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GeoStudio Example File
Triaxial Tests on Hyperbolic Soil

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Introduction

This example simulates a series of triaxial tests that can be used to verify that the Hyperbolic constitutive model is functioning properly. The simulations include:

1. Consolidating the sample to an initial isotropic stress state;
2. Drained strain-controlled tests;
3. A load-unload-reload test;
4. An extension test;
5. An undrained strain-controlled test; and
6. Consolidation at anisotropic stress conditions.

The verification includes comparisons with hand-calculated values and discussions relative to the Hyperbolic theoretical framework.

Background

The hyperbolic constitutive model is, in essence, a linear-elastic formulation, but the Young's Modulus E_t is a function of the shear stress level in the soil as described by:

$$E_t = \left[1 - \frac{R_f(\sigma_1 - \sigma_3)(1 - \sin\phi)}{2c(\cos\phi) + 2\sigma_3 \sin\phi}\right]^2 E_i$$

Equation 1

where E_i is the stiffness modulus when the soil is in an isotropic state; that is, there is no shear stress, ϕ is the soil friction angle, c is the soil cohesion, and R_f is a parameter controlling how close the stress-strain curve comes to the shear strength. The term $(\sigma_1 - \sigma_3)(1 - \sin\phi)$ represents the shear stress level. The term $2c(\cos\phi) + 2\sigma_3 \sin\phi$ represents the shear strength of the soil. Therefore, when $(\sigma_1 - \sigma_3)(1 - \sin\phi)$ divided by $2c(\cos\phi) + 2\sigma_3 \sin\phi$ is 1.0 or greater, it means that the shear stress is at the shear strength. If this ratio is computed as being greater than 1.0, SIGMA/W sets the ratio to 1.0.

When the shear stress is at the shear strength, then the tangent modulus is:

$$E_t = [1 - R_f(1.0)]^2 E_i$$

Equation 2

If, for example, R_f is 0.9, E_t then is 0.01 E_i or 100th of E_i, when the shear stress is at the shear strength. If R_f is 0.7, then E_t is 0.09 E_i. In other words, the higher the R_f values, the closer E_t is allowed to come to zero. R_f values also affect the shape of the stress-strain curve – higher R_f values result in stress-strain curves with a sharper bend than lower R_f values.

In addition to the specified R_f value, SIGMA/W controls the minimum E_t relative to the atmospheric pressure. SIGMA/W does not allow E_t to fall below 10% of the atmospheric pressure value. The reason for arbitrarily restricting the minimum E_t value is to reduce the possibility of encountering convergence difficulties.

E_i is a user defined constant, or a user-defined function, relative to the vertical effective stress in the ground.

Numerical Simulation

Figure 1 shows the problem configuration for all analyses in the example. The Analysis Tree includes three "Parent" analyses for each of the example scenarios (Figure 2). All analyses fix the left boundary in the x-direction and the bottom boundary in the y-direction. Symmetry is assumed about the vertical and horizontal centre-lines; consequently, only ¼ of the specimen is simulated. The dimensions of the simulation portion of the specimen are 0.025 m by 0.05 m, which is half of the width and height of a conventionally sized triaxial specimen. Only four elements are simulated in each of the analyses.

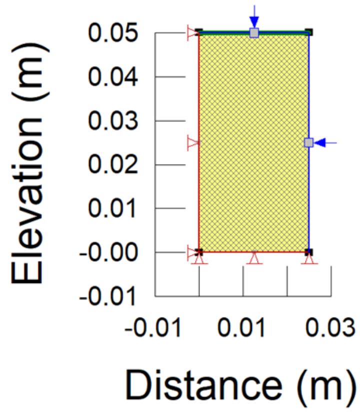

Figure 1. Problem configuration.

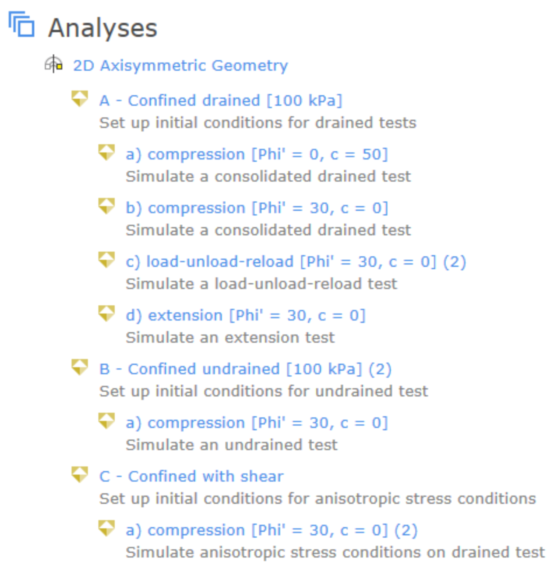

Figure 2. Analysis Tree for the Project.

Analysis A simulates consolidating the sample to an isotropic confining stress of 100 kPa. This analysis will become the "Parent" or initial condition for four subsequent tests: a) Phi' = 0, c = 50; b) Phi' = 30, c=0; c) load-unload-reload; and, d) extension.

The stress state is induced by applying a normal stress on the top and on the right side of the sample (Figure 1). Notice that Isotropic Elastic parameters are used when setting up confining stresses; non-linear models are not required for this and the value of E is not relevant.

The first subsequent "child" analysis (Analysis A-a) simulates a drained test on a cohesive material that has a ϕ = 0 degrees and c = 100 kPa. The second "child" analysis (Analysis A-b) is a drained test on a frictional material that has a ϕ = 30 degrees and c = zero. The third "child" analysis (Analysis A-c) examines the behavior of the frictional soil under loading, unloading, and then reloading (Figure 3). Lastly, the fourth "child" analysis simulates an extension test on the same frictional soil. The extension test is simulated by pulling upward on the sample at a total of 0.003 m for the simulation.

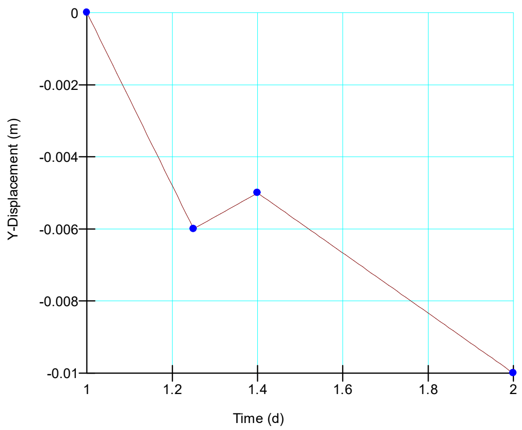

Figure 3. Loading-unloading function.

For a purely frictional soil, the principal stress ratio at the point where the stress level reaches the soil strength is:

$$\frac{\sigma_1}{\sigma_3} = \frac{1 + \sin\phi}{1 - \sin\phi}$$

Equation 3

which is equal to 3 if ϕ is 30 degrees.

Analysis B and Analysis B-a) simulate the initial conditions and frictional case for undrained conditions, respectively. The soil parameters are the same as Analysis A-b), except that the response type is changed to Undrained. Similar to Analysis A, the initial consolidated effective confining stress state is established by applying a normal stress of 100 kPa on the top and on the right side of the sample.

Analysis C and C-a) simulate the scenario with a confining initial shear. The initial tangent modulus E_i is affected by the initial shear stress state in the soil. We can demonstrate and confirm this by simulating a triaxial test consolidated to an anisotropic stress condition. In this case, the initial state of stress is induced by applying 100 kPa normal stress at the top and 50 kPa on the right side (Figure 4).

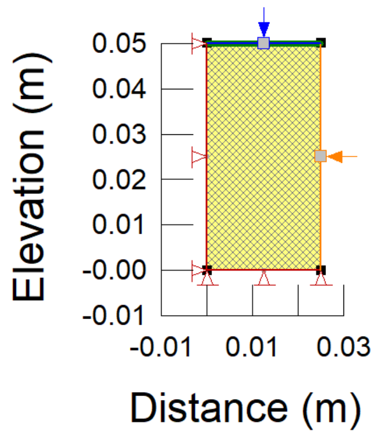

Figure 4. Configuration for anisotropic consolidation (stress state) in Analysis C-a).

Results and Discussion

Analysis A-a) – Confined Drained (c = 100 kPa)

In Analysis A-a), the maximum vertical stress when the sample is at its shear strength should be 300 kPa.

$$\tau_{max} = \frac{(\sigma_1 - \sigma_3)}{2}$$ Equation 4

The horizontal stress, σ_3, is 100 kPa, since this a confined test, making the τ_{max} (Equation 4) equal to 100 kPa. Therefore, σ_1 (vertical stress) at failure should be 200 kPa.

Figure 5 shows the SIGMA/W stress-strain curve. The final strain is 0.3 (30%), as specified for this analysis, and the maximum vertical stress approaches 300 kPa. The deviatoric stress curve is shown in Figure 6, where the maximum deviatoric stress approaches 200 kPa.

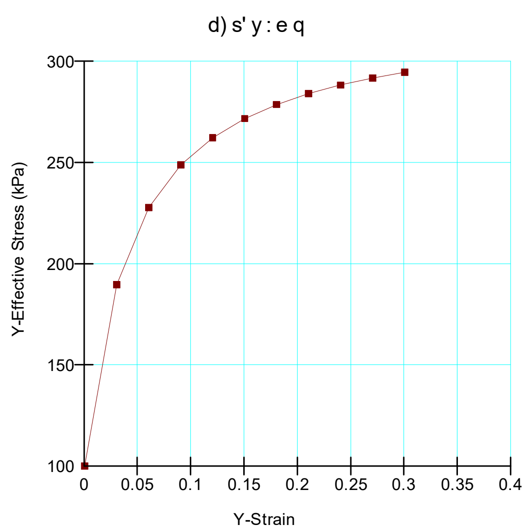

Figure 5. Vertical effective stress for confined test on cohesive soil.

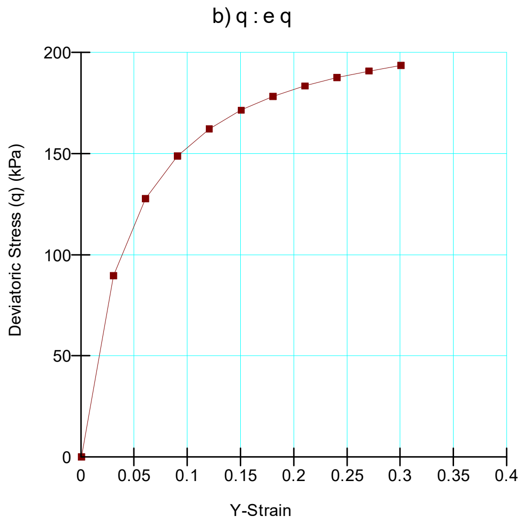

Figure 6. Deviatoric stress for confined test on cohesive soil.

Analysis A-b) – Confined Drained (Phi = 30, c = 0)

In Analysis A-b), the confining stress (σ_3) is 100 kPa. Therefore, σ_1 at failure should approach 300 kPa (Figure 7). Note the starting stress is 100 kPa and migrates to 300 kPa.

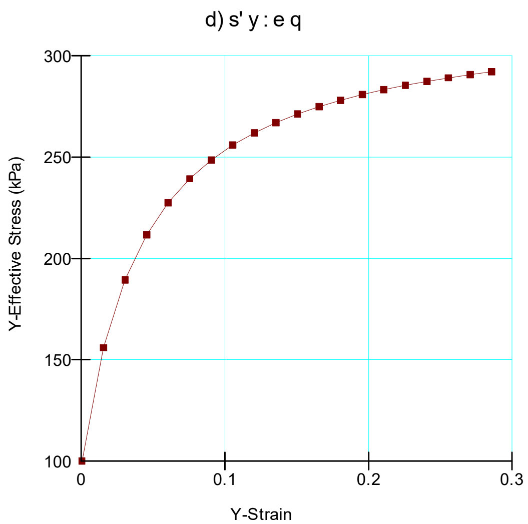

Figure 7. Vertical stress for confined test on frictional soil.

Analysis A-c) –Load-unload-reload

The behavior simulated in Analysis A-c) is the same as discussed above, and is as intended in the SIGMA/W formulation (Figure 8).

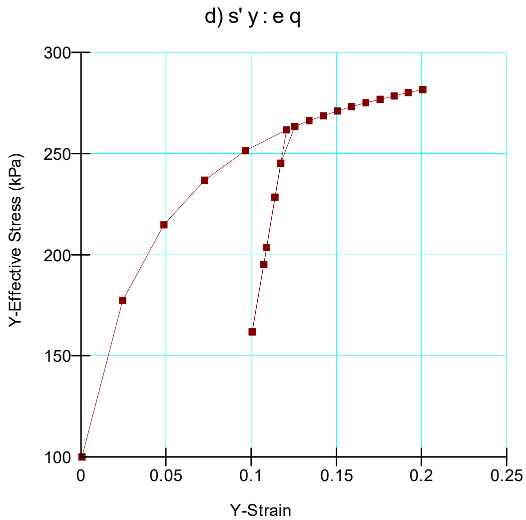

Figure 8. Loading, unloading, and reloading on frictional soil.

Analysis A-d) – Extension

In the extension case (Analysis A-d), the confining stress is 100 kPa and is the major principal stress, σ_1. The vertical stress is the minor principal stress, σ_3. Therefore, σ_3 at failure should approach 33.3 kPa (Figure 9). Note the starting stress is 100 kPa, and then drops to approximately 33.3 kPa.

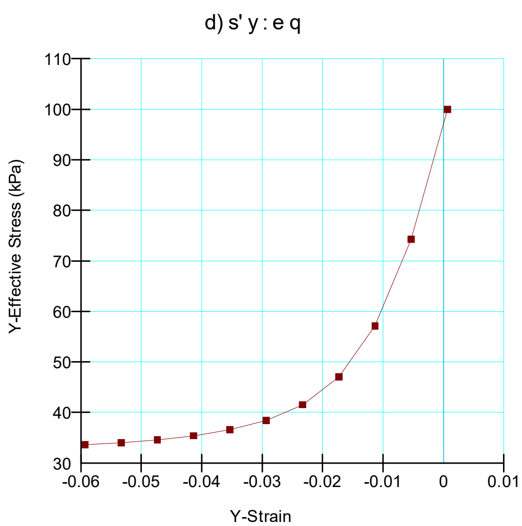

Figure 9. Unloading extension test.

The deviatoric stress at failure should be 100 – 33.3 = 67.7 kPa, as indicated in Figure 10.

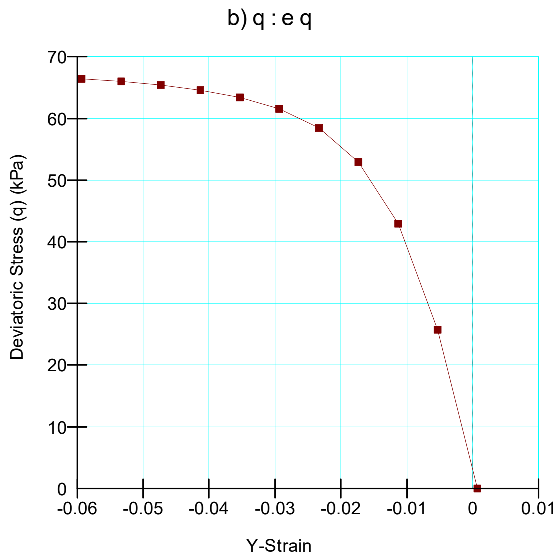

Figure 10. Deviatoric stress for extension test.

Analysis B – Confined undrained test

Figure 11 shows the effective stress versus strain curve for Analysis B-a). The effective stress starts at the initial effective confining stress of 100 kPa, and the final Y-effective stress approaches 180 kPa. The deviatoric stress at failure will be 120 kPa, which is confirmed in Figure 12.

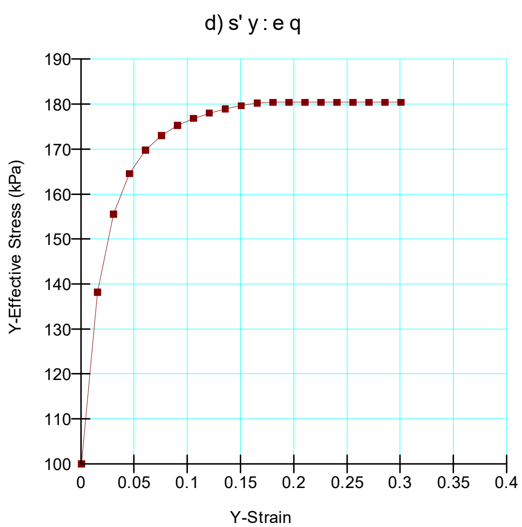

Figure 11. Effective stress-strain curve for undrained test.

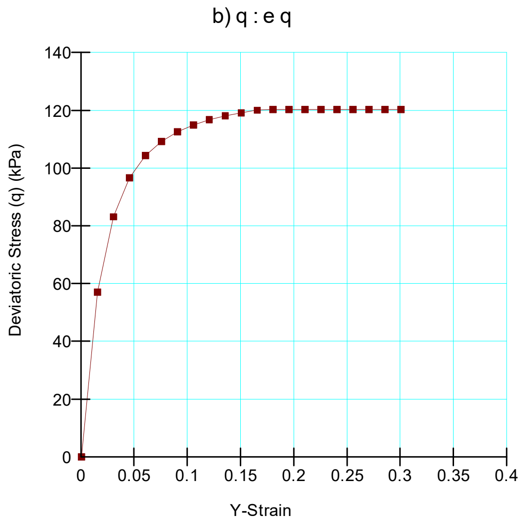

Figure 12. Deviatoric stress for undrained test.

Analysis C – Confined with shear

Figure 13 shows the effective stress versus strain curve for Analysis C-a). The effective stress starts at the initial effective confining stress of 100 kPa, and the final Y-effective stress approaches 150 kPa. In this analysis, σ_1 = 100 kPa and σ_3 = 50 kPa, and the initial deviatoric stress is 50 kPa (Figure 14). The final deviatoric stress is 100 kPa.

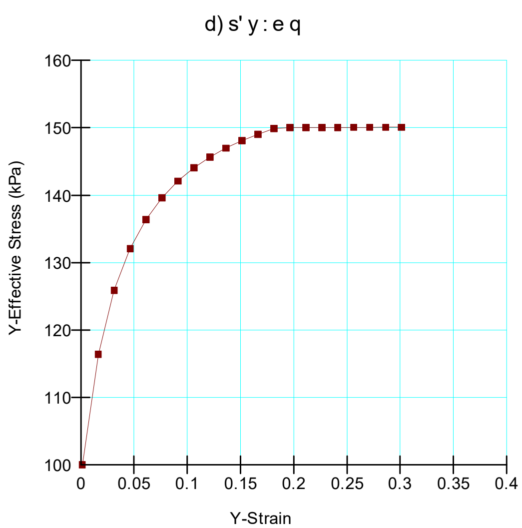

Figure 13. Effective stress-strain curve for Analysis C-a).

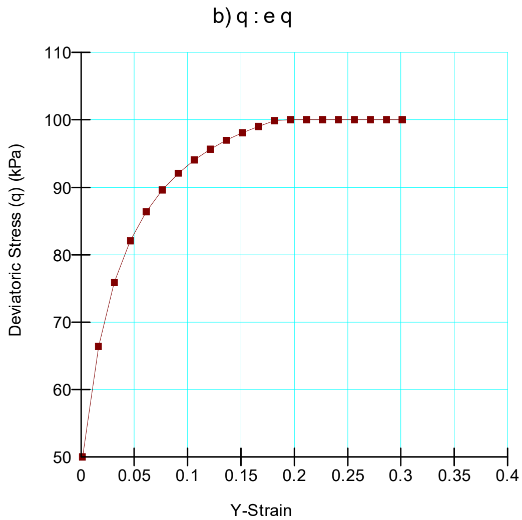

Figure 14. Deviatoric stress starting at an elevated level.

Summary and Conclusions

These triaxial test simulations verify that the hyperbolic constitutive relationship in SIGMA/W is functioning and behaving correctly.