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*Published in:*
Get Underground 2009

Published: 02/10/2009

**Document Version**
Peer reviewed version

**Please cite the original version:**
SPALLING PREDICTION METHODS IN HIGH STRESS CONDITIONS

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ABSTRACT/TIIVISTELMÄ

Ever deepening mines and deep nuclear waste disposal facilities with strict safety regulations face spalling problem that is not well understood. Spalling phenomenon occurs as a strong compressive pressure inducing crack growth behind excavated surface and buckling of thin rock slabs. In this paper we describe how sophisticated spalling prediction methods can be applied to determine adequate tunnel support design in Posiva’s ONKALO. The general methods and a case study are described. The results of different prediction methods are compared to achieve an understanding of outcome range and a comparative analysis. The main analysis method is state of the art Three-Dimensional Finite Element Method (3-D FEM). The 3-D FEM mesh density is enhanced with a control surface and its limits and optimization is discussed. The result validity is studied with Kirsch equations and with two-dimensional indirect boundary element program to examine the tangential boundary stress. Shaft shape and required support is studied for the design process. Also a statistical reference analysis was done using Monte Carlo Spalling – simulation developed in year 2009 by Derek Martin and Rolf Christiansson.

1. INTRODUCTION

In the deep underground tunnels and facilities the high in-situ stresses magnitudes can cause brittle failures in hard rock. As the mines and nuclear waste disposal facilities pursue deeper the stress magnitudes increasing with depth cause failure probability to grow. The understanding and reliable prediction of the failure process is the key to optimal layout and adequate rock support measures that enable possible cost-effective and safe construction of a deep facility.

When stresses at the excavation boundary exceed the rock mass strength a brittle failure occurs that is often called as “spalling”. Spalling phenomenon occurs as a strong compressive pressure inducing crack growth behind excavated surface and buckling of thin rock slabs. The spalling is initiated in the region of tangential maximum stresses and result in a V-shaped notch (Martin & Christiansson 2008).

To predict spalling an approximate value of in-situ stress, stress direction and rock mass spalling strength is required. The shape and direction of the tunnel has a drastic effect to tangential stresses that affect at the tunnel boundary. Therefore a tunnel oriented to the principal stress direction suffers minimal spalling damage compared to a tunnel that is oriented orthogonal that suffers maximum damage. The complex geometrical forms affect to stress vector directions and to boundary stresses and are hard to predict without three-dimensional numerical models.
2. METHODS

The tangential stress on the tunnel surface can be determined using Kirsch equations or advanced numerical methods. Both methods can be used but three-dimensional numerical model provides accurate results for complex geometries.

Using equations by (Hoek & Brown 1980) the tangential stress can be calculated as follows:

\[ \sigma_{\theta\theta} = \sigma_3 (A \cdot k - 1) \]  

where  
\[ \sigma_{\theta\theta} \] tangential stress (MPa)  
\[ \sigma_3 \] minor principal stress (MPa)  
\[ A \] shape parameter  
\[ k \] principal stress ratio

The direction and depth of the tunnel has effect to the tangential stress. The principal stresses can be calculated using equations 2-4 and geometrical formulas to match the direction of the tunnel cross section.

Theoretical equations are useful for simple geometries with less importance whereas three-dimensional numerical methods can handle complex geometries. Different three-dimensional numerical methods are suitable for different tasks. Boundary element method (BEM) is based on integral equations. In the Boundary element method the discretizations are restricted only to boundaries, making the data processing fast, but restricting the exact solution to surfaces only.

FEM also known as Finite Element Analysis or Technique is a numerical technique to solve partial differential equations by finding approximate solutions. While 3D-FEM model contains hundreds of thousands elements all to be approximated, the technique requires extreme computational power. The computational limits also limit the accuracy of the model as the element size at the boundary practically can be 0.5…1 meter when model features several tunnel geometries (Figure 1). In more detailed models the element size can be reduced even more, but the element size will still be limiting factor.

![Figure 1. 3D-FEM mesh elements](image)
3. CASE STUDY: TECHNICAL ROOMS OF ONKALO AT LEVEL -437

3.1 General about ONKALO and the case study

Posiva Oy is owned by the two nuclear power plant companies, TVO and Fortum. The company is responsible for the final disposal of spent nuclear fuel generated by the power plants of its owners, as well as the task of conducting associated research. In the summer of 2004 Posiva started excavation work on an underground rock characterisation facility called ONKALO. ONKALO consists of one access tunnel and three shafts (Figure 2). The shafts are excavated with the raise boring method. Supply and exhaust air shafts are 3.5 m in diameter while personnel shaft is 4.5 m.

![ONKALO layout, preliminary](image)

In 2010 the main characterization level at depth -437 m will be reached. The main characterization level consists of so called crossroads area and demonstration tunnels and technical rooms as well as shaft access drifts. Technical rooms and shaft access drifts are shown on Figure 3.

During the design of ONKALO the spalling assessment at the technical rooms and shaft access drifts were a point of interest. All together 10 elastic 3D-FEM models and 16 3D-BEM models were created for the assessment. Also displacements were calculated using plastic models. However this case study describes spalling prediction and support design process only at the shaft access drift area along with the affecting tunnels of technical rooms. The spalling is estimated to be at highest at the case study area.
The main characterization level at -437 m depth. Dash line is a pumping station to be at depth ~ -450 m.

3.2 Geology

The main rock type in Olkiluoto bedrock is migmatic gneiss. Due to heterogeneity of rock mass the strength of rock varies widely. Compressive strength of magmatic gneiss lies between 90 - 140 MPa. Rock mass strength doesn't seem to be dependent on depth.

The spalling strength is estimated to be between the laboratory crack initiation and crack damage strength. After the Åspö and URL experiences the spalling strength is estimated to be 57 % of the uniaxial compressive strength. The mean compressive strength of magmatic gneiss is 115 MPa and therefore the spalling strength is 66 MPa. (Posiva 2009-1)

Stress field in ONKALO area is anisotropic. The state of stress increases with depth (~ 0.03 – 0.04 MPa/m). Alignment of stress field varies with depth. In near surface depths maximum horizontal stress is approximately north-south orientated. Beneath the levels -200…-300 m the maximum horizontal stress orientates to east-west. The largest rock facilities, that are technical rooms, are designed to orientate parallel to maximum horizontal stress to minimize spalling risk (Posiva 2009-1). The upper limits (90 %) of the stress components according to Posiva 2009-1 can be calculated as follows:

\[
\sigma_H = 19.6 + 0.030 \, z \, \text{(MPa)} \quad (2)
\]

\[
\sigma_h = 13.45 + 0.015 \, z \, \text{(MPa)} \quad (3)
\]

\[
\sigma_v = 0.0292 \, z \, \text{(MPa)} \quad (4)
\]

The Technical rooms are located at level -436 where the stress components are 32.7 MPa, 20.0 MPa and 12.7 MPa and respectively at level -425 (5 m above tunnel at the shaft point of interest) components are 32.4 MPa, 19.8 MPa and 12.4 MPa.

Temperature of bedrock is about +12 °C at depth -500 m. After the nuclear waste canisters have been emplaced raises the temperature in bedrock. Raise in temperature takes place earliest after 4 decades. Due to thermal expansion of the rock, it is estimated that ~20 MPa must be added to the horizontal in situ stress components (Posiva 2009-1). However the calculations at this case study do not take into account the future stress increase.
Spalling assessments have been made for the ONKALO depth interval of -195 m to -296 m. It was found i.a. that there is only the potential for minor spalling within assessment area. Also with optimal orientation of facilities the depth of excavation-induced spalling can be reduced. Results were in good agreement with generic results (Hakala et al 2008).

3.3. Theoretical results and 2D-BEM model

At the first stage of the spalling assessments the rock mass spalling strength was compared to the values calculated theoretically and also with simple 2D-BEM models generated with Examine 2D. For round excavations the shape parameter 3.0 can be used to estimate the tangential stresses (Hoek & Brown 1980). The theoretical tangential stress calculated with equation 1 is 77.4 MPa. The Examine2D 2D-BEM model result in similar values and the model estimates that the depth where rock mass spalling strength is exceeded is 265 mm (Figure 4). One must bear in mind that the values are calculated only at the boundaries and are extrapolated between the boundaries so that the results about the spalling volume are not reliable.

![Figure 4. Tangential stresses at round shaft.](image)

3.4 The effect of excavation in stages to spalling

The effect of excavation in stages to spalling is studied with Midas GTS 3D-FEM software using elastic model. In normal excavation process the spalling occurs before final support such as rock bolts and reinforced shotcrete are installed and the spalled area has either scaled or fallen down. In technical rooms of ONKALO the two adjacent levels and shaft excavation causes the spalled area in previously excavated tunnels to grow as the excavation proceeds (see Figure 5). The predicted spalling volume is shown in the figure. As can be seen in the Figure 5 between stages B and C the area that is predicted to spall grows around the upper shafts and in the connected tunnels arches. The spalled area is considered to be highly conservative because of the coarse elements size in the model.
A. The upper level is excavated

B. The shafts are excavated to the upper level

C. The lower level is excavated

D. The lower shafts are excavated

Figure 5. The effect of excavation in stages to spalling

3.5 Shaft shape optimization

Round shafts cause extensive spalling as the tangential stresses are high at the excavation surfaces at the minor stress direction. The problem can be approached by changing the geometry to favorable in this case elliptical. The upper shafts in the Figure 5 are raise bored and the geometry cannot be affected. However the short 13 meter shafts connecting lower levels are excavated by drill and blast method and the shape can be transformed into elliptical. The ellipses major and minor axis ratio is determined as follows:

\[ \frac{A}{B} = \frac{\sigma_1}{\sigma_2} \]  

The ellipse axis ratio is 6.0 m / 4.5 m in the personnel shaft and 4.9 m / 3.5 m in the ventilation shafts. Also a new and more detailed Midas GTS 3D-FEM model with ellipse shafts is created in order to study the behavior of the transformed shape (Figure 6). 3D-FEM model suggests that spalling is reduced, but the model still indicates minor spalling.
3.6 Spalling assessment with 3D-FEM model

The actual spalling assessment was done with the 3D-FEM models created with Midas GTS. The element density was optimized so that at the boundaries the size was from 1...2 m to 0.5 m at the point of interests. For example at the tunnel roof the mesh size was 0.5 m and 0.5 above the tunnel in the rock the element size was also controlled with a guideline to 0.5 m spacing between nodes. Around the shafts a surface was offset to ensure a uniform 0.5 m mesh. Quadratic elements were used, to gain the accuracy of elements half the size or even smaller. Altogether the model consisted of 120000 nodes and 90000 quadratic elements. The model for the current computational resources is still fluent to use. The model was calculated elastically using stress field increasing as a function of depth (Equations 2...4) and following parameters:

<table>
<thead>
<tr>
<th>Young's modulus, E</th>
<th>Poisson's Ratio, ν</th>
<th>Unit Weight, γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.872 GPa</td>
<td>0.25</td>
<td>26.487 kN/m³</td>
</tr>
</tbody>
</table>

By creating an ISO-surface by the value of the spalling strength, areas where the tangential stress exceeds the spalling strength can be clearly visualized. The model results indicate that shafts and shaft access drifts face a serious spalling hazard (Figure 7) that has to be prepared for.
3.7 The depth of the spalling
The depth of the spalling can also be measured to give an idea of the magnitude of the damage (Figure 8). However one must bear in mind that even a small deviations on the spalling strength can have large effects on the size and depth of the estimated damage.

Figure 8. The spalling volume estimation

The spalling volume is approximated as a cone with dimensions shown in the Figure 8 and the volume of the cone is estimated to be 2.7 m³. The support measures are designed to hold weight of the cone. Bolt length is also confirmed to be adequate with 2.9 m of bond length (Figure 8).

3.8 The boundary stress estimation with 3D-BEM model
Due to the size of 3D models and the nature of FEM, it is sometimes difficult to obtain accurate peak stress values on the surface of the tunnels. Therefore 3D-BEM analyses were carried out to verify the results. The material properties and the results are shown in the Figure 9.

Figure 9. 3D-BEM model
The tangential stresses of 3D-BEM and 3D-FEM correspond within a 10 % margin the 3D-FEM stresses being lower than 3D-BEM stresses (which may be considered more accurate). The difference may originate from coarse FEM mesh or from cumulative rounding error.

3.9 Support of the round shafts

As noticed above a spalling slaps are estimated to the round raise bored shaft surfaces. As the shape cannot be altered the optimal design is achieved by inducing a supporting pressure in the direction of the weaker principal stress. This may be achieved by installing rock bolts (Figure 10). Due to uncertainties with stress field direction and intensity the bolts are placed in 90 degrees fans to cover a maximum of 45 degree deviation in initial data.

![Figure 10. The supports are installed to intermediate stress direction in order to control the spalling rock.](image)

4. COMPARISON OF THE RESULTS AND CONCLUSIONS

The deviation of the 3D-BEM and 3D-FEM results is small in comparison to inaccuracy of initial data, so there is no need to study the deviation from a practical point of view. The location and extent of the spalling damage correlates consistently between the two methods. The results may be compared to results obtained with the Monte Carlo method first applied by Martin & Christiansson 2008 gives a spalling probability of 66 % and nominal damage depth of 60 mm at depth of -436 m. The tangential stress for circular cross section is 82 MPa. For elliptical shape the corresponding values are spalling probability of 15 %, nominal damage depth of 0 mm (not defined) and maximum tangential stress of 55 MPa. The calculation steps and design assumptions used are described in Uotinen et al. 2009.

The results suggest that optimal support method in shafts is to choose an optimal shape when possible. Due to uncertainty with stress field orientation and limitations of certain excavation methods the shape optimization may not always be possible. The ellipse shape distributes the tangential stresses more evenly compared to circular shape where the stresses tend to concentrate to the intermediate stress direction and exceed the spalling strength locally.
As figures 5A through 5D show, significant spalling is to be expected during the excavation of the shafts. By installing support along the edge of the shaft this damage may be reduced greatly. The effect of EDZ has not been taken in account and it may cause the stress field to bend around the tunnel which may reduce damage or change the predominant damage mode to wedge failure.

5. REFERENCES


