GEOMECHANICS OF THE CLIMAX MINE-BY,
NEVADA TEST SITE

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THE MINE-BY EXPERIMENT AT CLIMAX/NTS

Spent Fuel Test (SFT/C) Mine-By

The Lawrence Livermore National Laboratory (LLNL) is conducting a generic test of retrievable geologic storage of nuclear spent fuel assemblies, in an underground chamber, at the Nevada Test Site (NTS), Nevada [1]. This generic test is located 420 m below the surface, in the Climax granitic stock.

Eleven canisters of spent fuel approximately 2.5 years out of reactor core (about 1.6 kW/canister thermal output) are now emplaced in a storage drift, along with 6 electrical simulator canisters. Two adjacent drifts contain electrical heaters, which will be operated to simulate the thermal field of a large repository. The three drifts are shown on Fig. 1. The excavation was performed in three steps: the two heater drifts were excavated first, then the top heading of the canister drift was mined, and finally, the bench was removed.

Prior to the "mine-by" of the center (canister) drift, deformation and stress gauges were emplaced from the heater drifts, near two cross sections labeled stations 2+83 and 3+45. (Fig. 2). The Climax stock, at the Nevada Test Site, is composed of quartz monzonite and granodiorite [2]. The Spent Fuel Test Site is located in the quartz monzonite, which contains three sets of joints nearly perpendicular to each other. In addition, there are a number of shears intersecting the three chambers.

Previous Comparison of Field Data and Model Calculations

The relative displacements due to the mine-by, between the anchors and the sensing heads for the 12 multi-position extensometers are shown in Fig. 3. The numbers in brackets are values calculated from previous elastic and isotropic finite element models using the ADINA code, as discussed below.

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The few case extensometer data were judged unreliable, and are not discussed here. The only stress data obtained during the nine-by were stress changes in three vibrating wire streamometers (VSM-4) installed in the north pillar. Two were at station 2+60 and one at station 3+02. Only one of them was in the center of the pillar (VSM-2). The VSM data for vertical pillar stress changes due to the nine-by are shown in Table 1, next to ADINA values previously calculated.

Table 1: Comparison of Measured and ADINA Calculated Vertical Stress Changes, as a Result of the Nine-by (1).

<table>
<thead>
<tr>
<th>Stress Meter No.</th>
<th>Station (Fig. 1)</th>
<th>Dist. from Center Drift (m)</th>
<th>VSM Bearing Stress (MPa)</th>
<th>Calculated* Stress Change (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSW-1</td>
<td>2+40</td>
<td>1.0</td>
<td>~3.7</td>
<td>~4.1</td>
</tr>
<tr>
<td>VSW-2</td>
<td>2+40</td>
<td>1.0</td>
<td>~5.5</td>
<td>~5.6</td>
</tr>
<tr>
<td>VSW-3 (new)</td>
<td>1+42</td>
<td>1.0</td>
<td>~1.0</td>
<td>~1.0</td>
</tr>
</tbody>
</table>

*Vibrating wire stress meters (VSM) calculations assumed a rock modulus of 61 GPa. Values indicate a decrease in compression. Rock modulus assumed at 61 GPa. Horizontal to vertical stress ratio taken as 0.8.

Prior to this new analysis, two series of models were run regarding the nine-by. Prior to nine-by, LLNL performed scouring calculations with the ADINA code. After the nine-by, Terra-Tek Inc. performed calculations with the YPLAX (finite element) and the 30X (boundary element) codes (2). The results of the three calculations were similar; this was to be expected considering the similarity of the input. None of the above models explicitly included the geological discontinuities such as joints and shears. The rock mass modulus was taken from handbook values, since no field estimates had been obtained, at that time. The ratio of horizontal to vertical stress was varied between 0.8 and 1.25. The highest value of 1.25 is close to that derived from overcoring measurements conducted by the U.S. Geological Survey around the south heater drift (3). None of these models could have the capability to represent strain-softening or dilatancy of the rock mass in the post-peak condition.

The results of the above modeling can be summarized as follows:

- The models did not show a reduction in vertical stresses in the pillars during nine-by of the center drift, as reported from the field.
- The models did not show a horizontal contraction of the pillars during nine-by, as reported from the field.
- The relative movements of anchors for the extensometers at 30° to the horizontal generally were several times larger than calculated with ADINA.
- The relative movements of anchors for the extensometers at 30° to the horizontal were in slightly better agreement with the predicted values.
- An attempt at correlating the pattern of inclined VWM data with local shears fared better in the North pillar than in the South pillar (4).

Discussion

The decrease in vertical pillar stress and the horizontal contraction of the pillars were hypothesized to be due to stress arching over the caverns (2). However, this arching hypothesis was not substantiated. Although ADINA results showed a stress increase for VSM-1 and VSM-3, a stress decrease can be explained and modeled. ADINA calculations did not include a zone of rock softened by blasting and stress relief around the center drift. Our new calculations, with the YPLAX finite element program are summarized later in this paper. They include the softened zone, and indeed they predict a vertical stress decrease at the locations of VSM-1 and VSM-3. As for VSM-2, the YPLAX models also show that localized stress decrease can take place in the pillars depending upon the geometry of the joints and shears.

The main riddle lies with the pattern of horizontal movements reported from the field, supposedly showing the pillars to shrink horizontally because of the nine-by. It is easy to show that the ADINA results are at least internally consistent, even if their absolute values are questionable because the modulus chosen for the in-place Climax granite was obtained from test on small cores. This disregards the effect of scale. A simple model for the calculated movements of points A to F on Fig. 3 is:

\[
\begin{array}{cccccccc}
\text{Station} & A & B & C & D & E & F \\
\text{Horizontal} & 0.2 & 0.5 & 0.9 & 0.9 & 0.5 & 0.2 \\
\text{Vertical} & 0.2 & 0.5 & 0.9 & 0.9 & 0.5 & 0.2 \\
\end{array}
\]

No such models could be constructed to explain the data reported from the field, unless one is prepared to accept that the center drift widened upon mining. This behavior was not observed either in a YPLAX elastic isotropic calculation where the horizontal to vertical stress ratio was varied between 0.5 and 3.5. Such widening also would be contrary to all mining experience.

Turning to the arching argument, arching would mean that the pillars unloaded through some load redistribution on the abutments. The lack of stress gages in the abutments prevents confirmation of this. However, a simple calculation shows the strange conclusion that an unloading assumption would lead to: using an average 1.06 mm horizontal pillar shrinkage, a 1.0 GPa rock mass modulus, and a 0.25 Poisson's ratio, the vertical stress relief should be 36 MPa. Admittedly, the pillars start out in a triaxial state of stress, whereas the above calculation is uniaxial. Also, this is an elastic analysis. Nevertheless, the 36 MPa figure is considerably in excess of the 1.3 MPa from VSM-1. In fact, it is considerably larger than the in situ vertical stresses of 7.9 MPa reported at SGM (3). Hence the pillars would end up in a state of large net tension. This would be a unique occurrence, indeed. Besides, our limited pillar stress measurements have indicated compression to exist (5). In summary, it appears that the unique horizontal shrinkage of the pillars, reported earlier, is neither consistent with model studies, nor is it explained from stress-strain relations for the rock mass. On the other hand, there is no difficulty in providing reasonable explanations for the reported localized decreases in vertical pillar stress.

The New Project

In light of the need for a better understanding of the geomechanics of the nine-by, a 2-phase project...
was initiated. First, a program of geomechanics was conducted to estimate the in-situ deformability of the Climax granite and to refine the in-situ stress field data. Second, a new modeling of the mine-by was completed with a more realistic geology and better rock mass properties input.

The next two chapters summarize the results of the field program and of the new modeling, respectively. Full details are contained in two published reports (5,6).

IN-SITU TESTING IN CLIMAX GRANITE

In-Situ Deformability

Six different approaches were used to estimate the field modulus of the Climax granite.

1. NX borehole jack tests in holes MBI-7 and -14 (Fig. 1): Typical results of horizontal and vertical measurements in the south pillar are given in Fig. 4, where RQD values from the same holes also are shown.

2. Modified NX borehole jack tests (7), also in MBI-7 and 14: the best estimated mean value was high, when compared to others. This indicates some potential difficulty with using this test in jointed rock.

3. Petite sismique measurements (8) across both pillars: the traverses are shown in Fig. 5; a typical trace and its power spectrum are shown in Fig. 6. The mean frequency was about 1050 Hz±3% in all traverses, giving an estimated modulus of 50 GPa (Fig. 7).

4. Tunnel relaxation: both ADINA and DIG models seemed to indicate by back-calculation that a reasonable estimate would be 25 to 30 GPa.

5. Rock Mass Rating (RMR) correlation (9): the RMR of 64 to 79 obtained for the Climax granite would indicate an igneous rock mass modulus of 20 to 32 GPa (Fig. 8).

6. Q-rating correlation (10): the mean Q of 9.6 obtained for the Climax granite would give an in-situ modulus of 25 GPa (Fig. 9).
The above estimates are summarized in Fig. 10, where they are compared to laboratory obtained moduli. The best field estimate is $E_p = 26$ GPa; the best laboratory estimate is $E_p = 70$ GPa. This gives a ratio $E_p/E_p = 0.37$ which is very compatible with the reduction factors summarized by the author for a variety of rock masses (11).

This $K_n$ value can be taken as representative of the normal stiffness under the average field stress existing at Climax. However, it is well documented that $K_n$ is a highly non-linear quantity which is normal stress dependent (14). The normal stress - normal stiffness relationship for the granite joints should be determined in the field. As in the case of the shear stiffness, $K_n$ is also likely to be a scale dependent quantity, and the minimum sample size should be of the order of the block size in situ (15).

In-situ Stresses at SFT-C

Three series of stress measurements have been performed in the Climax granite since 1979: one by the USGS and two on this project (Fig. 11). Overcoring tests by Ellis of the U.S. Geological Survey (USGS) in one hole plunging 77° (OC-1), and two near-horizontal holes (OC-2 and OC-3), drilled from the South heater drift (3). Undercoring tests by Neuse and Patrick at 6 locations in the heater drifts (pillar, crown and abutment, in each drift). Borehole jack fracturing tests by de la Cruz and Yous in holes NH-1-7 and 14.

<table>
<thead>
<tr>
<th>Component</th>
<th>Magnitude (MPa)</th>
<th>Bearing</th>
<th>Plunge* (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_1$ (max)</td>
<td>11.56</td>
<td>N 36 E</td>
<td>-20</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>7.13</td>
<td>N 26 E</td>
<td>+57</td>
</tr>
<tr>
<td>$\sigma_3$ (min)</td>
<td>2.75</td>
<td>N 43 W</td>
<td>-14</td>
</tr>
</tbody>
</table>

*Negative plunge is below the horizontal plane.

From these results, and using a combination of stereographic projection and three-dimensional Mohr constructions, we calculated the horizontal stresses parallel and perpendicular to the axis of the drifts, and the vertical stress as:
- horizontal stress parallel to tunnels: $\approx 4.2$ MPa
- horizontal stress perpendicular to tunnels: $\approx 9.2$ MPa
- vertical stress: $\approx 7.9$ MPa

This gives a vertical stress substantially lower than the overburden stress which was calculated as 10.9 MPa.

The borehole jack fracturing tests (16) gave results in the north pillar only; the horizontal stresses were calculated between 4 and 5 MPa, which...
is reasonable, but the calculated vertical stresses of 2 to 3.5 MPa seemed unreasonably low. This is probably due to the influence of rock joining on data analysis from borehole jack fracturing.

The undercoring method (17) was used successfully to obtain tangential stresses in the crowns of both heater drifts. The results are summarized in Fig. 12. Four other tests in the abutments and pillars did not succeed due to discrete joint relaxation, and hitting of the reference pins during the tests.

\[ \text{Figure 12: Summary of } \sigma_{y2} \text{ Values at SFT-C} \]

Based on all the above test results, initial stress values were selected for input into the new models, with a stress ratio \( \sigma_{v}/\sigma_{h} = 1.2 \).

**In-situ Poisson's Ratio**

If we assume the tunnels to be in a plane strain condition in their central portion, where the stresses were measured, we can estimate an in-situ Poisson's ratio from:

\[ \nu = \frac{\sigma_{h2}}{2(\sigma_{h1} + \sigma_{v})} = 0.206 \]

It is important to note that this value is independent of any assumption made on the rock modulus to calculate the above stresses. This value of Poisson's ratio was the one used in the new finite element models of the mine-by.

**NEW ANALYSIS OF THE MINE-BY**

**JPLAXD Finite Element Models**

JPLAXD is a plane and axisymmetric finite element program developed by the author for the analysis of structures in rock. To that end, it contains a library of solid and joint elements; both the solids and the joints can exhibit strain softening and dilatancy in the post-peak region (18,19). The program also includes such features as mesh generation, restart capability for sequential excavation or construction, and plotting routines for stresses and displacements.

To refine the analysis of the SFT-C mine-by we provided the following features which were not included in the previous models:

- representation of discrete geological discontinuities, such as major joints and shears observed around the tunnels.
- strain-softening and dilatancy of rock elements in the post-peak region.
- a field-measured input of rock mass modulus.
- a field-measured input of in-situ stresses.
- a Poisson's ratio derived from field stress measurements.
- a parametric variation of the ratio of horizontal to vertical stresses, between 0.5 and 3.5.

Two types of models were adopted: unjointed and jointed. The jointed models were constructed after consultation with the SFT-C field geologist (4), to illustrate typical geometries of shears and master joints at stations 2+63 and 3+43. The unjointed models were used primarily to study the effect of the stress ratio on pillar response during mine by.

With all the models, jointed or not, the calculations were performed in a sequence of four so-called runs:

1. run 1: obtain an equilibrium of the full mesh, without excavation.
2. run 2: excavate the two side drifts.
3. run 3: excavate the heading of the center drift.
4. run 4: excavate the bench of the center drift.

Runs 2, 3, and 4 were restarted from the equilibrium obtained in the previous run. In cases when rock or joint failure takes place, the equilibrium is attained through a few iterations in the run (5 to 7). The program automatically updates solid and joint properties, to be compatible with the input of constitutive relations.

Because of space limitations we will only summarize the results from the model at station 2+63 (Fig. 13) They are representative of the overall analysis.

\[ \text{Figure 13: Jointed Mesh of SFT-C at Station 2+63} \]

(381 Nodes, 380 Elements)
Results of the Analysis

The results of the calculations at station 2+83 can be summarized as follows:

- during the mine-by portion of the mining, all caverns close vertically, the center drift closes horizontally and the walls of the two heater drifts move towards the center drift, with a slight net opening of those drifts. Both pillars expand laterally.

- neither the JPLAXD nor the ADINA calculations are well matched by data reported from the field. For the inclined extensometers, the percentage of anchor movements where the field values and the code calculations differ by a factor of two or more is 50% with ADINA and 87% with JPLAXD. For the horizontal extensometers the discrepancy is 100% since all reported movements are in the opposite direction of those calculated with both JPLAXD and ADINA.

- the vertical pillar stress changes during mine-by, obtained with JPLAXD (Fig. 11), are consistent with the field observations from VSM stress gages at station 2+80 (Table 1). This was not true of pillar stresses calculated by previous models (2). The agreement is particularly good for stress relief in the skin of the pillars. The 10.1 MPa decrease obtained in the North pillar is quite close to the 9.7 MPa reported from VSM-1. The calculation gave 9.2 MPa in the South pillar, which did not have stress gages. The model also shows a 1.2 MPa localized decrease in the core of the South pillar, due to the particular jointing. This is similar to the 1.3 MPa reported in the core of the North pillar. Whereas our jointing model of the North pillar may not be complete, it is shown that a localized stress decrease can be evidenced because of joint patterns.

- notwithstanding localized decreases, the models show that the average vertical pillar stress increases during the mine-by. The calculated increments are 2.05 and 1.75 MPa for the North and South pillars, respectively.

- the vertical stress is also shown to increase in the abutments, beyond the walls of the heater drifts. The lack of stress gages in the field at those locations does not permit a comparison with these calculations.

- for the shear strength parameters selected, only minor damage is calculated around the caverns during complete mining. This is consistent with the field observations.

Discussion

Whereas, the reported pillar stress changes have been explained, no explanation was found for the deformation reported from the majority of capes and MPE's. In such a case, does the problem lie with the models, with the field readings, or with both? The diagram below should help to answer the question. The yes or no refer to whether or not the various results are consistent with each other, inside the models, in the field, or between field and models.

![Diagram](image)

The most logical conclusions to reach from this discussion are that:

- both finite element models, which have been tested extensively, are internally consistent because displacements are used to calculate stresses.

- the pillar stress changes were correctly recorded and correctly modeled.

- the displacements calculated in the pillars are correct, because they are the values used to calculate pillar stresses.

- the pillar displacements reported from horizontal MPE's are not consistent with the reported pillar stress changes.

- however, data from the inclined MPE's, which have a high discrepancy rate with the models are not unreal. Local jointing can be responsible for these discrepancies. In this case, the models could be further improved if additional geologic exploration were performed in the region above the caverns.

For now, it seems that the combination of the in-situ geomechanics performed at SFT-C and of the new analysis provides a coherent, although not totally complete, representation of the Climax mine-by.
Acknowledgements

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References


