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Structural control on stress variability at Forsmark

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1 INTRODUCTION

The *in situ* stress state is a key rock mechanics parameter and it must be well understood for the design of an underground repository of spent nuclear fuel. The current stress state in the Fennoscandia area is dominated and driven by Mid-Atlantic ridge push and collision of the Eurasian and African plates in the Alps. Additionally, earlier glaciation cycles have changed stress conditions remarkably and promoted the shear of brittle fault zones thereby causing changes in the stress field. In the thrust fault conditions that have been dominant for a long time, shallow dipping faults have been, and are still, prone to slip.

The Swedish Nuclear Fuel and Waste Management Company (SKB) has selected the Forsmark site for the construction of a repository at a depth of -470 m. So far approximately 130 overcoring and 240 hydraulic stress measurements have been completed and interpreted by Martin (2007) while also making use of borehole breakout, core disking and non-linear strain rock sample data. This interpretation indicated notable variation in both horizontal stress components but did not address the variability.

This study aimed to examine the interaction of brittle deformation zones (DZ) and the *in situ* stress state in the Forsmark area using the discontinuous numerical simulation software *3DEC* (Itasca 2016). The primary goal was to understand the observed and expected variation in stress magnitudes and orientations at repository depth, but also to verify rock parameters.

2 BACKGROUND AND APPROACH

The volume to be studied and the brittle fault geometry was defined by the local geological model, resulting in a total of 110 DZ's. Out of these zones, the Singö DZ has been investigated significantly and is a well-known DZ that has a length over 30 km and is a 200 m thick vertical zone (Glamheden et al. 2007). The simulation model geometry included all 110 zones, resulting in a 15 × 11 × 2.1 km (l × w × h) size model, with small geometrical modifications to some DZ's necessary for optimal simulation geometry (Hakala et al. 2019). The *in situ* stress state used in simulations was according to the interpretation detailed in Martin (2007). Rock mass and DZ parameters (Table 1) were based on data acquired from earlier investigations (Glamheden et al. 2007), (Glamheden et al. 2008), (SKB 2008).

The work was performed in two phases and the results of Phase 1 guided Phase 2 (Hakala et al. 2019). In Phase 1 the main studied factors were the brittle fault surface geometry and shear strength: DZ's were simulated both as planar best-fit planes and as the interpreted undulating surfaces. The *in situ* stress state was pre-set in the model according to the interpretation in Martin (2007). The selected sensitivity study approach was similar to earlier studies by Hakami (2006), Hakami & Min (2009), Valli et al. (2011) and Valli et al. (2016).

Table 1. Basic stiffness and strength values for DZs. kn: normal stiffness, ks: shear stiffness, coh: cohesion, fric: friction angle, ten: tensile strength (Hakala et al. 2019).

Parameter	kn (MPa/mm)	ks (MPa/mm)	coh (MPa)	fric (°)	ten (MPa)
Deformation zone					
All, except Singö	80	20	0.7	36	0.001
Singö	0.2	0.01	0.4	31.5	0.001

The second phase made use of only the undulating fault geometry and the *in situ* stress state was established by normal velocity boundary conditions instead of being set directly. It was reasoned that if DZ shear deformation starts during the thrust boundary process, it could lead to a larger amount of total shear deformation as thrust continues until the target stress state is reached. This could therefore lead to larger variations in the resulting stress state (Hakala et al. 2019). This approach was also used to determine if the measured low stress magnitudes near the surface (up to a depth of about 200 m) could solely be a result of DZ shear deformation, or if achieving the low stresses requires modified boundary conditions. The thrust orientation relative to the fault geometry was varied by ±20 degrees. A glaciation cycle with pore pressure changes as defined in Hökmark et al. (2010) was also added to all the simulations and two different fault shear strength values were tested. Phase 1 included seven cases with both planar and undulating DZ geometry and Phase 2 included 14 cases. The goal was to study and compare following results:

- The variation of the *in situ* stress state, especially at repository depth
- The correlation with the *in situ* stress measurements
- The sensitivity of the results to changes in DZ parameters
- The sensitivity of the results to the orientation of applied thrust

3 RESULTS AND DISCUSSION

Phase 1 simulations indicated that at large scale, the shear behavior of planar and undulating models was similar (Fig. 1), but summarizing the number of sheared contacts and the accumulated shear for the model indicates that undulating DZs shear more and shear extends to a greater depth. Further comparison of the vertical Singö and the sub-horizontal DZs indicated that especially the sub-horizontal undulating DZs shear more.

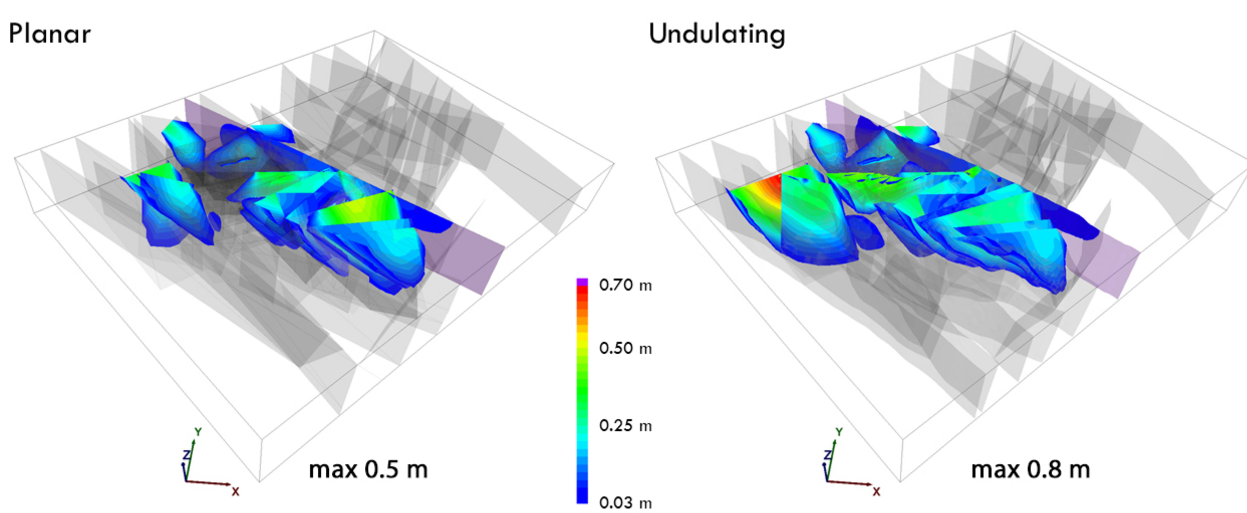

Figure 1. Planar vs undulating geometry, DZ total shear displacements. Shear displacements below 0.03 m are not displayed (Hakala et al. 2019).

The difference between the two geometrical approaches was somewhat more apparent when considering the influence on the stress state: the undulating models exhibited a larger variation in σ_1 magnitude and trend, especially at shallow depths. The volume of influence was also significantly larger in the undulating models. Due to the applied modelling approach and observed shear, all the simulated cases exhibited a moderate to poor correlation with *in situ* stress measurements if compared using the closest elements to actual measurement locations.

The most notable differences of Phase 2 simulations compared to Phase 1 simulations was the higher variation of the resulting stresses and their orientations. Variation was already higher than in Phase 1 simulations after primary thrust and was further increased during the glacial cycle. The glaciation cycle did, however, decrease the major principal stress magnitudes above the 300 m level, but the difference was less than 5 MPa. The magnitude variation originated by thrust extended below the 1000 m level compared to Phase-1 simulations, where it was already minimal at the repository level. The variation of the major principal stress trend extended to greater depths but was minor below the 300 m level.

4 CONCLUSIONS

The results indicated that the simulation of the realistic variation of *in situ* stress measurements requires that the stress state is established by boundary thrust conditions and includes disturbances caused by the latest major glaciation cycle (Hakala et al. 2019). The use of undulating DZ surface geometry was also found to be more realistic. Additionally, a good match with the measurement results was obtained with simple constant thrust boundary conditions. When the stress state is established by thrust, the resulting mean stresses are fairly insensitive to the studied DZ parameter values. If the DZ parameters are in a realistic range, the lower shear strength will mainly increase the resulting variation in stress magnitudes and orientations (Hakala et al. 2019).

A comparison of the simulated principal stresses with the Martin (2007) interpretation indicated that all the simulated cases in Phase 2 provided a fairly good general correlation with stress measurements although the point to point variation was high (Fig. 2). Above the 300 m level the variation matched measured σ_1 magnitudes fairly well (Hakala et al. 2019). Very low magnitudes are, however, common in the simulation results indicating that low stress measurement results could be possible and should thus not be discarded per se. Conversely, simulation result variation also indicates higher magnitudes, but not to the level of observed extremely high measurement results which probably have suffered from thermal effects induced by heating associated with overcoring. This study demonstrated that is it possible to construct a *3DEC* model with very complicated non-planar DZ geometry, including over a hundred faults, and compute solutions in reasonable timeframes (Hakala et al. 2019).

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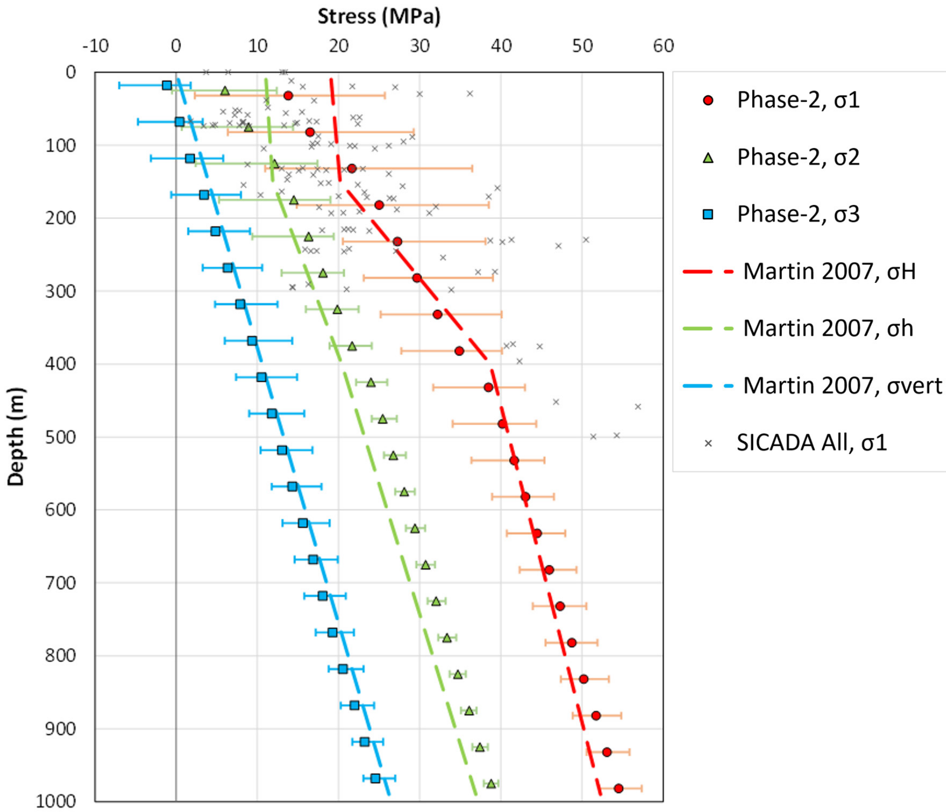

Figure 2. The resulting mean principal stress with 90% variation limits for a Phase 2 case with the Martin (2007) stress model and all major principal stress results measured using the overcoring method (Hakala et al. 2019).

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