Influence of lithophysal porosity on stress-strain properties of Topopah Spring Tuff - numerical analysis

Nick Hudyma
*University of Nevada, Las Vegas*

Moses Karakouzian
*University of Nevada, Las Vegas*

Amy J. Smiecinski
*University of Nevada, Las Vegas*, smiecins@unlv.nevada.edu

Follow this and additional works at: [https://digitalscholarship.unlv.edu/yucca_mtn_pubs](https://digitalscholarship.unlv.edu/yucca_mtn_pubs)

*Part of the Geology Commons*

Repository Citation


*Available at: [https://digitalscholarship.unlv.edu/yucca_mtn_pubs/81](https://digitalscholarship.unlv.edu/yucca_mtn_pubs/81)*
Complete only applicable items

<table>
<thead>
<tr>
<th>(1) Analysis</th>
<th>Check all that apply:</th>
<th>(2) Model</th>
<th>Check all that apply:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Analysis</td>
<td>☒ Scientific</td>
<td>Type of Model</td>
<td></td>
</tr>
<tr>
<td>☐ Conceptual Model</td>
<td>☐ Mathematical Model</td>
<td>☐ Process Model</td>
<td></td>
</tr>
<tr>
<td>☐ Abstraction Model</td>
<td>☐ System Model</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intended use of Analysis</th>
<th>Intended use of Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐ Input to Calculation</td>
<td>☐ Input to Calculation</td>
</tr>
<tr>
<td>☐ Input to another Analysis or Model</td>
<td>☐ Input to another Analysis or Model</td>
</tr>
<tr>
<td>☒ Input to Technical Document</td>
<td>☐ Input to a Technical Document</td>
</tr>
<tr>
<td>☐ Input to other Technical Products</td>
<td>☐ Input to other Technical Products</td>
</tr>
</tbody>
</table>

Describe use:
Analysis performed to investigate the influence of lithophysal porosity on the stress-strain properties of Topopah Spring tuff

| (3) Title: |
| Influence of Lithophysal Porosity on Stress-Strain Properties of Topopah Spring Tuff – Numerical Analysis |

| (4) Document Identifier (including Revision No.): | MOD-01-003 Revision 0 |

| (5) Total Attachments: | N/A |

| (6) Attachment Numbers-Pages in each: | N/A |

<table>
<thead>
<tr>
<th>(7) Originator</th>
<th>Printed Name: Nick Hudyma</th>
</tr>
</thead>
<tbody>
<tr>
<td>(8) Checker</td>
<td>Moses Karakouzian</td>
</tr>
<tr>
<td>(9) QA Manager</td>
<td>Amy Smiecinski</td>
</tr>
<tr>
<td>(10) Principal Investigator</td>
<td>Moses Karakouzian</td>
</tr>
</tbody>
</table>

| (11) Remarks: |

QAP-3.3-1 Rev. 11/09/01
<table>
<thead>
<tr>
<th>(1) Page</th>
<th>2 of 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Analysis or Model Title:</td>
<td>Influence of Lithophysal Porosity on Stress-Strain Properties of Topopah Spring Tuff - Numerical Analysis</td>
</tr>
<tr>
<td>(3) Document Identifier (including Revision No.):</td>
<td>MOD-01-003</td>
</tr>
<tr>
<td>(4)</td>
<td>0</td>
</tr>
<tr>
<td>(5) Description of Revision</td>
<td>Initial Issue</td>
</tr>
</tbody>
</table>
1. **Purpose**

The purpose of the numerical analysis effort of Task 27 of cooperative agreement DE-FC08-98NV12081 was to investigate the effect of lithophysal porosity on the elastic stress-strain properties of the tuff rock mass. Rock mass properties without lithophysal cavities are designated matrix properties. Rock mass properties with lithophysal cavities are designated effective properties. The analysis will be performed for a 6" by 6" square cross-section with a uniform distribution of lithophysal cavities for a variety of porosities. The analyses will be performed using FLAC 2D version 3.5, a Department of Energy qualified software. The analyses will compare the matrix properties to the effective properties.

2. **Quality Assurance**

The modeling was performed in accordance with the UCSSN QA Program and specifically Quality Assurance Procedures:

- QAP 3.0 "Scientific Investigation Control"
- QAP 3.1 "Control of Electronic Data"
- QAP 3.2 "Software Management"
- QAP 3.3 "Analysis and Models"

The portions of the scientific notebook, UCCSN-UNLV-022 Volume 1 "The Influence of Lithophysal Porosity on the In-Situ Stress-Strain Properties..." pertaining to this report were technically reviewed.

3. **Computer Software**

The computer software that was used for the numerical analysis efforts of Task 27 was FLAC 2D version 3.5. The software is installed on a stand alone, 850 MHz Pentium III PC running Microsoft Windows NT 4.0. The software activity number is LV-2000-174 and the Software Tracking Number is 10167-35-00. FLAC 2D version 3.5 is a Department of Energy qualified software. Microsoft Excel version 2000 was also used in the analysis. All formulas entered into the Microsoft Excel version 2000 files were verified using a hand calculator as required by UCCSN QAP-3.2.

4. **Inputs**

The data tracking number (DTN) for the inputs and outputs supporting this analysis is UN0110MWD027MK.001.
4.1 Data and Parameters

Several sets of inputs were used in the modeling. The inputs are grouped into three categories: Boundary Conditions, Material Model Properties, Vertical Displacement and Cavities. These categories are explained below.

**Boundary Conditions**

The FLAC computer code was run under plane strain conditions. Two other boundary conditions were used as input parameters: Free Sides and Constrained Sides. In Free Sides, the cross-section was allowed to expand horizontally when subjected to the vertical displacement. In Constrained Sides, the cross-section was not allowed to expand horizontally when subjected to the vertical displacement (see Figure 1).

**Material Model Properties**

The analysis was performed using a linear elastic material model. This material model was chosen because the analysis is to determine the effect of lithophysal cavities on the elastic stress-strain properties of tuff rock.

Two initial elastic properties of the matrix were required as input into the FLAC program, Young’s Modulus and Poisson’s Ratio. The choice of the value of Young’s Modulus for the analysis is arbitrary because the material is linear elastic and failure does not occur. A Young's Modulus value of 10,000 psi was arbitrarily chosen. For Poisson’s Ratio, a range of values was chosen. Poisson’s Ratio was either: 0.1, 0.2, 0.3, 0.4, 0.45 or 0.49.

**Vertical Displacement**

The vertical displacement input is how much the cross-section is deformed so that stresses and strains can be computed throughout the cross-section. A vertical displacement of 0.5 inches was arbitrarily chosen and was applied only to the top nodes of the model. Since the material model is linear elastic and failure does not occur, the amount of vertical displacement is arbitrary. The value 0.5 inches corresponds to an engineering strain of 8.33% in the vertical direction (see Figure 1).

**Cavities**

Cavities consisted of uniformly distributed circles. Three different cavity scenarios were used in the numerical analysis: 1 cavity, 9 cavities or 36 cavities. Porosity was defined as the area of cavities divided by the total cross sectional area (see Figure 1). For each scenario, the size of the cavities was determined by setting the porosity equal to 5%, 10%, 20%, 30% and 40%. The geometries of the cavities are provided in the table below.
Figure 1. Boundary conditions and porosity distribution configurations

(A) Boundary conditions

Constrained (Fixed) Sides
specimen not allowed to expand horizontally

Free Sides
specimen allowed to expand horizontally

vertical displacement of 0.5 inches

(B) Porosity distribution configurations

1 Hole

9 Holes

36 Holes
Table 1. Circular Cavity Geometries

<table>
<thead>
<tr>
<th>Porosity</th>
<th>Number of Cavities</th>
<th>Cavity Radius (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>36</td>
<td>0.757</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.252</td>
</tr>
<tr>
<td>10%</td>
<td>9</td>
<td>0.126</td>
</tr>
<tr>
<td>20%</td>
<td>36</td>
<td>0.1785</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.515</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.5045</td>
</tr>
<tr>
<td>30%</td>
<td>36</td>
<td>0.2525</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.855</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.618</td>
</tr>
<tr>
<td>40%</td>
<td>36</td>
<td>0.309</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.14</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.714</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>0.357</td>
</tr>
</tbody>
</table>

4.2. Criteria
There are no specific criteria that are directly applicable to the numerical analysis.

4.3. Codes and Standards
There are no specific codes or standards that are directly applicable to the numerical analysis.

5. Assumptions
There are two assumptions in this analysis, the analysis was performed in 2D under plane strain conditions and the material model chosen was a linear elastic material model.

6. Analysis
The model used in this analysis was a six by six inch square cross-section. Rock mass properties without lithophysal cavities are designated matrix properties. Rock mass properties with lithophysal cavities are designated effective properties. Circular cavities were placed within the cross-section. The cross-section was then subjected to a vertical displacement and the resulting stresses and strains were computed by FLAC throughout the cross-section. Using the matrix elastic properties and the computed stresses and strains, the effective elastic properties could be calculated for the cross-section containing circular cavities. The effective elastic properties were calculated using Microsoft
Excel. All formulas entered in the Microsoft Excel files were verified using a hand calculator, as required by UCCSN QAP-3.2.

FLAC output provides stresses and strains. From the stresses and strains, the effective Young's Modulus and Poisson's ratio can be calculated for the body containing cavities. To calculate Young's Modulus and Poisson's ratio, Hooke's law for plane strain conditions was used. These equations can be found in Timoshenko and Goodier (1987).

**Free Sides Condition**

For plane strain conditions and free sides boundary conditions, Hooke's law can be written as:

\[
\varepsilon_x = \frac{1}{E_m} \left[ (1 - \nu^2) \sigma_x - \nu (1 + \nu) \sigma_y \right]
\]

\[
\varepsilon_y = \frac{1}{E_m} \left[ (1 - \nu^2) \sigma_y - \nu (1 + \nu) \sigma_x \right]
\]

Rearranging the equations and solving for \( E_{\text{eff}} \) and \( \nu_{\text{eff}} \),

\[
E_{\text{eff}} = \frac{\varepsilon_y (\sigma_y)^2 - 2 \varepsilon_x (\sigma_y)^2 + \sigma_x \varepsilon_x \sigma_y + \sigma_y \varepsilon_y \sigma_x - 2 \varepsilon_y (\sigma_x)^2 + \varepsilon_x (\sigma_x)^2}{(\varepsilon_y - \varepsilon_x)(\varepsilon_y \sigma_x + \varepsilon_y \sigma_y - \varepsilon_x \sigma_y - \varepsilon_x \sigma_x)}
\]

\[
\nu_{\text{eff}} = \frac{\varepsilon_y \sigma_x + \varepsilon_x \sigma_y}{(\varepsilon_y \sigma_x + \varepsilon_y \sigma_y - \varepsilon_x \sigma_y - \varepsilon_x \sigma_x)}
\]

**Fixed Sides Condition**

Hooke's Law for the case of confined sides can be written as follows:

\[
0 = \frac{1}{E_m} \left[ (1 - \nu^2) \sigma_x - \nu (1 + \nu) \sigma_y \right]
\]
8 of 22

(Note that strain in the horizontal (X) direction is zero due to confined sides.)

\[ \varepsilon_y = \frac{1}{E_m} \left[ (1 - \nu^2) \sigma_y - \nu (1 + \nu) \sigma_x \right] \]

Rearranging the equations and solving for \( E_{\text{eff}} \) and \( \nu_{\text{eff}} \),

\[ E_{\text{eff}} = \frac{\left( \sigma_y \right)^2 + \sigma_x \sigma_y - 2 \left( \sigma_x \right)^2}{\varepsilon_y (\sigma_x + \sigma_y)} \]

\[ \nu_{\text{eff}} = \frac{\sigma_x}{\sigma_x + \sigma_y} \]

7. Conclusions

Results of the numerical analysis are presented as graphs. The graphs comparing the ratio of \( E_{\text{eff}} \) to \( E_m \) are provided in Figures 2 through 7. The graphs comparing the ratio of \( \nu_{\text{eff}} \) to \( \nu_m \) are provided in Figures 8 through 13. Figures 2 through 13 each contain six curves, representing the combinations of boundary conditions and porosity distributions presented in Figure 1. In some of the figures the curves are very close to each other and overlap thus making it difficult to distinguish all six curves. In these figures, it is important to look at the trend of the curves rather than the values associated with individual curves.

**Young's Modulus**

For all Poisson's Ratios, there is a decrease in effective Young's Modulus as the lithophysal porosity increases. At 5% lithophysal porosity, the ratio \( E_{\text{eff}} / E_m \) is approximately 0.9 and at 40% lithophysal porosity, the ratio is approximately 0.4. There is a slight dependence on Poisson's Ratio, the higher the Poisson's Ratio, the greater the \( E_{\text{eff}} / E_m \) ratio. At 5% lithophysal porosity, \( E_{\text{eff}} / E_m \) is 0.9 (\( \nu=0.1 \)) and 0.92 (\( \nu=0.49 \)). Similarly at 40% lithophysal porosity, \( E_{\text{eff}} / E_m \) is 0.38 (\( \nu=0.1 \)) and 0.45 (\( \nu=0.49 \)). These trends hold true regardless of the boundary conditions (free or constrained sides).
**Constrained Sides Poisson’s Ratio**

For a matrix Poisson’s Ratio of 0.1, the effective Poisson’s Ratio is always greater than the matrix Poisson’s Ratio. The dependence on lithophysal porosity is clear. From 5 to 20%, the effective Poisson’s Ratio increases. After 20% lithophysal porosity, the effective Poisson’s Ratio decreases but is never lower than the matrix Poisson’s Ratio. This behavior is seen in the 1-cavity, 9-cavity and 36-cavity analysis.

For a matrix Poisson’s Ratio of 0.2, the effective Poisson’s Ratio is greater than or equal to the matrix Poisson’s Ratio for lithophysal porosities of 5 and 10%. At greater lithophysal porosities, the effective Poisson’s Ratio is less than the matrix Poisson’s Ratio. This behavior is seen in the 1-cavity, 9-cavity and 36-cavity analysis.

At matrix Poisson’s Ratios greater than 0.2, the effective Poisson’s Ratio is always less than the matrix Poisson’s Ratio. The largest value of effective Poisson’s Ratio is at the lowest lithophysal porosity and the smallest value of effective Poisson’s Ratio is at the highest lithophysal porosity. This behavior is seen in the 1-cavity, 9-cavity and 36-cavity analysis.

**Free Sides Poisson’s Ratio**

For a matrix Poisson’s Ratio of 0.1, the effective Poisson’s Ratio is dependent upon the distribution of the lithophysal porosity. For cross-sections containing 1 cavity, the effective modulus increases linearly from 0.124 at 5% lithophysal porosity to 0.232 at 40% lithophysal porosity. For cross-sections containing 9 cavities, the effective modulus increases parabolically from 0.118 at 5% lithophysal porosity to 0.15 at 40% lithophysal porosity. For cross-sections containing 36 cavities, the effective modulus increases from 0.108 at 5% lithophysal porosity to a maximum of approximately 0.135 at 25% porosity and back down to 0.123 at 40% lithophysal porosity.

For a matrix Poisson’s Ratio of 0.2, the effective Poisson’s Ratio is dependent upon the distribution of the lithophysal porosity. For cross-sections containing 1 cavity, the effective modulus increases linearly from 0.208 at 5% lithophysal porosity to 0.261 at 40% lithophysal porosity. For cross-sections containing 9 cavities and 36 cavities, the effective modulus decreases parabolically from 5% lithophysal porosity to 40% lithophysal porosity. For cross sections containing 9 cavities, the decrease is from 0.204 to 0.188. For cross sections containing 36 cavities, the decrease is from 0.2 to 0.168.

For a matrix Poisson’s Ratio of 0.3, the effective Poisson’s Ratio for the cross-sections containing one cavity is approximately 0.29, regardless of the percentage of lithophysal cavities. For cross-sections containing 9 and 36 cavities, the effective Poisson’s Ratio decreases with increasing lithophysal porosity.

For matrix Poisson’s Ratios higher than 0.3, regardless of the lithophysal porosity distribution, the effective Poisson’s Ratio decreases with increasing lithophysal porosity. The cross-section containing 1 cavity has the least decrease and the cross-sections containing 9 and 36 cavities have the same decreases in effective Poisson’s Ratio.
8. Inputs, Outputs and References

*Inputs and Outputs*
The data tracking number (DTN) for this for the inputs and outputs supporting is analysis is UN0110MWD027MK.001.

*References*

9. Attachments

Not applicable. There is no documentation for this report than cannot be included in the text.
Figure:

Porosity (%) vs. E eff / E m ratio for different configurations:
- 36 Hole - Coat
- 9 Hole - Coat
- 1 Hole - Coat
- 36 Hole - Free
- 9 Hole - Free
- 1 Hole - Free

Porosity (%) from 0 to 50 and E eff / E m ratio from 0.20 to 0.00.
Figure 3. $E_{\text{eff}}/E_m$ for Poisson's Ratio 0.2
Figure 4. $\frac{E_{m}}{E_{m}}$ for Poisson's Ratio 0.3
Figure 0 Poisson's Ra 0.4

- 1 Hole - Free
- 9 Hole - Free
- 36 Hole - Free
- 1 Hole - Const.
- 9 Hole - Const.
- 36 Hole - Const.
Figure 6. $E_{eff}/E$ for Poisson's Ratio 0.45
Figure 7. \( \frac{E_{\text{eff}}}{E_{\text{m}}} \) for Poisson's Ratio 0.49

- 36 Hole - Const
- 9 Hole - Const
- 1 Hole - Const
- 36 Hole - Free
- 9 Hole - Free
- 1 Hole - Free
Figure 8. \( \varepsilon_{\text{eff}}/\varepsilon_m \) for Poisson's Ratio 0.1

Porosity (%)

<table>
<thead>
<tr>
<th>Porosity (%)</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
<th>0.25</th>
<th>0.30</th>
<th>0.35</th>
<th>0.40</th>
<th>0.45</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hole - Free</td>
<td>0.95</td>
<td>0.85</td>
<td>0.75</td>
<td>0.65</td>
<td>0.55</td>
<td>0.45</td>
<td>0.35</td>
<td>0.25</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>9 Hole - Fixed</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
<td>0.60</td>
<td>0.50</td>
<td>0.40</td>
<td>0.30</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>1 Hole - Fixed</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
<td>0.60</td>
<td>0.50</td>
<td>0.40</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>36 Hole - Free</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
<td>0.60</td>
<td>0.50</td>
<td>0.40</td>
<td>0.30</td>
</tr>
<tr>
<td>9 Hole - Free</td>
<td>1.25</td>
<td>1.15</td>
<td>1.05</td>
<td>0.95</td>
<td>0.85</td>
<td>0.75</td>
<td>0.65</td>
<td>0.55</td>
<td>0.45</td>
<td>0.35</td>
</tr>
<tr>
<td>1 Hole - Fixed</td>
<td>1.30</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
<td>0.60</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>36 Hole - Free</td>
<td>1.40</td>
<td>1.30</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
<td>0.60</td>
<td>0.50</td>
</tr>
<tr>
<td>9 Hole - Free</td>
<td>1.45</td>
<td>1.35</td>
<td>1.25</td>
<td>1.15</td>
<td>1.05</td>
<td>0.95</td>
<td>0.85</td>
<td>0.75</td>
<td>0.65</td>
<td>0.55</td>
</tr>
<tr>
<td>1 Hole - Fixed</td>
<td>1.50</td>
<td>1.40</td>
<td>1.30</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
<td>0.60</td>
</tr>
<tr>
<td>36 Hole - Free</td>
<td>1.60</td>
<td>1.50</td>
<td>1.40</td>
<td>1.30</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
</tr>
<tr>
<td>9 Hole - Free</td>
<td>1.65</td>
<td>1.55</td>
<td>1.45</td>
<td>1.35</td>
<td>1.25</td>
<td>1.15</td>
<td>1.05</td>
<td>0.95</td>
<td>0.85</td>
<td>0.75</td>
</tr>
<tr>
<td>1 Hole - Fixed</td>
<td>1.70</td>
<td>1.60</td>
<td>1.50</td>
<td>1.40</td>
<td>1.30</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>36 Hole - Free</td>
<td>1.80</td>
<td>1.70</td>
<td>1.60</td>
<td>1.50</td>
<td>1.40</td>
<td>1.30</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>9 Hole - Free</td>
<td>1.85</td>
<td>1.75</td>
<td>1.65</td>
<td>1.55</td>
<td>1.45</td>
<td>1.35</td>
<td>1.25</td>
<td>1.15</td>
<td>1.05</td>
<td>0.95</td>
</tr>
</tbody>
</table>
Figure 9. Volume for Poisson's Ratio 0.2
Figure 10. $v_{eff} / v_m$ for Poisson's Ratio 0.3
Figure 1. Velocity for Poisson's Ratio 0.4
Figure 12. $\frac{v_{eff}}{v_m}$ for Poisson's Ratio 0.45
Figure 13. $\frac{\varepsilon_{eff}}{\varepsilon_m}$ for Poisson's Ratio 0.49.
[X] (1) Analysis
Type of Analysis
[X] Scientific

Intended use of Analysis
[] Input to Calculation
[] Input to another Analysis or Model
[X] Input to a Technical Document
[] Input to other Technical Products

Describe Use:
Analysis performed to investigate the influence of lithophysal porosity on the stress-strain properties of Topopah Spring Tuff.

(2) Model
Type of Model
[] Conceptual Model
[] Mathematical Model
[] Process Model
[] Abstraction Model
[] System Model

Intended use of Model
[] Input to Calculation
[] Input to another Analysis or Model
[] Input to a Technical Document
[] Input to other Technical Products

Describe Use:

Title:
Influence of Lithophysal Porosity on Stress-Strain Properties of Topopah Spring Tuff – Numerical Analysis

Document Identifier (Including Revision No.):
MOD-01-003 Revision 0

Total Attachments:
None

Attachment Numbers-Pages in each:
N/A

Printed Name: Nick Hudyma
Signature: Date:

Originator
Moses Karakouzian
Principal Investigator
Moses Karakouzian

Remarks:
I must verify that the portions of your scientific notebook associated with this report have undergone technical review on 11/8/01.

Mandatory comments are indicated here and within by an asterisk. AP 11-6-01

all comments resolved 11-16-01
### ANALYSIS and MODEL REVISION HISTORY

**Complete only applicable items**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Page</td>
<td>2</td>
<td>of</td>
<td>21</td>
</tr>
<tr>
<td>(2) Analysis or Model Title:</td>
<td>Influence of Lithophysal Porosity on Stress-Strain Properties of Topopah Spring Tuff - Numerical Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) Document Identifier (including Revision No.):</td>
<td>MOD-01-003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(5) Description of Revision</td>
<td>Initial Issue</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

QAP-3.3-2 Rev 10/26/00
1. Purpose

The purpose of the numerical analysis effort of Task 27 was to investigate the effect of lithophysal porosity on the elastic stress-strain properties of the tuff rock mass. Rock mass properties without lithophysal cavities are designated matrix properties. Rock mass properties with lithophysal cavities are designated effective properties. The analysis will be performed for a 6" by 6" square cross-section with a uniform distribution of lithophysal cavities for a variety of porosities. The analyses will be performed using FLAC 2D version 3.5, a Department of Energy qualified software. The analyses will compare the matrix properties to the effective properties.

2. Quality Assurance

The modeling was performed in accordance with the following Quality Assurance Procedures:

- QAP 3.0 "Scientific Investigation Control"
- QAP 3.1 "Control of Electronic Data"
- QAP 3.2 "Software Management"
- QAP 3.3 "Analysis and Models"

You will attest that the portions of the scientific notebook, annexes and appendices contained in this report were technically reviewed.

3. Computer Software

The computer software that was used for the numerical analysis efforts of Task 27 was FLAC 2D version 3.5. The software is installed on a stand alone, 850 MHz Pentium III PC running Microsoft Windows NT 4.0. The software activity number is LV-2000-174 and the Software Tracking Number is 10167-35-00. Microsoft Excel was also used in the analysis. FLAC 2D version 3.5 is a Department of Energy qualified software.

4. Inputs

The data tracking number (DTN) for the inputs and outputs supporting the analysis is UN0110MWD027MK.001.

4.1 Data and Parameters

Several sets of inputs were used in the modeling. The inputs are grouped into three categories: Boundary Conditions, Material Model Properties, Vertical Displacement and Cavities. These categories are explained below.

**Boundary Conditions**

The FLAC computer code was run under plane strain conditions. Two other boundary conditions were used as input parameters: Free Sides and Constrained Sides. In Free Sides, the cross-section was allowed to expand horizontally when subjected to the vertical displacement. In Constrained Sides, the cross-section was not allowed to expand horizontally when subjected to the vertical displacement (see Figure 1).
Figure 1. Examples of specimens, boundary conditions and explanation of matrix and effective properties

(A)

All specimens are constrained on the bottom (as indicated by the thick black bottom boundary) and subjected to a vertical displacement of 0.5 inches (as indicated by the arrows on the top of the specimens).

The specimen represented by Figure 1 (A) contains no cavities. Specimen elastic properties are designated matrix properties.

The specimen represented by Figure 1 (B) contains one cavity and has constrained sides. Matrix elastic properties are used for the portions of the specimen not containing the cavity. Stresses and strains computed using FLAC are used to compute the effective elastic properties of the specimen.

The specimen represented by Figure 1 (C) contains nine cavities and has free sides. Matrix elastic properties are used for the portions of the specimen not containing the cavities. Stresses and strains computed using FLAC are used to compute the effective elastic properties of the specimen.
Material Model Properties

The analysis was performed using a linear elastic material model. This material model was chosen because the analysis is to determine the effect of lithophysal cavities on the elastic stress-strain properties of tuff rock.

Two initial elastic properties of the matrix were required as input into the FLAC program, Young's Modulus and Poisson's Ratio. The choice of the value of Young's Modulus is arbitrary because the material is linear elastic and failure does not occur. A Young's Modulus value of 10,000 psi was arbitrarily chosen. For Poisson's Ratio, a range of values was chosen. Poisson's Ratio was either 0.1, 0.2, 0.3, 0.4, 0.45 or 0.49.

Vertical Displacement

The vertical displacement input is how much the cross-section is deformed so that stresses and strains can be computed throughout the cross-section. A vertical displacement of 0.5 inches was arbitrarily chosen and was applied only to the top nodes of the model. Since the material model is linear elastic and failure does not occur, the amount of vertical displacement is arbitrary. The value 0.5 inches corresponds to an engineering strain of 8.33% in the vertical direction (see Figure 1).

Cavities

Cavities consisted of uniformly distributed circles. Three different cavity scenarios were used in the numerical analysis: 1 cavity, 9 cavities or 36 cavities. Porosity was defined as the area of cavities divided by the total cross-sectional area (see Figure 1). For each scenario, the size of the cavities was determined by setting the porosity equal to 5%, 10%, 20%, 30% and 40%. The geometries of the cavities are provided in the table below.

Table 1. Circular Cavity Geometries

<table>
<thead>
<tr>
<th>Porosity</th>
<th>Number of Cavities</th>
<th>Cavity Radius (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>1</td>
<td>0.757</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.252</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>0.126</td>
</tr>
<tr>
<td>10%</td>
<td>1</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.357</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1785</td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td>1.515</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2525</td>
</tr>
<tr>
<td>30%</td>
<td></td>
<td>1.855</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.618</td>
</tr>
<tr>
<td>40%</td>
<td></td>
<td>0.309</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.714</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.357</td>
</tr>
</tbody>
</table>
4.2. Criteria
There are no specific criteria that are directly applicable to the numerical analysis.

4.3. Codes and Standards
There are no specific codes or standards that are directly applicable to the numerical analysis.

5. Assumptions
There are two assumptions in this analysis, the analysis was performed in 2D under plane strain conditions and the material model chosen was a linear elastic material model.

6. Analysis
The model used in this analysis was a six by six inch square cross-section. Rock mass properties without lithophysal cavities are designated matrix properties. Rock mass properties with lithophysal cavities are designated effective properties. Circular cavities were placed within the cross-section. The cross-section was then subjected to a vertical displacement and the resulting stresses and strains were computed by FLAC throughout the cross-section. Using the matrix elastic properties and the computed stresses and strains, the effective elastic properties could be calculated for the cross-section containing circular cavities. The effective elastic properties were calculated using Microsoft Excel.

FLAC output provides stresses and strains. From the stresses and strains, the effective Young's Modulus and Poisson's ratio can be calculated for the body containing cavities. To calculate Young's Modulus and Poisson's ratio, Hooke's law for plane strain conditions was used. These equations can be found in Timoshenko and Goodier (1987).

Free Sides Condition
For plane strain conditions and free sides boundary conditions, Hooke's law can be written as:

\[ \varepsilon_x = \frac{1}{E_m} \left[ (1 - v^2) \sigma_x - v (1 + v) \sigma_y \right] \]

\[ \varepsilon_y = \frac{1}{E_m} \left[ (1 - v^2) \sigma_y - v (1 + v) \sigma_x \right] \]
Rearranging the equations and solving for $E_{\text{eff}}$ and $v_{\text{eff}},$

$$E_{\text{eff}} = \frac{\left(\varepsilon_y \left(\sigma_y\right)^2 - 2 \varepsilon_x \left(\sigma_x\right)^2 + \sigma_x \varepsilon_x + \sigma_y \varepsilon_y - 2 \varepsilon_y \left(\sigma_x\right)^2 + \varepsilon_x \left(\sigma_x\right)^2\right)}{\left[\varepsilon_y - \varepsilon_x\right] \left[\varepsilon_x \sigma_x + \varepsilon_y \sigma_y - \varepsilon_x \sigma_y - \varepsilon_y \sigma_x\right]}$$

$$v_{\text{eff}} = \frac{-\left(-\varepsilon_y \sigma_x + \varepsilon_x \sigma_y\right)}{\left[\varepsilon_y \sigma_x + \varepsilon_y \sigma_y - \varepsilon_x \sigma_y - \varepsilon_y \sigma_x\right]}$$

**Fixed Sides Condition**

Hooke's Law for the case of confined sides can be written as follows:

$$0 = \frac{1}{E_m} \left[\left(1 - \nu^2\right)\sigma_x - \nu \left(1 + \nu\right)\sigma_y\right]$$

(Note that strain in the horizontal (X) direction is zero due to confined sides.)

$$\varepsilon_y = \frac{1}{E_m} \left[\left(1 - \nu^2\right)\sigma_y - \nu \left(1 + \nu\right)\sigma_x\right]$$

Rearranging the equations and solving for $E_{\text{eff}}$ and $v_{\text{eff}},$

$$E_{\text{eff}} = \frac{\left(\sigma_y\right)^2 + \sigma_x \sigma_y - 2 \left(\sigma_x\right)^2}{\varepsilon_y \left(\sigma_x + \sigma_y\right)}$$

$$v_{\text{eff}} = \frac{\sigma_x}{\left(\sigma_x + \sigma_y\right)}$$
7. Conclusions

Results of the numerical analysis are presented as graphs. The graphs comparing the ratio of $E_{eff}$ to $E_m$ are provided in Figures 2 through 7. The graphs comparing the ratio of $v_{eff}$ to $v_m$ are provided in Figures 8 through 13.

**Young's Modulus**

For all Poisson's Ratios, there is a decrease in Young's Modulus as porosity increases. At 5% lithophysal porosity, the ratio $E_{eff} / E_m$ is approximately 0.9 and at 40% lithophysal porosity, the ratio is approximately 0.4. There is a slight dependence on Poisson's Ratio: the higher the Poisson's Ratio, the greater the $E_{eff} / E_m$ ratio. At 5% lithophysal porosity, $E_{eff} / E_m$ is 0.9 ($v=0.1$) and 0.92 ($v=0.49$). Similarly, at 40% lithophysal porosity, $E_{eff} / E_m$ is 0.38 ($v=0.1$) and 0.45 ($v=0.49$). These trends hold true regardless of the boundary conditions (free or constrained sides).

**Constrained Sides Poisson's Ratio**

For a matrix Poisson's Ratio of 0.1, the effective Poisson's Ratio is always greater than the matrix Poisson's Ratio. The dependence on lithophysal porosity is clear. From 5 to 20%, the effective Poisson's Ratio increases. After 20% lithophysal porosity, the effective Poisson's Ratio decreases but is never lower than the matrix Poisson's Ratio. This behavior is seen in the 1-cavity, 9-cavity and 36-cavity analysis.

For a matrix Poisson's Ratio of 0.2, the effective Poisson's Ratio is greater than or equal to the matrix Poisson's Ratio for lithophysal porosities of 5 and 10%. At greater lithophysal porosities, the effective Poisson's Ratio is less than the matrix Poisson's Ratio. This behavior is seen in the 1-cavity, 9-cavity and 36-cavity analysis.

At higher matrix Poisson's Ratios, the effective Poisson's Ratio is always less than the matrix Poisson's Ratio. The largest value of effective Poisson's Ratio is at the lowest lithophysal porosity and the smallest value of effective Poisson's Ratio is at the highest lithophysal porosity. This behavior is seen in the 1-cavity, 9-cavity and 36-cavity analysis.

**Free Sides Poisson's Ratio**

For a matrix Poisson's Ratio of 0.1, the effective Poisson's Ratio is dependent upon the distribution of the lithophysal porosity. For cross-sections containing 1 cavity, the effective modulus increases linearly from 0.124 at 5% lithophysal porosity to 0.232 at 40% lithophysal porosity. For cross-sections containing 9 cavities, the effective modulus increases parabolically from 0.118 at 5% lithophysal porosity to 0.15 at 40% lithophysal porosity. For cross-sections containing 36 cavities, the effective modulus increases from 0.108 at 5% lithophysal porosity to a maximum of approximately 0.135 at 25% porosity and back down to 0.123 at 40% lithophysal porosity.
For a matrix Poisson's Ratio of 0.2, the effective Poisson's Ratio is dependent upon the distribution of the lithophysal porosity. For cross-sections containing 1 cavity, the effective modulus increases linearly from 0.208 at 5% lithophysal porosity to 0.261 at 40% lithophysal porosity. For cross-sections containing 9 cavities and 36 cavities, the effective modulus decreases parabolically from 5% lithophysal porosity to 40% lithophysal porosity. For cross-sections containing 9 cavities, the decrease is from 0.204 to 0.188. For cross-sections containing 36 cavities, the decrease is from 0.2 to 0.168.

For a matrix Poisson's Ratio of 0.3, the effective Poisson's Ratio for the cross-sections containing one cavity is approximately 0.29, regardless of the percentage of lithophysal cavities. For cross-sections containing 9 and 36 cavities, the effective Poisson's Ratio decreases with increasing lithophysal porosity.

For matrix Poisson's Ratios higher than 0.3, regardless of the lithophysal porosity distribution, the effective Poisson's Ratio decreases with increasing lithophysal porosity. The cross-section containing 1 cavity has the least decrease and the cross-sections containing 9 and 36 cavities have the same decreases in effective Poisson's Ratio.

8. Inputs, Outputs and References

Inputs and Outputs
The data tracking number (DTN) for this for the inputs and outputs supporting is analysis is UN0110MWD027MK.001.

References

9. Attachments
Not applicable. There are no documentation with this report that cannot be included in the text.
Figure 2. $E_{\text{eff}}/E_m$ for Poisson's Ratio 0.1

- 1 Hole - Free
- 9 Hole - Free
- 36 Hole - Free
- 1 Hole - Const.
- 9 Hole - Const.
- 36 Hole - Const.

Porosity (%)
Figure for Poisson's Ratio 0.2

Porosity (%)
Figure 4: $\frac{E_i}{E_m}$ for Poisson's Ratio 0.3

Porosity (%)
Figure 5: $E_{\text{eff}}/E_{\text{m}}$ for Poisson's Ratio 0.4

Porosity (%)
Figure 6. $E_{\text{eff}}/E_{\text{m}}$ for Poisson's Ratio 0.45
Figure 7: $E'/E_m$ vs. Porosity for Poisson's Ratio 0.49
Figure 8. $c_{nf}/v$ for Poisson Ratio 0.1
Figure 9. $V_{\text{eff}}/V_{\text{m}}$ for Poisson's Ratio 0.2.
Figure 10. $v_{\text{eff,m}}$ for Poisson's Ratio 0.3
Figure 11: $\frac{\varepsilon_{eff}}{\varepsilon_{m}}$ for Poisson's Ratio 0.4
Figure 12: V_{eff}^\gammam for Poisson's Ratio 0.45
Figure 13. $v_{\text{eff}}/v_m$ for Poisson's Ratio 0.49

- 1 Hole - Free
- 9 Hole - Free
- 36 Hole - Free
- 1 Hole - Fixed
- 9 Hole - Fixed
- 36 Hole - Fixed

Porosity (%)

$V_{\text{eff}}/V_m$

0 5 10 15 20 25 30 35 40 45 50