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GeoStudio Example File
Triaxial test on NorSand soil

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Introduction

This example simulates a series of triaxial tests which can be used to verify that the NorSand constitutive model is functioning properly. The simulations include both isotropically consolidated drained tests (CID) and isotropically consolidated undrained tests (CIU):

1. Consolidating the sample to an initial isotropic stress state;
2. A) Drained test on dense soil;
3. B) Drained test on loose soil;
4. C) Undrained test on dense soil; and
5. D) Undrained test on loose soil.

The verification includes comparisons with results from an Excel VBA implementation and discussions relative to the NorSand theoretical framework. Results from corresponding laboratory tests are also used to highlight NorSand's excellent behaviour modelling capabilities. Users are encouraged to consult the SIMGA/W user guide while reading through this example.

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 varying for each analysis, following the initial conditions listed in Table 1. The isotropic stress state is simulated by applying a normal stress on the top and on the right side of the sample equal to the desired confining pressure. The consolidation stage is set as the "Parent"; that is, the initial condition for the subsequent simulation involving shearing.

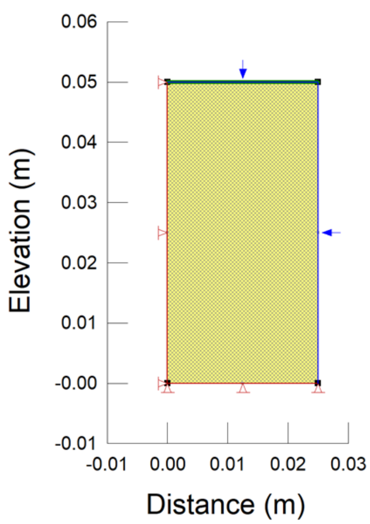

Figure 1. Triaxial test configuration for establishing initial isotropic stress state.

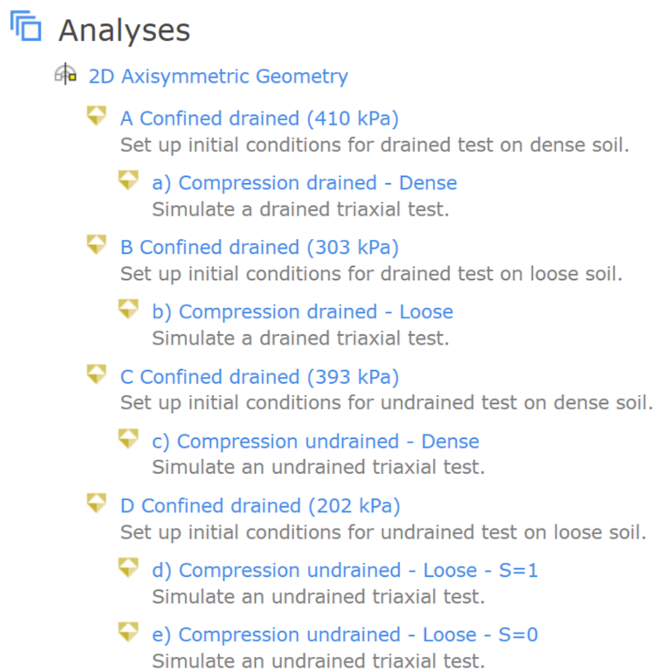

Figure 2. Analysis tree for the project.

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 500. The y-displacement function has been defined to decrease a total of -0.01 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 simulated 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 0.01 m produce axial strains of 0.2 (or 20%).

Table 1. Initial conditions and material parameters

Test name	a) CID – Dense	b) CID – Loose	c) CIU – Dense	d) CIU – Loose
Initial conditions				
Response type	Drained	Drained	Undrained	Undrained
$p_0^{'}[kPa]$	410	303	393	202
e_0	0.704	1.005	0.832	0.973
ψ_0	-0.158	0.127	-0.032	0.076
OCR	1.1	1.2	1.15	1.1
Stiffness				
$G_{ref}[kPa]$	22 900	9 000	16 700	11 500
ν	0.2			
m	0.47			
Strength				
C_a	1.010			
C_b	0.087			
C_c	0.380			
M_c	1.45			
N	0.45			
χ_c	5.3			
H_0	61			
H_y	247			
S	0	0	0	1

All analyses use the Load/Deformation analysis type. “Parent” analyses use the Isotropic Elastic soil model to set up confining stresses; non-linear models are not required for this and the values of elastic modulus E and void ratio e are not relevant for the rest of the analysis.

NorSand materials are defined for each “Child” analysis, as summarized in Table 1. Response type “Drained” will be attributed to examples a) and b) as they represent CID tests, and “Undrained” to examples c) and d) as they represent CIU tests. Most of the material parameters are kept constant for each simulation to showcase NorSand’s ability to simulate many response types by only varying the initial state (ψ_0). The chosen parameters were inspired by those proposed by Jefferies *et al.* (2015) and Ghafghazi (2011) for the Fraser River sand. The three categories of parameters shown in Table 1 are discussed below:

- Initial conditions
  - Initial conditions for each analysis include the initial mean effective pressure $p_0^{'}$ (determined by the “Parent” analysis), the initial void ratio e_0 and the overconsolidation ratio OCR. In the case of NorSand the overconsolidation ratio is calculated using the mean effective stress (as opposed to the vertical effective stress). The initial state parameter ψ_0 is also included in Table 1 for reference.
- Stiffness
  - Stress-dependant isotropic elasticity is assumed in NorSand. Three parameters are required to initialize the material stiffness: Poisson’s ratio ν, the reference elastic shear modulus at the reference stress G_{ref} (with the reference stress set as $p_{ref} = 100kPa$) and the elastic exponent m. The elastic exponent value determines the shear modulus’ (G) dependency of the mean stress.
- Strength
  - Strength is multifaceted in NorSand, as many parts of the model influence how resistance will develop. The position of the critical state line is determined by either Γ and λ for a semi-ln idealization, or C_a, C_b and C_c for a curved idealization (as is the case in this example). The slope of the critical state line in stress space is set by M_c, where triaxial compression (the “*c*” subscript) is used as a reference condition. The volumetric coupling coefficient N, state-dilatancy parameter χ_c and hardening modulus H are NorSand-specific strength parameters. The hardening modulus can be made dependant on the state parameter (as is the case for this example) following $H = H_0 - H_y\psi$. If H_y is set to zero, then $H = H_0$. Finally, the additional softening index S is toggled on ($S = 1$) for the example *d*, which represents an undrained loose soil.

Results and Discussion

The four different analyses considered in this example are examined separately below. Each figure shown includes four subfigures, identified as part A to part D on the bottom left corner of each subfigure, that show various aspects of soil behaviour that develop during the tests. On each figure, the Excel VBA results are shown in Orange and the corresponding SIGMA/W are shown in blue. Dashed lines are used for the SIGMA/W results to distinguish them from the Excel VBA results, as both sets are essentially right on top of each other for all the simulations. The critical state line (CSL) was also identified by a grey line on the stress path diagrams (part B). Each figure also shows corresponding laboratory results of triaxial tests performed on Fraser River sand, taken from Jefferies *et al.* (2015), to highlight the model’s excellent modelling performance.

Analysis a) CID – Dense

Analysis a) showcases the behaviour of a dense sand subjected to drained triaxial compression loading (Figure 3). As the soil is initially dense ($\psi_0 < 0$, part D), it first contracts (part C) but subsequently dilates toward its critical state. NorSand’s maximum resistance is reached at around $q = 1\ 625$ kPa (part A), with resistance gently decreasing as the soil moves toward its critical state ($\psi \rightarrow 0$ as $\varepsilon_y \rightarrow \infty$, part D). The stress path is therefore moving over the critical state line (CSL), to eventually fall back toward it (part B). Also note the stress path moves at a ratio of $dq/dp^{'} = 3$, as is expected for a drained triaxial test. NorSand closely captures the dilatant behaviour exhibited by the laboratory test results.

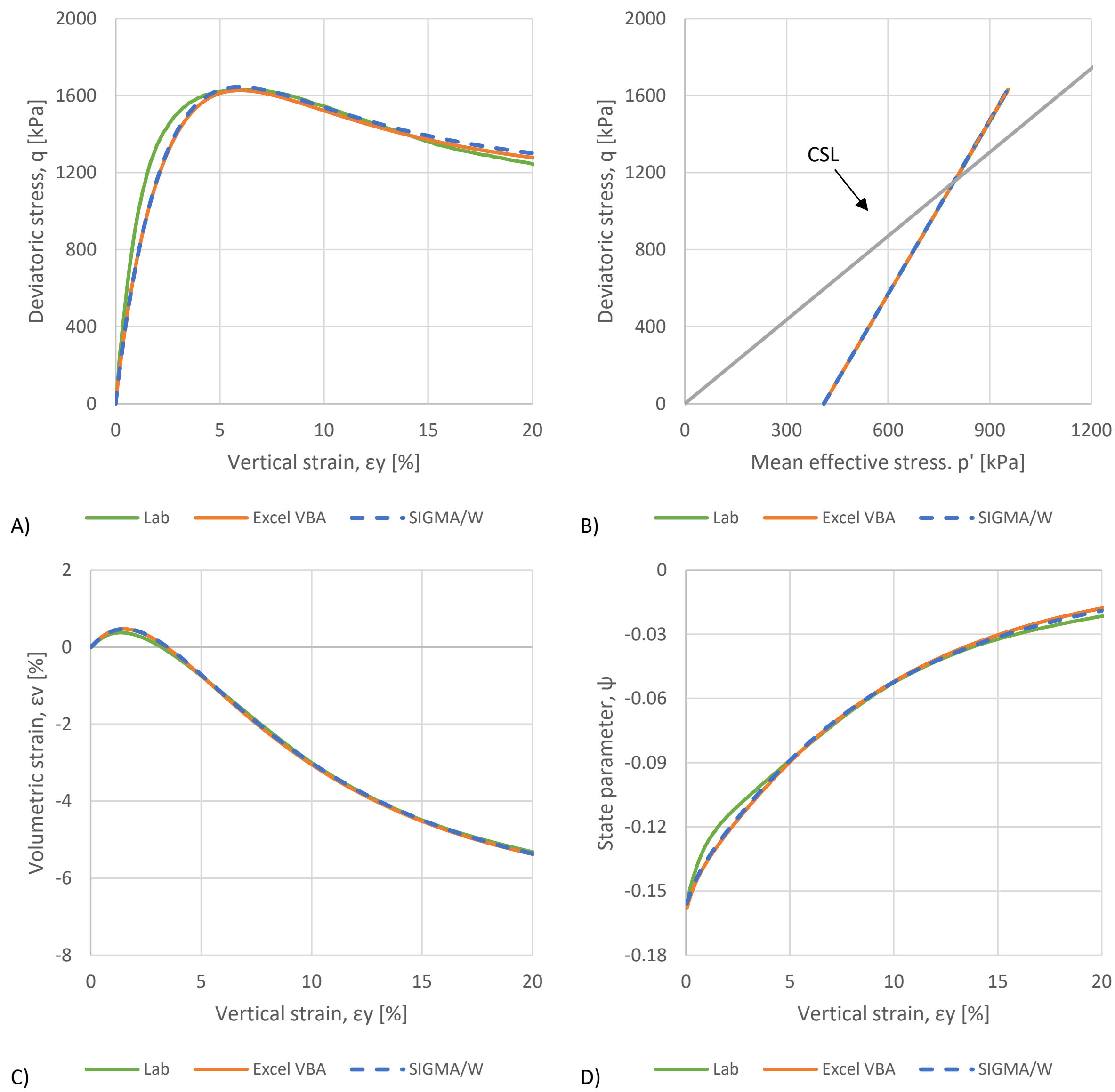

Figure 3. Comparison between Excel VBA and SIGMA/W results for a drained triaxial test on dense sand.

Analysis b) CID – Loose

Analysis b) showcases the behaviour of a loose sand subjected to drained triaxial compression loading (Figure 4). The sample exhibits volumetric contraction (part C) throughout the test as its state parameter remains positive and will reach 0 at large deformations (part D). As the sample is loose, its stress path will move directly toward the critical state (part B), without overpassing the critical state line, as was the case for Analysis a). Again, NorSand shows good agreement between the behaviour modelled and what is shown from the laboratory results.

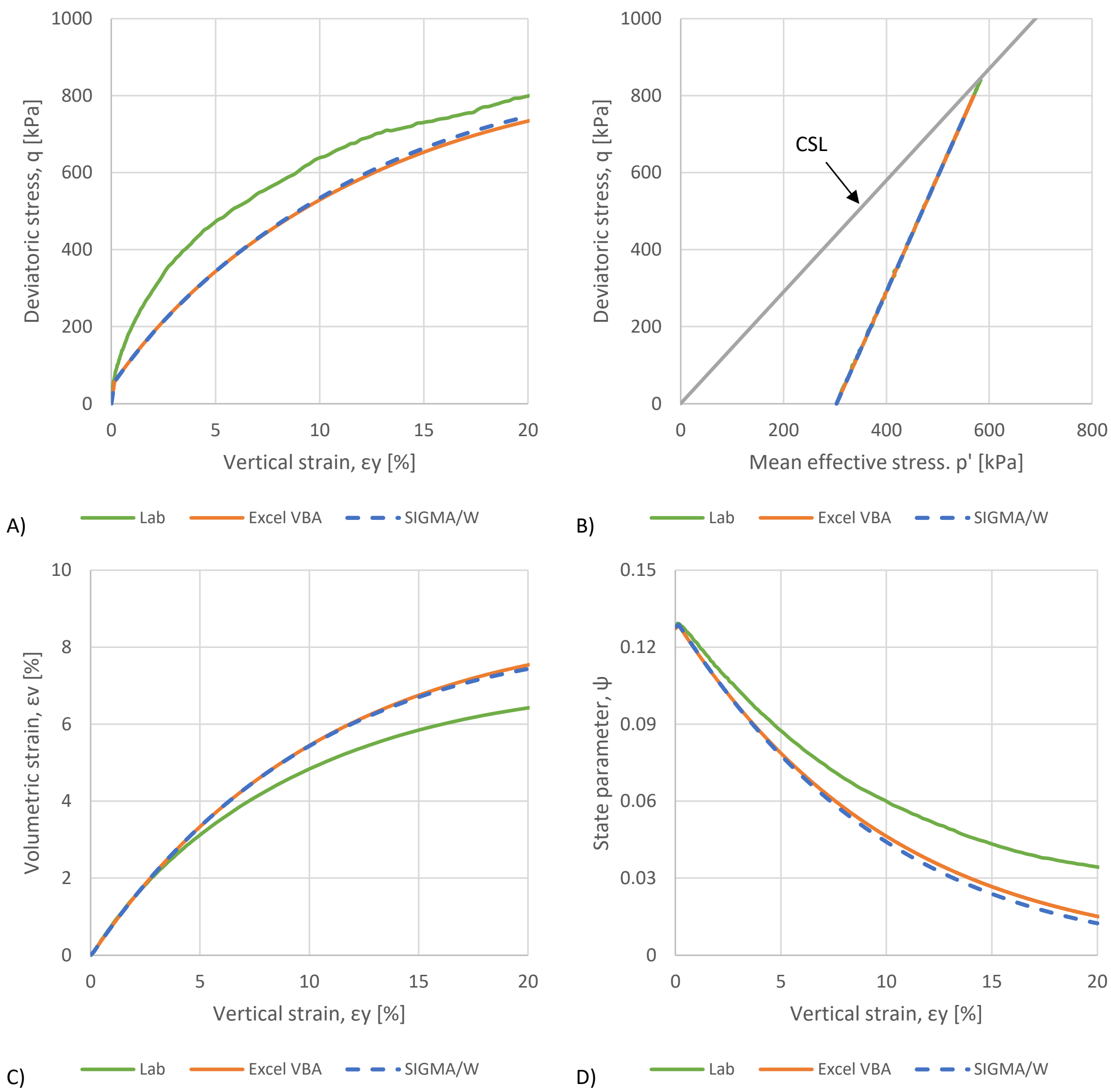

Figure 4. Comparison between Excel VBA and SIGMA/W results for a drained triaxial test on loose sand.

Analysis c) CIU – Dense

Analysis c) showcases the behaviour of a dense sand subjected to undrained triaxial compression loading (Figure 5). During undrained loadings, volumetric strains are prevented, which leads to the build-up of pore water pressure (part C), which forces the stress path (part B) to depart from the drained stress path loading rate of $dq/dp' = 3$. The slight overconsolidation ($OCR = 1.15$) applied to this sample is also apparent in the stress path diagram (part B), where the stress path initially rises at constant mean effective stress until the yield surface is encountered around $q = 50kPa$. Analogously to the drained triaxial test on dense soil (Analysis a), the soil initially shows a tendency toward contraction, but eventually dilates toward its critical state (part D). The NorSand simulation closely follows the laboratory results in every aspect of soil behaviour shown in Figure 5.

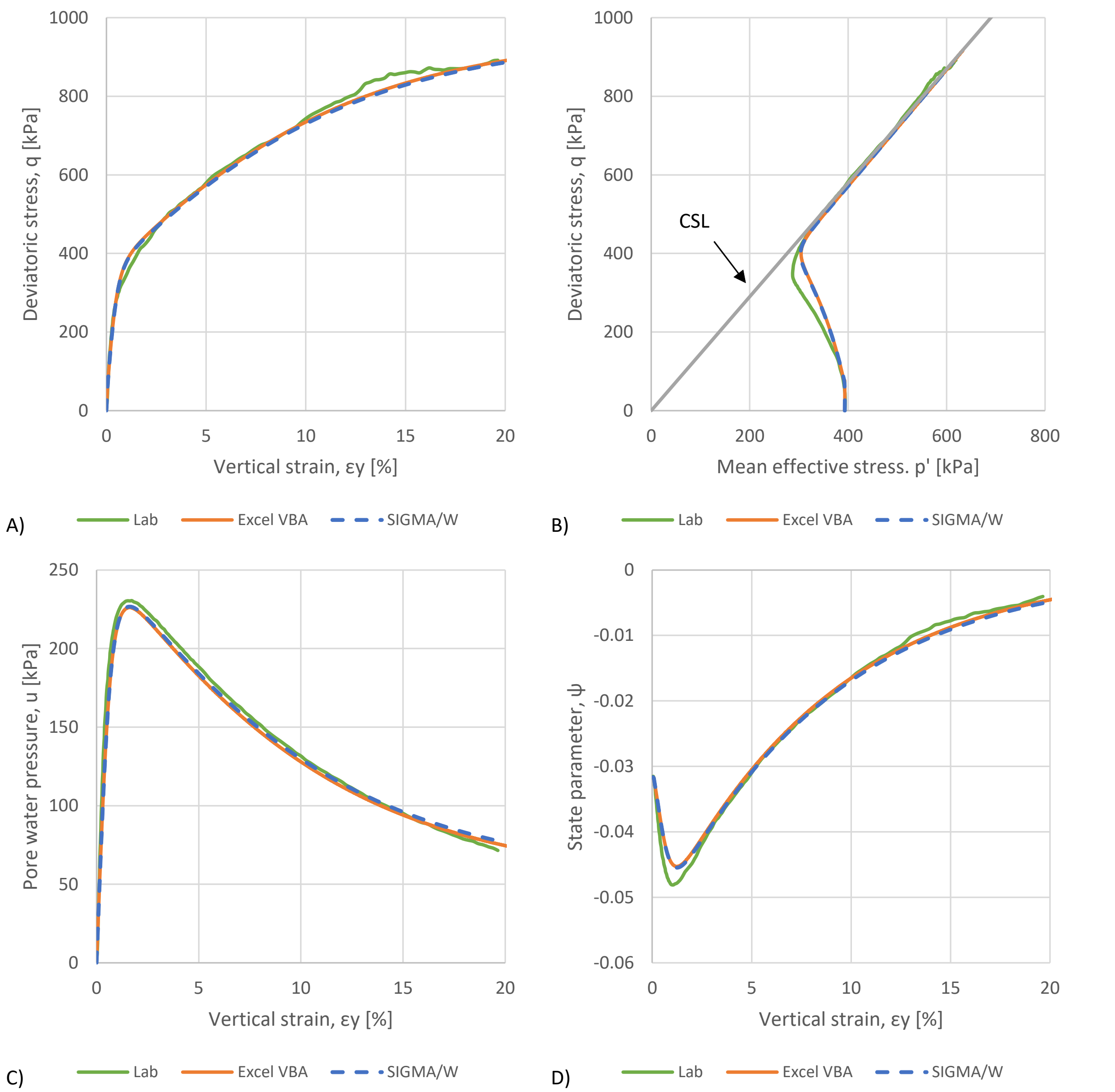

Figure 5. Comparison between Excel VBA and SIGMA/W results for an undrained triaxial test on dense sand.

Analysis d) CIU – Loose

Analysis d) showcases the behaviour of a loose sand subjected to undrained triaxial compression loading (Figure 6). As for the other analyses shown previously, the Excel VBA and SIGMA/W results are shown in orange and blue respectively, while the corresponding laboratory results are shown in green. These simulations were carried out with the additional softening index turned on ($S = 1$). To show the effect of this additional softening available for undrained loading of loose soils, a third set of results, analysis e), is also shown in Figure 6 (yellow curves), showcasing the results of the SIGMA/W analysis with the additional softening turned off, which is the default value ($S = 0$).

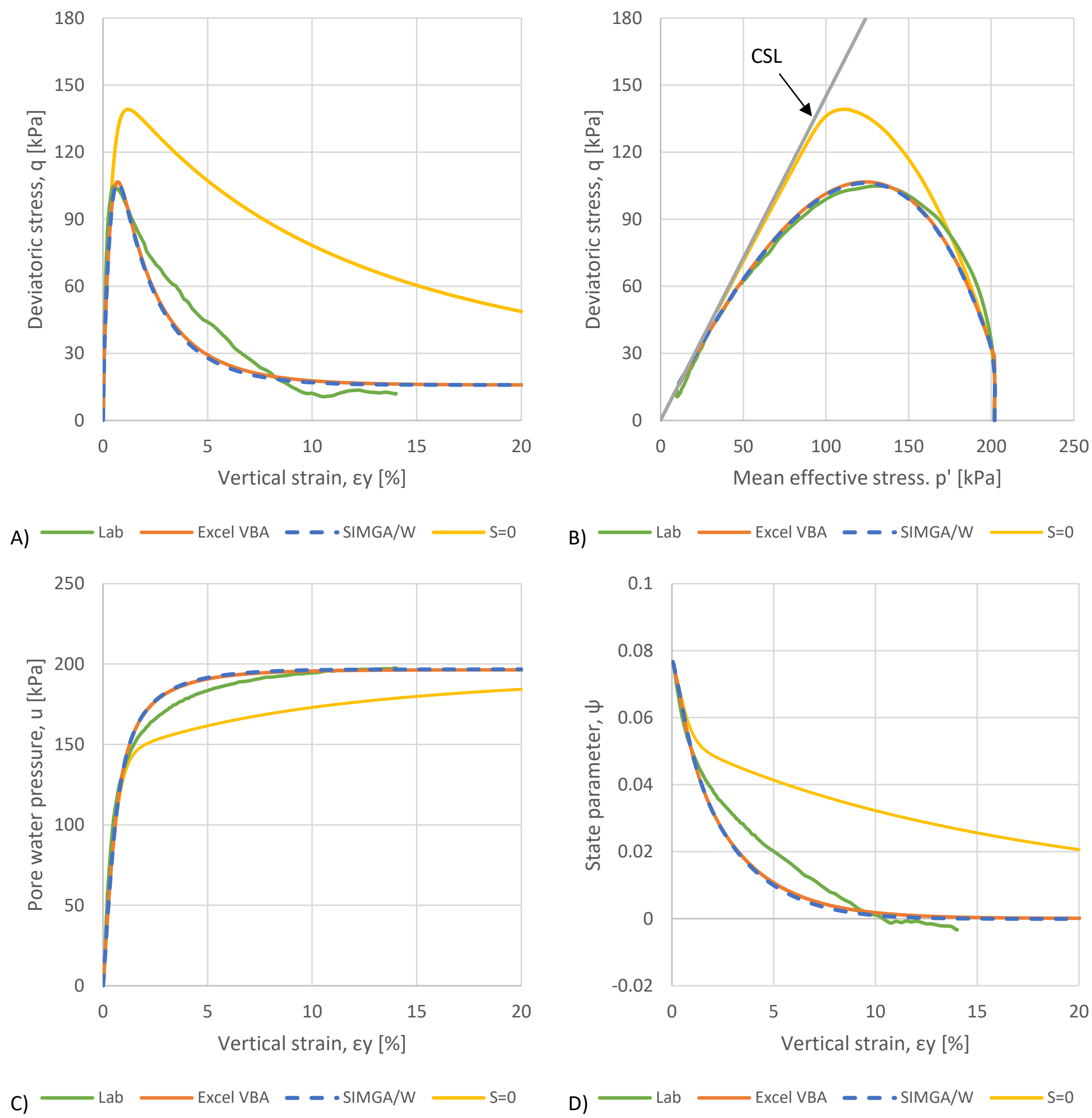

Figure 6. Comparison between Excel VBA (S=1) and SIGMA/W (S=1 and S=0) results for an undrained triaxial test on loose sand.

Focusing first on the results for $S = 1$ (orange and blue curves in Figure 6), the behaviour modelled is associated to static liquefaction. The state parameter is initially strongly positive ($\psi \approx 0.8$, part D) which leads to large pore water pressure being generated (part C) early in the test as the sample strongly contracts. The resulting stress path (part B) exhibits an initial increase in shear resistance, followed by a very sudden loss of resistance, as the soil rapidly moves toward its critical state after the peak strength is reached. This static liquefaction behaviour leads to very large deformations associated to very small resistance post-peak (part A).

In comparison to results for $S = 1$, results for $S = 0$ (yellow curves in Figure 6) show more limited softening after the maximum resistance is reached (part B). While the maximum pore water pressure generated is similar (as the same critical state will eventually be reached), the rate at which deformations are occurring is much slower for $S = 0$ (notice the difference in state parameter values, part D). The sudden drop of resistance that is very characteristic of static liquefaction is not as pronounced when $S = 0$ compared to when $S = 1$ (part A).

While static liquefaction could be considered a complex phenomenon, NorSand handles it very well (when additional softening is allowed, $S = 1$) and shows excellent agreement with the corresponding laboratory results.

Summary and Conclusion

All the simulations presented in this example showed very good agreement between SIGMA/W and Excel VBA. Both sets of results were consistently quasi-indistinguishable from the other. This example hence verified the NorSand constitutive model is functioning properly in SIGMA/W. Several triaxial tests were simulated and discussed, with varied initial states, both for drained and undrained loading conditions. The comparison of NorSand simulations with corresponding laboratory results from triaxial tests performed on Fraser River sand demonstrated the ability for the model to correctly simulate a varied array of initial and test conditions with a constant set of input parameters.

References

Ghafghazi, M. (2011). Towards comprehensive interpretation of the state parameter from cone penetration testing in cohesionless soils. Ph.D. thesis, University of British Columbia.

Jefferies, M., Shuttle, D. and Been, K. 2015. Principal stress rotation as cause of cyclic mobility. Geotechnical Research, 2(2), pp. 66-96 (downloadable content).