PLAXIS

The SHANSEP NGI-ADP model 2018

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TABLE OF CONTENTS

1 INTRODUCTION

The SHANSEP NGI-ADP model (Stress History and Normalised Soil Engineering Properties) constitutes a soil model implemented in PLAXIS, intended for anisotropic undrained soil strength conditions. It enables the analysis of dikes and embankments according to the new design requirements (based upon undrained Critical State calculations) within a FEM environment. The model is based on the NGI-ADP model (Grimstad, Andresen & Jostad (2010)), but modified such that it is able to simulate potential changes of the undrained shear strength S_u, based on the effective stress state of the soil. The model takes into account the effects of stress history and stress path in characterising soil strength and in predicting field behaviour.

1.1 NORMALISED BEHAVIOUR AND THE SHANSEP CONCEPT

Laboratory tests conducted at the Imperial College using remolded clays (Henkel (1960) and Parry (1960)) and at the Massachusetts Institute of Technology on a wide range of clays, give evidence that clay samples with the same over-consolidation ratio (*OCR*), but different consolidation stress σ'_c and therefore different pre-consolidation stress σ'_{pc}, exhibit very similar strength and stress-strain characteristics when the results are normalised over the consolidation stress σ'_c.

Figure 1.1 illustrates idealised stress-strain curves for isotropically consolidated undrained triaxial compression tests on a normally-consolidated clay, with consolidation stresses σ'_c of 200 kPa and 400 kPa. As depicted in Figure 1.2, the stress-strain curves are plotted on top of each other when they are normalised over the consolidation stresses.

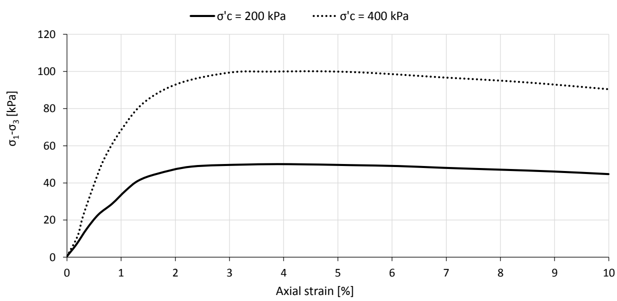

Figure 1.1 Triaxial compression test data of homogeneous clay (Ladd & Foott, 1974)

In practice, normalised behaviour is not as perfect as shown in Figure 1.2. Usually, there is discrepancy in the normalised plots caused by different consolidation stresses, soil deposit heterogeneity or even the fact that the conditions from one soil test to another are not identical. However, this discrepancy is reported to be quite small (Ladd & Foott, 1974) and as a result the observed normalised soil behaviour is adopted in engineering practice. It is worth mentioning that tests on quick clays and naturally cemented soils, which have a high degree of structure, will not exhibit normalised behaviour because the structure is significantly altered during the deformation process (Ladd & Foott, 1974).

The observations of normalised soil behaviour lead to the Normalised Soil Parameter

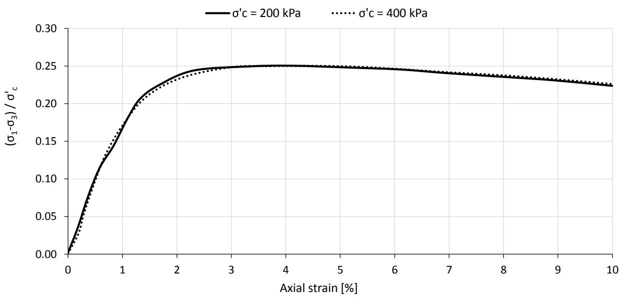

Figure 1.2 Normalised triaxial compression test data of homogeneous clay (Ladd & Foott, 1974)

(NSP) concept. According to NSP, Figure 1.3 illustrates data from Ladd & Foott (1974) which show the variation of the undrained shear strength S_u normalised over the current vertical effective stress σ'_{v0} against the over-consolidation ratio OCR, for five cohesive soils, in correspondence with their index properties. The data show a similar trend of increasing S_u/σ'_{v0} with OCR.

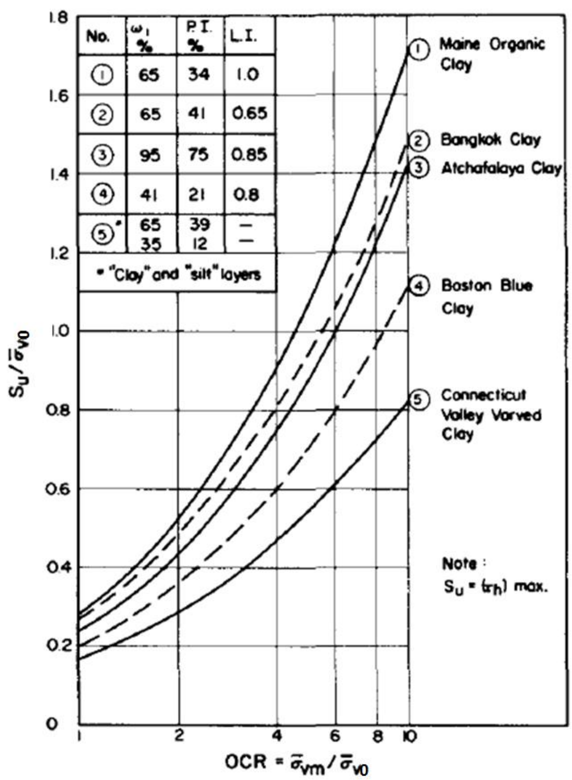

Figure 1.3 Variation of S_u/σ'_{v0} with OCR for five different clays (Ladd & Foott, 1974)

2 THE SHANSEP NGI-ADP CONSTITUTIVE MODEL

Stress History and Normalised Soil Engineering Properties (SHANSEP) is the basis of the constitutive model hereby presented. The stress history of the soil deposit can be evaluated by assessing the *OCR* variation via the current and the pre-consolidation stress profiles. Based on the NSP concept, the undrained shear strength S_u is estimated as:

$$S_u = \alpha\sigma'_1 \left(\frac{\sigma'_{1,max}}{\sigma'_1}\right)^m = \alpha\sigma'_1 (OCR)^m \tag{2.1}$$

in which α and m are normalised soil parameters.

The model is implemented in PLAXIS such that the effective major principal stress σ'_1 is considered to compute the *OCR* and the undrained shear strength. This is thought to be a more objective parameter in comparison with the vertical effective stress σ'_v, as it is the most compressive value, independent of the Cartesian system of axes. Assuming horizontal soil layering, both parameters would result in the same value of *OCR*. However, if the vertical effective stress σ'_v was considered in case of soil slopes, the rotation of principal axes for soil elements adjacent to the slope would result in slightly lower values of *OCR* and S_u respectively.

2.1 THE NGI-ADP MODEL

The NGI-ADP model may be used for bearing capacity, deformation and soil-structure interaction analyses, involving undrained loading of clay. The basis of the material model is:

- Input parameters for (undrained) shear strength for three different stress paths/states, i.e. Active (s_u^A), Direct Simple Shear (s_u^{DSS}) and Passive (s_u^P).
- A yield criterion based on a translated approximated Tresca criterion.
- Elliptical interpolation functions for plastic failure strains and for shear strengths in arbitrary stress paths.
- Isotropic elasticity, given by the unloading/reloading shear modulus, G_{ur}.

The NGI-ADP model is formulated for a general stress state, matching both undrained failure shear strengths and strains to that of selected design profiles (Andresen & Jostad (1999), Andresen (2002), Grimstad, Andresen & Jostad (2010)). The reader may refer to to Chapter 13 of the PLAXIS Material Models Manual for further details upon the model formulation and implementation.

2.2 ON THE USE OF THE SHANSEP NGI-ADP MODEL

The SHANSEP NGI-ADP model is implemented in PLAXIS as a user-defined soil model (UDSM). Prior to using this model, the 'ngiadps64.dll' should be placed in the sub-folder 'udsm' of the folder where PLAXIS 2D and PLAXIS 3D have been saved.

In order to use this model after starting a new project or opening an existing one, the *User-defined* option should be selected through the *Material model* combo box in the

General tabsheet of the *Material sets* window. In the *Parameters* tabsheet, the 'ngiadps64.dll' should be selected as the *DLL file* from the drop-down menu. The 'NGI-ADP-S' is used as the *Model in DLL*. Subsequently, the model parameters can be specified (Section 2.3).

The reader may refer to Chapter 17 of the PLAXIS Material Models Manual for further study on the use of user-defined soil models.

2.2.1 THE 'SWITCH' TO THE SHANSEP CONCEPT

The 'switch' to the SHANSEP concept is done at the beginning of a chosen phase by inserting 1 (or any other odd number) as a *Special option* parameter in the *General* section of the phase calculation parameters (in the Phases menu). This triggers the initialisation of the SHANSEP concept for the activated materials. After the switch, the undrained shear strength s_u^A is calculated by Eq. (2.1) based on the current stress state and the maximum stress in the past, $\sigma'_{1,max}$, according to previous calculation phases or predefined input values.

After the first switch, the calculated undrained shear strength s_u^A is kept constant. The re-initialisation of the s_u^A is possible at a subsequent phase in the same way, by inserting 1 (or any other odd number) as a *Special option* in the *General* section of the phase calculation parameters. The re-initialisation can be done as many times as the user desires. This feature is available as from PLAXIS 2D 2018 and PLAXIS 3D 2018.

In case of using the model in PLAXIS 2D 2017 or PLAXIS 3D 2017, the 'switch' to the SHANSEP concept is activated differently, namely by storing a file in the project folder, i.e. inside the $^*.p2dxdat$ folder for PLAXIS 2D and inside the $^*.p3dat$ folder for PLAXIS 3D. This file should have the following file name format:

data.shansep.rs#

in which the special character # represents the calculation phase number at which the model is switched from the NGI-ADP model to SHANSEP NGI-ADP. Note that depending on the user actions in the *Staged construction* mode, the number mentioned in the name of the calculation phase might be different than the actual phase number used to activate the switch. For instance, this could happen if a new calculation phase is inserted or an already existing one is deleted. Therefore, it is better to verify the phase number by writing the command 'echo phase_#.number ' in the command line, where 'phase_# ' stands for the phase ID.

The SHANSEP NGI-ADP model can also be used in the *Soil Test* facility. In this case, the different activation procedure has to be used. Before each run, the *Soil Test* will search for the presence of a file named 'data.shansep.rs0' . If the file is found then the SHANSEP activation will be executed. Firstly, one run of the *Soil Test* has to be performed in order to create a temporary *Soil Test* facility folder with the path %temp%\VL_xxxx. Then the arbitrary file named 'data.shansep.rs0' has to be stored within that folder.

2.2.2 TRACKING OF $\sigma'_{1,max}$

At the end of each calculation step the Cartesian stress components are transformed to principal stress components (σ'_1, σ'_2, σ'_3) and the maximum major principal stress, $\sigma'_{1,max}$, is kept as a general state parameter. During calculations, $\sigma'_{1,max}$ is updated if the current major principal stress is larger than it. This feature is available as from PLAXIS 2D 2018 and PLAXIS 3D 2017.01.

2.2.3 STATE VARIABLES

The SHANSEP NGI-ADP model provides output on five *State variables*. These parameters can be visualised by selecting the *State parameters* option from the *stresses* menu in the Output program. The *State variables* are:

State variable 1: $\sigma'_{1,max}$ (compression is positive)

State variable 2: s_u^A (shansep)(equals zero before the switch)

State variable 3: γ^p (plastic shear strain)

State variable 4: r_κ (hardening function)

State variable 5: s_u^A (equals s_u^A (shansep) after the switch)

Before the switch to the SHANSEP concept, state variable 2 (s_u^A (shansep)) equals zero. After the switch, it is calculated based on Eq. (2.1). State variable 5 (s_u^A) is calculated based on the input parameters s_u^A and $s_{u,inc}^A$ (Section 2.3). After the switch it is set equal to the state variable 2 (s_u^A (shansep)).

Also, note that during a Safety analysis the value of state variable 2 (s_u^A (shansep)) remains constant and equal to the value obtained after the last (re-)initialisation of the active undrained shear strength (see Eq. (2.1)), while the value of state variable 5 (s_u^A) graudually decreases in order to compute the factor of safety.

The first time that the SHANSEP NGI-ADP model is used in a sequence of calculation phases, the state variables are initialised. The first state variable ($\sigma'_{1,max}$) is the preconoslidation stress and is initialised with the general state variable $\sigma'_{1,max}$ representing the maximum major principal effective stress ever reached. The state variables 1 and 2 are kept constant during the analysis unless the model is re-initialised again.

Hint: In order to create charts of the *State variables* via the *Curves manager* in the Output program, one or more stress points have to be selected after the calculation is completed (post-calculated stress points).

2.3 MODEL PARAMETERS

The SHANSEP NGI-ADP model is formulated such that it initially behaves as the NGI-ADP model until it is switched to the SHANSEP concept by the user (see Section 2.2). It should preferably be used in combination with undrained behaviour. This drainage type can be ignored before switching to the SHANSEP concept by using the calculations option *Ignore undrained behaviour* in the *Phases* window. However, the strength will still be an undrained strength as defined by the initial shear strength profile.

The NGI-ADP model is intended to be used for Undrained (B) analysis. However, for user-defined soil models, such as SHANSEP NGI-ADP, the only available drainage type for undrained behaviour is Undrained (A). Nevertheless, since the strength is defined as udrained shear strength, the SHANSEP NGI-ADP model will actually behave according to the Undrained (B) drainage type.

Since the SHANSEP NGI-ADP model is an extension of the NGI-ADP model, the model parameters can be classified in two groups, i.e. the NGI-ADP model parameters and the SHANSEP parameters. For the 'pre-switching' behaviour only the NGI-ADP model parameters are used.

Since there are dependencies in the NGI-ADP model parameters, there are limitations as to which combinations of values are acceptable. The standard NGI-ADP model in PLAXIS includes checks to evaluate whether or not a valid combination of parameters has been specified. Such checks are not available for user-defined soil models. Therefore, it is strongly recommended to first define a material data set using the standard NGI-ADP model and ONLY IF the parameters are accepted as a valid combination of parameters, a data set should be created using the SHANSEP NGI-ADP model as a user-defined soil model with the same NGI-ADP model parameters. If an invalid combination of model parameters is used in the SHANSEP NGI-ADP model, an error will occur during the calculation.

Table 2.1 gives an overview of all model parameters. Only the SHANSEP parameters will be discussed in the next section. For the NGI-ADP model parameters the reader may refer to Section 13.2 of the PLAXIS Material Models manual.

Table 2.1 SHANSEP NGI-ADP model parameters

Parameter	Symbol	Description	Unit
NGI-ADP model parameters	G_{ur}/s_u^A	Ratio unloading/reloading shear modulus over (plane strain) active shear strength	-
	γ_f^C	Shear strain at failure in triaxial compression	%
	γ_f^E	Shear strain at failure in triaxial extension	%
	γ_f^{DSS}	Shear strain at failure in direct simple shear	%
	$s_{u,ref}^A$	Reference (plane strain) active shear strength	kN/m^2
	y_{ref}	Reference depth	m
	$s_{u,inc}^A$	Increase of shear strength with depth	kN/m^2/m
	s_u^P/s_u^A	Ratio of (plane strain) passive shear strength over (plane strain) active shear strength	-
	τ_0/s_u^A	Initial mobilisation	-
	s_u^{DSS}/s_u^A	Ratio of direct simple shear strength over (plane strain) active shear strength	-
	ν'	Poisson's ratio	-
	ν	Poisson's ratio (undrained)	-
SHANSEP parameters	α	Coefficient	-
	m	Power	-
	$s_{u,min}^A$	Minimum shear strength	kN/m^2

2.3.1 SHANSEP PARAMETERS α AND m

Based on Eq. (2.1), the α parameter represents the value of s_u^A/σ'_1 for a normally-consolidated soil (*OCR* = 1). The power *m* is the value to which the *OCR* is raised. The magnitude of *m* represents the rate of strength increase with *OCR*.

Ladd & DeGroot (2003) indicate that for most clayey soil types, α = 0.22 $\pm$ 0.03 and *m* = 0.80 $\pm$ 0.1. Results of SHANSEP tests performed by Seah & Lai (2003) on soft Bangkok clay, which is a marine silty clay in the central area of Thailand, suggest the values of α_c = 0.265 and m_c = 0.735 for compression tests and α_e = 0.245 and m_e = 0.890 for extension tests.

Santagata & Germaine (2002) studied the effects of sampling disturbance by conducting single element triaxial tests on normally-consolidated resedimented Boston blue clay (RBBC). The SHANSEP parameters obtained by undrained triaxial compression are α_i = 0.33 and m_i = 0.71 for the intact RBBC, and α_d = 0.33 and m_d = 0.83 for the disturbed RBBC.

Based on the studies presented above, it can be concluded that both SHANSEP parameters α and *m* are stress path dependent. Even though the range of variation of both parameters α and *m* is not wide, the proper way to estimate them is via calibration of SHANSEP triaxial test results.

Figures 2.1 and 2.2 present the influence of both parameters on the normalised shear strength over the *OCR*. In Figure 2.1 the power *m* is constant and equal to 0.80, while the coefficient α varies from 0.20 to 0.35. In Figure 2.2 the coefficient α is constant and equal to 0.20, while the power *m* varies from 0.75 to 0.90. As expected, both parameters result in an increase of the undrained shear strength as they grow. Variation of the coefficient α has greater influence on the resulting S_u/σ'_1.

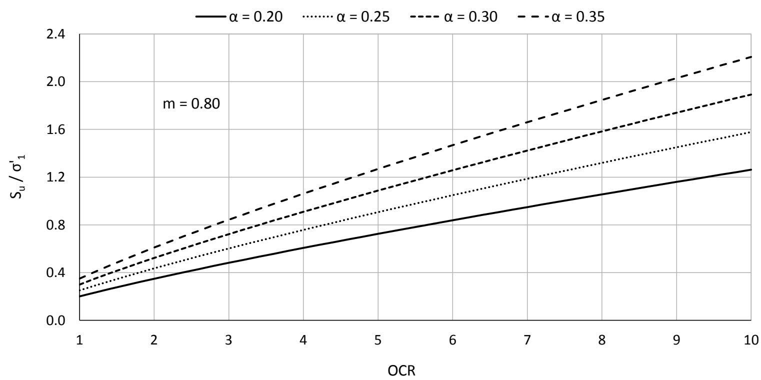

Figure 2.1 Influence of the coefficient α on the normalised undrained shear strength

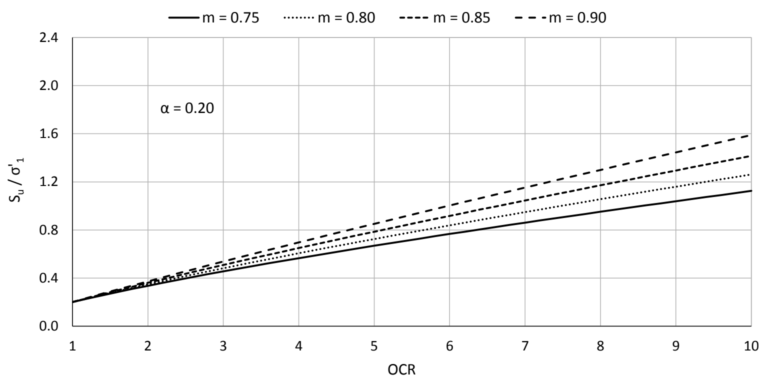

Figure 2.2 Influence of the power *m* on the normalised undrained shear strength

2.3.2 MINIMUM UNDRAINED SHEAR STRENGTH

To prevent zero or very small stiffness (G_{ur}) and strength (s_u^A) at small depths where σ'_1 is equal to or approximately zero, a minimum value of the undrained shear strength $s^A_{u,min}$ can be selected as input parameter. PLAXIS determines the value of s_u^A as:

$$s_u^A = \max\left(\alpha\sigma'_1\left(\frac{\sigma'_{1,max}}{\sigma'_1}\right)^m,\ s^A_{u,min}\right) \tag{2.2}$$

Additionally, the calculated ratio $\sigma'_{1,max}/\sigma'_1$ is not allowed to be smaller than 1.

A proper value for $s^A_{u,min}$ can be determined from the field and/or laboratory characterisation of the soil deposit.

2.3.3 INTERFACES TABSHEET

The *Interfaces* tabsheet contains the material data for interfaces, i.e. the interface oedometer modulus, E^{ref}_{oed}, and the interface strength parameters c'_{inter}, ϕ'_{inter} and ψ_{inter}. Hence, the interface shear strength is directly given in strength parameters.

In addition, two parameters are included to enable stress-dependency of the interface stiffness according to a power law formulation:

$$E_{oed}(\sigma'_n) = E^{ref}_{oed}\left(\frac{\sigma'_n}{\text{UD-P}^{ref}}\right)^{\text{UD-Power}} \tag{2.3}$$

where UD-Power, is the rate of stress dependency of the interface stiffness, UD-P^{ref} is the reference stress level (usually 100 kN/m^2) and σ'_n is the effective normal stress in the interface stress point.

> **Hint:** PLAXIS will give a warning when a zero interface stiffness or strength is defined, even if no interface elements are being used. In order to avoid this warning, a non-zero cohesion and E^{ref}_{oed} should be specified.

2.3.4 INITIAL TABSHEET

Based on the value of ϕ'_{inter} selected in the *Interfaces* tabsheet, the lateral stress coefficient at rest K_0 is automatically calculated as a default value to set up the initial horizontal stress as:

$$K_0 = 1 - \sin(\phi'_{inter}) \tag{2.4}$$

However, note that this value is based on the *interface friction angle* rather than the soil friction angle, since SHANSEP NGI-ADP does not have friction angle as a model parameter. The suggested value may be changed by the user.

2.4 MODELLING THE UNDRAINED BEHAVIOUR

During the initial phase(s), before switching to the SHANSEP concept, undrained behaviour can be ignored by selecting the calculations option *Ignore undrained behaviour* in the *Phases* window. After switching to the SHANSEP concept, the model behaves similarly to the *Undrained (B)* NGI-ADP model. However, as discussed below, the SHANSEP NGI-ADP model is advantageous in comparison to the classic *Undrained (B)* drainage type of the NGI-ADP model in the sense that the shear strength can be defined and updated based on the (changed) effective stress level.

2.4.1 NGI-ADP MODEL LIMITATION

The undrained shear strength in the NGI-ADP model is given by Eq. (2.5). Such variation of the s_u^A over depth is valid only in case that horizontal soil layers are considered. The reference depth (y_{ref}) is a fixed value throughout the whole model. If the soil deposit is inclined (in case of slope, embankment etc.), according to Eq. (2.5), as depth increases, s_u^A increases as well along the surface. This leads to a non-realistic distribution of the undrained shear strength.

$$s_u^A(y) = s_{u,ref}^A + (y_{ref} - y)\, s_{u,inc}^A \qquad y < y_{ref} \tag{2.5}$$

2.4.2 THE ADVANTAGE OF THE SHANSEP NGI-ADP MODEL

The SHANSEP NGI-ADP model gives the advantage of a realistic, empirical way of modelling the undrained shear strength s_u. Figure 2.3 illustrates a comparison between the real behaviour of a soft soil (a) and the SHANSEP NGI-ADP concept (b) in terms of the effective stress path (ESP) in $p' - q$ plot. During the first undrained loading the model behaves as the NGI-ADP model Undrained (B). A consolidation phase is introduced afterwards and the effective stress increases, reaching the Re-initiation Point 1 (RP_1). At that point the switch to the SHANSEP model occurs (see Section 2.2) and the undrained shear strength is updated from its initial value $s_u^{initial}$ to $s_u^{updated\_1}$. The same process is repeated again after the next undrained loading and the subsequent consolidation, leading to the updated undrained shear strength $s_u^{updated\_2}$. This behaviour constitutes a better approach to reality in comparison with the standard NGI-ADP model, in which no update of the undrained shear strength occurs.

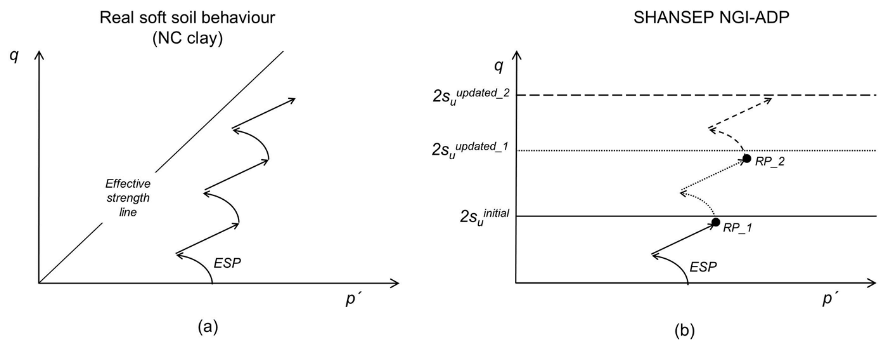

Figure 2.3 Undrained behaviour of real soft soil (a) and SHANSEP NGI-ADP model (b)

Hint: It is suggested that the consolidation phase does not lead to deviatoric stress equal to the undrained shear strength, e.g. that the Re-initiation Point 1 (*RP*_1) in Figure 2.3 stays below the $2s_u^{initial}$ cap. If the opposite occurs, it is suggested to split the consolidation phase in more than one phases with shorter consolidation times and then re-initiate the undrained shear strength after each one of them.

2.5 THE SHANSEP NGI-ADP MODEL IN COMBINATION WITH OTHER CONSTITUTIVE MODELS

Apart from using the SHANSEP NGI-ADP model merely as a NGI-ADP model and then switching to the SHANSEP concept as described in Section 2.2, it is possible to use it as an 'extension' of any other constitutive model implemented in PLAXIS.

To switch from another soil model to the SHANSEP NGI-ADP model, the process described in Section 2.2 has to be followed. However, apart from the use of the *Special option* parameter to activate the SHANSEP concept, as described in Section 2.2.1, the material of the soil cluster also has to be changed to the SHANSEP NGI-ADP model.

$\sigma'_{1,max}$ is always calculated at the beginning of the calculations and updated during the calculation progress, irrespective from the constitutive model being used. So, after an advanced constitutive model (or any other PLAXIS model) has been used, if the material is switched to the SHANSEP NGI-ADP model and the SHANSEP concept is activated, then the current $\sigma'_{1,max}$ is used in relation to the current effective stress state to calculate (re-initiate) the undrained shear strength according to the SHANSEP formula (Eq. (2.1)). The evaluation of the SHANSEP formula based on $\sigma'_{1,max}$ is available as from PLAXIS 2D 2018 and PLAXIS 3D 2017.01.

3 CONCLUSIONS

The SHANSEP NGI-ADP model is an advanced constitutive model developed to enable the analysis of dikes and embankments according to the new design requirements (based upon undrained Critical State calculations) within a FEM environment. It overcomes limitations of the traditional NGI-ADP model with respect to the varying undrained shear strength of soils due to load history. Three additional input parameters are needed for this model, namely α, m and $s^A_{u,min}$. They are used to calculate (update) the undrained shear strength s^A_u dependent on the effective stress history by using the SHANSEP concept. The effect of parameters α and m was investigated and the results show that the effect of α is more dominant. However, the range of variation of these two parameters is short.

4 REFERENCES

[1] Andresen, L. (2002). Capacity analysis of anisotropic and strain-softening clay. Ph.d. thesis, University of Oslo, Institute of Geology.

[2] Andresen, L., Jostad, H.P. (1999). Application of an anisotropic hardening model for undrained response of saturated clay. Proc. NUMOG VII, 581–585.

[3] Grimstad, G., Andresen, L., Jostad, H.P. (2010). Anisotropic shear strength model for clay. International Journal for Numerical and Analytical Methods in Geomechanics, (Accepted for publication).

[4] Henkel, D.J. (1960). The shear strength of saturated remolded clays. In Proceedings of the ASCE Specialty Conference on Shear Strength of Cohesive Soils. University of Colorado, Boulder, 533–554.

[5] Ladd, C.C., DeGroot, D.J. (2003). Recommended practice for soft ground site characterization: Arthur casagrande lecture. In Proceedings of the 12th Panamerican Conference on Soil Mechanics and Geotechnical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.

[6] Ladd, C.C., Foott, R. (1974). New design procedure for stability of soft clays. Journal of the Geotechnical Engineering Division, 100(7), 763–786.

[7] Parry, R.H.G. (1960). Triaxial compression and extension tests on remoulded saturated clay. Géotechnique, 10(4), 166–180.

[8] Santagata, M.C., Germaine, J.T. (2002). Sampling disturbance effects in normally consolidated clays. Journal of Geotechnical and Geoenvironmental Engineering, 128(12), 997–1006.

[9] Seah, T.H., Lai, K.C. (2003). Strength and deformation behavior of soft bangkok clay. Geotechnical Testing Journal, 26(4), 421–431.