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Back-calculation of in-situ stress condition based on the performed secondary stress measurements: Connected to the West Link Project, Sweden

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ABSTRACT

A large underground cavern design at a shallow depth requires reliable estimation of in-situ stress conditions. Geological conditions, topography, and tectonic activity influence the magnitude of the in-situ stresses. The objective of this paper is to predict and evaluate the in-situ stress state before the excavation of two pilot tunnels in a railway access cavern. The access cavern, named Mellanplan, is a part of the Korsvägen section at the West Link Project in Gothenburg, Sweden. The first phase of the construction sequence at Mellanplan involved excavation of two pilot tunnels in the top heading, where a rock pillar remained in between the pilots. Before excavating the rock pillar, SINTEF Community performed secondary stress measurements from the roof of the two pilots, utilising the 2D doorstopper method. The results from these stress measurements are assessed and an interpretation of the stress field at Mellanplan is carried out. The concepts from the final rock stress model (FRSM) suggested by Stephansson and Zang (2012) are applied in the back-calculation of the initial stress state. A 3D numerical program, *RS3*, is applied for parameter stress analyses, where various stress inputs are evaluated. The results from stress analyses are validated with the induced stresses obtained from doorstopper measurements. The final rock stress model demonstrates the stress field at Mellanplan as $\sigma_H > \sigma_v > \sigma_h$. The findings in this study reveal that tectonic stress and residual stress have greater contribution towards the major horizontal stress component. Furthermore, σ_v and σ_h. are suggested as gravity induced stresses. Due to the complexity of stresses at shallow depths, there is a possibility of geological structures reducing the already low magnitude of σ_h.

KEYWORDS

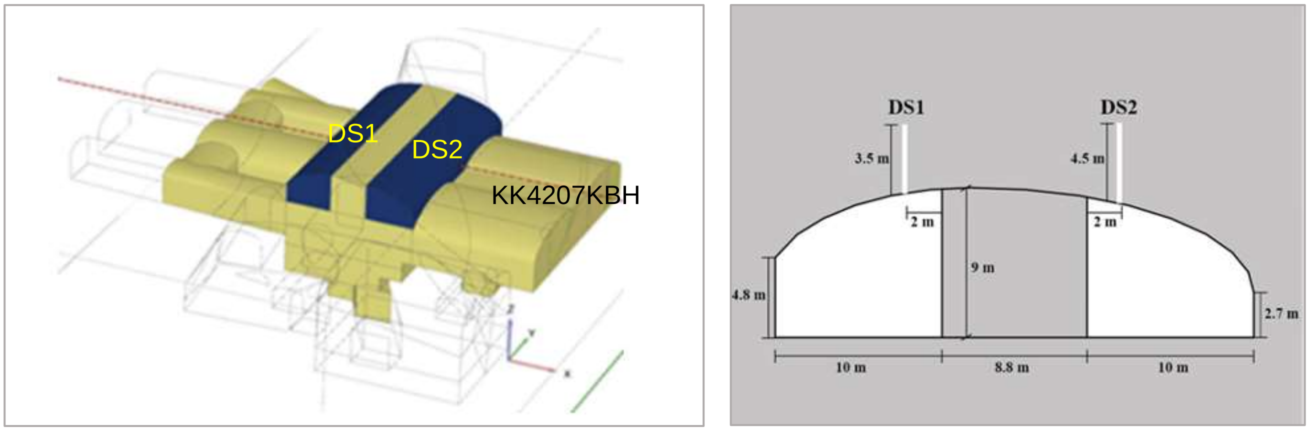
Back-calculation; Estimation of in-situ stresses, Rock cavern; 3D modelling, Scandinavian geology

INTRODUCTION

Underground caverns are used for a variety of purposes in civil engineering, e.g., caverns for the installation of turbines, generators and transformers in hydropower projects, rock caverns for storage, underground sports facilities, and caverns for underground train stations. Large cavern spans combined with a small overburden are often more challenging than narrow caverns due to confinement issues and the requirement of securing an arching effect. Underground excavations near the ground surface tend to have arching deformations directed towards the free ground. In such cases, it is beneficial to have high horizontal stresses. The horizontal stresses that are at least equal to or greater than the vertical stress is favourable for the stability of caverns with large spans at shallow depths (Barton and Hansteen, 1978). Furthermore, a combination of large cavern spans and low overburden can result in stress-confinement reduction, which can contribute to structurally controlled failure. This form of instability issue involves gravity-driven processes leading to block falls from roof and sidewalls of underground openings. Alongside stress conditions, pre-existing geological structures have an important influence on the formation of wedges and block falls, and hence affect the stability of an underground opening (Martin et al., 2003).

Since cavern stability issues depend on stress conditions, the knowledge regarding in-situ stresses is important. The estimation of in-situ stress state can be based on elasticity theory, various stress measurement methods, monitoring or numerical modelling. In-situ stresses at a shallow depth are often complex and relatively less measured and reported. The reported stresses in the literature are generally at a depth greater than 50 m. The results from the stress measurements near the ground surface often have widespread data. According to Stephansson and Zang (2012), in addition to stress measurements, numerical modelling can contribute to the estimation of the variability of in-situ stresses.

This study is connected to the West Link (Västlänken), which is a railway infrastructure project, located in Gothenburg, Sweden. The project includes constructions of a six-kilometre underground tunnel and three new underground stations: Gothenburg Central Station, Haga and Korsvägen. The stress conditions at the shallow seated access cavern in Korsvägen, called Mellanplan (Figure 1), has been studied. Prior to the West Link, few rock stress measurements were conducted in the Gothenburg region. In order to estimate the in-situ stress state at the location, results from the secondary stress measurements conducted by SINTEF Community are utilised. The predicted in-situ stresses depict stress state before any excavation at Mellanplan.



a) b)

Figure 1. a) Overview of Mellanplan, where the blue volumes represent the excavated pilot tunnels in the top heading; b) Location of the two doorstopper measurements.

The construction of Mellanplan started in 2021, where the first step in the excavation sequence was the removal of two pilot tunnels at the top heading. The excavation method applied in this section is drill-and-blast. The next step in the construction sequence involves excavation of the rock pillar between the pilots. The benching under the top heading will be conducted in accordance with the excavation of track- and station tunnels (Trafikverket, 2016). During the study of the access cavern, only pilot tunnels at the top heading of Mellanplan were excavated. The length of both pilots is 50 m and are termed as East pilot and West pilot. The orientation of Mellanplan is N11W.

Before the excavation of the rock pillar, SINTEF Community performed secondary stress measurements on the roof of both East and West pilot in Mellanplan 28 m inwards from the south of Mellanplan, as shown in Figure 1. The measurements were carried out in April 2022, where the 2D Doorstopper method was utilised. Stress measurements were performed on vertical boreholes from the pilot roofs and are referred to as DS1 (West pilot) and DS2 (East pilot). The 2D stress measurement in DS1 was performed in a 3.5 m long vertical hole above the roof, and in DS2 the vertical hole length was 4.5 m. In DS1, measurements were registered between 0.6 m and 3.5 m hole depth. While in DS2, measurements were registered between 1.3 m and 4.1 m.

1. ROCK STRESS MODEL FOR MELLANPLAN

Formation of the final rock stress model (FRSM), suggested by Stephansson and Zang (2012), comprises of various steps, presented in Figure 2. The first step involves the best estimate stress model (BESM), which is developed by collecting and analysing the existing data on morphology, topography, geology, borehole and drill core.

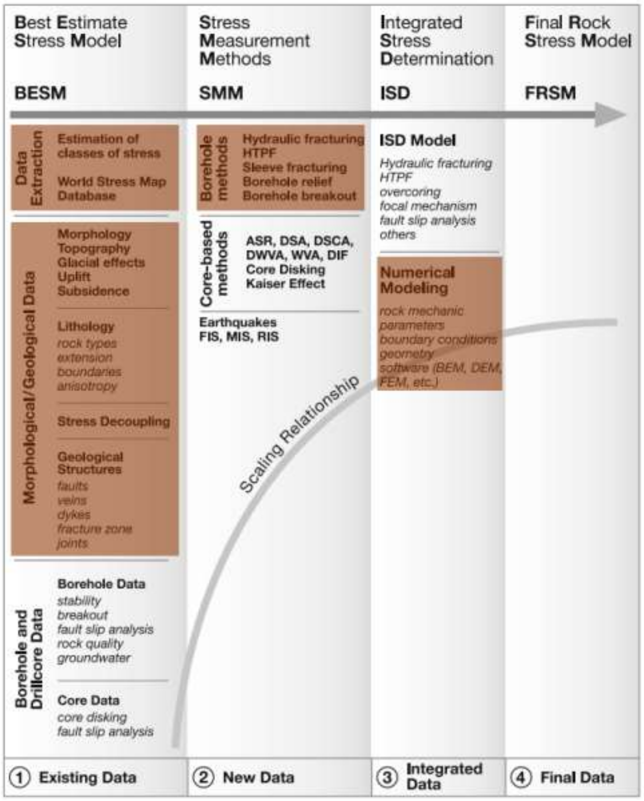


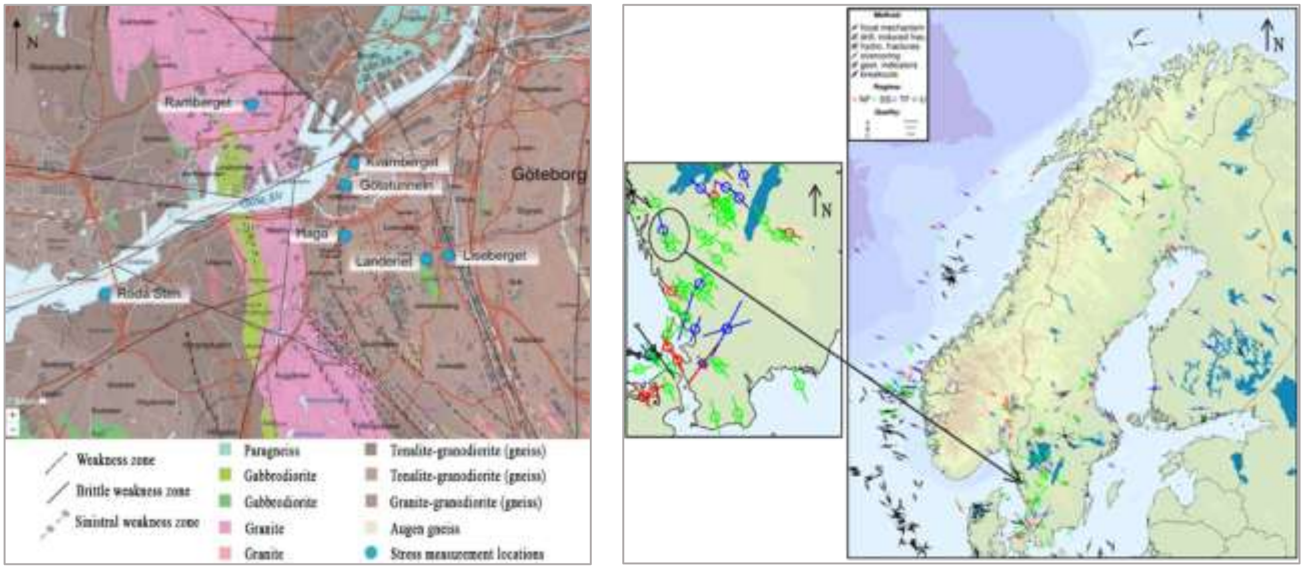
Figure 2. Establishment of the final stress model (FRSM) by combining best estimate model, new stress data and integrated stress determination. Brown highlights present data utilised for this paper. From: Stephansson and Zang (2012).

Generally, BESM should be established before conducting stress measurements, as its function is to guide the engineering geologists and geologists to select appropriate stress measurement techniques and assist in measurement planning. Since the stress measurements at Mellanplan were conducted prior to the BESM formulated for this study, the best estimate model in this case is valuable to predict factors influencing the stress field at Mellanplan. The second step in FRSM is the selection and performance of stress measurement method (SMM). In the West Link Project, 2D doorstopper method was selected as the measurement technique at Mellanplan. The stress measurements were conducted after the excavation of pilot tunnels, thus cannot be considered virgin stress measurement procedure. Nevertheless, the reported secondary stresses can be utilised to back-calculate the in-situ stress state. It should be stressed that the scope of the study presented in this paper involve the application of 2D doorstopper results for back-calculation. Hence, the results from previous stress measurements conducted nearby Mellanplan are not utilised directly for the back-calculation but are useful for the evaluation of the stress field at the location of the access cavern.

The final step in developing a rock stress model includes the integrated stress determination model (ISD). ISD model involves a combination of various stress measurement techniques to determine the in-situ stress conditions. This is more beneficial than the conventional single measurement method as it increases the reliability of in-situ stress determination. As presented in Figure 2, ISD can also incorporate numerical modelling to predict rock stresses. The results from the conducted stress measurements should be used to validate the results from numerical modelling. Since only 2D measurements have been carried out at Mellanplan, the ISD is achieved in this case by combining the doorstopper results with numerical analysis. The stresses from doorstopper measurements are evaluated before utilising them to generate the best-fit in-situ stress model through 3D stress analyses and back-calculations.

2. GEOLOGY AND ROCK STRESSES

According to the Geological Survey of Sweden, SGU, the bedrock of Sweden consists of three principal components: 1) Precambrian crystalline rocks, 2) remains of a younger sedimentary rock cover from the Phanerozoic period and 3) Caledonides. Figure 3 displays that the tectonics in the area are dominated by slip-strike faults and thrust faults (BeFo, 2022; Heidbach et al., 2018). The majority of the weakness zones have a strike in the NW-SE directions. It should be noted that not all fault regimes and stress orientations from the World Stress Map database are presented in the figure below.



a) b)

Figure 3. a) Bedrock map of Gothenburg with weakness zones and locations of former stress measurement sites. Modified after: SGU (2022) and BeFo (2022); b) Horizontal stresses in Fennoscandian Shield and Gothenburg (circled). Various fault types are presented in the legend: green (Slip-strike) and blue (Thrust fault).

Based on the detailed tunnel mapping of the pilots, the main rock types in Mellanplan are granodiorite gneiss and metabasite. In addition, two major joint sets are registered, foliation joints and cross joints. The foliation joints have an average strike/dip of N149E/63°SW. Cross joints fall on the opposite direction of foliation joints with an average strike/dip value of N43W/30°NE. The foliation joints are dominating joints along the pilots in the top heading. The rock cover above the top heading crown of Mellanplan varies between 7 m to 15 m, where the mean rock surface level is estimated to be 11 m. The average soil thickness above the rock surface is predicted as 5.2 m.

The stress data from the Gothenburg region are based on the World Stress Map (Heidbach et al., 2018) and estimated rock stresses by Rock Engineering Research Foundation in Sweden (BeFo, 2022). In addition, results from previously conducted 3D overcoring stress measurements are utilised to formulate an estimation regarding the stress orientations. Figure 3 depicts orientations of major horizontal stresses, σ_H, in Scandinavia. The major horizontal stresses in the Fennoscandian Shield typically have orientations in NW-SE directions. According to the World Stress Map, this trend correlates with the horizontal stress conditions in the Gothenburg region.

In general, few rock stress measurements have been conducted in Gothenburg. Rock stress measurements are relatively costly and technically complex. Therefore, for the future underground projects, previously conducted stress measurements and documentations are important. Landeriet and Liseberget are locations near Mellanplan, where 3D overcoring stress measurements were performed in relation to the West Link Project. At both locations, the orientation of σ_H is estimated perpendicular or close to perpendicular to the access cavern (N80E ± N10E). While σ_h is predicted perpendicular to σ_H.

The results from stress measurements at Landeriert and Liseberg (borehole id: KK4207KBH and KK4222KBH) are depicted in Figure 4. The points in the graph present the measured in-situ minor and maximum horizontal stresses. Best-fit lines are derived from the measurements. The measured horizontal stresses at the overcoring sites differ from each other, since Liseberget is closer to a weakness zone (Figure 3). The results from the 3D overcoring measurements were complex due to widespread of data.

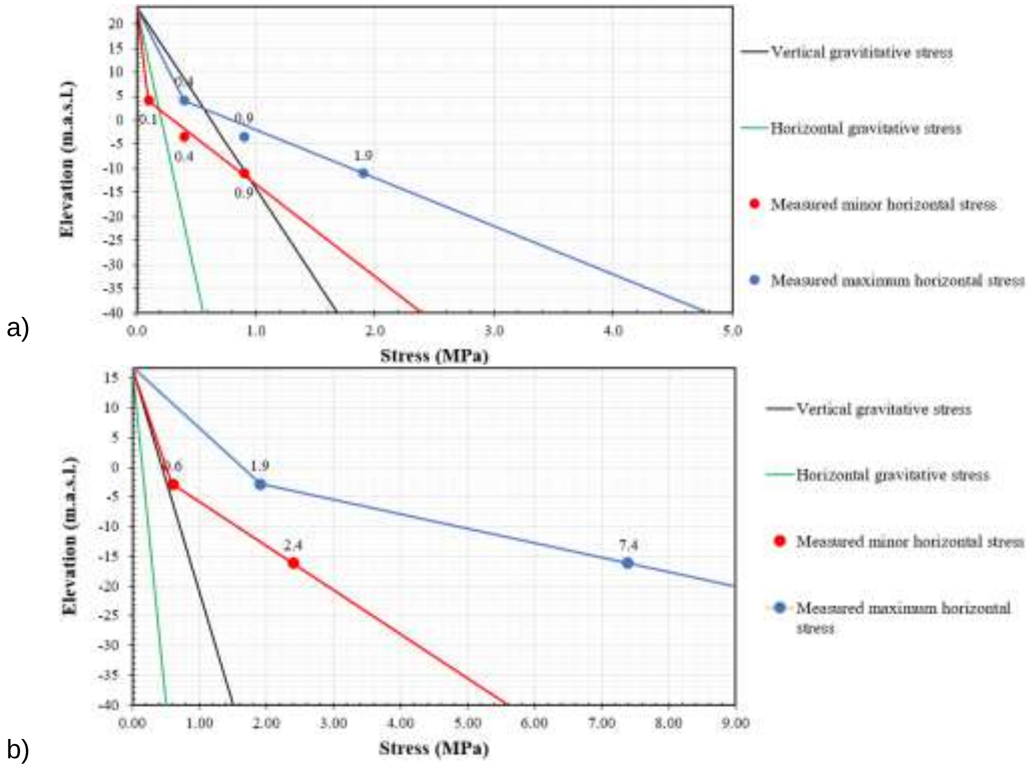


Figure 4. a) In-situ horizontal stress measurements conducted at Landeriet, borehole KK4207KBH (location is shown in Figure 1 and 3). b) In-situ horizontal stress measurements conducted at Liseberget, borehole KK4222KBH (location is shown in Figure 3).

Rock Engineering Research Foundation in Sweden (BeFo) has interpreted the in-situ stress state in Gothenburg on the basis of the previously performed stress measurements. BeFo (2022) suggests the following stress state for Gothenburg. The notation for stress orientation of the major horizontal stress is presented as α_H in Table 1, while z presents depth and ρ is density of the rock.

Table 1. In-situ stress state in Gothenburg, estimated by BeFo (2022).

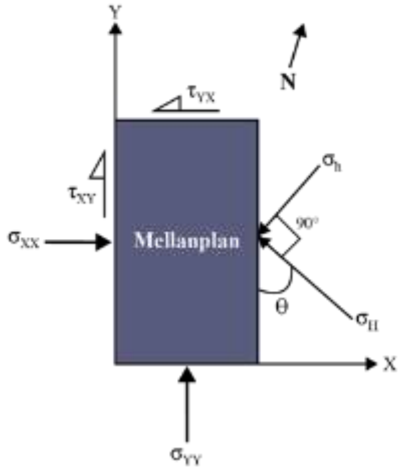
	σ_H [MPa]	σ_h [MPa]	σ_v [MPa]	α_H [°]
Minimum	0.077 z	0.007 z	0.021 z	N80E
Best estimated	0.104 z	0.016 z	ρgz	N130E
Maximum	0.171 z	0.037 z	0.032 z	N115E

3. DOORSTOPPER MEASUREMENTS

Assessment of the doorstopper measurements showed some uncertainties in relation to negative stress components and effect of anisotropy on stress measurements. Certain secondary horizontal stresses are calculated as negative stress components based on the doorstopper measurements. The absence of information regarding the occurrence of these negative stress components resulted in neglection of these data points for further estimation of the in-situ stress state at Mellanplan. Moreover, evaluation of the stress measurements showed that the doorstopper results from the East pilot are less likely to be affected by rock mass anisotropy than from the West pilot. The analysis of 2D doorstopper measurements is based on linear elasticity and assumes isotropic rock conditions. Therefore, it is considered reasonable to select East pilot for further estimation of in-situ stress field.

The horizontal stresses, reported by SINTEF Community, have magnitudes and orientations with respect to the north direction. The directions of the major horizontal stresses are given as angles from the north, with the minor horizontal stresses oriented perpendicular to σ_H. For the back-calculation of in-situ stresses from the 3D numerical program, *RS3*, the secondary stresses have to be resolved with respect to the orientation of Mellanplan. In the *RS3* models, the normal stress along Z axis (σ_{ZZ}) represents stresses due to the vertical overburden (z) of the rock mass. The 3D numerical models present induced horizontal stresses along the X and Y axes (σ_{XX} and σ_{YY}), where the length axis of the top heading is in the direction of the Y axis.

In order to compare σ_{XX} and σ_{YY} obtained from the *RS3* models with the measured secondary stresses, the latter is resolved to stresses in the X and Y directions of Mellanplan. Consider that measured σ_H makes an angle θ with the Y axis (length axis of Mellanplan) as illustrated in Figure 5, where the orientation of σ_h is perpendicular to σ_H. The horizontal stresses along the X and Y directions of Mellanplan, σ_{XX} and σ_{YY} are calculated by using σ_H and σ_h in Equations 1 and 2, suggested by Basnet and Panthi (2019). These equations consider the effect of horizontal shear stresses τ_{YX} and τ_{XY} (Figure 5). The equations below are derived for a linearly elastic model, where the material is anticipated to exhibit linear stress-strain behaviour.



$$\sigma_{XX} = \sigma_H \cos^2\theta + \sigma_h \sin^2\theta \qquad (1)$$

$$\sigma_{YY} = \sigma_H \sin^2\theta + \sigma_h \cos^2\theta \qquad (2)$$

Figure 5. Resolved horizontal stresses, σ_{XX} and σ_{YY} at Mellanplan.

Table 2 introduces the calculated σ_{XX} and σ_{YY} at the East pilot, by applying Equations 1 and 2. For clarification, the resolved secondary stresses from the doorstopper will have the stress notifications: $\sigma_{XX(D)}$ and $\sigma_{YY(D)}$.

Table 2. Resolved secondary stresses $\sigma_{XX(D)}$ and $\sigma_{YY(D)}$ from the doorstopper at the East pilot. The angle between Mellanplan and σ_H is given as positive in the counterclockwise direction.

Hole depth [m]	**σ_h [MPa]**	**σ_H [MPa]**	**α_H [°]**	**Angle between Mellanplan and σ_H**	**$\sigma_{XX(D)}$ [MPa]**	**$\sigma_{YY(D)}$ [MPa]**
1.3	-1.1	0.2	N142E	27	-0.8	-0.1
2.5	-1	3.6	N22E	147	0.4	2.2
2.8	-0.4	3.6	N136E	33	0.8	2.4
3.2	-2.3	0.2	N132E	37	-1.4	-0.7
3.6	-0.3	1.5	N172E	-3	-0.3	1.5

4.1	0.4	3.7	N0E	169	0.5	3.6
				Mean value of positive components	0.6	2.4
				Std. deviation of positive components	0.2	0.9

Figure 6 presents the calculated values of $\sigma_{XX(D)}$ and $\sigma_{YY(D)}$ against hole depth at East Pilot as a scatter plot. The mean rock cover above the stress measurement site at the East pilot is approximately 12 m. While the borehole depth with stress measurements above the East pilot end at 4.1 m. The spread of stress data shown in the scatter plot below is as anticipated for stress conditions at shallow depths. The effect of weathering and geological structures on stresses is more likely to occur near surface grounds due to the open joints. Such complexity at shallow depths leads to scattering results, where the stress measurement does not provide a certain trend in data. Since, it is challenging to obtain similar scattering results in numerical modelling, an average interval for the entire borehole length is used to validate the results from the numerical analyses. In conclusion, the average intervals for $\sigma_{XX(D)}$ and $\sigma_{YY(D)}$ are determined by the mean values and standard deviations of the positive stress components as presented in Table 2 and Figure 6.

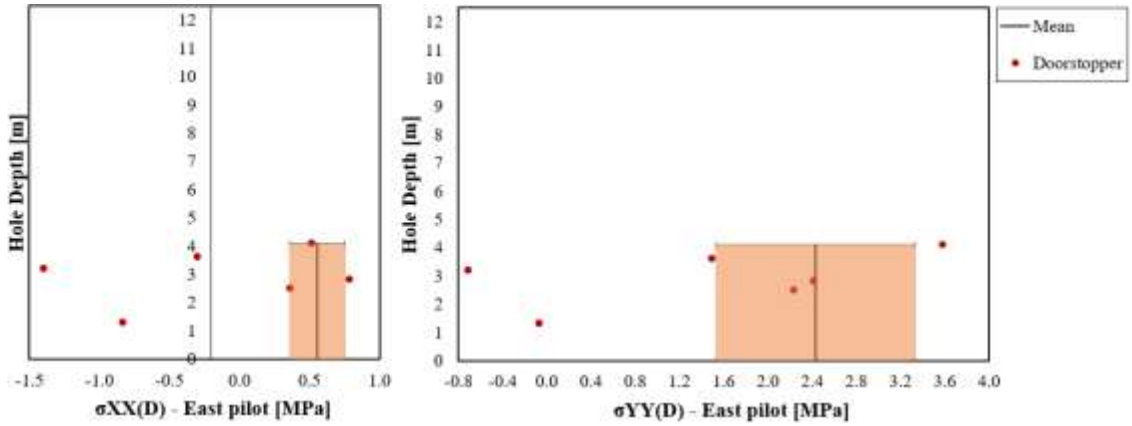


Figure 6. Resolved horizontal stresses, $\sigma_{XX(D)}$ and $\sigma_{YY(D)}$ at East pilot. The vertical line depicts the mean value of the positive stress components, while the marked area is the standard deviation.

4. NUMERICAL MODELLING

A 3D numerical program *RS3*, is applied for parametric stress analyses. The induced stress results from *RS3* are compared with the $\sigma_{XX(D)}$ and $\sigma_{YY(D)}$ and represents the development of the ISD. *RS3* is based on the finite element method (FEM), which describes the rock mass as a continuous medium. A continuous rock mass poses limitations regarding the representation of discontinuities. Although the rock mass displays some degree of anisotropy, the 3D models are generated as linear elastic where the rock mass is considered isotropic and homogeneous material on a large scale. This choice fits well since the calculated stresses from doorstopper measurements are based on linear elasticity and assume isotropic and homogeneous rock mass conditions. Figure 7 presents the model setup used in 3D modelling, where the red volume depicts the volumes removed in the excavation stage. Note that 40 metre long rock pillar remains between the pilots. Joint planes are not generated directly in the *RS3* models.

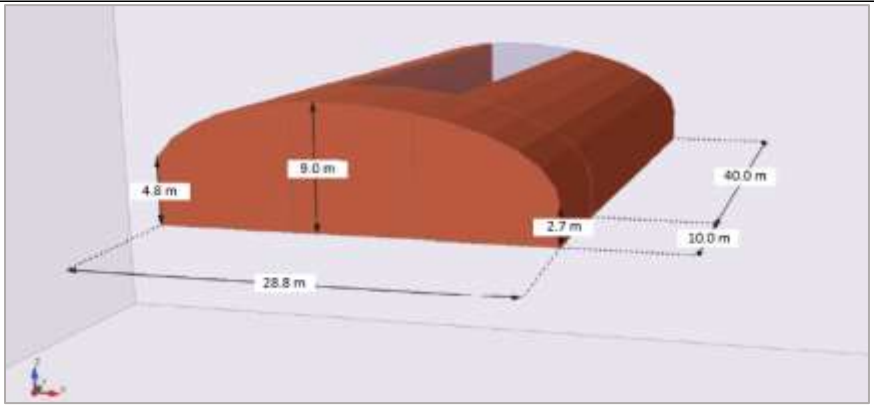


Figure 7. Model setup in RS3. The brown volumes are removed during the excavation stage.

The stress results from RS3 are obtained from a specific section at the top heading. The doorstopper measurement at the East pilot was conducted at 28 m inwards from the south of Mellanplan. Therefore, the query line for stress analyses in the RS3 models has been placed at the same location, as shown in Figure 8. Following the excavation stage, the secondary stress (σ_{XX} and σ_{YY}) results from the query line are plotted and compared with the stresses from the doorstopper measurements ($\sigma_{XX(D)}$ and $\sigma_{YY(D)}$).

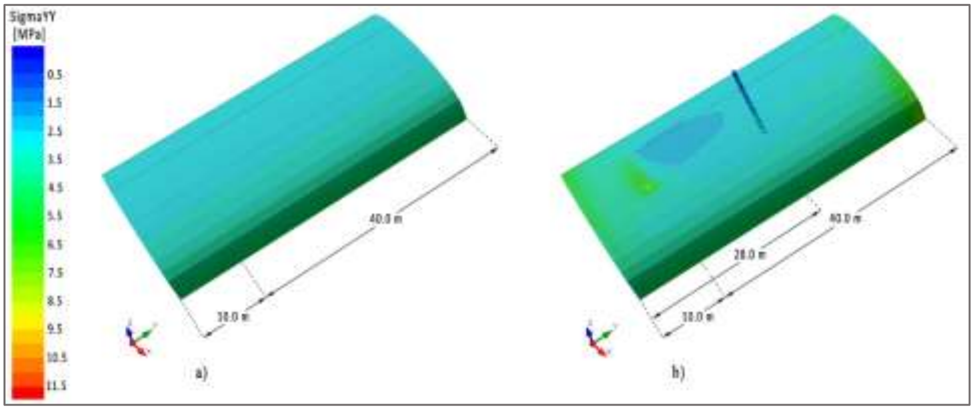


Figure 8. a) Initial stage and b) Excavation stage with query line on the roof. The figures display an example of σ_{YY} results on the tunnel contour.

Table 3 presents the rock mass properties as input parameters for granodiorite gneiss at Mellanplan. The rock mass parameters utilised for the numerical models are quantified and based on detailed pilot mappings, background material received from the West Link Project and laboratory investigations.

Table 3. Input parameters for rock mass in RS3.

Parameter	Unit	Value
Density	kg/m^3	2680
Poisson's ratio, v	-	0.25
Intact rock strength (UCS), σ_{ci}	MPa	140
Rock mass strength, σ_{cm}	MPa	20.6
Young's modulus, E_i	GPa	70
Deformation modulus, E_{rm}	GPa	44
GSI	-	65
Hoek-Brown constant, m_i	-	28
Disturbance factor	-	0

The back-calculation of in-situ stresses in this study is conducted by parametric analysis of stresses. The stress parameters such as K-values (horizontal to vertical stress ratio), stress orientations and locked-in stresses are the main stress input that can induce changes in the stress field. In-situ stresses as input in numerical modelling are given notations σ_H and σ_h, for major horizontal stress and minor horizontal stress, respectively. The vertical stress (σ_v) is considered equivalent to the vertical gravitational stress since it is a common estimation. The orientations of σ_H parallel or close parallel to Mellanplan (N160E-180E) are ignored as input in this study, considering they indicate a complete rotation of the stresses compared to stress directions derived from overcoring estimation. Even though the possibility of a complete stress rotation is plausible, it is considered unlikely and is therefore not investigated further.

For stress analyses, the rock properties and vertical stress (σ_v) are kept as constant parameters. With the purpose of determining representative in-situ stresses at Mellanplan, the stress data from 3D overcoring and stress estimation data provided by BeFo are initially applied as input in the numerical analyses. Following these methods, a trial and error approach with different stress magnitudes and orientations is carried out. The stress magnitudes are dependent on the K-values, where K_H values range from 0.33 to 14, and K_h values range from 0.33 to 3. Furthermore, the stress orientations are varied between N80E to N150E for the numerical trial. After the various numerical trials, the best method to determine the in-situ stress state at Mellanplan involved assumption of the minor horizontal stress, σ_h, as gravity induced stress only. While the major horizontal stress, σ_H, varies with different K_H values as input. K_H values represent ratio between the major horizontal stress (σ_H) and the gravitational vertical stress (σ_v). Due to the time and constraint, only the K_H values of 4, 6, 8, 10, 12 and 14 are selected as variable input parameters. The orientation of the major horizontal stress is presented as α_H in the results below.

The results demonstrating the best fits between the induced stresses from numerical analyses and the doorstopper measurements are obtained when σ_H has an orientation of N150E (Figure 9). Table 4 shows the input parameters used for the stress analyses in this direction. As the figure below indicates, the results achieved with a K_H value of 10 correlate best with the average stress interval for both $\sigma_{XX(D)}$ and $\sigma_{YY(D)}$. Throughout the doorstopper hole depth, up to 4.1 m, the induced stresses resulting from K_H = 10 lie within the standard deviations and are close to the mean stress value in correlation with measured stresses at East pilot.

Table 4. Input parameters for RS3 models providing results in Figure 13.

K_H	K_h	α_H
4, 6, 8, 10, 12, 14	0.33	N150E

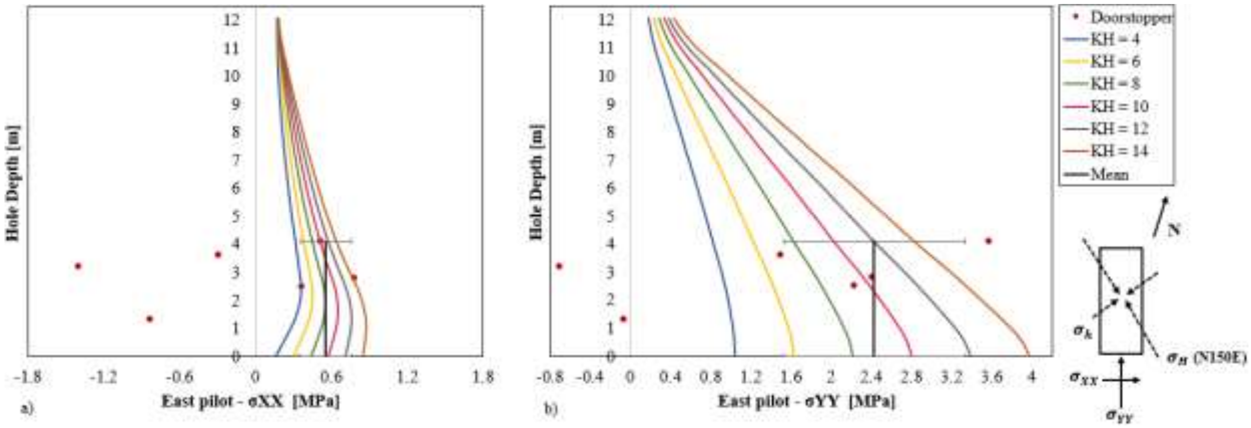


Figure 9. Secondary stresses from 3D models compared with scattered doorstopper stresses, when α_H is N150E.

The K_H values of 8 and 12 also provide secondary stresses within the average stress intervals throughout the entire borehole length. However, the best fit occurs when the input is K_H = 10. Therefore, a combination of K_H = 10 and K_h = 0.33 with major horizontal stress oriented in N150E is selected to be utilised to determine the best estimate in-situ stress state at the top heading location of Mellanplan.

5. IN-SITU STRESS STATE

The results from 3D modelling showed that the best fits between numerical and doorstopper stresses are achieved when the major horizontal stress has an orientation of N150E. Table 5 presents a range of input stress parameters that showed optimal results when secondary stresses from numerical analyses are compared with the doorstopper stresses.

Table 5. Input parameters in RS3 models that showed optimal results.

	K_H	K_h	α_H
Minimum	8	0.33	N150E
Best estimated	10	0.33	N150E
Maximum	12	0.33	N150E

Considering the vertical stress in Mellanplan is assumed to be gravitational, in-situ horizontal stresses, σ_H and σ_h, can be back-calculated. Based on the back-calculation, Figure 10 present the in-situ stresses at a shallow depth in Mellanplan. The rock stresses σ_h and σ_v are presented as gravity induced stresses, while σ_H is greater than the gravitational stress. The minimum and maximum estimation for σ_H is depicted as a stress range for the major horizontal stress in Figure 10. Although doorstopper measurement at the East pilot was conducted above the tunnel roof, the rock stresses presented in the figure below are extrapolated until the elevation at 0 masl. The back-calculated virgin stresses are assumed to be viable from an elevation of 0 masl. to 15.8 masl.

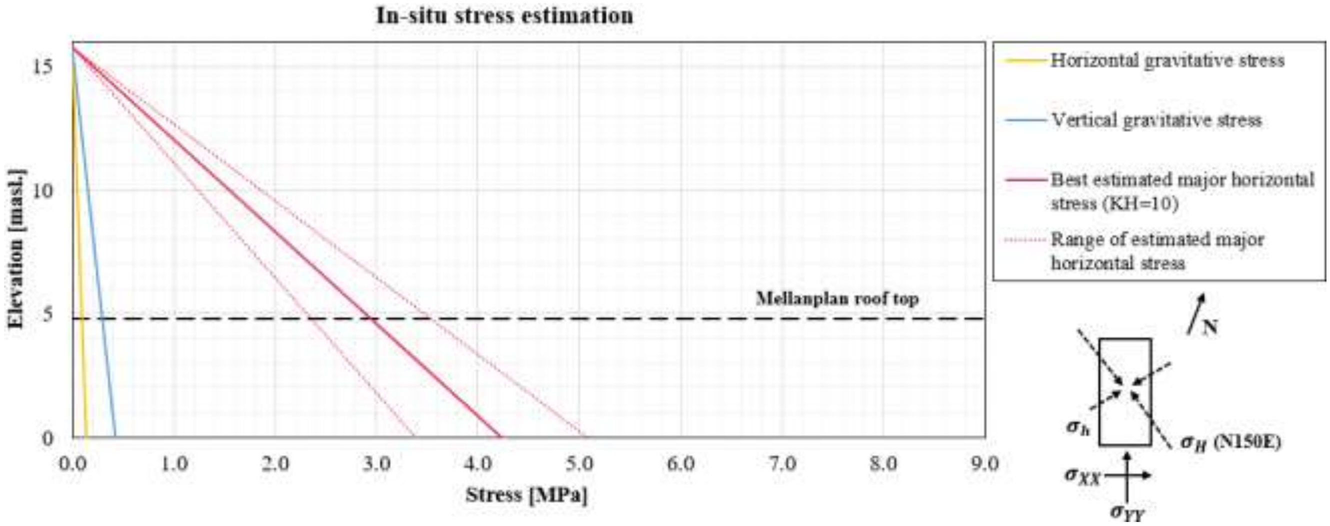


Figure 10. Final rock stress model with estimated in-situ stresses at a shallow depth in Mellanplan. The stress domain applies for elevation from 0 masl. to 15.8 masl.

6. CONCLUSIONS

The final rock stress model (FRSM) achieved in this study demonstrates the stress field at Mellanplan as $\sigma_H > \sigma_v > \sigma_h$. This stress state is only viable at a shallow depth, from 0 masl. to 15.8 masl. Such stress condition correlates with the suggested stress state by Martin et al. (2003) for Scandinavia. Nonetheless, this proposal also includes stress measurements at greater depths. The in-situ stresses at shallow depths can show complexity. Based on the best estimated stress model (BESM) and the results from numerical analyses, the major horizontal stress indicates to be highly influenced by the tectonic stress. It is likely to predict that the tectonic stress contributes greater to the major horizontal stress, than other stress components. Moreover, residual stress from periods with glaciation and deglaciation in Sweden, may also have greater influence on the major horizontal stress component. Due to the low overburden, the relatively low magnitude of minor horizontal stress is assumed as gravity-induced stress. However, weathering and geological structures may have reduced the already low magnitude of σ_h. The indications of low stress magnitudes, σ_h and σ_v, are also validated by the observed block falls from pilot roofs at Mellanplan.

The estimated orientation of σ_H differs from the predicted stress directions by overcoring measurements and BeFo. Geological structures may have attenuated the stress orientations slightly. As mentioned previously, there is a correlation between the strike of the faults and the orientation of σ_H. On the other hand, open joints can also influence stress distribution, which can be the cause of the rotation of stresses. The integrated stress determination

(ISD) for the study involved combining the doorstopper results with numerical analyses. Further improvement of the final rock stress model can be accomplished, provided different stress measurement method is utilised at Mellanplan in the future, e.g., 3D overcoring or hydraulic fracturing tests. The results from two different measurement methods can increase the reliability in rock stress determination.

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