POLITECNICO DI TORINO
Repository ISTITUZIONALE

Extensive sensitivity analysis of the Kivenlahti metro center using DEM

Original
Extensive sensitivity analysis of the Kivenlahti metro center using DEM / Van Der Weij, Oskar; Martinelli, Daniele. - ELETTRONICO. - (2023), pp. 129-134. (ISRM 15th International Congress on Rock Mechanics and Rock Engineering & 72nd Geomechanics Colloquium Salisburgo 9-14 ottobre 2023).

Availability:
This version is available at: 11583/2990893 since: 2024-07-16T11:19:50Z

Publisher:
Austrian Society for Geomechanics

Published
DOI:

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright
GENERICO preprint/submitted version accettata

(Article begins on next page)

13 May 2026

Extensive sensitivity analysis of the Kivenlahti metro center using DEM

Oskar van der Weij
Rockplan ltd., Helsinki, Finland

Daniele Martinelli
DIATI - Politecnico di Torino, Torino, Italy

ABSTRACT: The Kivenlahti metro center is a combined residential and commercial building complex designed on top of a metro station in Espoo, Finland. Rock mechanical modelling was carried out using 3DEC to ensure the integrity of the metro station. A detailed sensitivity analysis was conducted consisting of simulating the effects of reduced horizontal in-situ stress, increased loading and weaker rock mass. Whilst the base case scenario confirmed that the proposed design should not lead to critical deformations within the metro station, the results of the sensitivity analysis indicated vulnerable locations if the loading is increased from the current design. An in-situ stress significantly lower than expected could lead to critical deformations within the metro station. Whilst the sensitivity analysis was conducted using extreme values, it successfully demonstrated areas for concern and thus aided in designing measures for mitigating the risks for the metro station.

Keywords: DEM, 3DEC, sensitivity analysis, metro station.

1 INTRODUCTION

The Kivenlahti metro center is a planned set of buildings including a 4-storey commercial center and 2 high-rise buildings, one 15-storeys and the other 18-storeys high (including cellar levels), located in Espoo in the Finnish capital region. The construction project is especially challenging from a rock mechanical perspective, as the buildings are on top of the Kivenlahti metro station, at parts entering the construction restriction perimeter around the metro. Most notable features of the project to rock engineering are an escalator shaft of the metro station that enters the new shopping center and a relatively thin rock cover between the station and the metro center. Rockplan was commissioned to produce the rock engineering design for the metro center, and as a part of this work, a rock mechanical analysis of the effects of the metro center on the metro station.

The rock mechanical analysis aimed to determine the overall effect the metro center would have on the metro station and to assess whether the rock support within the metro station would be adversely affected. At first, this was done by constructing a model of the metro center, the metro station and the relevant environment, and a base case scenario where the effect of a conservative estimate of the metro center loading was implemented, after which the model was solved for the displacements, changes in the stress state and rock material and reinforcement yielding. At a later time, due to a request by Länsimetro Oy, the organization in charge of operating the metro station, an extensive sensitivity analysis was conducted. In addition to a conventional sensitivity analysis mainly focused on simulating the effects of an increased loading, the sensitivity analysis by Rockplan also included investigating the effects of a change in the rock mass quality and reduced horizontal stress magnitude.

2 MODELLING THE METRO CENTER AND THE METRO STATION

2.1 Modelling principles and parameters

In a typical Finnish hard crystalline bedrock environment, the most suitable method for analyzing shallow excavation is to use a model where the rock mass is discrete and the majority of the deformations occur along joint boundaries. In addition, for such a problem with a complex geometry, three-dimensional analysis is important. The modelling software used for the rock mechanical analysis is 3DEC (Itasca 2020), which uses 3D-DEM with capability of handling deformable blocks and perform fully discontinuum modelling.

The modelling was conducted in phases corresponding with the construction. After the in-situ phase, the excavation of the currently existing metro station and service infrastructure was modelled, followed by the metro center foundation excavations. The final phase for the base case was the implementation of the building load.

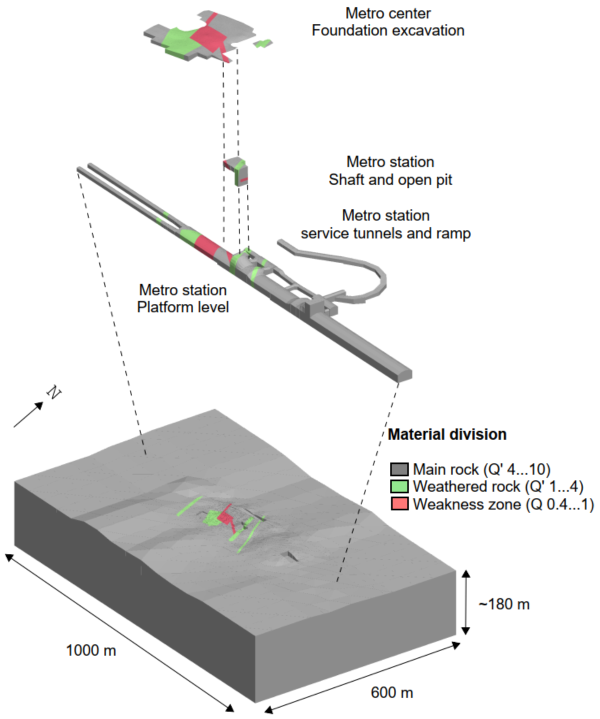

Figure 1. The components of the rock mechanical model.

The rock mass is mainly a granitic gneiss, and it has been modelled using the Mohr-Coulomb model. Due to the extensive mapping done during the construction of the metro station, the host rock could be divided into 3 modelling materials based on a range of Q-values; this allowed, most importantly, weakness zones of the rock to be identified and modelled. Furthermore, extensive joint mapping had been done in the metro station during its construction. The mapped joints could be grouped into four distinct joint sets. The jointing was modelled within 3DEC with a certain variation. The material model in the analysis was formed by using various laboratory test results conducted on intact rock. Since 3DEC uses the distinct element method, the rock mass can be modelled using intact rock parameters, and the weakening of the rock mass due to fracturing can be represented by joint surfaces. However, due to limitations in portraying reality within a model, it is necessary to weaken the rock mass to account for the extent of fracturing not included in the model.

The in-situ stress of the area is characterized, as common in the Fennoscandian Shield, by a moderate to intense crustal rock stress. This phenomenon usually creates favorable conditions for excavating shallow caverns due to the relevant horizontal component of the stress. According to measurements conducted close to the site, the main horizontal components σ_H and σ_h are quite similar and not out of the ordinary. The in-situ stresses used in the base case and sensitivity analysis are shown in Figure 2.

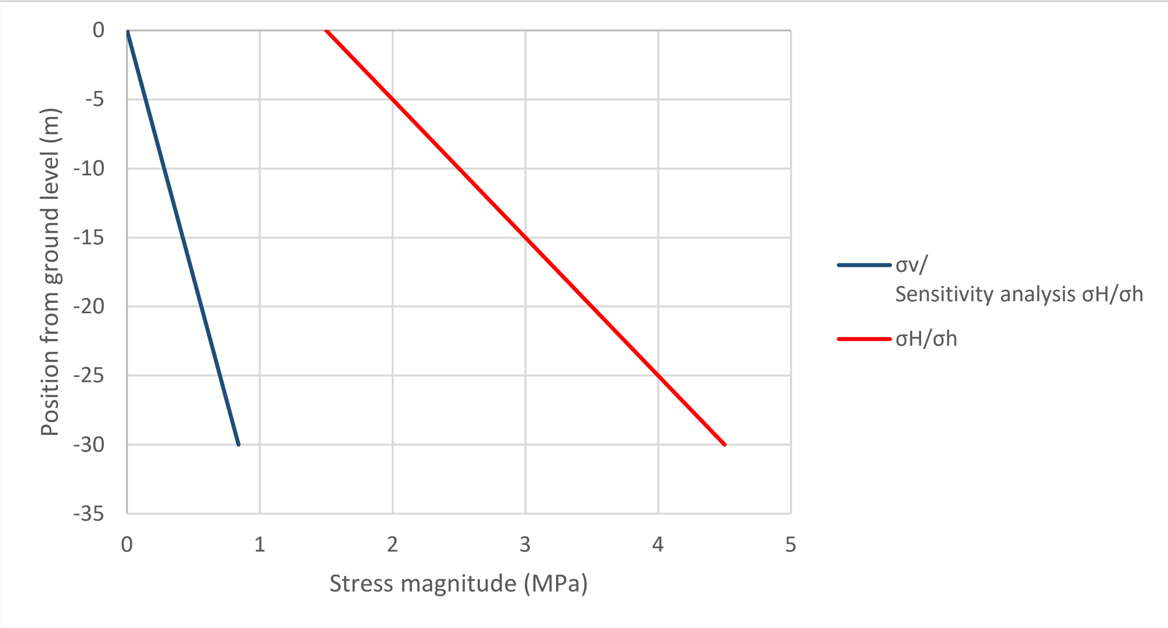

Figure 2. The modelled in-situ stress magnitudes.

2.2 *The metro station and -center*

The metro station is constructed using the drill and blast method. The construction works on the station were finished in May 2020, and it was opened for use in December 2022 along with the rest of the metro extension. The station is designed using modern rock engineering design: it is supported using a combination of systematic rock bolting with grouted bolts and drillbolts and fiber reinforced shotcrete. The designed bolting pattern has been included in the model, whilst the shotcrete was later disregarded from the sensitivity analysis due to modelling instability issues caused by large stresses and displacements.

The full geometry of the station has been included in the model. The main part of the station under the metro center is 24 meters wide and has a crown height of 12.5 meters. Besides the metro station, this includes the two escalator shafts, a parallel service tunnel and a service ramp to the surface. The commercial center is situated right on top of the metro station, whereas the high-rise buildings are located slightly to the side. The rock cover between the metro center and the station is only 10 meters by the escalator shaft.

2.3 *Sensitivity analysis*

For the extended sensitivity analysis, three scenarios were modelled. Firstly, the effect of a lowered in-situ stress state was investigated. As the in-situ stress in the base case scenario could be expected to provide a net supporting effect for the metro station, it was important to study whether a lowered in-situ stress would pose a risk to the integrity of the metro station. Furthermore, the stress measurement campaign conducted in the area was inconclusive on the direction of the stress and the measured magnitude of the stress was imprecise.

Secondly, a scenario was modelled where the material parameters for the weakest material have been further weakened. The reduction in material parameters was done by reducing the deformation modulus to portray an especially weak rock and back calculating the material parameters. Consequently, the material parameters were reduced as shown in Table 1.

Table 1. Reduction of the rock mass parameters for the sensitivity analysis. The original values are for a rock mass where the GSI = 60 and the reduced values for a rock mass where the GSI = 50.

Parameter	Original value	Reduced value	Reduction (%)
Young's modulus (E_{rm})	35.9 GPa	21.4 GPa	40
Uniaxial compressive strength (σ_{cm})	21.4 MPa	12.0 MPa	44
Tensile Strength (σ_{tm})	0.5 MPa	0.23 MPa	54
Cohesion (c)	1.9 MPa	1.02 MPa	46

Finally, the effect of increased loading was investigated. This helps in identifying the possible points of uncertainty and finding out limiting factors and locations. The sensitivity analysis was performed with a loading 1.5, 2 and 3 times the originally estimated load.

3 COMPARING THE BASE CASE RESULTS WITH THE SENSITIVITY ANALYSIS

With the current foundation layout, the model showed that an increase in the construction load of already 1.5 times the base case could lead to displacements in the station roof and walls that compromise the integrity of the shotcrete, with the damaging effect being clearer at loadings of 2 and 3 times the base case. Moreover, an increase in the loading revealed that the open pit at the entrance of the metro station and the metro station area beneath the center of the metro center are sensitive areas for load increases, which should be taken into account if the foundation layout is changed in future design.

The lowered in-situ stress most notably led to individual rock wedges that experience relatively large displacements, suggesting loose block formation due to a reduced confining stress. In a lower stress environment, the displacements occurred even more prominently along joint boundaries. On a macro level, the displacements in the roof of the metro station are considerably higher compared to the base case model. Whilst the displacement magnitudes themselves are not critical, significant joint slipping might cause uneven displacements in the shotcrete of the metro station, and thus cause damage. Hence, it was recommended that if there is reason to expect the in-situ stress to be exceptionally low, the loading in the deeper open pit at the metro station entrance shaft needs to be reduced.

A decrease in the rock quality caused a rather uniform increase in displacements within the parts of the roof of the metro station located in the weakness zone. The displacements are not at a critical level for the integrity of the metro station. The largest displacements, as in the original scenario, occur along the joint boundaries. However, a slight increase in the block yielding in the roof is present in locations of the weaker material.

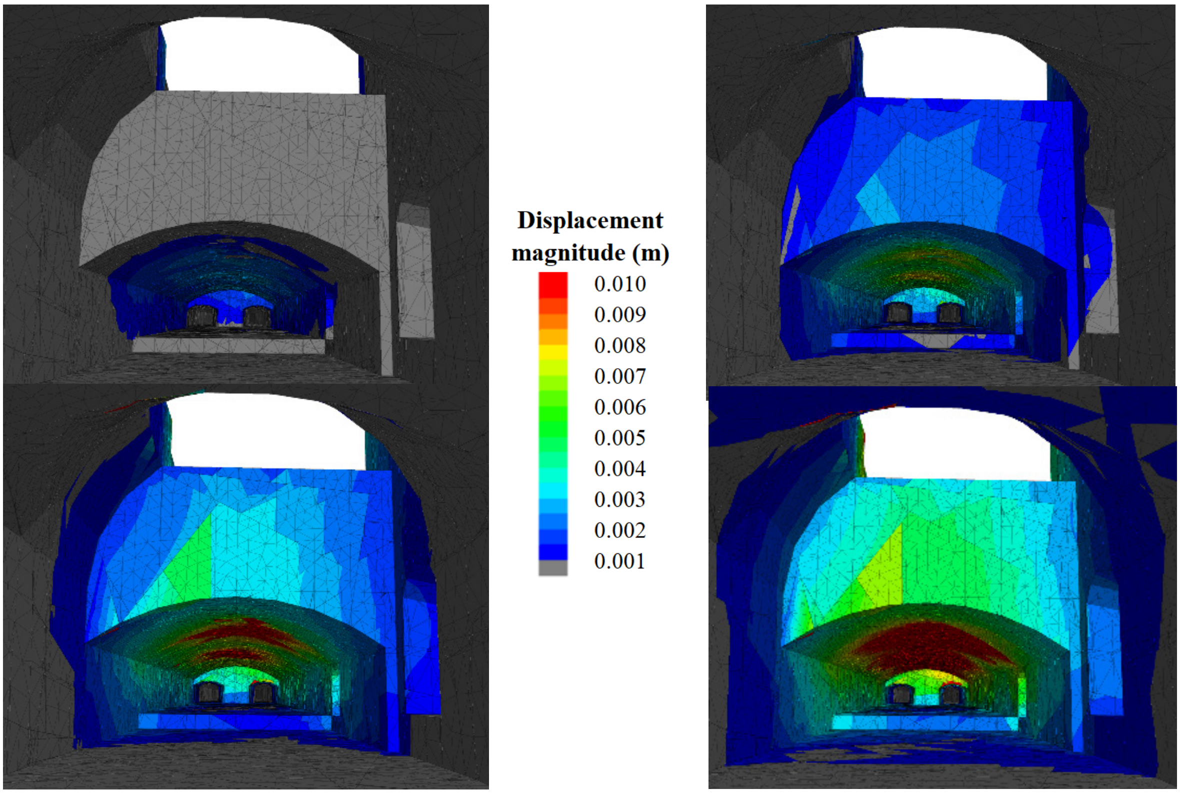

Figure 3. The displacements around the escalator shaft with the original loading on the top left, 1.5 times loading on the top the right, 2 times loading on the bottom left and 3 times loading on the bottom right.

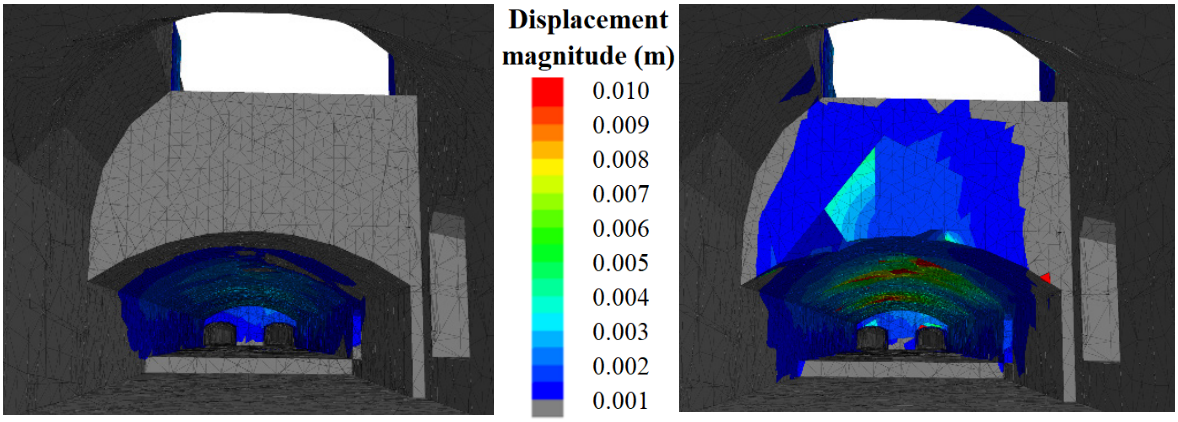

Figure 4. The displacements around the escalator shaft with the original in-situ stress on the left and the lowered in-situ stress on the right.

4 CONCLUSION AND DISCUSSION

The sensitivity analysis helped to confirm that adverse effects to the metro station are unlikely when the in-situ stress or the rock quality are, within reason, lower than expected. However, an increase in loading may lead to deformations within the metro station that are critical for the integrity of the shotcrete. The information acquired through the sensitivity analysis could be used to further optimize the foundation layout.

The experiences from conducting the extensive sensitivity analysis would indicate that a sensitivity analysis can be extended to include the in-situ stress and rock mass quality to be used to find sensitive locations within the model, however it is rather lacking if the intention is to compensate for deficient initial data. As the simulation of different scenarios is time consuming for large 3DEC models, if there is uncertainty with the initial parameters, it is unreasonable to simulate all the possible combinations. Whilst altering magnitudes of the input parameters is straight forward, uncertainty in weakness zone location or principal in-situ stress direction brings about a plethora of different combinations. Furthermore, drawing meaningful conclusions becomes harder as the number of results increases.

ACKNOWLEDGEMENTS

The authors would like to thank the kind people at SRV and Länsimetro for allowing the distribution of the relevant findings made during the Kivenlahti metro center simulation work in the form of this paper. The views presented in this article represent those of the authors.

REFERENCES

Itasca Consulting Group Inc. 2020. 3DEC - Three-Dimensional Distinct Element Code. (5.2.292). [Software].