GeoStudio Example File
Triaxial tests on Modified Cam-Clay soil

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Introduction

This example simulates a series of triaxial tests which can be used to verify that Modified Cam-Clay constitutive model is functioning properly. The simulations include:

1. Consolidating the sample to an initial isotropic stress state;
2. A drained strain-controlled test;
3. An undrained test on overconsolidated soil;
4. An undrained strain-controlled test; and
5. A load-unload-reload test.

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

Numerical Simulation

The problem configuration for the example is shown in Figure 1. The simulated shearing phases are preceded by the simulation of the consolidation phase of a triaxial test (Figure 2). Consolidation is isotropic with the confining pressure equal to 100 kPa and 150 kPa in Analyses A/C and Analysis B, respectively. The isotropic stress state is simulated by applying a normal stress on the top and on the right side of the sample equal to 100 kPa or 150 kPa. The consolidation stage is set as the “Parent”; that is, the initial condition for the subsequent simulations involving shearing.

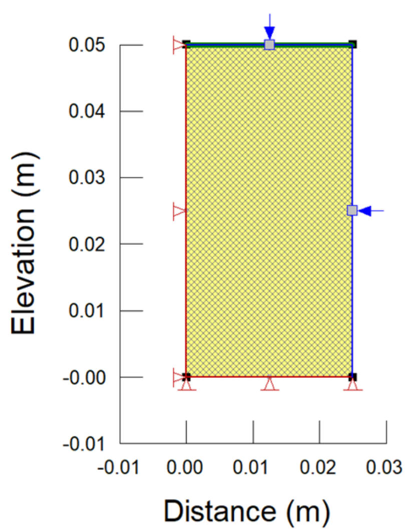

Figure 1. Triaxial test configuration for establishing initial stress state.

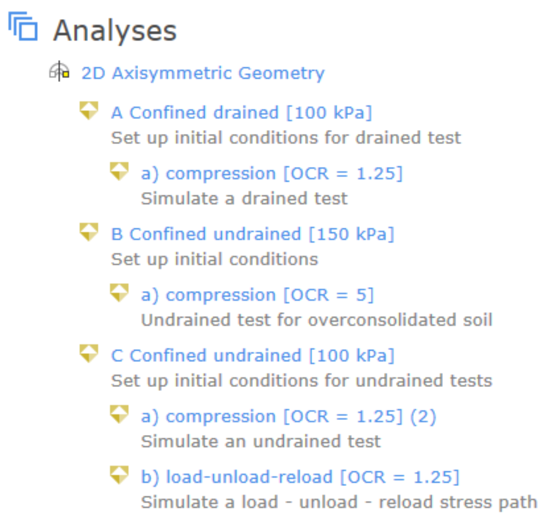

Figure 2. Analysis Tree for the Project.

The shearing phase of the analysis is simulated as a strain-rate controlled test. The definition of the strain-rate involves defining the number of ‘time’ steps and the displacement that occurs over each step. Although the ‘time’ steps are being defined, it is more appropriate to think of the time steps as load steps. Absolute time has no meaning in the context of these analyses. The number of load steps defined in the shear stage simulations is generally 50. The y-displacement function has been defined to decrease a total of -0.02 m over the load steps, where the negative sign indicates downward displacement.

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. Total vertical y-displacements of 0.02 m produce axial strains of 0.4 (or 40%).

All analyses use the Load/Deformation analysis type. The first “Parent” and “child” analyses simulate a drained test, considering the initial conditions with the confining pressure of 100 kPa (Analysis A). 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.

In Analysis A-a), the material has a ϕ of 25.6 degrees and an OCR of 1.25. A ϕ of 25.6 is equivalent to an Mc value of 1.0.

The first step in using the Cam-clay models is to establish the yield surface created sometime in the past under some particular stress state condition. In the field, this would be some past *in situ* condition. This is referred to as the past or initial yield surface.

SIGMA/W uses the initial vertical stress specified, together with a specified ϕ value and a specified OCR (over-consolidation ratio) value, to establish the past or starting yield surface.

The initial confining stress is 100 kPa. The past vertical effective stress then is:

$$\sigma_y' = 100 \times OCR = 100 \times 1.25 = 125\ kPa$$ **Equation 1**

$$K_o = 1 - \sin\phi = 1 - 0.45 = 0.55\ (formula\ in\ SIGMA/W\ code)$$ **Equation 2**

$$\sigma_x' = \sigma_z' = 125 \times 0.55 = 68.69\ kPa$$ **Equation 3**

$$\sigma'_{mean} = \frac{(125 + 68.69 + 68.69)}{3} = 87.46\ kPa$$ Equation 4

The shear stress, q, at the past mean stress is:

$$q = \frac{1}{\sqrt{2}}\sqrt{(\sigma_y - \sigma_x)^2 + (\sigma_z - \sigma_y)^2 + (\sigma_x - \sigma_z)^2} = 56.31\ kPa$$ Equation 5

This is one point on the yield surface created by the past stresses. Since the sample is slightly over-consolidated, the past stress state was higher than the current stress state. Currently, the sample is isotropically consolidated to 100 kPa ($\sigma'_x = \sigma'_y = \sigma'_z$).

The past maximum-mean stress (pre-consolidation pressure) is:

$$p'_c = \frac{1}{M^2 \times p'}(q^2 + M^2 p^2) = \frac{1}{1^2 \times 87.46}(56.31^2 + 1^2 87.46^2) = 123.71\ kPa$$ Equation 6

p'_x is at the center of the yield surface where q is at its maximum value on the initial yield surface; p'_x = 123.71 / 2 = 61.86 kPa.

Now that p'_c is known, we can draw the initial yield surface for an assumed range of p' values between 0 and p'_c using the equation:

$$q = \sqrt{M^2 p'_c p' - M^2 p'^2}$$ Equation 7

Figure 3 shows the initial or past yield surface. The three mean stresses computed above are marked on the diagram. The maximum q value occurs where the yield surface passes through the CSL (critical state line), as it properly should.

The q_{past} and p'_{past} values form the starting point for establishing the initial yield surface.

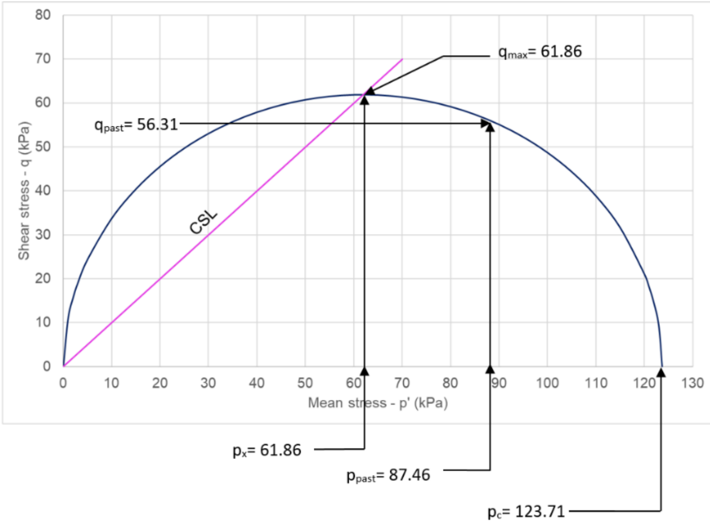

Figure 3. Initial yield surface for the past stresses at OCR = 1.25 (produced in EXCEL).

In the second set of analyses (Analysis B), the sample is subjected to a cell pressure of 150 kPa. The cell pressure is simulated with normal stress boundary conditions equal to 150 kPa. The next step is to simulate a consolidated undrained test for an over-consolidated soil (Analysis B-a).

With an initial effective confining stress at 150 kPa, the past vertical effective stress is:

$$\sigma_y^{'} = 150 \times OCR = 150 \times 5 = 750\ kPa$$ **Equation 8**

$$K_o = 1 - \sin\phi = 1 - 0.45 = 0.55\ (formula\ in\ SIGMA/W\ code)$$ **Equation 9**

$$\sigma_x^{'} = \sigma_z^{'} = 750 \times 0.55 = 412.17\ kPa$$ **Equation 10**

$$\sigma_{mean}^{'} = \frac{(750 + 412.17 + 412.17)}{3} = 524.78\ kPa$$ **Equation 11**

The shear stress q at the past mean stress is:

$$q = \frac{1}{\sqrt{2}}\sqrt{(\sigma_y - \sigma_x)^2 + (\sigma_z - \sigma_y)^2 + (\sigma_x - \sigma_z)^2} = 337.83\ kPa$$ **Equation 12**

This is one point on the yield surface created by the past stresses. Since the sample is slightly over-consolidated, the past stress state was higher than the current stress state. Currently, the sample is isotropically consolidated to 150 kPa ($\sigma_x^{'} = \sigma_y^{'} = \sigma_z^{'}$).

The past maximum-mean stress (pre-consolidation pressure) is:

$$p_c^{'} = \frac{1}{M^2 \times p^{'}}(q^2 + M^2 p^2) = \frac{1}{1^2 \times 524.78}(337.83 + 1^2 524.78^2) = 742.26\ kPa$$ Equation 13

$p_x^{'}$ is at the center of the yield surface where q is at its maximum value on the initial yield surface; $p_x^{'}$ = 742.26 / 2 = 371.13 kPa.

Now that $p_c^{'}$ is known, we can draw the initial yield surface for an assumed range of p' values between 0.0 and $p_c^{'}$ using the equation,

$$q = \sqrt{M^2 p_c^{'} p^{'} - M^2 p^{'2}}$$ Equation 14

Figure 6 shows the initial or past yield surface. The three $p^{'}$ stresses computed above are marked on the diagram. The maximum q value occurs where the yield surface passes through the CSL (critical state line) as it properly should.

The q_{past} and $p_{past}^{'}$ values form the starting point for establishing the initial yield surface.

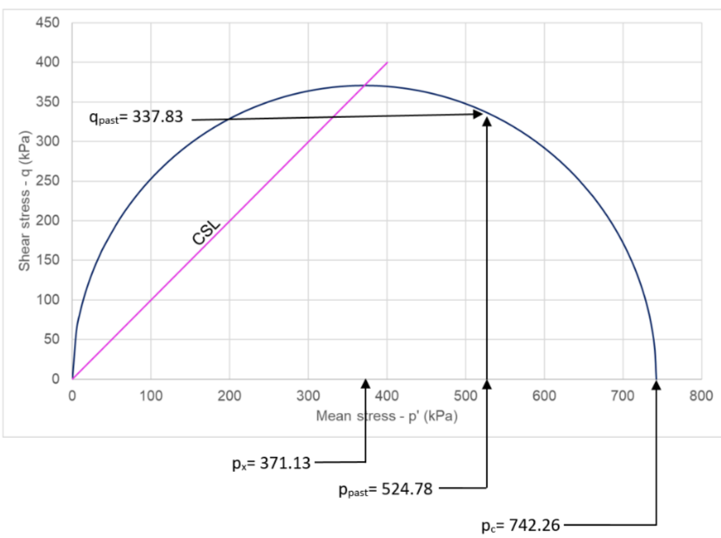

Figure 6. Initial yield surface for OCR = 5.

The third set of “Parent” and “child” analyses consider an undrained test (Analysis C), with the same confining stress of 100 kPa as the first set of analyses. The first “child” analysis uses similar material parameters as Analysis A-a); however, the response type has been changed to simulate undrained conditions.

In the last “child” analysis, Analysis C-b), the previous analysis is repeated, but the sample is loaded, then unloaded, and then reloaded. The top of the sample is pushed down, pulled up, and then pushed down according to the function in Figure 5.

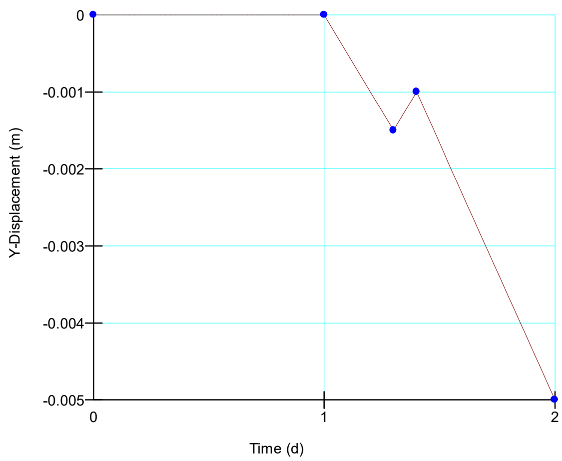

Figure 5. Load-unload-reload boundary condition for Analysis C-b).

Results and Discussion

Analysis A-a) – Drained-load deformation

During drained loading, the yield surface continues to increase in size (Figure 7). The total stress path (which is equal to the effective stress path in this case) on a $q - p'$ plot for a triaxial test will have a slope of 1h:3v. This being the case, the stress path intersects the CSL at 150 kPa.

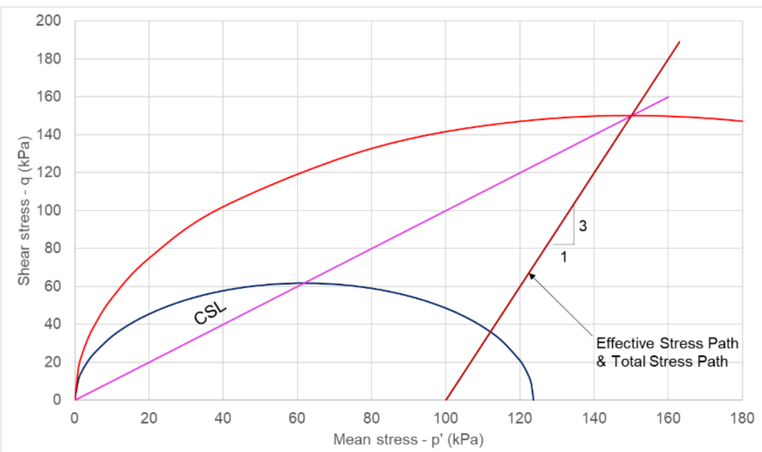

Figure 7. Total stress path and final yield surface under drained loading.

The final deviatoric stress (q) will be 150 kPa (Figure 8). The final vertical (y) stress will be the confining stress plus the deviatoric stress; that is, 100 + 150 = 250 kPa (Figure 9).

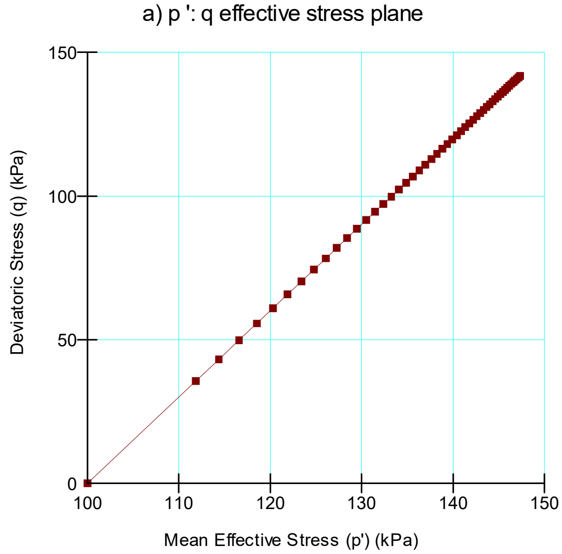

Figure 8. Stress path under drained loading.

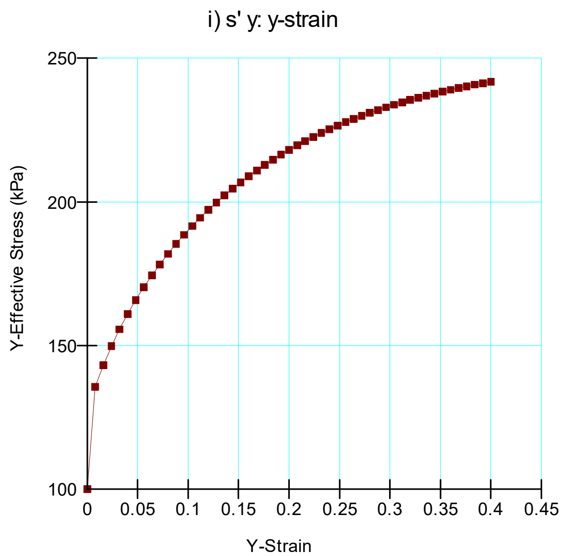

Figure 9. Vertical stress versus vertical strain.

Moreover, this being a drained test, the sample will undergo some volumetric strain (Figure 10).

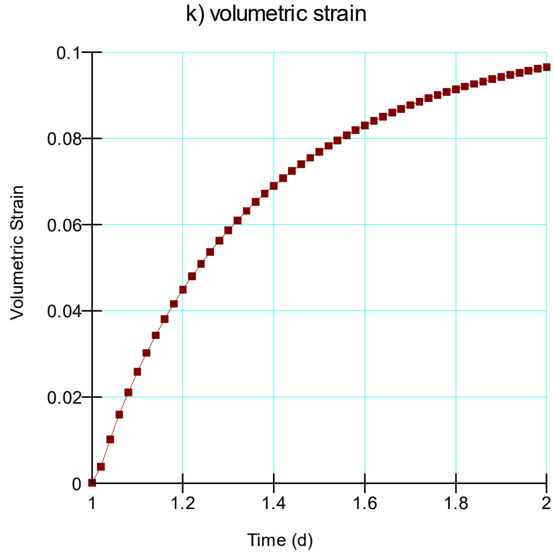

Figure 10. Volumetric strain versus load step number.

Analysis B-a) - Undrained OCR 5.0

In Analysis B-a), the effective stress path starts at 150 kPa and rises vertically until it hits the initial yield surface. The soil behaves elastically up to this point, as illustrated in Figure 10.

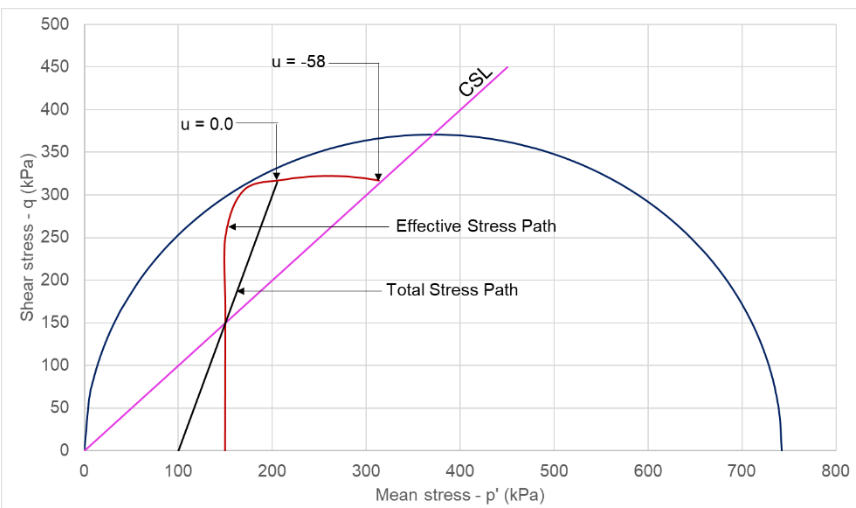

Figure 10. Effective stress for over-consolidated case (produced in EXCEL).

After meeting the yield surface, the effective stress path bends to the right and rises slightly until it intersects the total stress path. This is the point at which the excess pore-water pressure is zero. After this point the excess pore-water pressure diminishes until the effective stress path intersects the CSL. Beyond this point the soil behaves in a plastic manner with no further change in load or pore-water pressure.

Of significance in this case is the fact that the effective stress path remains below the initial yield surface. This is in response to dilation that occurs once the stress path meets the initial yield surface.

The effective stress path is vertical until it meets the initial yield surface (Figure 11). Then it bends over to the right and continues to the right until the path meets the CSL.

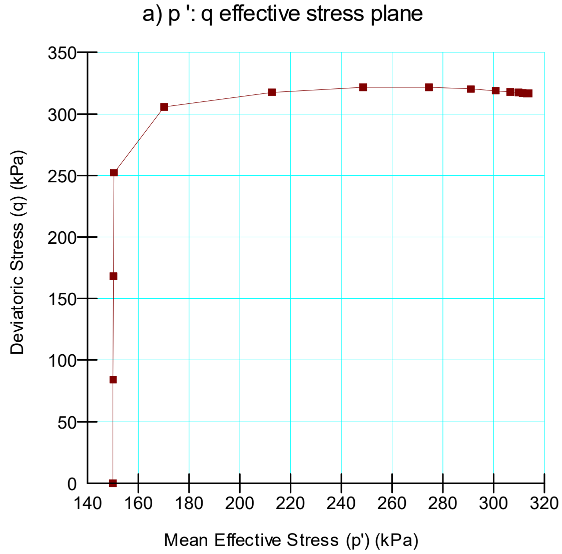

Figure 11. Effective stress path with OCR = 5.

The pore-water pressure starts at 0 kPa (Figure 12). The pore-water pressure then rises until the effectives stress path meets the initial yield surface. After that, the pore pressure diminishes due to the tendency for dilation until it approaches the CSL. The ending pore-water pressure is around -60 KPa.

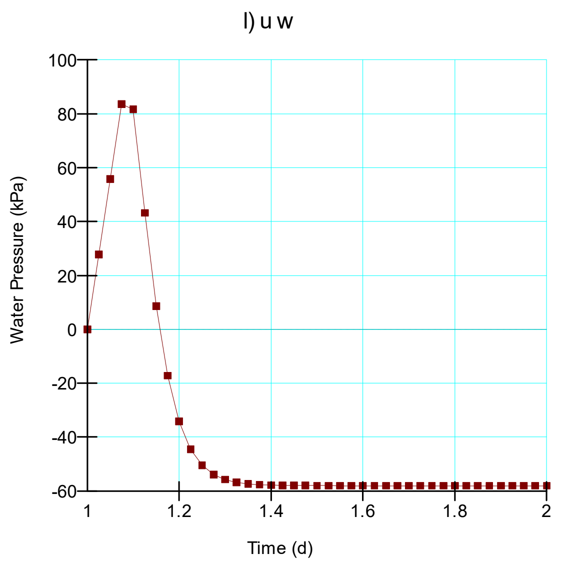

Figure 12. Pore-water pressure variations with OCR = 5.

Analysis C-a) – Undrained OCR 1.25

Based on theoretical consideration for the MCC model, the effective stress path should be vertical until it meets the past maximum yield surface as in Figure 13 for Analysis C-a). Once the effective stress path meets the past yield surface, the path bends to the left and continues to rise slightly until it hits the CSL. The total stress path again is straight line rising at a 1h:3v slope. The difference between the total and the effective stress paths is the excess pore-water pressure.

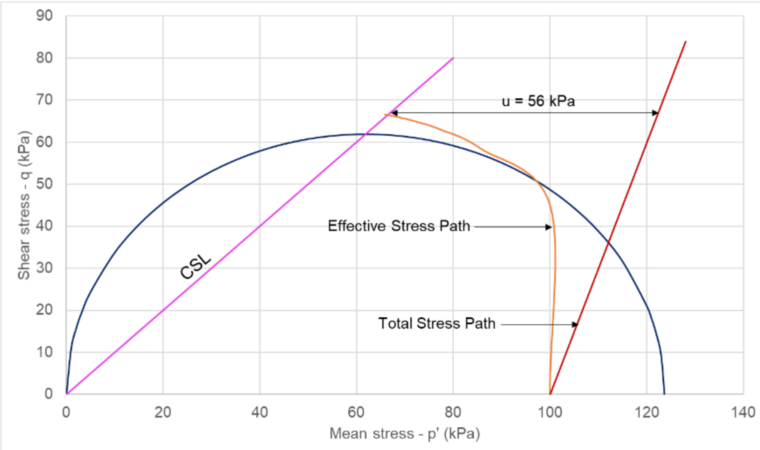

Figure 13. Stress paths for undrained loading.

The final total mean stress is 122 kPa. The effective mean stress where the effective stress path hits the CSL is 66 kPa. The final pore-water pressure therefore is 122 – 66 = 56 kPa.

The SIGMA/W $q - p'$ plot ends at $p' = q =$ 66 kPa (Figure 14). The SIGMA/W pore-water pressure versus load step plot indicates the maximum pore-water pressure is 56 kPa (Figure 15).

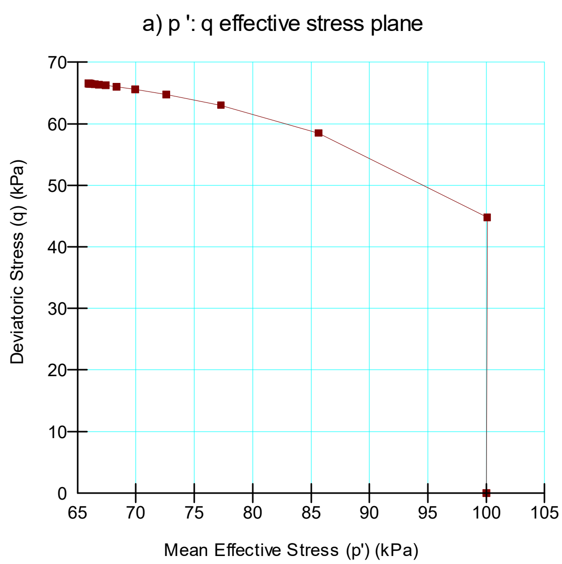

Figure 14. Effective stress under undrained loading.

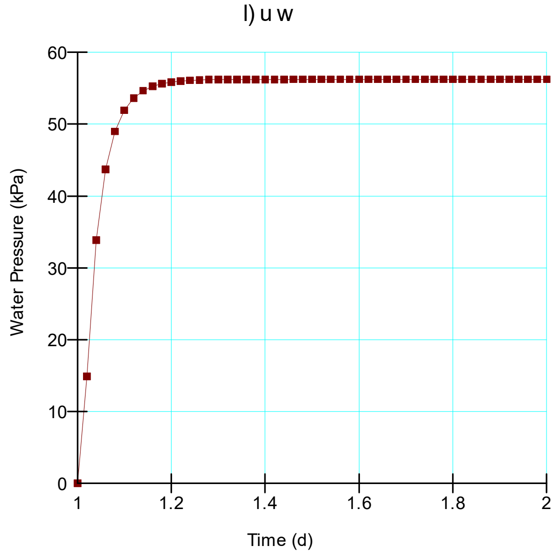

Figure 15. Pore-water pressure in undrained test.

The volumetric strain for this test is zero, as it properly should be. The sample, however, undergoes some plastic strain, which results in some strain-hardening and the yield surface consequently expands such that it passes thorough the point where the effective stress path meets the CSL.

Analysis C-b) – Load-unload-reload

The MCC model treats the soil as elastic when the stress state is under the past maximum yield surface. In an undrained test, the effective $p':q$ stress path is vertical inside the yield locus whether the loading path is one of unloading or loading. Figure 16 reveals that this is indeed the case: the stress path resumes its non-linear behavior once the yield locus is crossed upon re-loading.

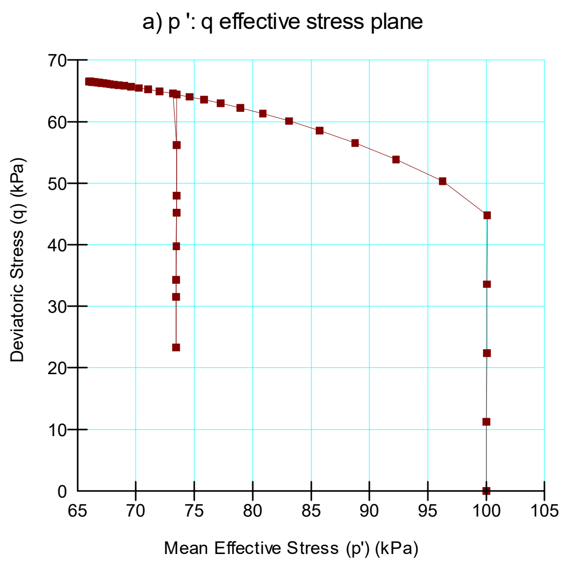

Figure 16. Effective loading – unloading stress path.

Summary and Conclusion

This example verified the Modified Cam-Clay constitutive model is functioning properly in SIGMA/W. Several triaxial tests were simulated and discussed.