<td>m²</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>7800</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Young’s modulus, $E$</td>
<td>183</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson's ratio, $\nu$</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>Compressive strength, $F_{ck}$</td>
<td>214</td>
<td>kN</td>
</tr>
<tr>
<td>Tensile strength, $F_{\gamma}$</td>
<td>214</td>
<td>kN</td>
</tr>
<tr>
<td>Tensile elongation limit, $\epsilon_g$</td>
<td>4.3</td>
<td>%</td>
</tr>
</tbody>
</table>

Table 4.6 Shotcrete material properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$</td>
<td>2300</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Young’s modulus, $E$</td>
<td>11</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>Shear strength, $\tau_b$</td>
<td>1.33</td>
<td>MPa</td>
</tr>
</tbody>
</table>

4.6 UnWedge models

4.6.1 Tunnel and joint geometries

In UnWedge the cross-section dimensions for both the single and T-junction tunnel were constructed directly in the software according to the dimensions presented in 4.1, see Figure 4.5 and Figure 4.6. The intersection was made by creating the top outline of the intersection as an opening section, setting the length to 7.4 meters and the plunge to 90°. Due to geometrical limitations in the software, the roof had to be made flat for the intersection, making the cross-section a rectangle with a width of 7.5 meters and a height of 7.4 meters.

Figure 4.5 Single tunnel. Front view (left) and perspective view (right).
For the deterministic analysis with three joint sets, the joint set orientations were added according to Table 4.1. The joints were assumed to have an infinite length and their position was automatically generated by UnWedge to create the largest possible wedges for the specific tunnel geometry and joint orientations.

A probabilistic analysis was conducted for case 7 (DFN case) by applying joint orientation and size parameters presented in Table 4.2. The probabilistic analyses were performed using a Monte Carlo sampling method (Rocscience, 2023). The number of samples were set to 1000 and the seed was fixed, meaning that the sampling is pseudo-random resulting in an identical sampling every time the analysis is run. Joint density was not possible to include in the analysis.

### 4.6.2 Stress field

A gravitational stress field was added to the shallow cases according to Equation 4.1 and 4.2, using the rock mass densities and Poisson’s ratios presented in Table 4.3. When modelling the deep and very deep cases, constant stress fields were added according to Equations 4.3 through 4.5, using the corresponding densities presented in Table 4.3.

### 4.6.3 Rock mass and joint properties

The rock mass densities corresponding to each case was added, no further rock mass properties could be considered. The joint strength properties considered by UnWedge were friction angle, cohesion, and tensile strength. Properties were added with a Mohr-Coulomb joint model according to Table 4.4. Since joint tensile strength was not provided, it was assumed to be zero.

### 4.6.4 Rock support

Support was installed in UnWedge for the single tunnel as cable bolts and shotcrete. Initially, the support design presented in 4.6.4 was installed. The shotcrete and bolts were then modelled separately, with the shotcrete properties set according to Table 4.6 and the initial thickness was set according to 4.6.4. Different thicknesses were then tested, and the
corresponding wedge factors of safety were noted. The tunnel cross-section with the shotcrete is shown in Figure 4.7.

![Figure 4.7 Shotcrete installed in roof and walls with 40 mm thickness.](image)

Bolt length was set according to 4.6.4, the bolt tensile capacity was set according to Table 4.5 and the bond strength was set according to the Itasca Calibration Tool (Itasca, 2023d). This was conducted to enable direct comparisons with the 3DEC analysis results. Shear strength was enabled with the default value and plate capacity was set to the default value. Different bolt patterns were tested, and their respective wedge factor of safety were noted. An example of installed bolts is shown in Figure 4.8.

![Figure 4.8 Installed bolts in UnWedge, example.](image)
4.7 3DEC models

4.7.1 Tunnel geometries

The geometry described below was built directly in 3DEC by creating tunnel faces using the block cut tunnel command. Based on the tunnel geometries presented in 4.1, three different variations were built:

- Shallow tunnel, single
- Deep & Very deep tunnel, single
- Deep & Very deep tunnel, intersection

The same cross-section geometries were used for the deep and very deep tunnel, see Figure 4.9. For all cases, the total model size was set to 100x100x100 meters, see Figure 4.10.

![Figure 4.9 Cross-section dimensions, 3DEC.](image1)

![Figure 4.10 Model dimensions, 3DEC.](image2)
The shallow tunnel was placed higher up in the model to get a rock cover of half the tunnel width, 3.75 meters, while the deep and very deep tunnels were placed so that the distance from the top of the model to the top of the tunnels was 50 meters. See Figure 4.11 and Figure 4.12 for the constructed tunnels.

A "region of interest" was defined around the tunnels to simplify gradual zoning, see Figure 4.13. The model was constructed with a closed triangular surface mesh. Close to the tunnels in the region of interest, the mesh was finer to improve the calculation results and farther away the mesh was coarser to improve calculation time. In the tunnel, the zone size was set to 0.5 meters and in the rest of the region of interest the zone size was set to 1 meter. Zones outside the region of interest had an edge length of 4 meters. See Figure 4.14 for an overview of the different zone sizes.
4.7.2 Joint geometries

For the three joint sets, the joint set orientations were added according to Table 4.1. Unlike UnWedge, where the largest wedge is generated by default, the origin positions of the joints need to be specified in 3DEC. The origins of the joints were iterated to achieve a wedge similar to the one generated by default in the deterministic UnWedge analysis.

Since DFN is based on statistical distribution of joint length and density, a new joint network will be generated every time the model is run. To enable comparison, the model random command was used. The command can be used to fix the random seed, meaning that identical models are generated each time the model is run. The joint network generated when using the DFN parameters presented in Table 4.2 is shown in Figure 4.15.
4.7.3 Stress field and boundary conditions

Stresses were induced depending on the tunnel depth, using a gravitational stress field for the shallow cases and a constant stress field for the deep and very deep cases. The gravitational stress field was induced according to Equations 4.1 and 4.2 using the rock mass densities and Poisson’s ratios presented in Table 4.3. For the deep and very deep cases, a constant stress field was induced according to Equation 4.3–4.5 using the corresponding densities presented in Table 4.3. Gravity was set to 10 m/s² in all models.

When using the method with no redistribution of stresses in 3DEC, no boundary conditions were required. For the method where stress redistribution is considered, boundaries were added. To improve the calculation to equilibrium time, stress boundary conditions were used on all sides following the same gradient as the induced stress field, except for the top boundary for the shallow cases, which was simulated as a free surface. Roller (zero normal velocity) boundaries were used on all sides of the model for the deep and very deep cases since the top of the model does not represent the surface.

4.7.4 Rock mass and joint properties

When not considering stress redistribution, the joint mass was assigned an elastic material model. The only rock mass property required to perform the analysis was the density and it was added according to Table 4.3. Joint parameters were added according to Table 4.4.

When considering stress redistribution, a Mohr-Colomb material and joint model was used. Rock mass and joint properties were assigned to the blocks and the joints of the model according to Table 4.3 and Table 4.4.

Elastic construction joints were present in the model due to the creation of the tunnel as well as definition of the region of interest. Since these construction joints are fictitious, they need to be given properties that make them behave as part of the rock mass. The joint normal and shear stiffness of the elastic construction joints were calculated according to Kulatilake et al.
(1992), using the rock mass shear modulus, see Equation 4.6. Joint shear stiffness and normal stiffness were calculated using Equations 4.7 and 4.8, respectively.

\[
G = \frac{E}{2(1+\nu)} \tag{4.6}
\]

\[
JKS = \frac{G}{0.01} \tag{4.7}
\]

\[
JKN = JKS \cdot 2.5 \tag{4.8}
\]

where:

- \( G \) is rock mass shear modulus [Pa],
- \( \nu \) is Poisson’s ratio,
- \( JKS \) is joint shear stiffness [Pa/m], and
- \( JKN \) is joint normal stiffness [Pa/m].

### 4.7.5 Rock support

Rock bolts were modelled in 3DEC as hybrid bolt structural elements. Hybrid bolts were chosen since they, in additional axial loading, can also resist shearing perpendicular to the bolt when it crosses a joint. The bolts were given material properties using the Itasca Calibration Tool (Itasca, 2023d). Properties were then adjusted according to Table 4.5.

The support design presented in 4.6.4 was modelled first, followed by shotcrete and bolts modelled separately. For cases with three joint sets forming a single roof wedge, the bolt was installed in the middle of the wedge, see Figure 4.16. The bolt was divided into six segments, each 0.5 meters long, to be able to evaluate the axial force in more detail. The shotcrete was modelled as shell structural element, being assigned elastic parameters presented in Table 4.6. Figure 4.17 shows the installed shell.

![3DEC 9.00](image)

**Figure 4.16** Installed bolt.
4.7.6 Model control

For the 3DEC analysis considering stress redistribution, an elastic model was run first in 3DEC to check the initial stress field, boundary conditions and results. Stresses at the tunnel boundary after excavation were compared to results from stress analyses for different cross-section geometries Hoek & Brown (1980). When the elastic model was ready and expected to give accurate results, the modelling of the different cases began.

4.7.7 Modelling sequence

Two different types of 3DEC models were created, one where redistribution of stresses was not considered and one where they were. The modelling sequence for 3DEC without considering redistribution of stresses was performed using the following steps:

1. Creating model geometry
2. Creating joints in the region of interest
3. Applying material constitutive model and material properties
4. Applying joint constitutive model and joint properties
5. Defining boundary conditions and initializing stress field
6. Excavating the tunnel and analysing wedge stability

The modelling sequence for 3DEC with consideration of redistribution of stresses was then conducted as follows:

1. Creating model geometry
2. Creating joints in the region of interest
3. Applying material constitutive model and material properties
4. Applying joint constitutive model and joint properties
5. Defining boundary conditions and initializing stress field
6. Running the model to initial equilibrium
7. Saving equilibrium model
8. Resetting deformations to zero
9. Removing tunnel and installing support (support only for case 2)
10. Running the model to equilibrium
11. Saving model step
12. Analysing wedge stability by using the *block analyse stability* command.

4.8 Adaptability results summary

The possibilities of modelling the defined cases vary between the analysis methods used. Table 4.7 shows a summary of which aspects were considered when modelling.

*Table 4.7 Summary of adaptability for the different software.*

<table>
<thead>
<tr>
<th>Model aspect</th>
<th><em>UnWedge</em></th>
<th><strong>3DEC</strong></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No redistribution of stresses</td>
<td>Redistribution of stresses</td>
<td></td>
</tr>
<tr>
<td>Full 3D</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Three joint sets</td>
<td>Ubiquitous joints, largest wedges generated</td>
<td>Origin position of each joint needs to be specified</td>
<td>Origin position of each joint needs to be specified</td>
<td></td>
</tr>
<tr>
<td>DFN</td>
<td>Statistical distribution of joint orientations and size</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Stress field</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Rock mass properties</td>
<td>Density</td>
<td>Density</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Joint properties</td>
<td>Cohesion, tensile strength, and friction angle</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Rock support</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Stress redistribution</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
5 WEDGE STABILITY ANALYSIS RESULTS

5.1 Base cases

When modelling the base cases with three joint sets, the roof wedges shown in Figure 5.1 were created in *UnWedge* and *3DEC*, respectively. The wedge volume created in the deterministic *UnWedge* analysis was 34 m$^3$ and in *3DEC* it was 27 m$^3$. This difference in block volume is due to the difference in assumptions that the software makes when performing a fully deterministic analysis. In *UnWedge* the joints are assumed to be ubiquitous and infinite, and the largest possible wedge is displayed while joints in *3DEC* need to have specified origin positions.

![Figure 5.1 Wedge geometry. UnWedge (left) and 3DEC (right).](image)

A summary of the wedge factors of safety for the base cases depending on the analysis method used are presented in Table 5.1 below.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Rock mass quality</th>
<th>UnWedge</th>
<th>3DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No redistribution of stresses</td>
<td>Redistribution of stresses</td>
</tr>
<tr>
<td>Shallow</td>
<td>Typical</td>
<td>9.23</td>
<td>5.74</td>
</tr>
<tr>
<td>Deep</td>
<td>Typical</td>
<td>0.85</td>
<td>0.84</td>
</tr>
<tr>
<td>Very deep</td>
<td>Typical</td>
<td>0.80</td>
<td>0.73</td>
</tr>
<tr>
<td>Shallow</td>
<td>Low</td>
<td>7.96</td>
<td>6.54</td>
</tr>
<tr>
<td>Deep</td>
<td>Low</td>
<td>0.85</td>
<td>0.84</td>
</tr>
<tr>
<td>Very deep</td>
<td>Low</td>
<td>0.80</td>
<td>0.73</td>
</tr>
</tbody>
</table>
The wedge factors of safety when using *UnWedge* and *3DEC* with no redistribution of stresses are not affected by the rock mass in the deep and very deep cases. When using *3DEC* with redistribution of stresses, the factor of safety is lower when the rock mass quality is lower. The largest effect of the difference in rock cover when comparing *UnWedge* and *3DEC* can be seen when the rock cover is 3.75 meters (shallow cases).

Figure 5.2 shows the effect of running the *model solve* command in *3DEC*. The command leads to a redistribution of stresses around the opening and in the wedge. A stress concentration can be seen above the wedge for the case with redistribution of stresses.

![Figure 5.2 Difference in stress tensors between 3DEC without (left) and with (right) model solve command. Case 2.](image)

Figure 5.3 shows the difference between the plotted factor of safety per block face when using *3DEC* with and without redistribution of stresses. It can be seen that the factors of safety are more scattered for the case with stress redistribution. The figure only shows Case 2 but the difference can be seen for all cases. In *3DEC* with no stress redistribution, the difference in factor of safety per wedge face can easily be evaluated. In Figure 5.3 it can be seen that the wedge face with the highest factor of safety is the one created by the joint with dip-direction 110°, which is also the joint with the largest dip. Factor of safety per wedge face cannot be plotted in *UnWedge*.

![Figure 5.3 Difference of plotted factor of safety per block face. No stress redistribution (left) and stress redistribution (right). Case 2.](image)
The calculation with redistribution of stresses also enables studying possible failure of the rock mass (for a plastic material model simulated). An example of this can be seen in Figure 5.4 where the rock mass state for Case 6 is shown. When running the model without stress redistribution, the rock mass behaves elastically and when running it with stress redistribution, rock mass failure occurs for this combination of material properties.

Stress-induced rock mass failure occurred in all deep and very deep cases when running the model with stress redistribution. The volume of the failed rock mass increases with larger rock cover and lower rock mass quality. Table 5.2 shows in which cases stress-induced rock mass failure occurred.

Table 5.2 Rock mass failure per case.

<table>
<thead>
<tr>
<th>Case</th>
<th>Rock mass failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
</tr>
</tbody>
</table>

5.2 Intersecting tunnels, three joint sets

When using three joint sets 3DEC, the joint geometry and factor of safety was assumed to not be significantly affected by the addition of an intersecting tunnel. Hence, the intersecting tunnel case was not analysed for this joint pattern. In UnWedge however, the tunnel roof needed to be flat to enable analysis of the tunnel intersection. Due to these differences, the wedge was analysed for this case in UnWedge. The wedge geometry and factor of safety obtained when performing a deterministic analysis with infinite joint length is shown in Figure 5.5.

When modelling the intersection, the wedge becomes approximately 10 times larger than for the single tunnel. It also has a factor of safety of zero. This clearly shows the effect of infinite joint lengths for a deterministic analysis in Unwedge.
5.3 DFN and probabilistic analyses

When statistical parameters of the joint orientations were used for the single tunnel case in UnWedge, almost 12 000 possible wedges were generated. For the same case using DFN generated joints in 3DEC, around 1000 wedges were created, showing the difference in probabilistic approach by the different software.

Both the single tunnel and the intersection were modelled with probabilistic joint orientation and size parameters. Using both UnWedge and 3DEC, data for wedge volume and corresponding factor of safety was obtained. The data was processed by removing wedges smaller than 0.3 m$^3$ and with a factor of safety above 2.0. When analysing the intersection in UnWedge, no wedges with a factor of safety below 2.0 were generated. For that reason, the intersection case is not included in the following presentation of results.

Figure 5.6 through Figure 5.13 shows the distribution of wedge volume and wedge factors of safety when running a probabilistic analysis in UnWedge and a DFN analysis in 3DEC. In Figure 5.6 it can be seen that the wedge volume distribution follows something resembling a lognormal distribution. All possible wedges are smaller than the wedge created by joints with infinite length (34 m$^3$).

Figure 5.7 shows the wedges FS and the corresponding wedge volume. The wedge FS is between 0.6 and 1.3. Figure 5.8 shows the wedge FS distribution. For example, it can be seen that 70 % of the possible wedges have a FS below 0.9. Figure 5.9 shows that the wedge volume distribution in 3DEC does not follow even a lognormal distribution like in UnWedge. Most of the wedges have a volume below 3.1 m$^3$ and as the volume increases, the number of wedges become fewer.

Comparing Figure 5.9 and Figure 5.10, there are, as expected, more wedges created in the intersection compared to the single tunnel. The distribution of wedge volume is similar for both the single tunnel and the intersection. Comparing Figure 5.11 and Figure 5.12, the wedge FS relative to wedge volume is similar for both the single tunnel and the intersection, and most of the wedges have a FS above 0.8.
Figure 5.13 shows the FS distribution for both the single tunnel and intersection in 3DEC. The wedges in the intersection shows a slightly higher FS than the ones created for the single tunnel. For example, 50% of the wedges in the single tunnel case and 40% of the wedges in the intersection case have a FS below 1.6.

**Figure 5.6 Wedge volume distribution, UnWedge single tunnel.**

**Figure 5.7 Wedge factor of safety per wedge volume, UnWedge.**
Figure 5.8 Wedge FS distribution, UnWedge single tunnel.

Figure 5.9 Wedge volume distribution, 3DEC single tunnel.
Figure 5.10 Wedge volume distribution, 3DEC intersection.

Figure 5.11 Factor of safety per wedge volume, 3DEC single tunnel.
Figure 5.12 Factor of safety per wedge volume, 3DEC intersection.

Figure 5.13 Showing % of wedges with a factor of safety lower than a certain value, 3DEC.
In *UnWedge*, only the wedges created by the mean joint orientations and sizes could be displayed in a 3D-view. The mean roof wedge created on the single tunnel has a volume of 5.92 m$^3$ and is shown in Figure 5.14. The mean roof wedge created in the intersection has a volume of 5.16 m$^3$ and is shown in Figure 5.15.

In *3DEC* the wedges created by the DFN generated joint set can be displayed in a 3D-view. The number of wedges displayed can be set to only showing the wedges created on the tunnel face. It can be further adjusted to show wedges with factors of safety above or below a specified value. Figure 5.16 shows the wedges created on the tunnel face and Figure 5.17 shows wedges with a factor of safety below 1.5.
Figure 5.16 Wedges created on tunnel face. Single tunnel and intersection.

Figure 5.17 Wedges with a factor of safety <1.5 created on the tunnel face in 3DEC. Single tunnel and intersection.
5.4 Rock support

Rock support was added in Case 8 since the obtained factor of safety varied between 0.84 and 1.05 depending on the analysis method used. When studying the rock support, the shotcrete and bolts are evaluated both separately and together. The focus of the analysis was to test the initial support design presented in 4.6.4 and then determine the minimum amount of support required to obtain a factor of safety >1.5. Due to differences in how the software could display the effect of the support on rock wedge stability, the evaluation method differs between them.

In UnWedge the wedge factor of safety is adjusted when the rock support is installed. Firstly, the initial support design was installed for Case 8 (single tunnel with 100 m rock cover, deterministic analysis), which resulted in a factor of safety of 2.68, see Figure 5.18.

Following this, the shotcrete was analysed separately. A thickness of 40 mm resulted in a factor of safety of 2.47. The thickness of the shotcrete was gradually decreased with until the factor of safety was around 1.5, which resulted in a required thickness of 25 mm, see Figure 5.19 for the two cases with shotcrete support and the corresponding resulting wedge factor of safety. This indicates that when testing the initial support design, the shotcrete had a greater contribution to the increase in wedge factor of safety than the bolts.
Figure 5.19 Installed shotcrete and corresponding wedge factor of safety in UnWedge. 40 mm, wedge FS 2.47 (left) and 25 mm, wedge FS 1.58 (right). Figure not to scale.

Bolts were then analysed separately. One bolt installed in the middle of the wedge gave no increase of the factor of safety, and more bolts were added to the model. A factor of safety above 1.5 was obtained for a bolt pattern with 3 meter long bolts, 2.0 meters in-plane spacing and 3.0 meters out of plane spacing resulting in a total of 7 bolts. The bolt pattern and installation specifications are shown in Figure 5.20 and a 3D-view of the bolt pattern is shown in Figure 5.21.
In 3DEC, the wedge factor of safety was not affected by the installation of support due to the way in which the isolated block stability method calculated wedge factor of safety. Instead, the effect of the support was evaluated by determining the bolt factor of safety in the six segments that the bolt was divided into. Bolt factor of safety was determined by dividing the bolt strength with the bolt axial force for each segment. Since the model solve command is needed to induce axial forces in the bolt, support was only added to the 3DEC analysis with redistribution of stresses.
Similar to the *UnWedge* analysis, the initial support design was installed first, see Figure 5.22 and Figure 5.23. The maximum axial force is 57.6 kN and is obtained in the bolt segment where the bolt intersects one of the joint planes creating the wedge. Following this, the bolt was installed without shotcrete, see Figure 5.24. Without shotcrete, the maximum axial force is 64.1 kN, which is also obtained in the bolt segment where the bolt intersects one of the joint planes.

![Figure 5.22 Installed bolt and shotcrete in 3DEC. Axial force per bolt segment and bolt segment number shown.](image1)

![Figure 5.23 Installed bolt with intersecting joint plane in 3DEC.](image2)
The bolt factor of safety over the bolt length with and without shotcrete can be seen in Figure 5.25. Since the axial force is the highest in the segment containing the joint intersection, the factor of safety shows the lowest value there. When moving along the bolt further into the rock mass, the factor of safety increases. The bolt factor of safety is slightly higher when shotcrete is installed, and it shows the same behaviour of increasing when moving along the bolt further into the rock mass. Since lowest factor of safety is around 3, no portion of the bolt fails.
5.5 Results summary

A summary of the main findings of the analyses conducted is presented below.

- **Base cases:**
  - When assuming infinite joint length, a wedge with a volume of 34 m$^3$ is generated by *UnWedge* and a wedge with the volume of 27 m$^3$ is generated in *3DEC*.
  - Wedge FS was not affected by changing the rock mass quality when using *UnWedge* and *3DEC* with no redistribution of stresses.
  - Comparing *UnWedge* and *3DEC* without redistribution of stresses, the wedge FS was slightly lower in *3DEC*.
  - Using *3DEC* with redistribution of stresses, the factor of safety was lower for the low rock mass quality than for the typical rock mass quality.

- **Intersection *UnWedge*, infinite joint length:**
  - The generated wedge has a volume of approximately 338 m$^3$, around 10 times larger than the wedge generated for the single tunnel.

- **DFN and probabilistic analysis:**
  - *UnWedge* displays the possible wedges based on variation in joint orientation and size. No 3D view of possible wedges can be shown but FS versus wedge volume can be plotted.
  - In *UnWedge*, single tunnel, all possible wedges are smaller than the one generated with infinite joint length. The resulting FS is between 0.6 and 1.3 (excluding wedges with a volume below 0.3 m$^3$ and a FS above 2.0). There is a slight trend where the FS increases when wedge volume increases.
  - *3DEC* generates a joint network based on DFN parameters (specified joint density, variation in joint orientation and size). Wedges intersecting the tunnel face can be viewed and filtered to show wedges with a FS above or below a certain value, and FS vs wedge volume can be plotted.
  - In *3DEC* and for the single tunnel case, 93% of the wedges generated are smaller than the wedge generated by infinite joint length (excluding wedges with a volume below 0.3 m$^3$ and a FS above 2.0) and most of the wedges have a FS above 0.8.
  - Comparing the single tunnel and intersection in *3DEC*, the wedges in the intersection show a slightly higher FS than for the single tunnel.

- **Rock support:**
  - In *UnWedge*, 25 mm of shotcrete was sufficient to obtain a wedge FS above 1.5. Using only bolts, seven systematically installed bolts were required to obtain a wedge FS above 1.5.
  - Using *3DEC*, bolt factor of safety was evaluated. The bolt was divided into six segments and the bolt FS was lowest in the segment that intersected a joint. No segment of the bolt had a FS below three when using one bolt and no shotcrete. When shotcrete and bolt was used, the FS was slightly higher in all segments of the bolt.
6 DISCUSSION

The aim of this thesis was to compare the Limit Equilibrium Method (LEM) and Discrete Element Method (DEM) with respect to rock wedge stability analysis and support design, using the software UnWedge (LEM) and 3DEC (DEM). Furthermore, the work aimed to investigate how well different parameters and properties could be considered by the different software and compile recommendations for the use of the different methods.

Regarding the geometry creation in the different software, a single tunnel could be created in both while two intersecting tunnels could only accurately be created using 3DEC. In UnWedge the tunnel roof had to be made flat when constructing the tunnel intersection, due to required simplification imposed by the software that the excavation has to have a constant cross-section along its axis. This means that if the tunnel has a change in cross-section or is curved along its axis, the geometry can be created accurately only in 3DEC but not in UnWedge.

By default, UnWedge assumes the joints to be ubiquitous and infinite, thus generating the largest possible wedges that can form around the excavation. The wedges can be scaled by for example limiting the joint trace length. This was done for the probabilistic analysis which resulted in a roof wedge volume (mean joint orientations and size) for the single tunnel of approximately one sixth of the maximum roof wedge volume with infinite joint length. When using limited joint length for the intersection case, the roof wedge volume was approximately 66 times smaller than the roof wedge generated by infinite joint length. This clearly shows the effect of joint length on wedge volumes. Using infinite joint length can severely overestimate the wedge volumes, which consequently can lead to an excessive amount of support being used. If information about the joint length is available, it should be used in the analysis. In any case, engineering judgment needs to be applied when studying the results, in particular if excessively large wedges are formed.

When applying the DFN parameters, a full DFN generation of the joint network could be obtained in 3DEC. Statistical variation of the joint orientations and joint sized could be included in UnWedge when performing a probabilistic analysis, but joint density could not be considered. In UnWedge, multiple joint arrangements and consequently wedges are generated based on the variation in joint orientation and size. In 3DEC, a network of joints is generated based on the joint density and statistical distribution of joint orientation and size. Due to these differences, it is difficult to compare the results obtained when using the different methods. The results obtained from UnWedge are more suitable for statistical analysis but less so for directly application to tunnel and rock support design. In 3DEC it is easier to see the possible wedges formed and design the tunnel and support accordingly.

In 3DEC and using DFN, the wedges in the intersection shows a slightly higher FS than the ones created for the single tunnel. For example, 50% of the wedges in the single tunnel and 40% of the wedges in the intersection have a FS below 1.6. This could be due to the difference in major horizontal stress orientation. The added tunnel on the intersection strikes perpendicular to the single tunnel, making the major horizontal stress act perpendicular to the axis of the added tunnel, thus influencing wedge stability (different confining stress on joint faces).

The effect of different rock mass qualities can only be investigated when running a 3DEC analysis with redistribution of stresses. This is an advantage compared to UnWedge; for the
3DEC analysis without redistribution of stresses it is possible to study both the wedge factor of safety as well as other potential failure mechanisms of the rock. Therefore, UnWedge and 3DEC without stress distribution analysis should only be used when purely structurally controlled (wedge) failure is expected. If other failure mechanisms of the rock are expected, for example if the rock mass is weak or if the excavation is deep, DEM with redistribution of stresses should be used. If LEM or DEM without redistribution of stresses is used when expecting other possible failure mechanisms, complementary analyses investigating the rock mass state after excavation should be performed.

When comparing UnWedge and 3DEC with no redistribution of stresses, the wedge factors of safety were similar albeit with 3DEC showing a slightly lower factor of safety. This could be due to the way the software considers field stress, where the stress analysis in UnWedge treats the rock mass as a continuum without considering discontinuities.

Another difference was that in 3DEC the factor of safety per block face could be plotted. This means that it can be visualized where on the wedge the highest and lowest factor of safety is obtained. When considering redistribution of stresses, the values of the factor of safety became scattered over the wedge which makes it difficult to draw clear conclusions as to where on the wedge the highest and lowest factor of safety can be obtained.

When using the Discrete Element Method, the support was installed at the same time as excavation of the whole tunnel which leads to the support reaching its maximum load immediately. This is not a realistic application of the support process, but provides a conservative assessment of stability and support reaction.

Due to the differences when installing the support in the different software, the bolts could not be installed in the exact same place in the two methods. This means that the results cannot be compared directly. In 3DEC the bolt could be divided into segments to obtain calculated values (e.g., axial bolt forces) in greater detail. When analysing the bolt axial force, it could be seen that it was highest in the segment where it intersected one of the joints creating the wedge. This might be obvious to a rock mechanics engineer; however, the method with segment division could be efficient when performing a DFN analysis to see where along the bolt the highest force will be. When the bolt intersects multiple joint planes, it might not be as obvious where the highest axial force acting on the bolt will be.

When analysing shotcrete in UnWedge a thickness of 25 mm was indicated to be sufficient to obtain a factor of safety above 1.5. This is a support design that would not be applied when expecting failure of wedges this size. Larger wedges are generally stabilized with rock bolts while shotcrete is used to seal the rock surface to keep small blocks in place. Due to the methodology for determining the support force of shotcrete in UnWedge, a wedge with a larger area intersecting the tunnel face results in a higher support force. Furthermore, the only assumed failure mode of the shotcrete in UnWedge is direct shear. This shows the importance of critical judgement of modelling results and understanding of the underlying assumptions and calculations of the used software.
7 CONCLUSIONS AND RECOMMENDATIONS

Based on the conducted study, the following conclusions can be drawn:

- *UnWedge* and *3DEC* with no redistribution of stresses require similar input data and gives similar factors of safety for a single rock wedge in the tunnel roof. The benefits of *3DEC* are that full 3D geometries and full DFN can be investigated.

- *UnWedge* and *3DEC* with no redistribution of stresses does not take the rock mass quality into consideration.

- The only method studied with the ability to capture rock mass failure mechanisms in addition to wedge failure is *3DEC* where consideration is taken to the redistribution of stresses as well as material yielding using a plastic material model.

- Assuming infinite joint lengths can severely overestimate the wedge volumes, which, in turn, can lead to an excessive amount of support being used.

- Shotcrete has a greater contribution to the wedge factor of safety in *UnWedge* compared to *3DEC*. However, the only assumed failure mode of the shotcrete in *UnWedge* is direct shear, which may be misleading when using results for actual support design.

The following recommendations are given:

- For situations where the excavation geometry cannot be assumed as two-dimensional with constant cross-section, the Discrete Element Method should be used when analysing wedge stability.

- If stress-induced rock mass failure is expected, the Discrete Element Method with consideration of the redistribution of stresses should be used to capture both wedge failure as well as stress-induced failure mechanisms.

- If information about the joint lengths is available, it should be used in the analysis. In any case, engineering judgment needs to be applied when studying the results, in particular if excessively large wedges are formed.

- It is vital to understand how the software determines support force and use engineering judgement to determine whether the obtained quantity is sufficient, or overly conservative.

The following is suggested for further studies:

- Simulation of sequential excavation of a tunnel to simulate a more realistic rock support behaviour.

- Comparing the required amount of support for wedges generated with infinite joint length and DFN generated wedges to determine how the difference in wedge volume affects the support design.
8 REFERENCES


