GeoStudio Example File
Triaxial tests on SANICLAY soil

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Introduction

This example simulates a series of triaxial compression tests which can be used to verify that the SANICLAY constitutive model is functioning properly. The simulations include K_0-consolidated undrained (CAU) and drained (CAD) triaxial tests performed at various overconsolidation ratios (OCR), following two distinct stress initialization procedures.

The first procedure (A) simulates the complete consolidation stress history before triaxial loading is performed, which consists of drained K_0-loading, followed by drained K_0-unloading to the desired OCR. This procedure ensures proper initialization of SANICLAY's internal parameters (α, β and p_0) prior to the beginning of triaxial loading.

The second procedure (B) uses direct stress initialization to the desired stress state, using well-known relationships to estimate $K_{0_{nc}}$ and $K_{0_{oc}}$ based on the soil's friction angle ϕ. In this case, SANICLAY's internal parameters are initiated based on the estimated K_0 values, rather than a complete stress history initialization.

The simulation covers both versions of the model, which called RH 2006 and RH 2013, in this document. The verification includes comparisons with simulation results provided by Dafalias *et al.* (2006) and Dafalias and Taiebat *(2013*) and discussions relative to the SANICLAY theoretical framework. Results from corresponding laboratory tests are also used to highlight SANICLAY's superior soil 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 and represents a triaxial specimen. Symmetry is assumed about the vertical and horizontal centrelines; 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 0.005m produce axial strains of 0.1 (or 10%). As shown in the analysis tree (Figure 2), distinct geometries were used for the two series of simulations to ensure proper distinction between the two stress initialization procedures used. Nevertheless, both geometries are identical. The shearing phases of the analyses are simulated as strain-rate controlled tests. For compression loading a 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. Similar function has been used for extension loading with positive sign.

Although the upcoming figures present results for OCR= 1, 2, 4 and 7, the gsz file includes analyses only for OCR=1 and 7, to keep it brief.

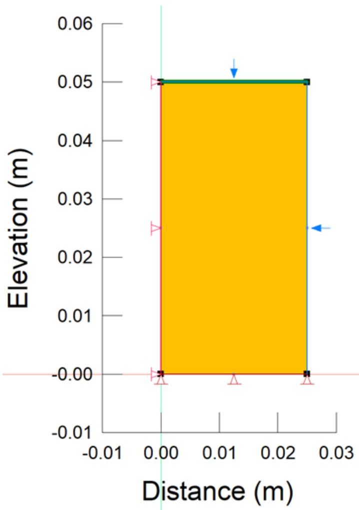

Figure 1. Triaxial test configuration.

Figure 2. Analysis tree for the project.

A) Complete stress history initialization

In analysis sequence A, where the complete stress history is used to initialize stresses and the associated SANICLAY internal parameters, K_0-consolidation is simulated. The first step (i.e. Aa, in Figure 2) initializes the stresses at a starting mean stress of $p = 1kPa$ using a linear elastic model. The subsequent steps, Ab and Ac, perform drained K_0-consolidation up to a vertical stress of $\sigma_y = 350kPa$ using the SANICLAY model with RH 2006 and RH 2013, respectively. This allows the model's yield and potential surfaces to evolve as anisotropy sets in during consolidation. When simulating K_0-consolidation, horizontal strains must be constrained, forcing horizontal stresses to develop in reaction to the increasing vertical stress, which is achieved by horizontally fixing nodes on both sides of the sample (Figure 3). The desired OCR for overconsolidated sample is achieved by unloading the vertical stress from $\sigma_y = 350kPa$ to the required value (i.e. $\sigma_y = 50kPa$ for $OCR = 7$).

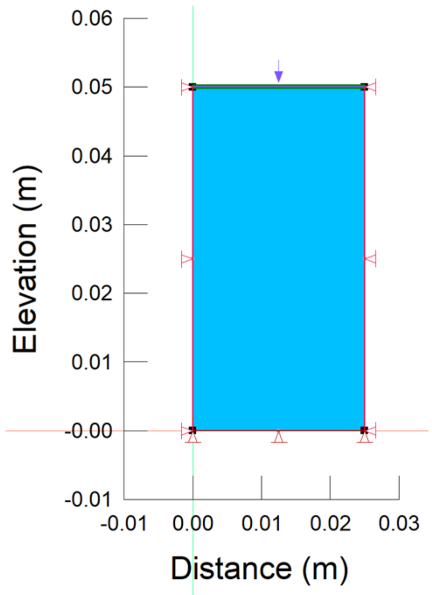

Figure 3. Configuration for K_0-consolidation.

During K_0-consolidation, a drained SANICLAY model is used, with ${K_0}_{nc} = 1$ and $OCR = 1$. As K_0-consolidation is simulated in SIGMA/W (with the appropriate loading and unloading phases), K_0 and OCR develop in response to the loading conditions. For the loading phases, either undrained or drained SANICLAY models are used, depending on which test is simulated (CAU or CAD), using again ${K_0}_{nc} = 1$ and $OCR = 1$. During this whole process, displacements, strains, and state variables are never reset so that SANICLAY's internal parameters are free to evolve and correctly represent the past stress history that developed during K_0-consolidation. Table 1 shows the initial ${K_0}_{nc}$, initial OCR and final OCR aimed for after K_0-unloading for each test simulated. An initial void ratio of $e_0 = 0.8$ is used for every test.

To compare two versions of the model, one branch (Ab) includes materials with rotational hardening rules of 2006 while another branch (Ac) has materials with the rotational hardening rule of 2013.

Table 1. Initial conditions for analysis sequence A (complete stress history initialization).

Test ID	e_0	Initial ${K_0}_{nc}$	Initial OCR	OCR after unloading
Ab1	0.8	1	1	1
Ab2				7
Ac1				1
Ac2				7

B) Direct stress initialization

In analysis sequence B, instead of simulating the complete stress history that led SANICLAY's internal parameters to evolve during K_0-consolidation in analysis sequence A, stresses are specified directly in SIGMA/W and the model's internal parameters that would correspond to K_0-consolidation are estimated based on $K_{0_{nc}}$. This procedure is similar to how other soil models are generally initiated (see for example the CamClay or NorSand triaxial examples).

To estimate the value of $K_{0_{nc}}$ that would exist at the end of K_0-consolidation, Jáky's relationship (Eq. 2) is used, which requires the soil's friction angle ϕ, calculated via Eq. 1. For $M_c = 1.18$ (see the material parameters shown in Table 3), the friction angle is $\phi = 29.5°$ and $K_{0_{nc}} = 0.51$. For each OCR value, a corresponding $K_{0_{oc}}$ can be calculated using Meyerhof's relationship (Eq. 3), which then allows the calculation of stresses that should exist at the end of unloading to produce each overconsolidated sample. These initial conditions are summarized in Table 2. An initial void ratio of $e_0 = 0.5$ is used in every simulation, which corresponds to the void ratio at the end of unloading.

$$\sin\phi = \frac{3M_c}{6 + M_c} \quad \text{Eq. 1}$$

$$K_{0_{nc}} = 1 - \sin\phi \quad \text{Eq. 2}$$

$$K_{0_{oc}} = K_{0_{nc}} \cdot OCR^{0.5} \quad \text{Eq. 3}$$

Table 2. Initial conditions for analysis sequence B (direct stress initialization).

Test ID	e_0	$K_{0_{nc}}$	OCR	$K_{0_{oc}}$	$\sigma_y\ [kPa]$	$\sigma_x\ [kPa]$
B1a to B1f	0.5	0.51	1	0.51	350	177.45
B2a to B2f			7	1.34	50	67.07

Common material parameters

Every SANICLAY material used in both analysis sequences uses a common set of material parameters, summarized in Table 3. These parameters are provided by Dafalias *et al.* (2006) and Dafalias and Taiebat (2013) and were calibrated on Lower Cromer Till (LCT) triaxial test results provided by Gens (1982).

Table 3. Material parameters for SANICLAY RH 2006 and RH 2013 for LCT.

Parameter	Dafalias et al. (2006)	Dafalias and Taiebat (2013)
	Symbol and value	
Stiffness		
Compressibility of normally consolidated cl	λ=0.063	λ=0.063

Compressibility of overconsolidated clay	κ=0.009	κ=0.009
Poisson's ratio	$\nu = 0.2$	$\nu = 0.25$
Strength		
Critical stress ratio in compression	$M_c = 1.18$	$M_c = 1.18$
Critical stress ratio in extension	$M_e = 0.86$	$M_e = 0.86$
Yield surface shape in compression	$N = 0.91$	$N_c = 0.8$
Yield surface shape in extension	$= N = 0.91$	$N_e = 0.58$
Saturation limit of anisotropy	$x = 1.56$	–
Rotational hardening parameter	–	$s = 1.72$
Rotational hardening parameter	–	$z = 1.72$
Rotational hardening parameter	–	$Xi = 1.1$
Rate of evolution of anisotropy	$C = 16$	$C = 200$

Other input parameters required for SANICLAY in SIGMA/W (e_0, OCR and $K_{0_{nc}}$) are indicated in Table 1 and Table 2.

Simulation results

The following section presents simulation results in three different subsections to simplify presentation. K_0-consolidation results associated with analysis sequence A are first presented to showcase how this procedure initiates stresses and internal parameters through consolidation. Simulation results are then presented for the undrained triaxial compression and extension tests, and finally for the drained compression tests, for both analysis sequences.

Some common parameters used in plots presented in the following subsections are defined below to avoid confusion: mean effective stress p' (Eq. 4), deviatoric stress q (Eq. 5), coefficient of earth pressure at rest K_0 (Eq. 6), overconsolidation ratio OCR (Eq. 7), in which σ_x and σ_y are the horizontal and vertical stresses respectively. Note that to simplify presentation, the deviatoric stress q is expressed as the difference between the vertical and horizontal stresses. Also note that for SANICLAY, the overconsolidation ratio OCR is calculated based on the vertical stress.

$$p' = \frac{\sigma_y' + 2\sigma_x'}{3}$$ Eq. 4

$$q = \sigma_y' - \sigma_x'$$ Eq. 5

$$K_0 = \frac{\sigma'_x}{\sigma'_y}$$ Eq. 6

$$OCR = \frac{\sigma'_{y,max}}{\sigma'_{y,current}}$$ Eq. 7

Some of the plots presented below are normalized to display multiple simulation result series on the same plots. $p'/\sigma'_{y,max}$ and $q/\sigma'_{y,max}$ are therefore respectively the mean effective and deviatoric stresses normalized by the maximum vertical effective stress that existed (350 kPa in these simulations).

K_0-consolidation

As mentioned earlier, the simulation of K_0-consolidation involves restraining deformations in the horizontal direction so that the horizontal stress develops in response to the increasing vertical stress. Figure 4 shows how stresses evolve during K_0-consolidation for analysis sequence A (complete stress history initialization, RH 2006). The blue part of the curve represents consolidation up to $\sigma_y = 350kPa$, which is the point where consolidation was stopped. The blue square represents the stress state corresponding to $OCR = 1$. The orange curve shows K_0-unloading from $OCR = 1$ to $OCR = 2$ ($\sigma_y = 175kPa$) and the corresponding orange square represents the stress state for $OCR = 2$. The grey and yellow curves and squares correspond to $OCR = 4$ and $OCR = 7$ respectively.

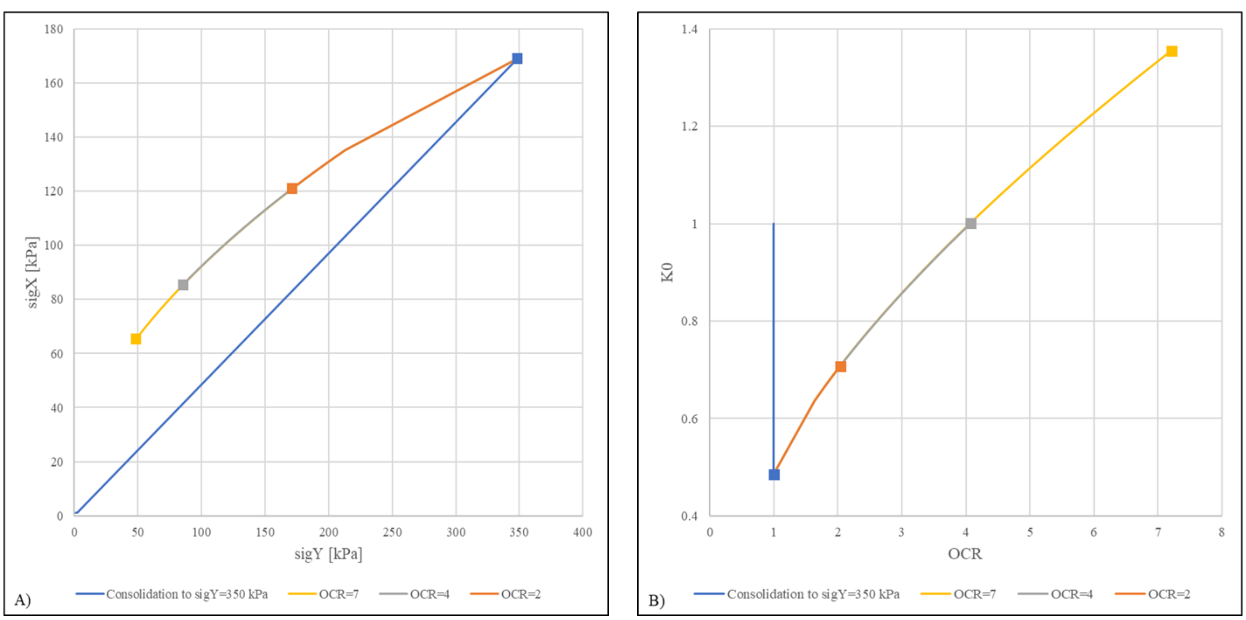

Figure 4. K_0**-consolidation for analysis sequence A (RH 2006).**

Figure 4 A) shows how horizontal stresses evolved with respect to vertical stresses. Another way to represent this data is to plot K_0 as a function of OCR (Figure 4B). K_0-consolidation starts at $K_0 = 1$ and $OCR = 1$ and progresses until consolidation stops at the blue square, where $K_0 = K_{0_{nc}} = 0.49$ and $OCR = 1$ (the start point of the $OCR = 1$ tests). Note that the $K_{0_{nc}}$ value reached at the end of consolidation is different than the value calculated in Table 2 using Jáky's relationship (analysis sequence B). This is expected since Jáky's $K_{0_{nc}}$ value is an approximation based on ϕ while the $K_{0_{nc}}$ value reached at the end of consolidation in Figure 4 is produced by SANICLAY in response to the loading conditions. For the overconsolidated tests, unloading will proceed until the desired OCR is reached for each test, which will correspond to larger $K_{0_{oc}}$ as OCR increases as shown in Figure 4B.

K_0-consolidation simulation sets the appropriate stresses that should exist within the soil sample prior to shearing. It also influences internal SANICLAY parameters (α, β, p_0) that are used to shape the yield and potential surfaces. Starting from initial isotropic conditions, where SANICLAY's yield surface would take a CamClay-like ellipsoidal shape, K_0-consolidation eventually develops anisotropy within the model to eventually produce the yield surface shown by the dashed green line in Figure 5. This particular yield surface exists at the end of K_0-consolidation, when $OCR = 1$. Also shown in this figure are consolidation and unloading stress paths, similar to the previous plots, with the associated starting points for the various $OCRs$ denoted by colored squares.

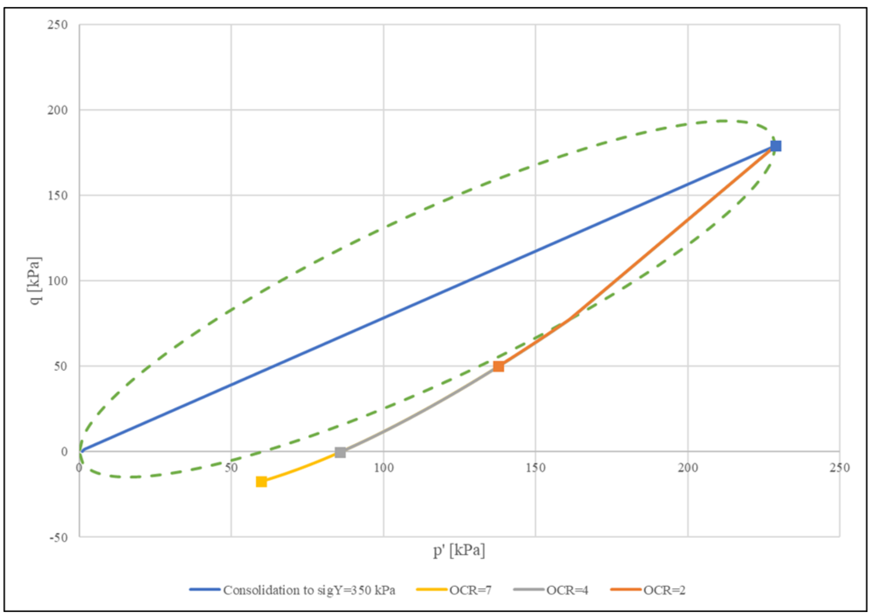

Figure 5. SANICLAY (RH 2006) yield surface at the end of K_0-consolidation.

Analysis sequence B (direct stress initialization) tries to replicate the work done during K_0-consolidation for analysis sequence A (complete stress history initialization) by using estimations for $K_{0_{nc}}$ and $K_{0_{oc}}$ (see Table 2). By using these estimates, one can effectively avoid having to simulate the whole stress history to initiate the stresses and SANICLAY internal parameters. A comparison between K_0 values calculated through analysis sequence A (triangles) and K_0 values estimated for analysis sequence B (squares) are shown in Figure 6 for each OCR. The difference between both method is generally small and compares similarly to laboratory test results, as shown in the following section.

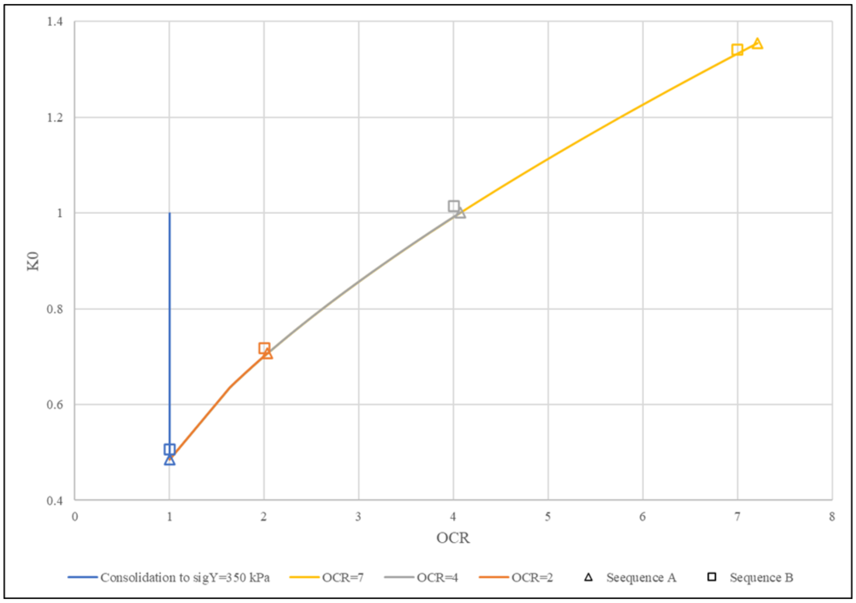

Figure 6. Comparison between K_0 values calculated through analysis sequence A, RH 2006 (triangles) and B (squares).

Once stresses are properly initialized using both analysis sequences, triaxial loading can be performed. Undrained and Drained triaxial compression results are shown in the following two sections. Due to similarity, graphs of RH 2013 are not presented for this section.

Undrained triaxial compression loading (CAU)

This section focussed on undrained compression and extension tests. The stress initialization procedure for these tests is the same, only the shearing portion of the test sequence is done undrained using y-displacement boundary condition with different signs.

Figure 7 compares simulation results from SIGMA/W (RH 2006) using the complete stress history initialization (analysis sequence A) and the SANICLAY simulation results provided by Dafalias *et al.* (2006). Bold and dashed lines denote SIGMA/W data for compression and extension triaxial tests, respectively. On the other hand, squares and filled squares show data reported by Dafalias *et al.* (2006) with each colour representing a specific OCR.

The undrained test results from SIGMA/W align very well with the model's authors' data, confirming the good implementation of SANICLAY in SIGMA/W. Both the stress path (Figure 7A) and the stress-strain (Figure 7B) plots show excellent agreement. SANICLAY display highly contractive behaviour (pore-water pressure generation, i.e. reducing mean stress) for $OCR = 1$, and dilatant behaviour for larger OCRs, as expected.

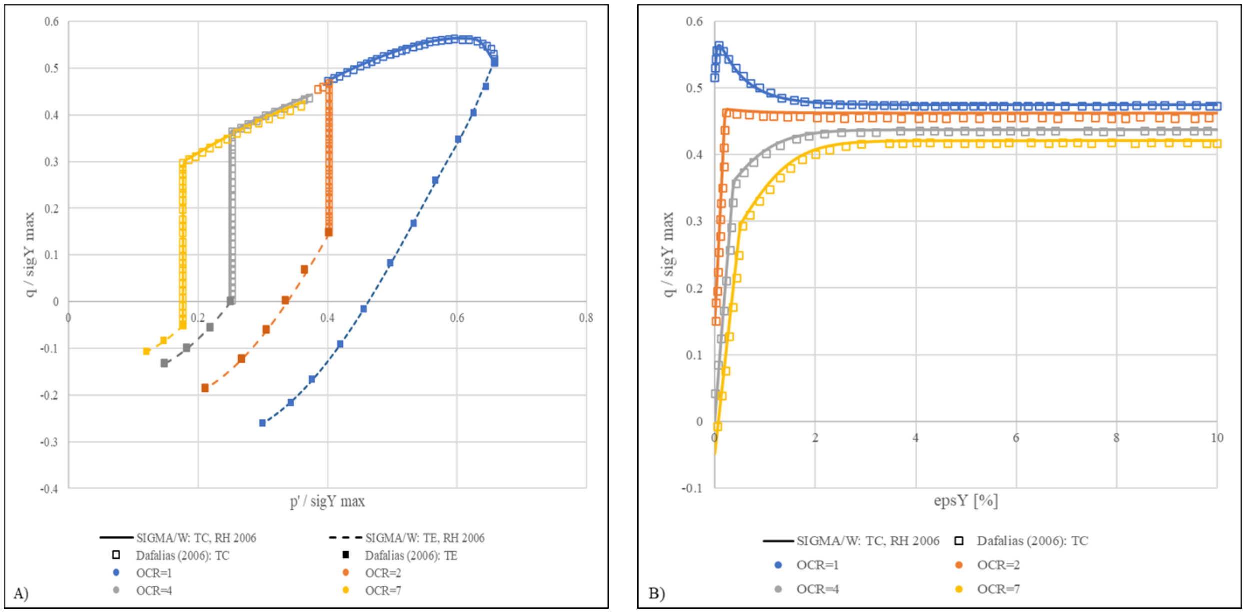

Figure 7. CAU: SIGMA/W Complete stress history (RH 2006) vs Dafalias *et al.* (2006).

A comparison between SIGMA/W simulation results (complete stress history, RH 2006) and the associated laboratory results is shown in Figure 8. In the triaxial compression tests, the simulations compare very favorably with the laboratory results for every OCR considered. Behaviour features exhibited in the lab are again well represented by SANICLAY (RH 2006). However, this version of the SANICLAY model provides different effective mean stresses at the failure state depending on the loading path, as highlighted in Figure 9 for OCR=1 sample. Comparing the stress paths of the triaxial compression (bold blue line) and triaxial extension (dashed blue line) tests on this figure and recalling that the loading is undrained, the simulation implies the same void ratio that existed at the end of the K0 consolidation will be associated with two different p’ values at failure state (marked with the bold green and dashed green arrows for TC and TE, respectively), thus implying two different critical state line in e–ln p’ space.

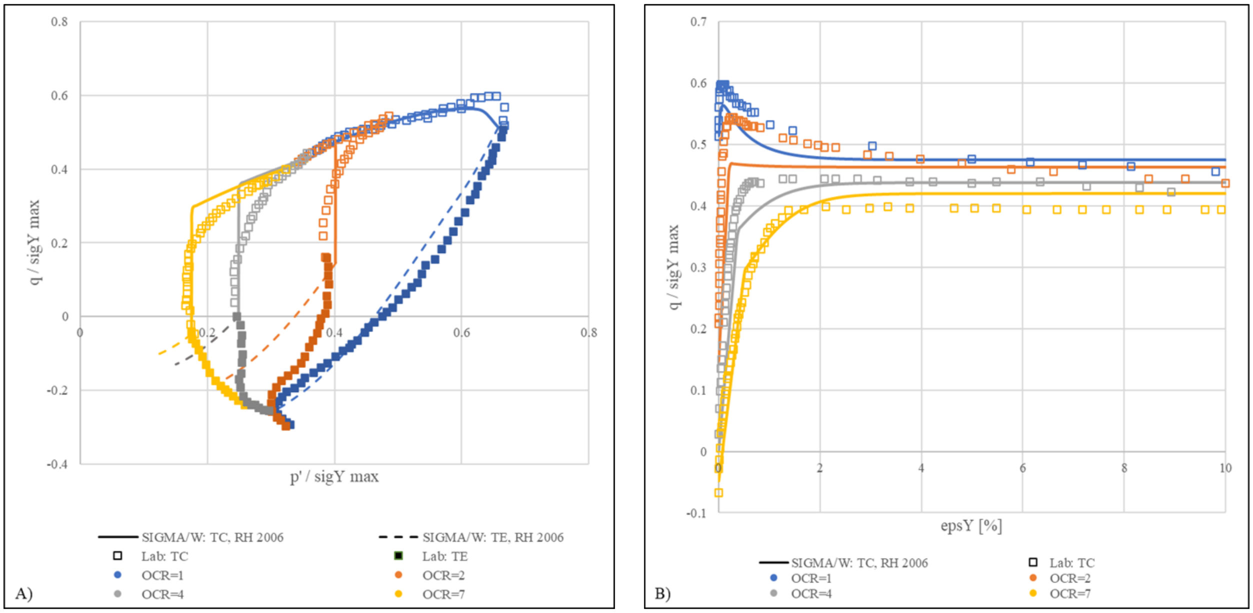

Figure 8. CAU: SIGMA/W Complete stress history (RH 2006) vs lab results (Gens, 1982).

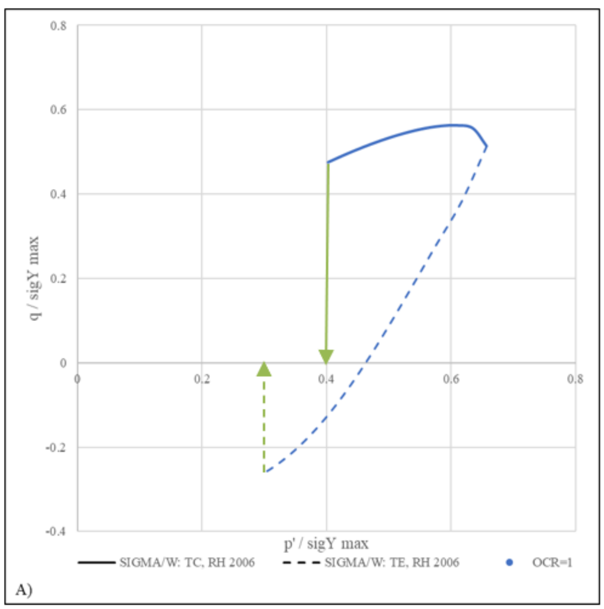

Figure 9. Lack of the uniqueness of the critical state line in the SANICLAY model with RH 2006.

Finally, laboratory test results are compared to SIGMA/W simulation results in Figure 10, this time for the direct stress initialization procedure (analysis sequence B, RH 2006). Again, in compression tests, the SANICLAY simulations compare favorably with the laboratory results, which confirms that this procedure can effectively be used to simplify the stress initialization procedure, while still providing good simulation results. Note since the lack of the uniqueness of the critical state line comes from the rotational hardening rules, it has been observed in this analysis sequence too.

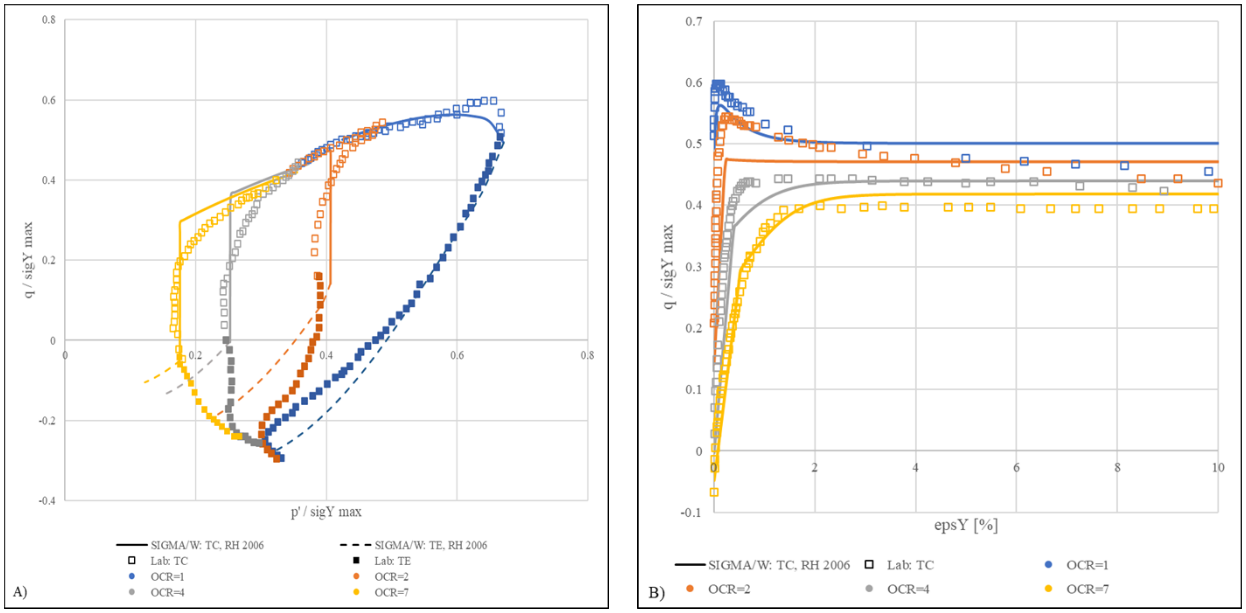

Figure 10. CAU: SIGMA/W Direct stress initialization (RH 2006) vs lab results (Gens, 1982).

The lack of the uniqueness of the critical state line has been addressed by the revised rotational hardening rules proposed by Dafalias and Taiebat (2013). Figure 11 compares simulation results from SIGMA/W using the complete stress history initialization (analysis sequence A, RH 2013) and the SANICLAY simulation results provided by Dafalias and Taiebat (2013). Bold and dashed lines denote SIGMA/W data for compression and extension triaxial tests, respectively. Squares and filled squares show data reported by Dafalias and Taiebat (2013) with each colour representing a specific OCR.

The undrained test results from SIGMA/W align very well with the model's authors' data, confirming the good implementation of this version of SANICLAY in SIGMA/W. Both the stress path (Figure 11A) and the stress-strain (Figure 11B) plots show excellent agreement.

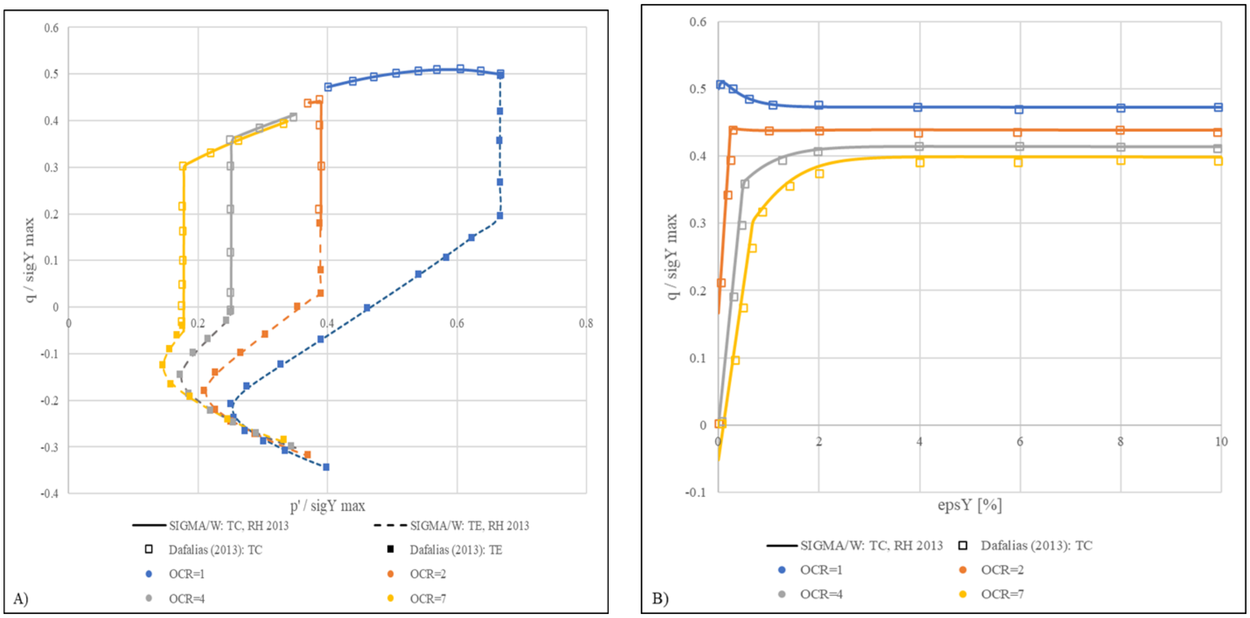

Figure 11. CAU: SIGMA/W Complete stress history (RH 2013) vs Dafalias and Taiebat (2013).

A comparison between SIGMA/W simulation results (complete stress history, RH 2013) and the associated laboratory results is presented in Figure 12. Although this version results in a unique critical state line, the remedy comes with the cost of loosing some abilities of the previous version. For example, consider the laboratory data of OCR=1 sample under compression, (blue squares in Figure 10 and Figure 12, A and B). Comparing the associated numerical results reveals that RH 2013 may not simulate the softening behaviour after K0 loading as successfully as the RH 2006 version.

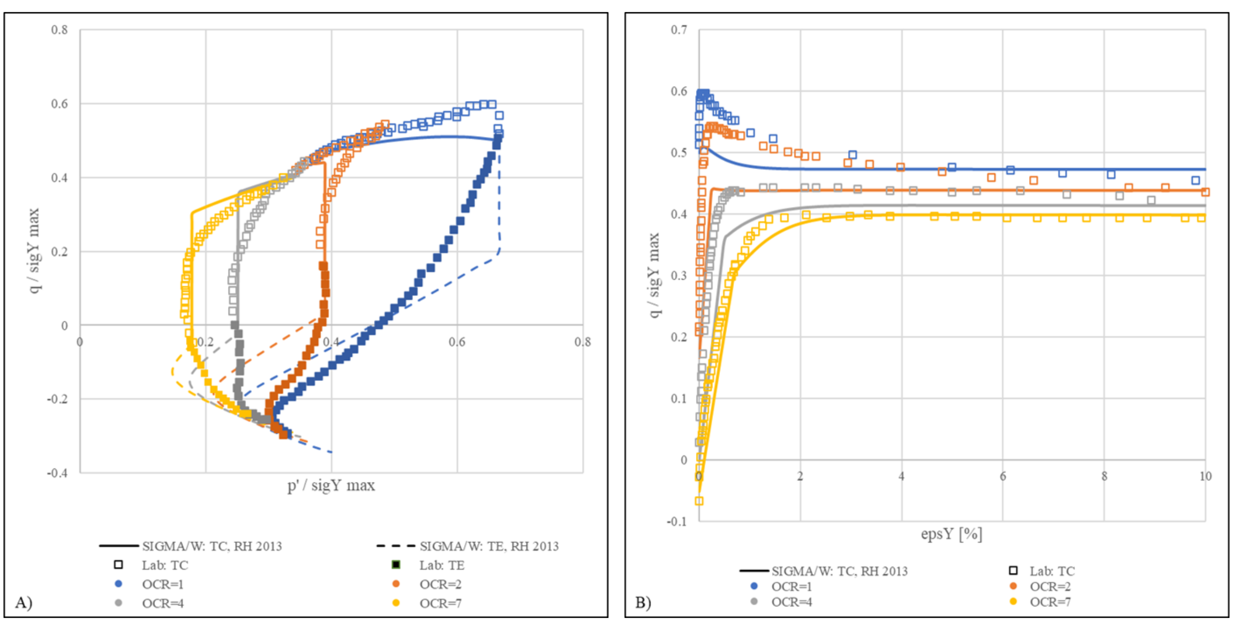

Figure 12. CAU: SIGMA/W Complete stress history (RH 2013) vs lab results (Gens, 1982).

Back to the stress initialization procedures, in the final part of this section, laboratory test results are compared to SIGMA/W simulation results in Figure 13, this time for the direct stress initialization procedure (analysis sequence B, RH 2013). Again, the SANICLAY simulations compare satisfactorily with the laboratory results, which confirms that this procedure can also be used to simplify the stress initialization procedure for the new version, too.

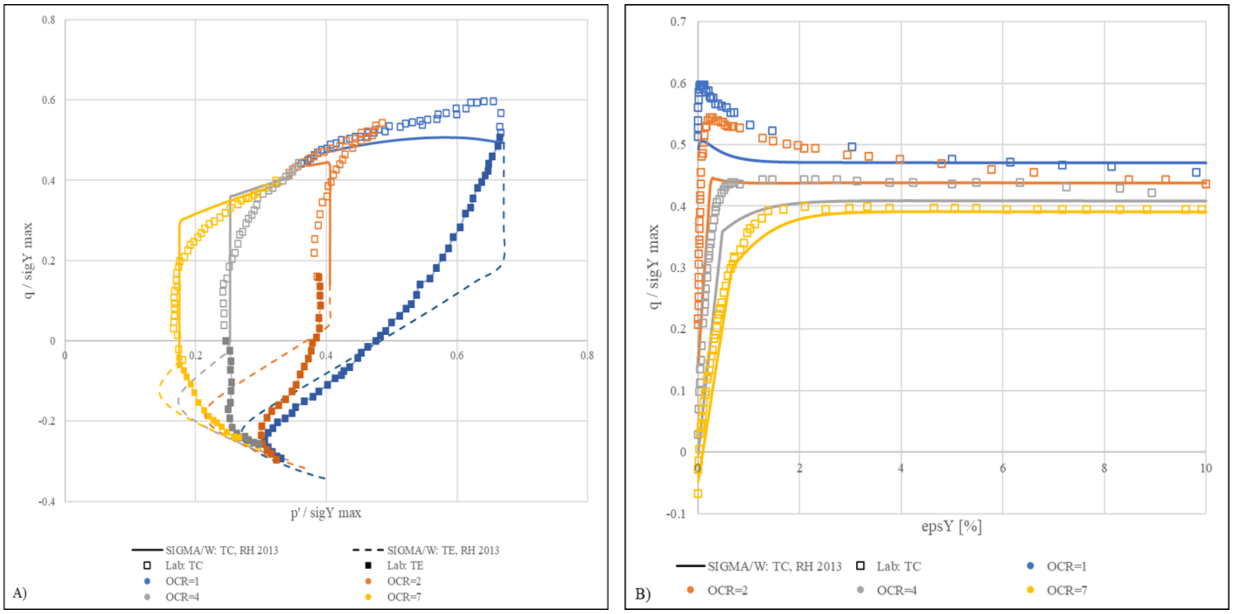

Figure 13. CAU: SIGMA/W Direct stress initialization (RH 2013) vs lab results (Gens, 1982).

Drained triaxial compression loading (CAD)

Figure 14 shows the comparison between SANICLAY simulation results reported by Dafalias *et al.* (2006) and SIGMA/W results using analysis sequence A (complete stress history initialization using RH 2006) for drained anisotropically consolidated triaxial compression tests (CAD). The figure also includes the associated lab results from Gens (1982).

While solid lines denote SIGMA/W data, dashed lines show data reported by Dafalias *et al.* (2006), and squares represent data from Gens (1982) with each colour representing a specific OCR.

Results shown in Figure 14 indicate that SIGMA/W's implementation of SANICLAY correctly represents the implementation of the model's authors (Dafalias *et al.*, 2006) for CAD tests. Both the volumetric strain plot (Figure 14 A) and the deviatoric stress plot (B) show excellent agreement between both sets of data. The $OCR = 1$ and $OCR = 2$ curves show contractive behaviour, while the $OCR = 7$ curve shows dilatant behaviour and $OCR = 4$ sits somewhere in between.

In addition, both in terms of volumetric strain and deviatoric stress, simulation results compare very favorably with the associated lab results. Behaviour features exhibited by the real soil in the laboratory are well represented by SANICLAY.

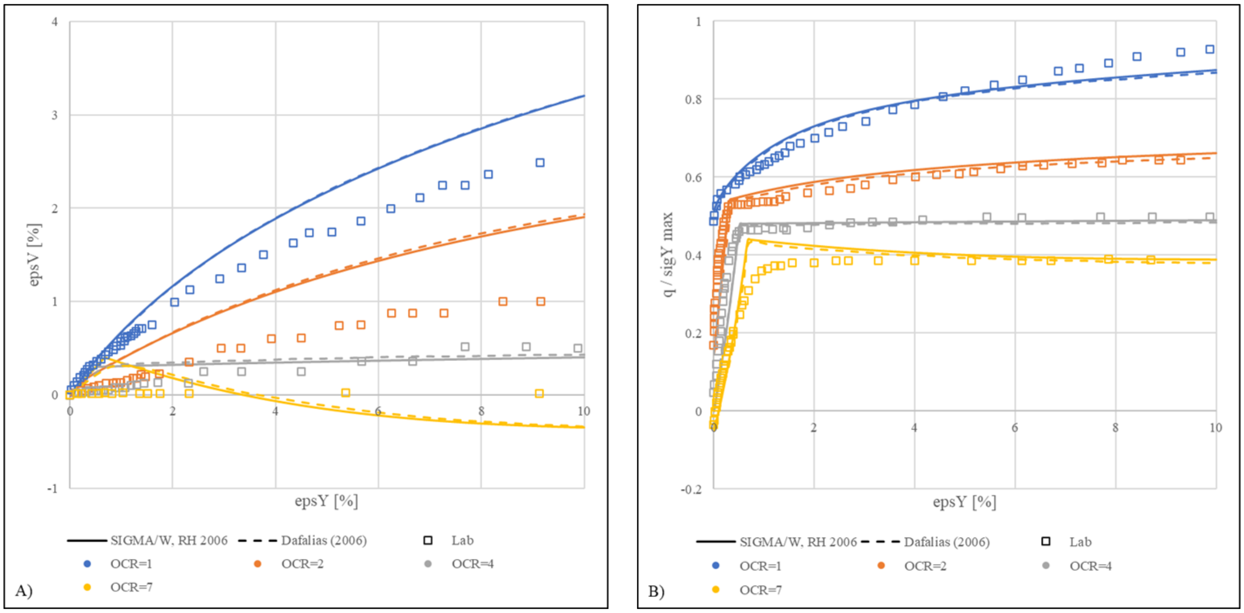

Figure 14. CAD: SIGMA/W Complete stress history (RH 2006) vs Dafalias *et al.* (2006) and lab results (Gens, 1982)

Similar to Figure 14, Figure 15 shows a comparison between the SIGMA/W simulation results and the associated laboratory results, but this time for analysis sequence B, where SANICLAY was initiated from the stresses directly, without modelling the whole stress history leading to overconsolidation. While simulation results from both initiation procedures are slightly different, Figure 15 shows very favorable comparison between simulation results from analysis sequence B and lab data, confirming that initiating SANICLAY from in-place stresses provides acceptable results.

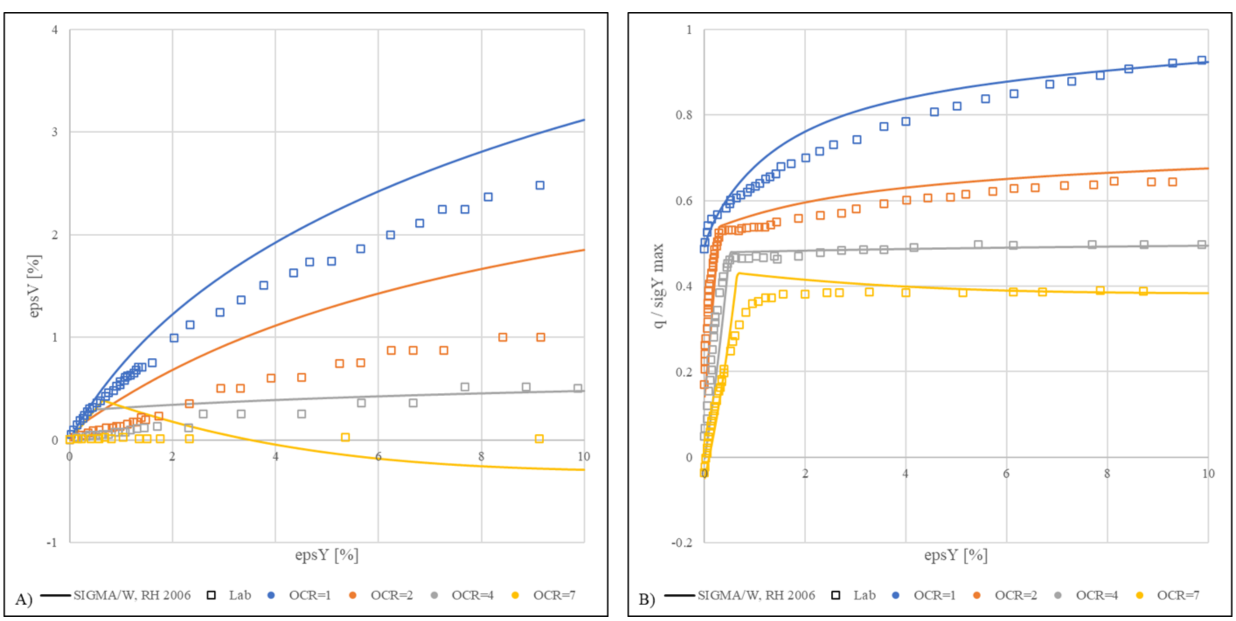

Figure 15. CAD: SIGMA/W Direct stress initialization (RH 2006) vs lab results (Gens, 1982).

As the final part Figure 16 shows the comparison between SIGMA/W results using analysis sequence A (complete stress history initialization using RH 2013) for drained anisotropically consolidated triaxial compression tests (CAD with the associated lab results from Gens (1982). Again, both in terms of volumetric strain and deviatoric stress, simulation results with the new version compare very well with the associated lab results.

Back to the stress initialization procedure, Figure 17 shows the SIGMA/W simulation results and the associated laboratory results, but this time for analysis sequence B. The figure illustrates very satisfactory comparison between simulation results and lab data, confirming that initiating SANICLAY from in-place stresses provides acceptable results for this version too.

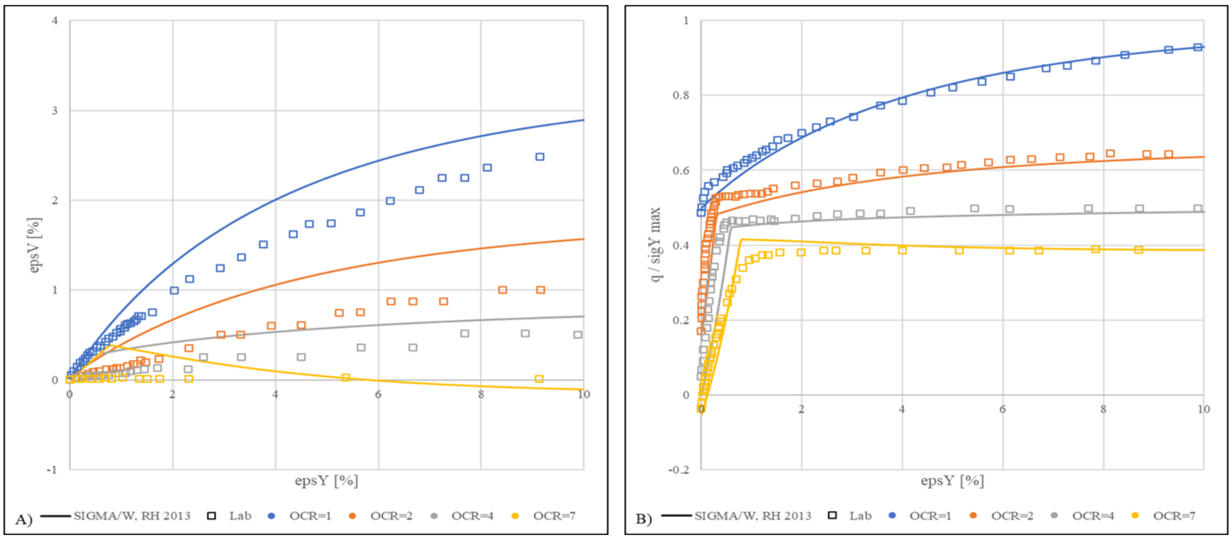

Figure 16. CAD: SIGMA/W Complete stress history (RH 2013) vs lab results (Gens, 1982).

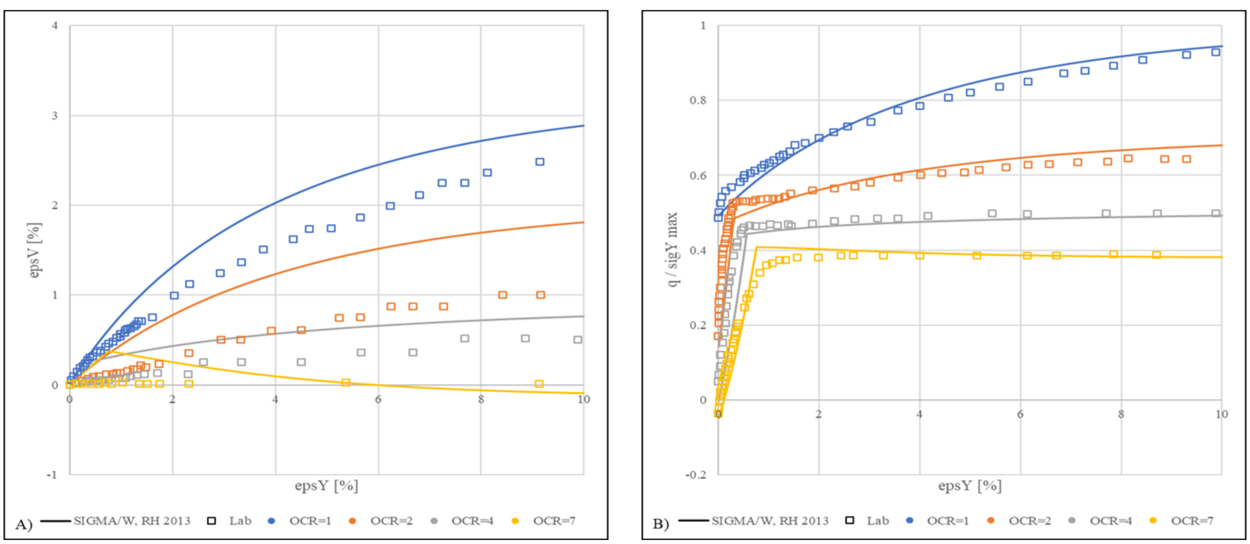

Figure 17. CAD: SIGMA/W Direct stress initialization (RH 2013) vs lab results (Gens, 1982).

Discussion

One of the objectives of this practical example using SANICLAY was to showcase the admissibility of various stress initiation procedures. For the cases presented herein, it was effectively shown that satisfactory results could be obtained from both analysis sequences used.

Analysis sequence A, which relied on simulating the whole stress history (K_0-consolidation followed by K_0-unloading), is the preferred way to be used for stress initialization as it properly tracks how SANICLAY's internal parameters will evolve as applied stresses are changing. On the other hand, analysis sequence B, which used well-known relationships from the literature to initiate stresses (and subsequently calculate SANICLAY's internal parameters) proved to be a reliable alternative. This procedure should preferably only be used when simulating the whole stress history is impossible because of other modelling constraints.

The other purpose was to mention to the difference between two versions of the model based on the rotational hardening rule. It was shown that RH 2013 overcomes the main shortcoming of the SANICLAY model with RH 2006 with loosing some of the model's abilities. Due to the unique aspects of each version, choosing the more fitting hardening rule depends on the observed characteristics of a clay.

Summary and Conclusion

In this example, SANICLAY simulation results from SIGMA/W using two stress initialization procedures were compared to simulation results presented by Dafalias *et al.* (2006) and Dafalias and Taiebat (2013) and to equivalent laboratory test results from Gens (1982). SIGMA/W results with two different rotational hardening rules compared favorably to the authors' data, which confirms the good implementation of the model in the software, both for undrained and drained anisotropically consolidated triaxial compression tests. The two stress initialization procedures compared favorably to laboratory test results, which confirmed that initializing stress directly, without simulating the whole stress history, produced adequate results for both versions of the model. This procedure (analysis sequence B) used well-known relationships from the literature to approximate the starting stresses and the associated SANICLAY inner parameters.

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