Alexandra Schuller

29689168

CIVI 437 – Advanced Geotechnical Engineering

Dr. Biao Li

Term Project

April 4, 2026

## 1. Introduction

The goal of this project is to analyze rock slope stability using the Hoek–Brown failure criterion and observe how differences in Geological Strength Index (GSI) can affect the slope stability. The analysis will consider intact rock at a GSI of 100, as well as a GSI of the same rock at 85. The Hoek-Brown criterion will be converted to the equivalent Mohr–Coulomb parameters and both evaluated in MATLAB. The analysis will also include an Abaqus simulation for the intact rock (GSI = 100).

The Hoek–Brown failure criterion is expressed as the equation below:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a$$

with

- $\sigma_1$= major principal stress at failure
- $\sigma_3$= minor principal stress
- $\sigma_{ci}$= uniaxial compressive strength (intact rock)
- $m_b, s, a$= Hoek–Brown parameters (depending on GSI)

The laboratory test results in question are from a slope site in northern Quebec. The results for the tests are displayed in Table 1 below. Other properties for the given sample include Poisson's ratio and young's modulus. The reduced Young's Modulus is 9020.55 Mpa.

*Table 1: Triaxial Test Results for Intact Rock Samples*

| **Number of Tests** | **x** | | **y** | **xy** | **$x^2$** | **$y^2$** |
|---|---|---|---|---|---|---|
| **n=5** | **$\sigma_3$** | **$\sigma_1$** | **$(\sigma_1 - \sigma_3)^2$** | **$\sigma_3$*$(\sigma_1 - \sigma_3)^2$** | **$\sigma_3^2$** | **$(\sigma_1 - \sigma_3)^4$** |
| **Units** | (MPa) | (MPa) | ($MPa^2$) | ($MPa^3$) | ($MPa^2$) | ($MPa^4$) |
| Specimen 1 | 0 | 38 | 1444.0 | 0 | 0.0 | 2085136.0 |
| Specimen 2 | 5 | 72 | 4489.0 | 22445 | 25.0 | 20151121.0 |
| Specimen 3 | 7 | 80 | 5329.0 | 37303 | 49.0 | 28398241.0 |
| Specimen 4 | 15 | 115 | 10000.0 | 150000 | 225.0 | 100000000.0 |
| Specimen 5 | 20 | 134 | 12996.0 | 259920 | 400.0 | 168896016.0 |
| Σ | 47 | 439 | 34258.0 | 469668 | 699.0 | 319530514.0 |

*Table 2: Given Properties*

| **Property** | **Unit** | **Value** |
|---|---|---|
| Unit weight | $kN/m^3$ | 26.1 |
| Poisson's ratio | — | 0.26 |
| Young's modulus | MPa | 9072 |

## 2. Methodology

### 2.1. Hoek-Brown to Mohr Coulomb Conversion

Using Excel, the intact uniaxial compressive strength was calculated as $\sigma_{ci} = 38.15$ Mpa. In addition, the intact material constant was determined as $m_i = 15.05$. Using $\sigma_{3,\max}$ as 20 MPa, $\sigma_{3n}$ was found to be 0.524. For GSI = 100, see Table 5 for the calculated Hoek–Brown parameters and Table 6 for the Mohr-

Coulomb conversion. The results show that decreasing GSI reduces both the cohesion and friction angle, making a weaker rock mass and thus a lower expected slope stability.

*Table 3: Derived Intact Rock Parameters*

| | |
|---|---|
| $\sigma^2_{ci}$ (Mpa$^2$) | 1455.6 |
| $\sigma_{ci}$ (Mpa) | 38.15 |
| $m_i$ | 15.05 |

*Table 4: Normalizing Confining Stress Parameters*

| | |
|---|---|
| $\sigma_3$,max (Mpa) | 20 |
| $\sigma_3$,n | 0.524208214 |

*Table 5: Hoek-Brown Rock Mass Parameters for Different GSI values*

| Parameter | GSI 100 | GSI 85 |
|---|---|---|
| $m_b$ | 15.046 | 5.153 |
| **s** | 1.000 | 0.036 |
| **a** | 0.500 | 0.501 |

*Table 6: Equivalent Mohr-Coulomb Parameters for GSI 100 and 85*

| **Parameter** | **GSI = 100** | **GSI = 85** |
|---|---|---|
| **φ′** | 41.97 | 33.74 |
| **c′** | 9.04 | 4.66 |

## 2.2. Abaqus Simulation for Intact Rock Behavior

Based on the Mohr–Coulomb parameters, an Abaqus 3D mechanical analysis was performed for an intact rock sample. Abaqus creates a finite element model to simulate the slope behavior. The principal stress contours on the sample can be seen in the next results section.

## 2.3. MATLAB Slope Stability Analysis

The converted parameters were input into the provided MATLAB script, and the slope stability analysis was performed twice, once for GSI = 100, and once for GSI = 85.

The results obtained from the MATLAB simulations were then compared to assess the influence of GSI on slope stability and rock mass behavior. The results and figures from these analyses can be seen in the next section.

## 3. Results

### 3.1. Abaqus

Please see the appendix for more screenshots of the principal stresses from the Abaqus simulation.

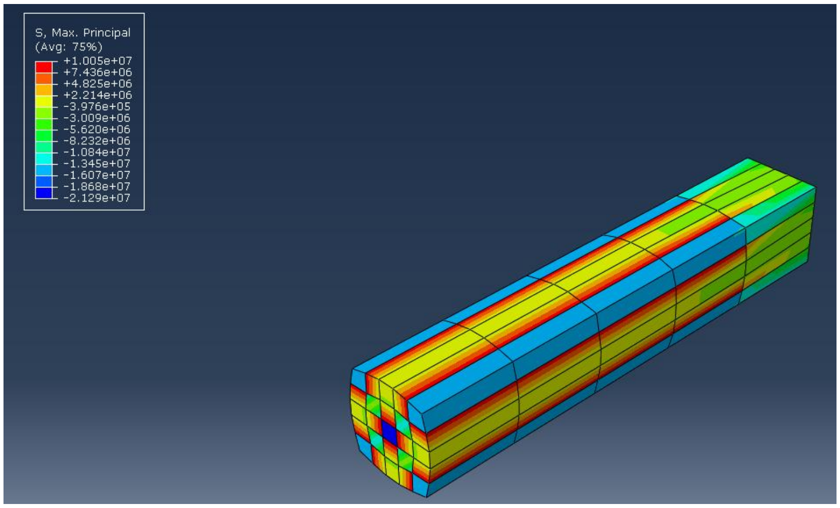


*Figure 1: Max Principal Stresses*

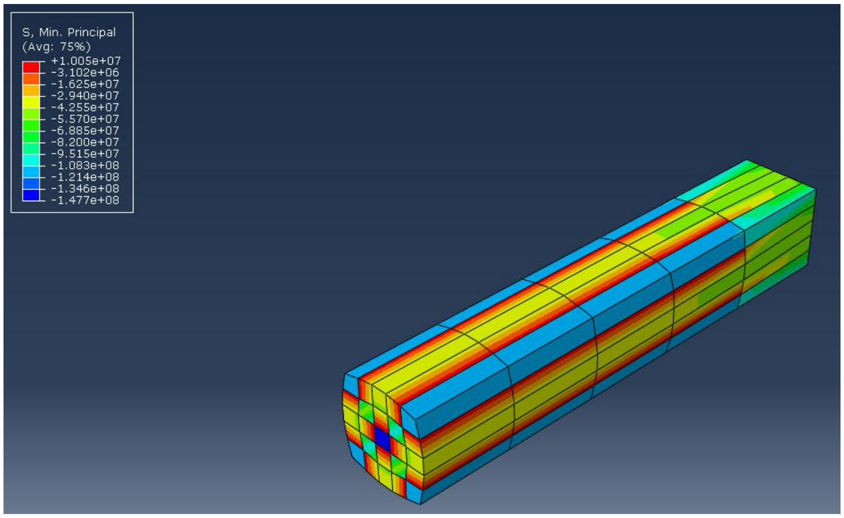


*Figure 2: Min Principal Stresses*

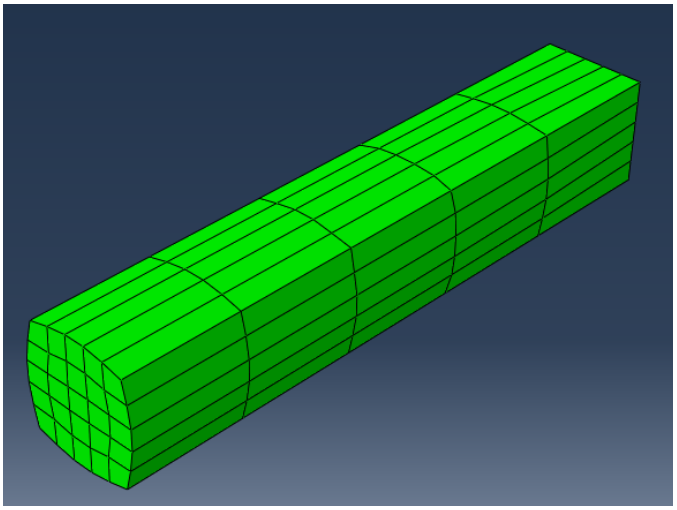

*Figure 3: Deformed Shape*

## 3.2. Matlab

### 3.2.1. GSI = 100

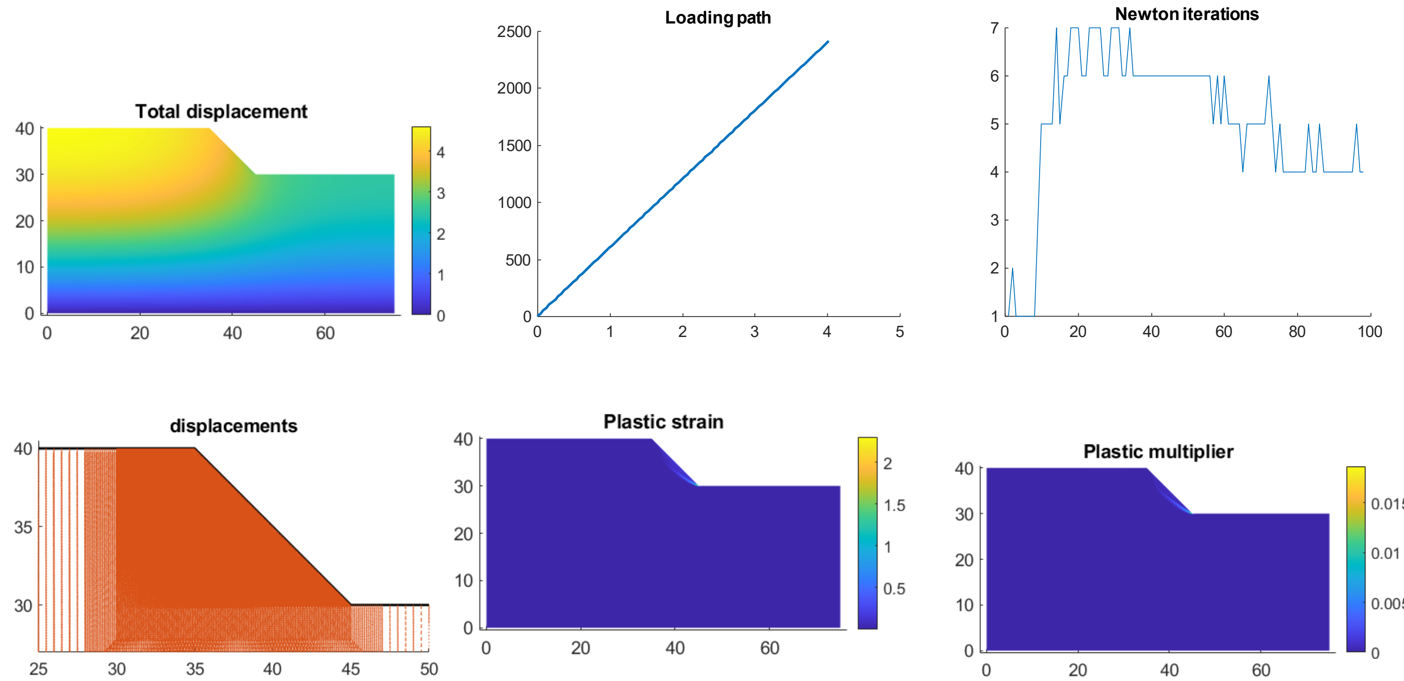


*Figure 4: MATLAB Generated Figures for GSI = 100*

### 3.2.2. GSI = 85

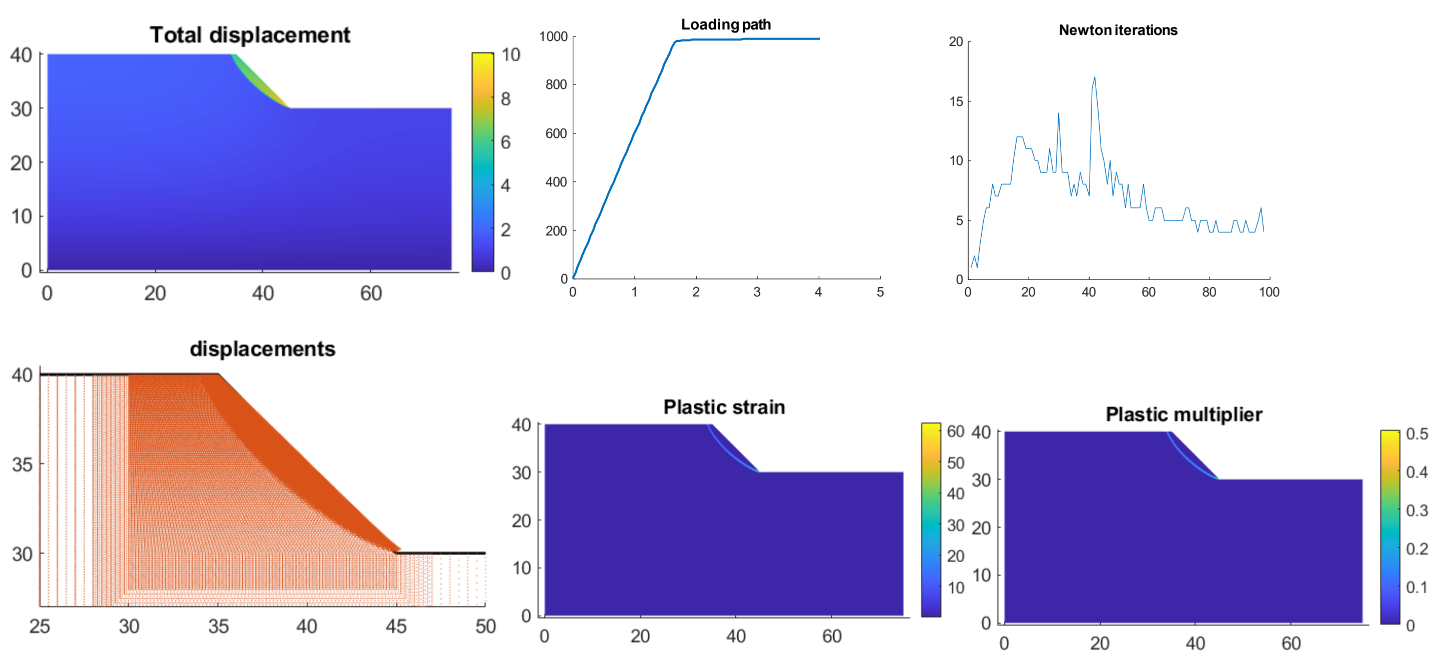


*Figure 5: MATLAB Generated Figures for GSI = 85*

The results compare intact rock with reduced rock mass quality (GSI = 85). As GSI decreases, both cohesion and friction angle get smaller, making a weaker rock mass. MATLAB shows that the decreased stability for a GSI of 85, and the Abaqus simulation confirmed realistic rock behavior.

## 4. Discussion

As the GSI decreased from 100 to 85, the friction angle decreased by 8.23° (from 41.97° to 33.74°). The cohesion reduced to almost half, from 9.04 MPa to 4.66 MPa. Thus, these reductions indicate weaker rock mass. These directly influence the stability of the slope.

GSI 100 shows minimal displacement and negligible plastic deformation, indicating stable conditions. On the other hand, GSI 85 shows more displacement and plastic strain near the slope surface, which means more failure zones.

These results show again, that reducing GSI both reduces shear strength and increases deformation, both affecting a reduced slope stability. Thus, realistic rock parameters should be used when making engineering calculations for slopes.

## 5. Conclusion

The key takeaways are that reducing GSI reduces friction angle and cohesion, which weaken rock mass and decrease slope stability. A key objective of this project was to learn how to simulate a finite element model in Abaqus, which was accomplished. A model cannot represent reality 100%, however it is very important to use realistic rock data when performing slope stability analysis in order to model the most realistic behavior of rock since errors in using GSI 100 can be great and cause harm.

## 6. Appendix

Please see the following tables and figures related to calculation and process.

*Table 7: Excel Formulas for Calculations (1)*

| **Parameter** | **Excel Formula** |
|---|---|
| **φ′** | =DEGREES(ASIN((6*I26*I24*(I25+I24*I15)^(I26-1)) / (2*(1+I26)*(2+I26)+6*I26*I24*(I25+I24*I15)^(I26-1)))) |
| **c′** | =(F15*((1+2*I26)*I25+(1-I26)*I24*I15)*(I25+I24*I15)^(I26-1))/((1+I26)*(2+I26)*SQRT(1+(6*I26*I24*(I25+I24*I15)^(I26-1))/((1+I26)*(2+I26)))) |

*Table 8: Excel Formulas for Calculations (2)*

| | |
|---|---|
| **$\sigma^2_{ci}$ (Mpa$^2$)** | =(H11/F1)-((F11/F1)*(I11-(F11*H11/F1))/(J11-((F11^2)/F1))) |
| **$\sigma_{ci}$ (Mpa)** | =SQRT(F14) |
| **$m_i$** | =(1/F15)*(I11-(F11*H11/F1))/(J11-((F11^2)/F1)) |

*Table 9: Excel Formulas for Calculations (3)*

| **Parameter** | **GSI 100** | **GSI 85** |
|---|---|---|
| **$m_b$** | =F16*EXP((G22-100)/(28)) | =F16*EXP((H22-100)/(28)) |
| **s** | =EXP((G22-100)/(9)) | =EXP((H22-100)/(9)) |
| **a** | =0.5 + (1/6)*(EXP(-G22/15) - EXP(-20/3)) | =0.5 + (1/6)*(EXP(-H22/15) - EXP(-20/3)) |

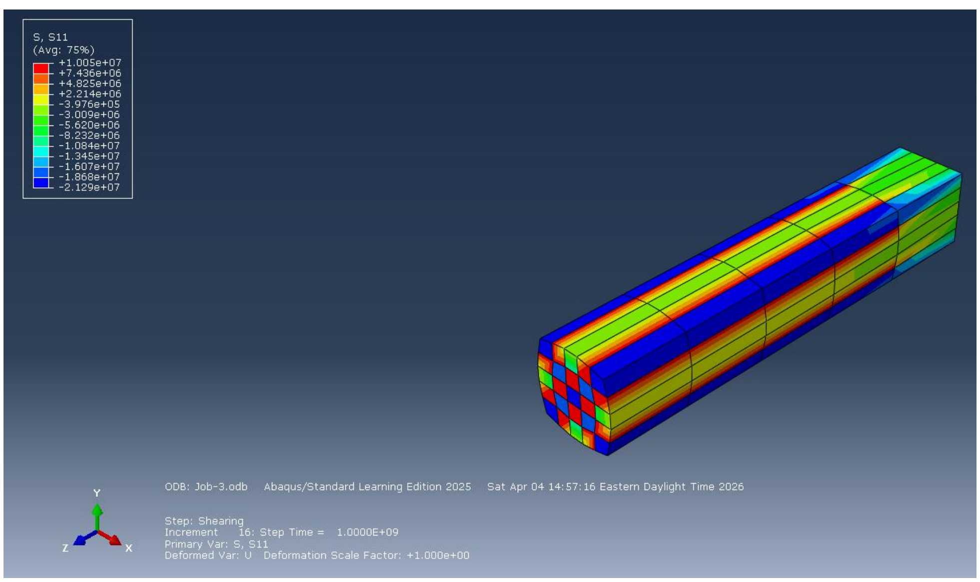


*Figure 6: S11*

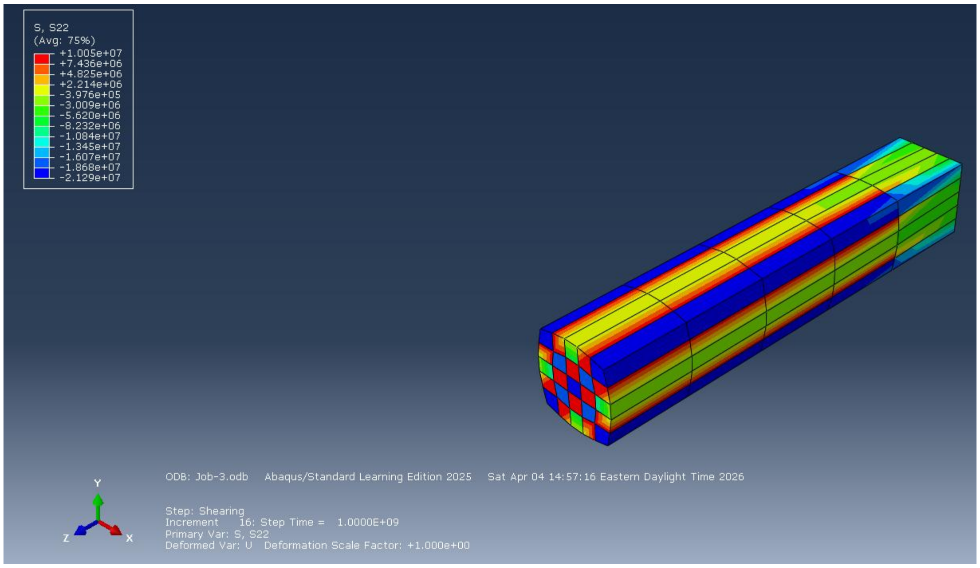


*Figure 7: S22*

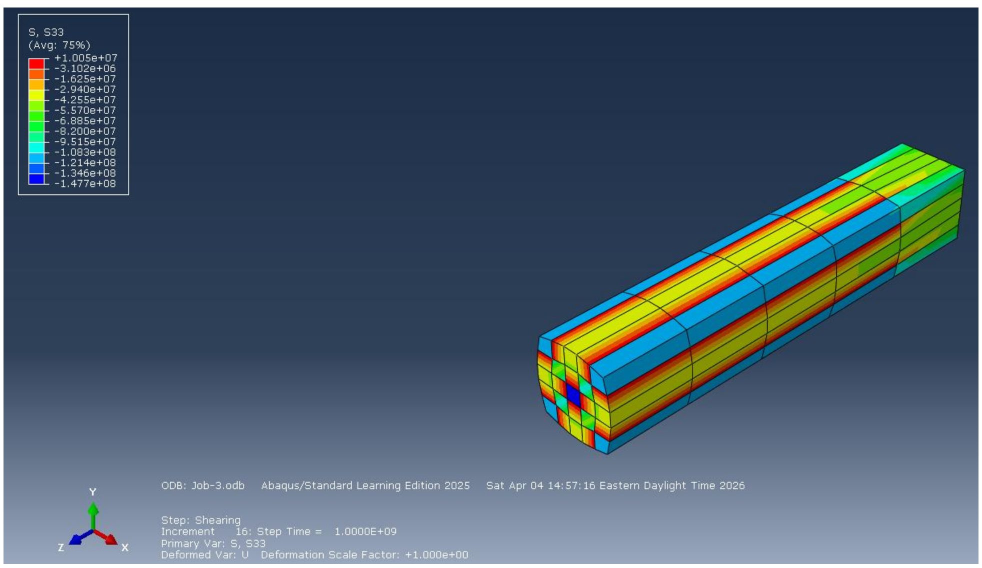


*Figure 8: S33*

```
Command Window
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Warning: Maximal settlement at the point A was achieved.
> In loading_process (line 143)
Computational time: 541.594 sec.
>>
```

*Figure 9: Steps for GSI = 100*

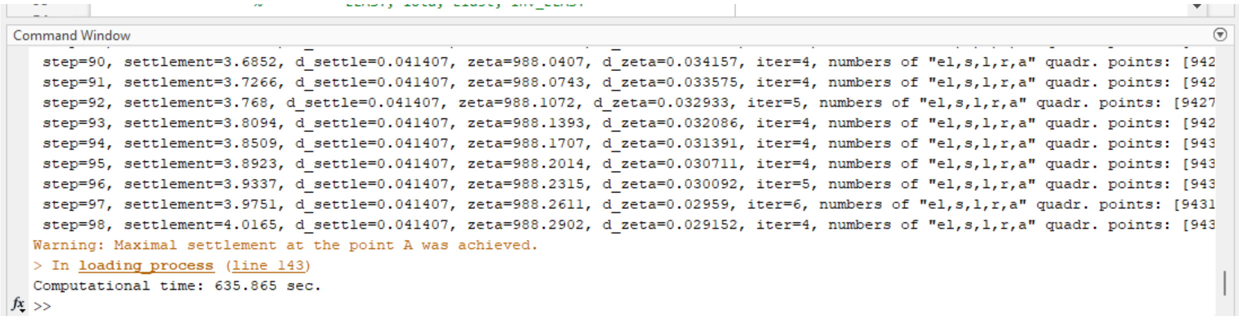


*Figure 10: Steps for GSI = 85*

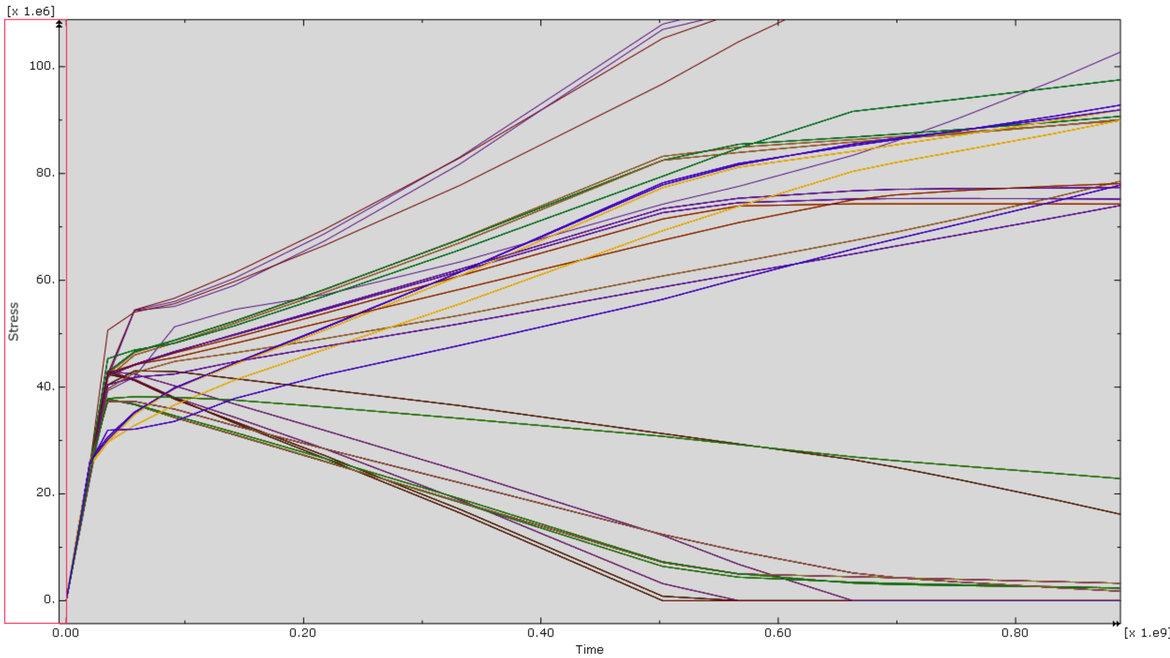


*Figure 11: Stress-Strain curves for all nodes*

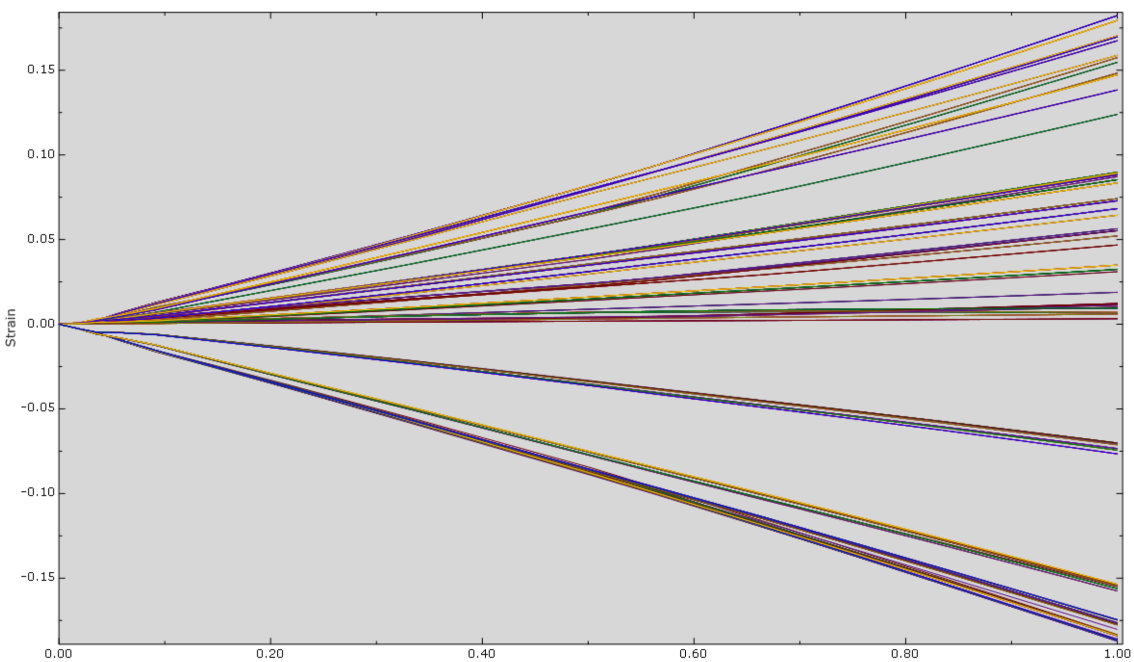


*Figure 12: Volumetric strain curve for all nodes*