ZSoil

for geotechnics & structures

VIRTUAL LAB USER GUIDE

Report 120201

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Contents

REFERENCES **87**

Disclaimer: the automatic parameter selection relies on statistical data and empirical correlations. It is user's responsibility to verify the suitability of parameters for a given purpose, in particular by verifying reproducibility of available experimental results and by adjustment of parameters. The validation of parameters should also be carried out for the parameters identified from experimental curves.

Sign convention: Throughout this report, the sign convention is the standard convention of soil mechanics, i.e. compression is assigned as positive.

List of Symbols

Stress and Strain Notation

ε	strain
ε_v	volumetric strain $= (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$
γ_s	shear strain
σ	stress
τ	shear stress
p	total mean stress $= \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$
p'	mean effective stress
q	deviatoric stress $= \frac{1}{\sqrt{2}}[(\sigma_1 - \sigma_2)^2 + + (\sigma_2 + \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$

Roman Symbols

s_u	undrained shear strength
E_0	maximal soil stiffness
e_0	initial void ratio
E_oed	tangent oedometric modulus
$E_\mathsf{oed}^\mathsf{ref}$	reference tangent oedometric modulus correpsonding to the vertical reference stress $\sigma_\mathsf{oed}^\mathsf{ref}$
E_0^ref	reference maximal soil stiffness corresponding to the reference stress σ_ref
E_s	secant modulus corresponding to 50% of q_f
E_s^ref	reference secant modulus corresponding to 50% the reference stress σ_ref
E_ur	unloading-reloading stiffness modulus
$E_\mathsf{ur}^\mathsf{ref}$	reference unloading-reloading stiffness modulus corresponding to the reference stress σ_ref
G_0	(or G_max) maximal small-strain shear modulus
I_P	plasticity index $(= w_L - w_P)$
K_0	coefficient of *in situ* earth pressure "at rest" ($K_0 > K_0^\mathsf{NC}$ for $\mathrm{OCR} > 1$)
K_0^NC	coefficient of earth pressure "at rest" of normally-consolidated soil
K_0^SR	stress reversal K_0 coefficient defining stress point position at intersection between hardening mechanisms
q^POP	($=\sigma'_{v0} + \sigma'_c$) preoverburden pressure
B_q	pore pressure parameter for CPTU
c	cohesion intercept
c^*	intercept for M^* slope in $q - p'$ plane ($=6c\cos\phi/(3 - \sin\phi)$)
C_c	slope of the normal compression line in $\log_{10}$ scale ($=2.3\lambda$)
C_k	coefficient of curvature ($=d_{30}^2/(d_{10}\cdot d_{60})$
C_N	overburden correction factor for SPT N_{60}-value
C_r	slope of unload-reload consolidation line in $\log_{10}$ scale
C_u	coefficient of uniformity ($=d_{60}/d_{10}$)
D	scaling parameter (by default =1.0 for HS-Std, =0.25 for HS-SmallStrain)
D_r	relative density
E	Young's modulus
e	void ratio
E_D	dilatometer modulus ($= 34.7(p_1 - p_0)$)
E_s	"static" stiffness modulus corresponding to $\varepsilon_1 = 0.1\%$
E_s^ref	reference "static" stiffness modulus corresponding to the reference stress σ_ref
e_{max}	maximal void ratio
f_p	fines content, content of particles smaller than 0.06 mm
f_t	limit tensile strength
G	tangent shear modulus

G_{ur}	unload-reload shear modulus
G_s	secant shear modulus
H	parameter which defines the rate of the volumetric plastic strain
I_C	consistency index ($= w_L - w_n / I_P$)
I_D	dilatometer material index ($= (p_1 - p_0)/(p_0 - u_0)$)
K_D	dilatometer horizontal stress index ($= (p_0 - u_0)/\sigma'_{v0}$)
M	parameter of HS model which defines the shape of the cap surface
m	stiffness exponent for minor stress formulation
M^*	(or M_c^*) slope of critical state line ($= 6 \sin \phi'_c/(3 - \sin \phi'_c)$)
M_e^*	slope of critical state line ($= 6 \sin \phi'_c/(3 + \sin \phi'_c)$)
M_{DMT}	constrained modulus derived from the Marchetti's dilatometer
M_{D}	one-dimensional drained constrained modulus
m_p	stiffness exponent for p'-formulation
n^{VG}	measure of pore-size distribution in the Van Genuchten model
p_0	corrected first DMT reading
p_1	corrected second DMT reading
p_c	effective preconsolidation pressure in terms of mean stress
p_{atm}	atmospheric pressure (average sea-level pressure is 101.325 kPa)
p_{co}	initial effective preconsolidation pressure
q_c	cone resistance
q_f	deviatoric stress at failure
Q_t	normalized cone resistance for CPT
q_t	corrected cone resistance
q_u	unconfined compressive strength
R_f	failure ratio ($= q_f/q_a$)
u	pore pressure
V_s	shear wave velocity
w_L	liquid limit
w_n	natural moisture content
w_P	plastic limit
z	depth
OCR	overconsolidation ratio ($= \sigma'_c/\sigma'_{vo}$)
PI	plasticity index

Greek Symbols

α	parameter of soil water retention curve (SWRC) by van Genuchten's model
γ_{SAT}	unit weight of saturated soil
γ_B	buoyant unit weight
γ_D	dry unit weight
γ_F	fluid unit weight
γ_S	skeleton unit weight
γ_s	shear strain
γ_w	water unit weight
$\gamma_{0.7}$	value of small strain for which G_s/G_0 reduces to 0.722
κ	slope of unload-reload consolidation line in $\ln$ scale
Λ	plastic volumetric strain ratio ($= 1 - \kappa/\lambda$)
λ	slope of primary consolidation line in $\ln$ scale
ν	Poisson's coefficient
ν_{ur}	unloading/reloading Poisson's coefficient
ϕ	friction angle
ϕ'_c	effective friction angle from compression test
ϕ'_e	effective friction angle from extension test
ϕ'_{tc}	effective friction angle determined from triaxial compression test
ψ	dilatation angle
ρ	soil density
σ'_c	effective vertical preconsolidation stress
σ_L	minimal limit minor stress
σ_{ref}	reference stress

Abbreviations

CAP	Cap model with Drucker-Prager failure criterion
CPTU	cone penetration test with pore pressure measurements (electric piezocone)
DMT	Marchetti's flat dilatometer test
M-C	Mohr-Coulomb model
MCC	Modified Cam clay model
OED	oedometric test
PMT	Menard's pressuremeter test

SBPT	self-boring pressuremeter test
SCPT	static penetration test with seismic sensor
SPT	standard penetration test
TX-CD	drained compression triaxial test
TX-CU	undrained compression triaxial test
USCS	unified soil classification system

Chapter 1

VIRTUAL LAB

Virtual Lab is an interactive module which provides users with:

- assistance in selecting a relevant constitutive law with regards to the general behavior of the real material
- first-guess parameter estimation based on field test records
- automated parameter selection (first-guess values of model parameters for soil for any incomplete or complete specimen data)
- user-engaged parameter selection (interactive parameter selection which involves browsing different parameter correlations including field test data)
- ranges of parameter values which can be considered in parametric studies
- automated parameter identification from laboratory experimental data including numerical curve-fitting, and filtering for high-resolution and noisy data
- graphical inspection of identification approaches and regression analyzes
- possibility of running numerical simulations of elementary laboratory tests in order to visualize the response of a constitutive model for freely defined model parameters
- possibility of comparing experimental laboratory curves with numerical predictions with identified parameters

1.1 OVERVIEW

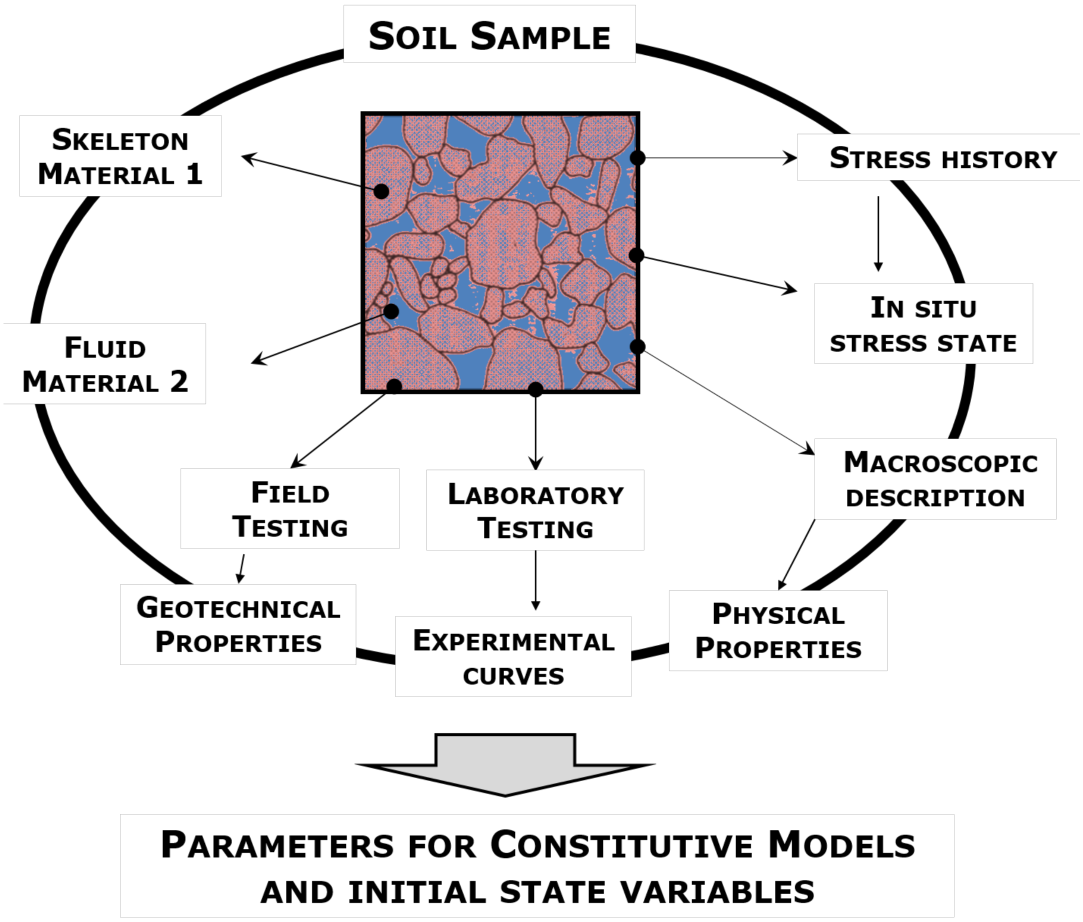
A parameter determination session with **Virtual Lab** corresponds to the analysis of a representative soil sample which can be described by general macroscopic behavior and available previously identified soil characteristics. Moreover, material behavior can be represented in the form of curves which have been obtained via the standard laboratory tests. All of this data can be used during parameter determination by means of one or more of determination approaches:

- Automatic parameter selection (suitable for a quick parameter estimation which relies on default, best-working correlations)

- Interactive parameter selection (detailed statistical analysis based on manual browsing the database of correlations)
- Parameter identification (based on laboratory curves, highly recommended for determinant soil layers which will have a strong influence on a given geotechnical study)

Window 1-1: Parameter determination from the representative soil sample

Z_Soil



Window 1-1

The toolbox can be initialized by clicking on Open Virtual Lab which is available when one of the following continuum models has been chosen as the material definition (Win. 1-2):

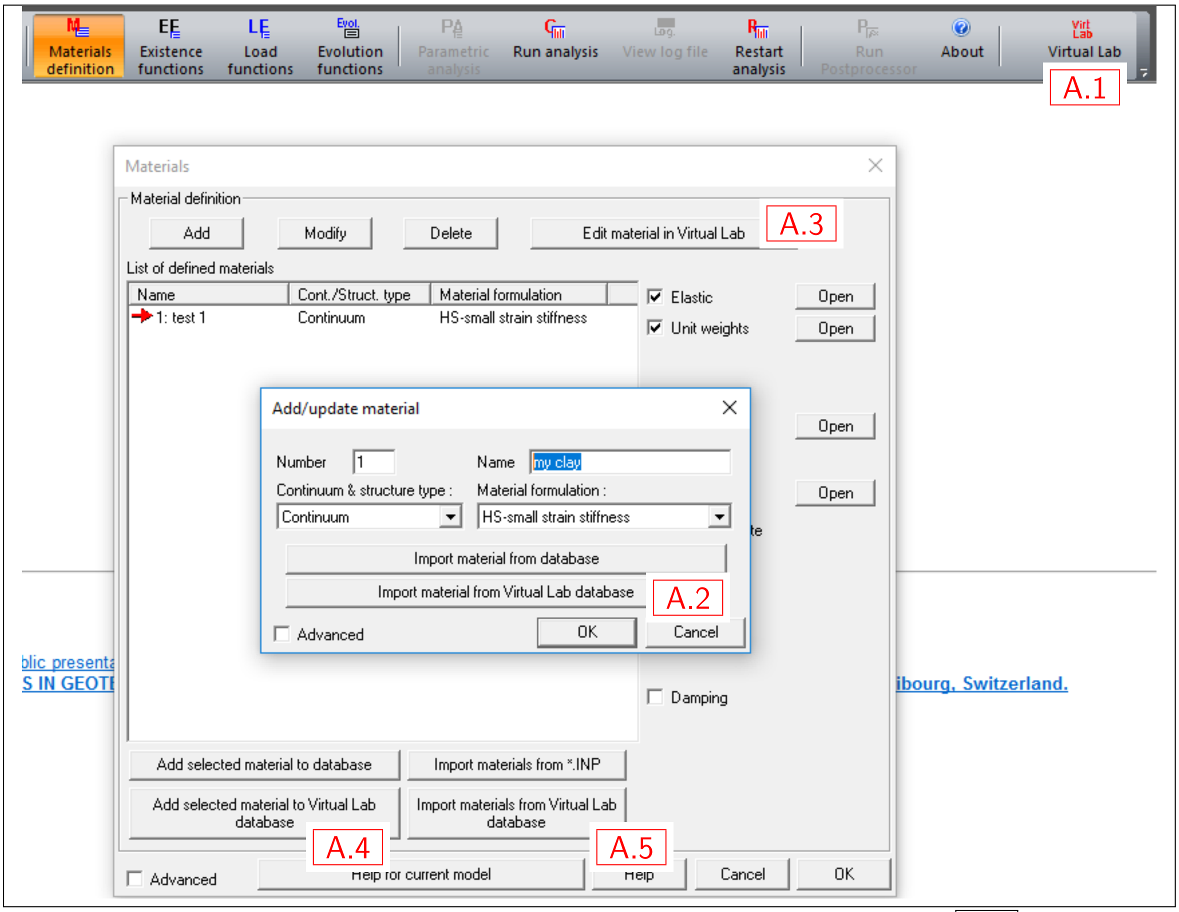
- Mohr-Coulomb
- Hardening-Soil small strain
- Cam-Clay
- Cap model

The current version of the Virtual Lab v2023 is limited to soil analysis with a special reference to the aforementioned constitutive laws. Moreover, the automatic or interactive parameter determination algorithms enables the user to identify parameters for the following groups of characteristics:

- Unit weights
- Fluid weight (considered as the second material filling the skeleton voids)
- Initial K_0 state
- Flow, including estimation of parameters for:
  - ⋆ Darcy's law which describes the fluid flow in a porous medium
  - ⋆ van Genuchten's model which defines the soil water retention curve (van Genuchten, 1980; Yang et al., 2004) in its simplified form implemented in ZSoil v2023

Window 1-2: Initializing the Virtual Lab

Z_Soil



The Virtual Lab can be directly called from the main ZSoil toolbar menu A.1. When opening, the Material Database Manager appears first to prompt the user to select a new or an existing material to be edited. Next the parameter identification session starts in the main module of the Virtual Lab.

The Virtual Lab can also be accessed from the *Material* dialog A.3 (NB. the button *Edit material in Virtual Lab* is visible only if Mohr-Coulomb, Hardening-Soil Small Strain, Cam-Clay or Cap model formulation is defined). Using A.3, a user will be asked whether a new material should be added to Virtual Lab 's Material Database; otherwise, the data generated during a parameter identification session will be saved in a *pid* file, in the same folder of the FE model.

The remaining buttons make it possible to access to the Virtual's Lab Material Database see Win.1-3: A.2 to import an existing material from the database, A.4 to add a new material to the database, and A.5 to import many materials to the model material list.

Window 1-2

Using the Virtual Lab v2023 , the following general rules apply for any parameter determination session or method:

§1

All-at-once principle: A single determination method extracts all possible knowledge from the soil sample regardless of the currently selected constitutive model.

The whole extracted knowledge is saved and can be reused for any available material model formulation.

§2

The user-predefined (known) parameters which describe the representative soil sample remain fixed and unchanged during any automatic or interactive parameter selection.

These fixed parameter values are also used by correlations for the inter-correlated parameters (parameters that are identified based on the fixed parameters).

§3

Stress dependent stiffness characteristics of soil are transformed to the user-defined reference stress value by means of the power law which is used in the standard formulation of the Hardening-Soil Model (Win.2-15).

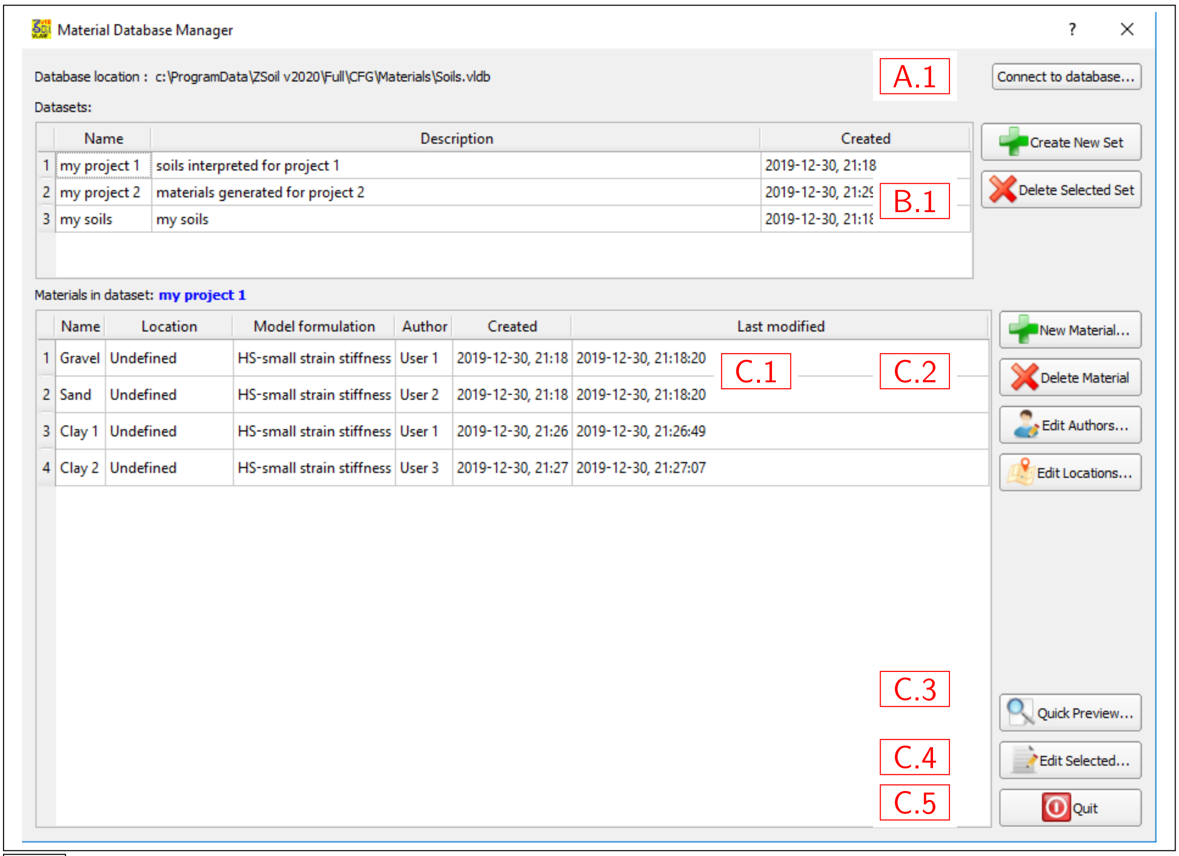
It means that soil stiffness depends on the stress level, and therefore in the *in-situ* stress state, it increases as depth below the ground surface increases.

1.2 MATERIAL DATABASE

The Virtual Lab offers an integrated material database management system. The Material Database Manager allows users to systematically collect, modify and access the analyzed materials. Since the database is developed based on SQL techniques, many users can work with a shared database (same connection) at the same time.

Window 1-3: Material Database Manager

Z_Soil



A.1 connect to different databases (databases can be stored in shared locations like servers); the default database is created in ZSoil's Program Data folder

B.1 manage data sets; e.g. groups of soils or specific projects

C.1 browse materials in the data set selected in B.1; name, location and author can be modified at any time

C.2 add/delete material, manage detailed records of authors and locations

C.3 preview values of model parameters which were modified and saved after the last modification

C.4 edit a material selected in C.1 by starting a Virtual Lab session

C.5 quit/exit Material Database Manager and Virtual Lab

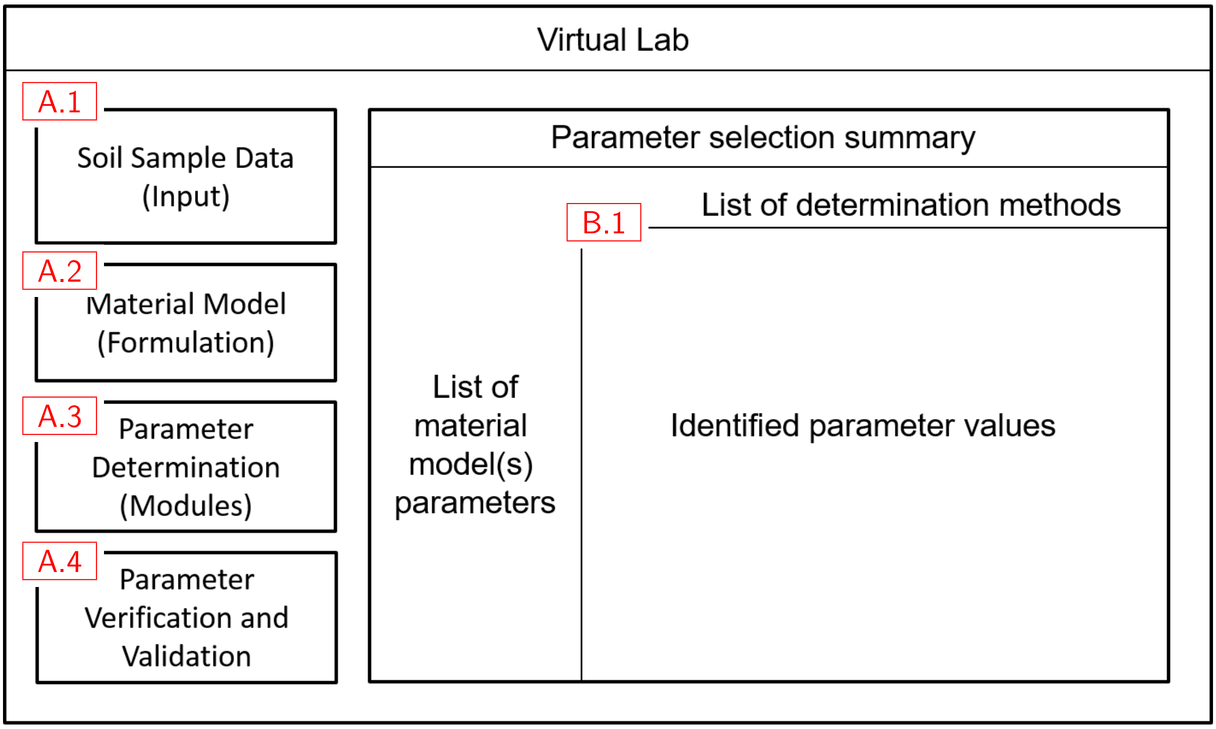
Window 1-3

1.3 ARCHITECTURE

A parameter identification session in the Virtual Lab is an analysis of the "representative sample" of a real material. Therefore, the real material should be described by means of representative values of material properties which can be obtained from a statistical analysis of a number of soil samples or field tests.

Window 1-4: General architecture of the Virtual Lab

Z_Soil



Window 1-4

The Virtual Lab consists of the following main modules:

A.1 **Soil sample data input** which allows the real material to be described by means of:

- its general behavior type
- known physical properties measured through laboratory tests or known mechanical characteristics
- field test results obtained in the considered soil layer

A.2 **Material model formulation** which makes it possible to:

- change the material model at anytime during a parameter determination session
- activate the assistance in material model selection which relies on user-preselected Material Behavior Type

A.3 **Parameter determination modules** which enables performing:

- quick, automated analysis of the representative soil sample based on default correlations
- interactive analysis of the representative material sample based on user-selected identifying correlations
- automated parameter identification based on laboratory curves obtained with standard laboratory tests

A.4 **Parameter verification and validation** module which makes it possible to:

- simulate standard elementary laboratory tests (triaxial drained, undrained compression and oedometric tests)
- compare the numerical model response with the laboratory curves used to identify the parameters

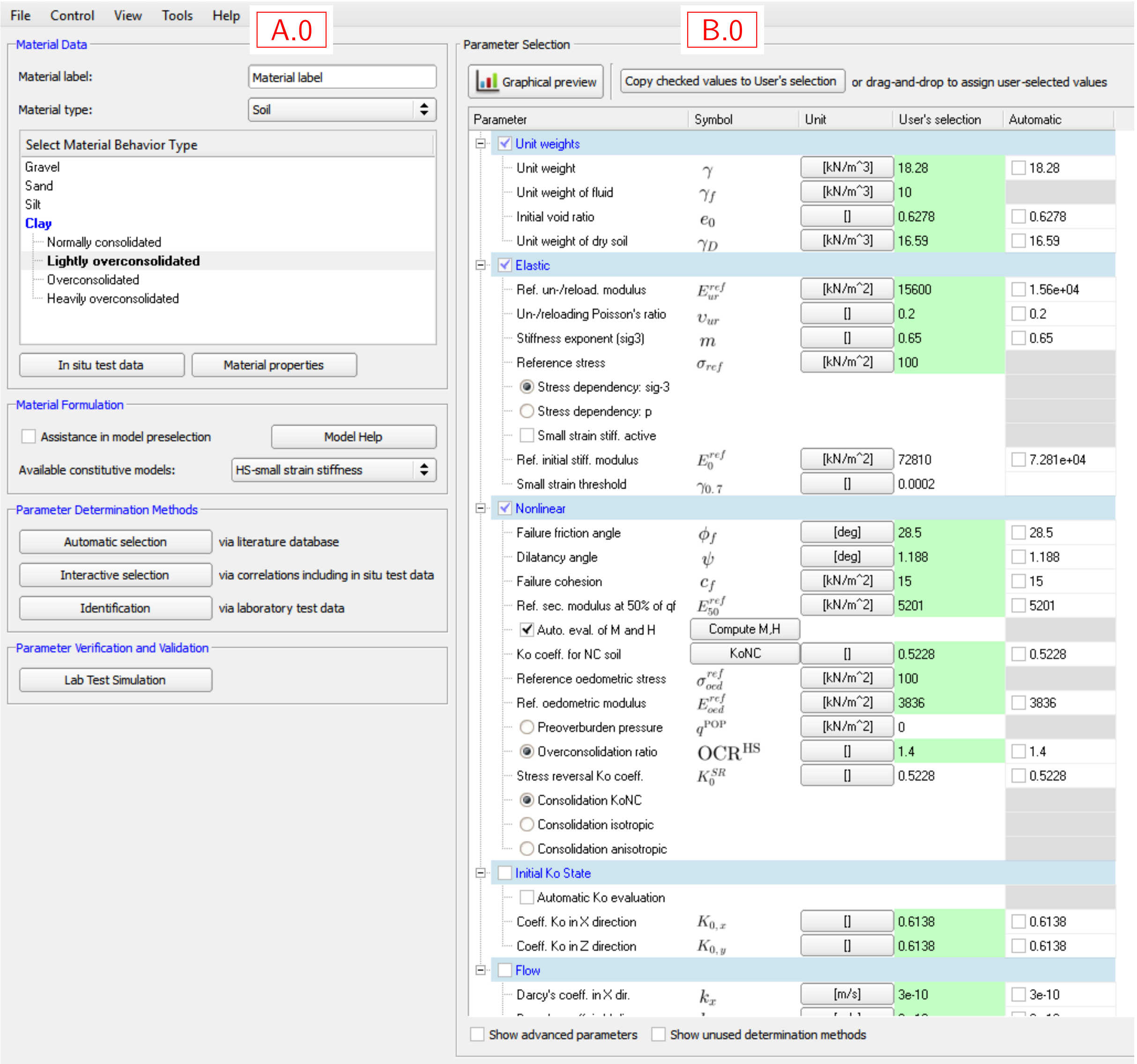
B.1 **Parameter selection summary** allows users to:

- follow the progress of a parameter determination session
- compare results obtained with different determination methods
- select and assign parameter values for the selected constitutive model(s)

1.4 ELEMENTS

Window 1-5: Main window of the Virtual Lab

Z_Soil



The dialog window of the Virtual Lab is divided into the following two main sections which are designed to:

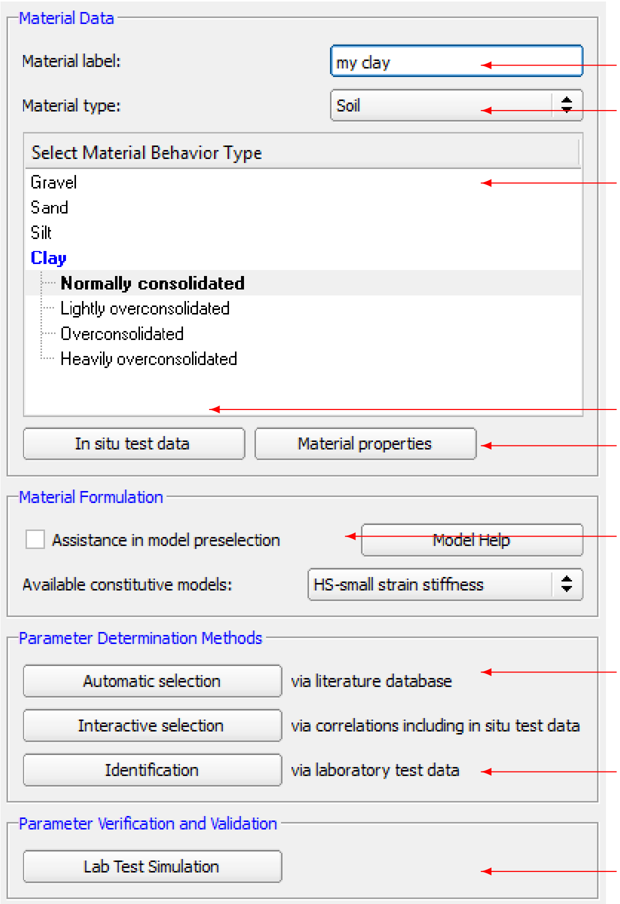
A.0 define material data input including definition of the material type and its main features, selection of the material formulation (a relevant constitutive law), performing parameter identification by means of the different determination approaches (automatic or interactive selection, parameter identification), running a simulation of standard laboratory tests with user-defined parameters.

B.0 post-process the model parameters which have been obtained by means of a number of different determination methods (columns on the right-hand side of the "User's selection" column). The columns with determination methods are hidden until the parameter identification based on a given method has been carried out. The parameters are arranged according to the groups of properties that define soil models in ZSoil v2023 .

Window 1-5

Window 1-6: Material setup and parameter determination methods

Z_Soil



Material label as in main `Material` dialog of ZSoil

General family of the material.
Only *Soils* are available in Virtual Lab v2023

Definition of *Material Behavior Type* and specific material feature which drives the preselection assistant for material model formulation

Definition of field test data
Some in situ tests can help to determine *Material Behavior Type*

Definition of basic material properties specific to preselected *Material Behavior Type*

Activation of the model formulation assistant.
Model is recommended based on the preselected *Material Behavior Type*.

Calls automatic or interactive parameter selection modules - fully automatic or user-engaged parameter determination, respectively

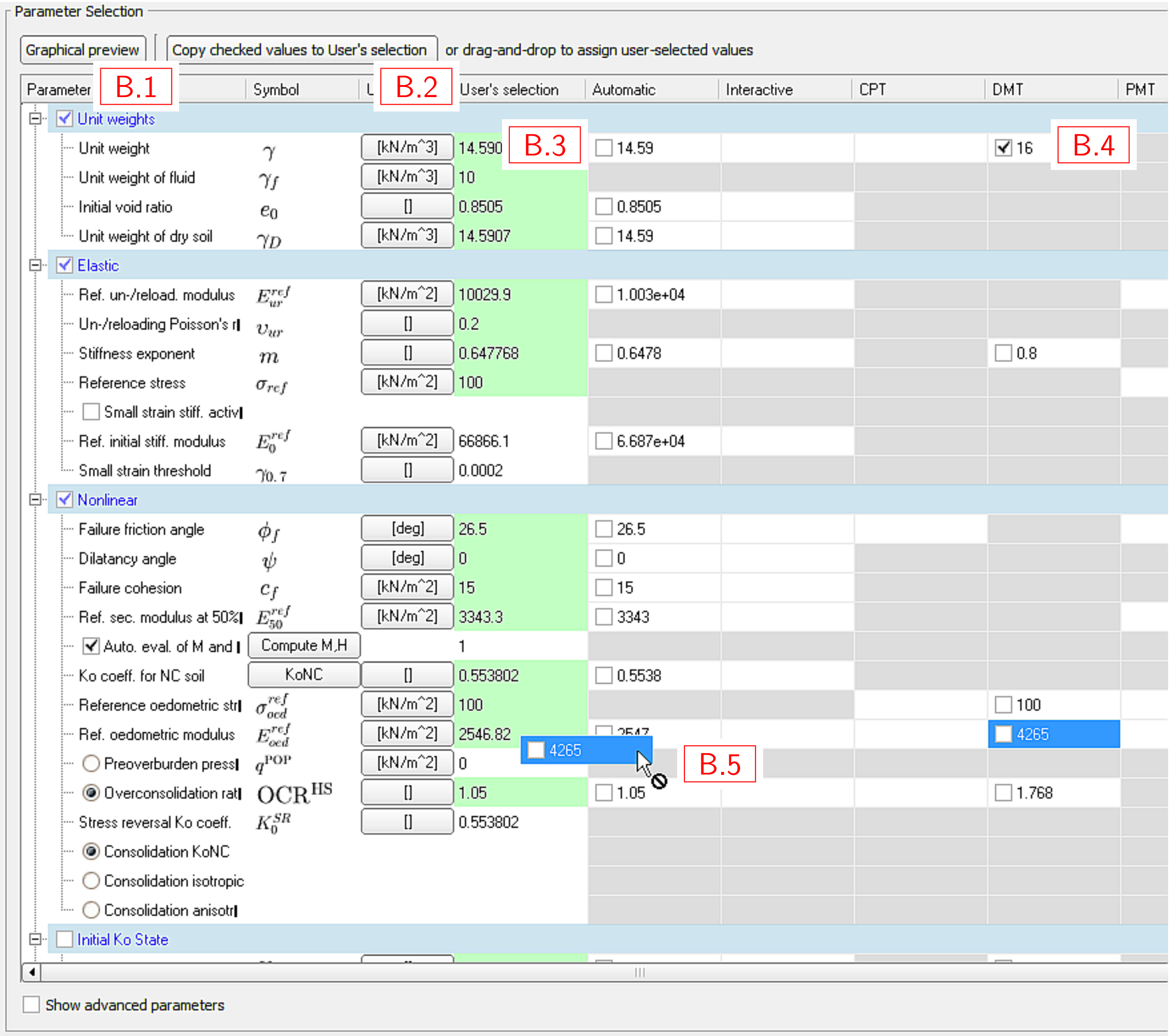
Calls parameter identification module
- automated interpretation of laboratory curves.

Enables running simulation of laboratory tests using user-defined or identified parameter vectors.

Window 1-6

Window 1-7: Post-processing - Parameter Summary

Z_Soil



Elements of the parameter selection summary:

B.1 calls graphical post-processing results

B.2 copy parameter values which are assigned by means of different determination methods (B.4) to the final selection (B.3)

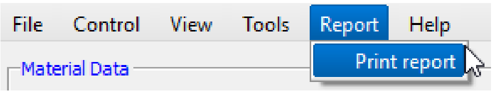
B.3 **values from the green column will be copied the active material in the main** `Material` **dialog of ZSoil** when closing the parameter determination session if the the Virtual Lab was opened with 'Edit material in Virtual Lab ' (see A.3 in Win. 1-2); the parameters from the User's selection will be also retrieved using the importing options A.2 or A.5 in Win. 1-2)

B.4 all checked parameters will be copied to the user's selection column on Copy checked values to User's selection B.5 fast assigning individual parameters with the aid of the drag-and-drop technique

Window 1-7

1.5 AUTOMATIC REPORTING

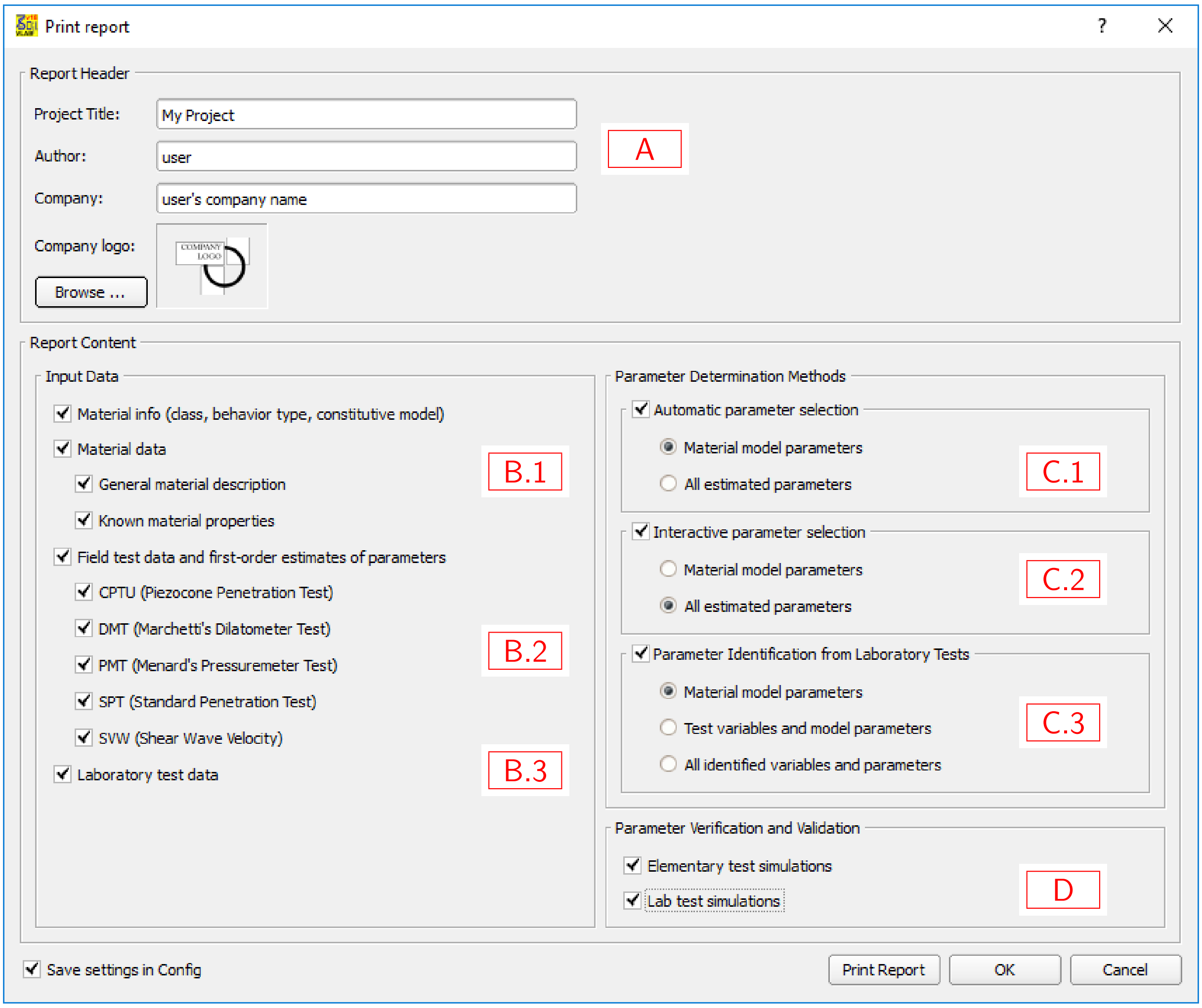
Virtual Lab v2023 offers an automated, user-configured and ready to print reporting. The report, can be printed out at any time during a parameter determination session. This option can be found in the main toolbar.



The report can be configured before printing as shown below.

Window 1-8: Configuration of report content

Z_Soil



The report content to be configured:

A project title, author, company and company's logo will be printed in the report header. This data will be remembered for the next project except for the project title

B.1 general material information including a material class, general behavior and selected constitutive law; all the known properties are listed in tables and charts

B.2 includes input data from *in situ* tests (tables and charts) and first-order predictions

B.3 includes defined experimental tests in the form of tables (initial state) and the most representative charts for a given test

C.1 gives a summary of Automatic Parameter Selection

C.2 gives a summary of Interactive Parameter Selection

C.3 gives a summary of Parameter Identification from experimental data including the selected configuration of identification options

D gives a summary of parameter verification (simulation runs of elementary laboratory tests) and parameter validation (experimental data vs numerical results obtained for identified parameters), including charts and tables with initial state variables and the applied model parameters

Window 1-8

1.6 HOW TO PERFORM A...

1.6.1 ... PARAMETER DETERMINATION

1. Define Material Behavior Type
2. Define macroscopic general material behavior and available material properties and field test data
3. Select the material formulation (constitutive model) for which you would like to determine parameters
4. Perform parameter identification if complete laboratory experimental data are available
5. Perform Automatic Parameter Selection and/or Interactive Parameter Selection
6. Post-process the identified parameters
7. Perform parameter verification or parameter validation by comparing numerical results with experimental data

1.6.2 ... AUTOMATED PARAMETER ESTIMATION

1. Define macroscopic general material behavior and available material properties and field test data
2. Perform Automatic Parameter Selection or/and Interactive Parameter Selection (semi-automated parameter estimation)
3. Perform parameter verification by running elementary laboratory tests

1.6.3 ... PARAMETER IDENTIFICATION FROM LABORATORY CURVES

1. Select the material formulation that you would like to use and press the button *Identification*
2. Insert experimental data from laboratory tests
3. Go to data interpretation, select the test that you would like to interpret and press the button *Interpret selected*
4. Close the parameter identification dialog and perform post-processing of identified results
5. Perform parameter validation by comparing numerical results with experimental data

1.6.4 ... SIMULATION OF A LABORATORY TEST

1. Select the material formulation (constitutive model) that you would like to use
2. Go to Laboratory Test Simulator
3. Choose the laboratory test that you would like to simulate

4. Define initial state variables
5. Define a loading program
6. Specify model parameters
7. Run simulation by pressing *Run selected test*

Chapter 2

MATERIAL DATA INPUT FOR SOILS

In the Virtual Lab , parameter determination algorithms identify material parameters based on the user-provided material data. These data can be specified by means of the two main dialog windows:

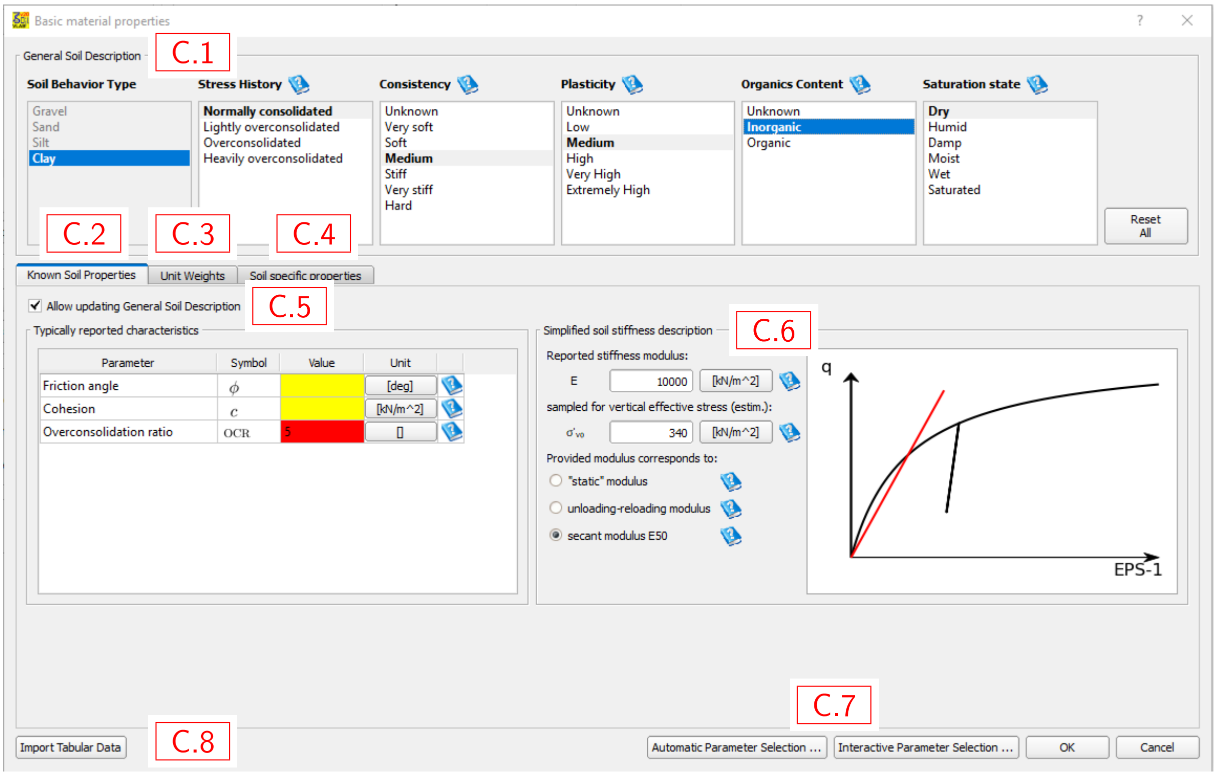
1. Basic material properties which makes it possible to specify:
   - General soil description
   - Generic material properties (commonly recognized geotechnical characteristics)
   - Material type specific properties (parameters of coarse- or fine-grained soils)
2. In situ test data which allows the representative results from field tests to be specified, as well as a quick, first-guess parameter estimation to be carried out for the following commonly applied *in-situ* tests:
   - Cone Penetration Test (CPT)
   - Marchetti's Dilatometer Test (DMT)
   - Menard's Pressurementer Test (PMT)
   - Standard Penetration Test (SPT)
   - Shear wave velocity measurements (SWV)

2.1 BASIC MATERIAL PROPERTIES

The Basic Material Properties dialog window enables the user to introduce physical and mechanical characteristics which are available for a given material.

Window 2-1: Basic material properties for soil

Z_Soil



Window 2-1

C.1 General soil description which best defines observed macroscopic material behavior

C.2 Input of material characteristics typically reported in geotechnical documentation and common for any type of soil

C.3 Input of physical properties such as w_n, γ, γ_s which are used to compute e_0, γ_D, γ_{SAT}, γ_B; they can also be used with many empirical correlations while performing interactive parameter selection

C.4 Group of parameters specific to the soil type, e.g. granular or cohesive soils

C.5 If enabled, the general soil description will be automatically updated when known parameters are specified or modified; if the general soil description is modified by changing any soil feature and the value of parameter is not compatible with the soil feature criterion, the cell with the parameter value will be highlighted in red, as illustrated with the example of OCR

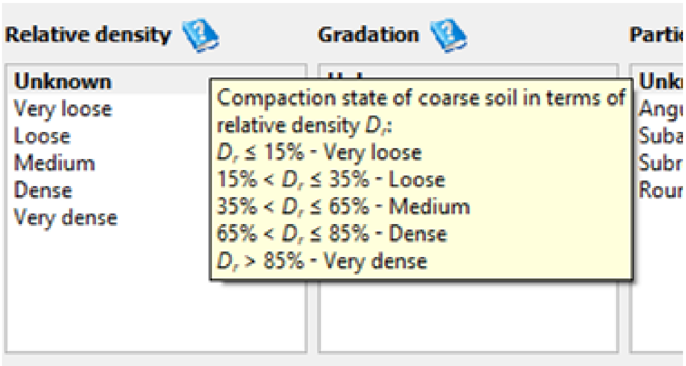
C.6 Simplified soil stiffness description; during parameter selection, the specified modulus will be kept unchanged, however its value will be transformed to the user-defined reference stress σ_{ref} by applying the stiffness power law and corresponding minor stress which is computed based on the provided value of the vertical stress σ'_{v0} and evaluated in situ K_0 coefficient

C.7 Quick access to parameter determination methods
C.8 Importing tabular data collected in ASCII file format

2.1.1 QUICK HELP

Window 2-2: Quick help

Z_Soil



A quick help pops up when the mouse cursor rests over the book icons.

Window 2-2

2.1.2 GENERAL SOIL DESCRIPTION

The general soil description allows the identification algorithm to filter best-working correlations when performing **Automatic Parameter Selection**. A more precise soil description will result in narrower confidence limits for parameters.

Window 2-3: General soil description (1/2)

Z_Soil

Soil Behavior Type	General soil type behavior according to the Unified Soil Classification System (USCS)
Stress History	Overconsolidation state according to geotechnical convention: • $1.0 < \mathrm{OCR} < 1.1$ normally consolidated • $1.1 < \mathrm{OCR} < 2.5$ lightly overconsolidated • $2.5 < \mathrm{OCR} < 5.0$ overconsolidated • $\mathrm{OCR} > 5.0$ heavily overconsolidated
Relative density/ Consistency	Relative soil density or soil consistency depending on general soil type behavior Compaction state of coarse-grained soils in terms of **relative density** D_r: • $D_r <= 15\%$ - Very loose • $15\% < D_r <= 35\%$ - Loose • $35\% < D_r <= 65\%$ - Medium • $65\% < D_r <= 85\%$ - Dense • $D_r > 85\%$ - Very dense Consistency of fine-grained soils in terms of **consistency** index I_C $(= (w_L - w_n)/\mathrm{PI})$: • $I_C < 0.05$ - Very soft • $0.05 < I_C < 0.25$ - Soft • $0.25 < I_C < 0.75$ - Medium • $0.75 < I_C < 1.00$ - Stiff • $I_C > 1.00$ and $w_n > w_s$ - Very Stiff • $I_C > 1.00$ and $w_n < w_s$ - Hard with w - moisture content, w_s - shrinkage limit

Window 2-3

Window 2-4: General soil description (2/2)

Z_Soil

Gradation/Plasticity	Gradation of coarse-grained soil or plasticity of fine-grained soil Coarse-grained soil classification in terms of **gradation**: • Poorly-graded sands $C_u \leq 6$ (and/or $C_k < 1$ $C_k > 3$) • Poorly-graded gravels $C_u \leq 4$ (and/or $C_k < 1$ $C_k > 3$) • Well-graded sands $C_u \leq 6$ (and $1 \leq C_k \leq 3$) • Well-graded gravels $C_u \leq 4$ (and $1 \leq C_k \leq 3$) with C_k - coefficient of curvature, C_u - coefficient of uniformity If the content of fines (particles smaller than 0.06mm) is larger than 12% then coarse-grained soil may be classified as silty or clayey: • Silty if $PI < 4$ or Atterberg's limits below "A" line in the plasticity chart ("A" line: $PI = 0.73(w_L - 20)$) • Clayey if $PI > 7$ or Atterberg's limits above "A" line in the plasticity chart. Fine-grained soil classification in terms of **plasticity** and liquid limit w_L: • $0 < w_L \leq 35\%$ - Low plasticity • $35 < w_L \leq 50\%$ - Medium plasticity • $50 < w_L \leq 70\%$ - High plasticity • $70 < w_L \leq 90\%$ - Very high plasticity • $w_L > 90\%$ - Extremely high plasticity
Shape/Organics	Shape of particles of a coarse-grained soil or existence of organics content in a fine-grained soil General classification in terms of organics content: • Inorganic soil $\mathrm{OC} \leq 3\%$ • Organic silt or clay $3 < \mathrm{OC} \leq 10\%$ • Medium organic soils $10 < \mathrm{OC} < 30\%$ (not supported in v2023) • Highly organic soils $\mathrm{OC} > 30\%$ (not supported in v2023) This classification controls the prediction of deformation characteristics
State	State of soil saturation Automatic Parameter Selection estimates always two types of unit weight: 1. Dry unit weight γ_D (used in *Deformation+Flow* analysis type) 2. Apparent unit weight γ based on the specified degree of saturation S (the apparent weight is used in *Deformation* analysis type) NB. For the *Deformation+Flow* analysis type, the apparent unit weight of each finite element is computed from the dry unit weight γ_D, the current degree of saturation S and the porosity n: $\gamma = \gamma_D + nS\gamma_F$ with γ_F - fluid unit weight

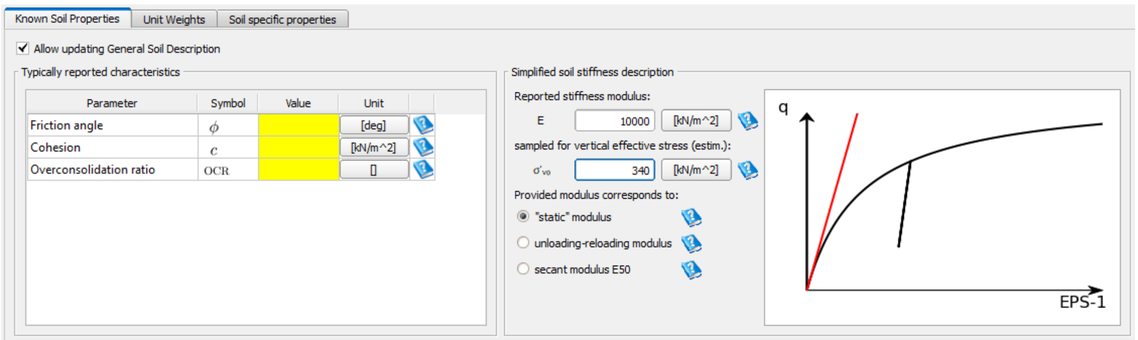
Window 2-4

2.1.3 AUXILIARY NUMERIC DATA

The dialog below makes it possible to specify known values for material characteristics typically reported in geotechnical reports. Some of these parameters are used to adjust the general soil description and can appear as the input in correlations which help to compute or estimate other parameters. **Notice that the user-defined parameters which describe the representative material sample will remain fixed and unchanged during any automatic or interactive parameter selection session**.

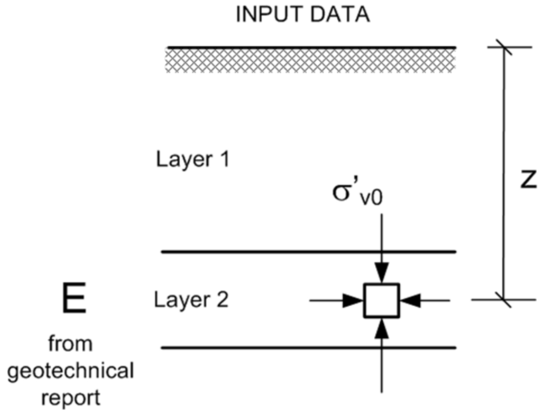
Window 2-5: Content of Known soil properties group and its description

Z_Soil



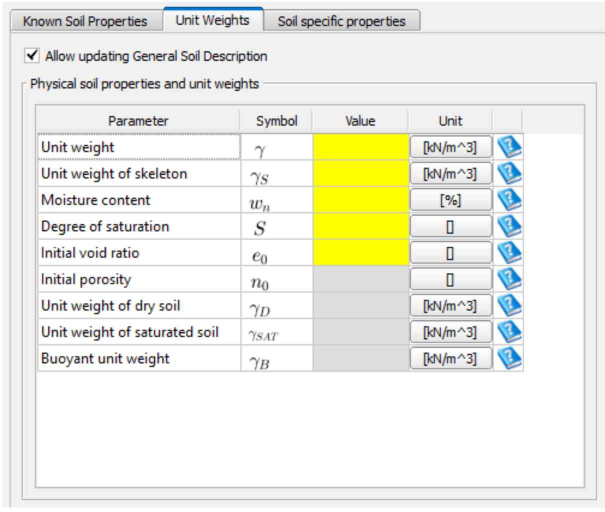
Friction angle	ϕ	Effective friction angle; if specified, it is used to estimate K_0^{NC} and K_0.
Cohesion	c	Effective cohesion which may account for effect of soil cementation (typically for remoulded and saturated soil $c \approx 0$ and the effect of partial saturation, i.e. an apparent cohesion due to suction, can be controlled by parameters α and S_r which define the behavior of partially saturated medium).
Overconsolidation ratio	OCR	Value of OCR which corresponds to the provided representative parameters E, ϕ, c derived at corresponding characterization depth. Specifying or modifying OCR updates *Stress History* setup which is taken into account in estimation of E_0^{ref} for coarse-grained soils.
Reported stiffness modulus	E	The stiffness modulus which is typically delivered in simplified geotechnical reports which provide a single modulus to describe soil stiffness. The modulus must correspond to the vertical effective stress σ'_{v0} at characterization depth or in the middle of a relatively thin geotechnical layer. Since the soil stiffness can be described by many different moduli, the user can precise to which type of modulus, the reported modulus corresponds to. The reported E is taken to assign E_s^{ref}, E_{50}^{ref}, $E_{\mathsf{ur}}^{\mathsf{ref}}$ and E_0^{ref}.
• "Static" modulus	E_s	In this case, it is assumed that the specified modulus is considered to be the stiffness modulus measured at the initial part of the $\varepsilon_1 - q$ triaxial curve (at $\varepsilon_1 \approx 0.1\%$). Note that $E_{50} < E_s < E_{\mathsf{ur}}$.
• Unloading - reloading modulus	E_{ur}	In this case, the specified modulus is considered as the modulus taken from the unloading/reloading part of the triaxial curve $\varepsilon_1 - q$ or other test which allowed the stiffness modulus to be measured in unloading/reloading test conditions.
• Secant modulus	E_{50}	In this case, the specified modulus is considered as that representing the secant stiffness measured at 50% of the failure deviatoric stress $q_f = \sigma_1 - \sigma_3$. If no indication about the genesis of E has been provided, then such an approach is the least conservative.

Window 2-5

Vert. eff. stress at characterization depth or in the middle of soil layer	σ'_{v0}	Estimated vertical effective stress at characterization depth; if not indicated σ'_{v0} can be taken as the effective stress in the middle of a representative soil layer. The stiffness moduli which are estimated based on the provided "reported" stiffness modulus will be scaled to the user-defined reference stress σ_{ref} with respect to the minor effective stress estimated as $\sigma_3 = \min(\sigma'_{v0}, \sigma'_{v0} \cdot K_0)$. If σ'_{v0} is not specified, the minor stress will be taken equal to the user-defined reference $\sigma_3 = \sigma_{\mathsf{ref}}$ kPa (no stiffness scaling applies). 

Window 2-6: Content of Unit weights parameters and its description

Z_Soil



Unit weight	γ	Total unit weight corresponding to natural moisture content w_n. Its magnitude with the value of natural moisture content w_n' and saturation degree S, is used to compute dry unit weight γ_D. In the numerical analysis, γ is used to describe the total soil unit weight for the single phase analysis (Deformation only). If specified, the value will be fixed during automatic or interactive parameter selection.
Unit weight of material skeleton	γ_s	Typical values of specific gravity G_s = solid density / water density: • Gravel - quartz 2.65 • Gravel - silty or clayey $2.66 - 2.68$ • Sand - quartz 2.65 • Sand - silty or clayey $2.66 - 2.68$ • Silt, inorganic $2.62 - 2.68$ • Clay of low plasticity, inorganic $2.67 - 2.70$ • Clay of medium plasticity, inorganic $2.69 - 2.72$ • Clay of high plasticity, inorganic $2.71 - 2.78$ • Clay, organic $2.58 - 2.65$ γ_s also appears in some correlations for C_c.
Natural moisture content	w_n	Typical void ratio and water content when saturated: Soil description: w_{sat} (%) and e (-) • Poorly graded sand: 32 and 0.85 • Poorly-graded sand dense: 19 and 0.51 • Well-graded sand, loose: 25 and 0.67 • Well-graded sand, dense: 16 and 0.43 • Glacial till, very mixed-grained: 9 and 0.25 • Soft glacial clay: 45 and 1.2 • Stiff glacial clay: 22 and 0.6 • Soft slightly organic clay: 70 and 1.9 • Soft very organic clay: 110 and 3.0 • Soft bentonite: 194 and 5.2 The value w_n is used to calculate porosity n_0 and e_0: $e_0 = \gamma_S/\gamma_W \cdot w_n/S$ for $S > 0$ w_n also appears in some correlations which estimate the compression index C_c.

Window 2-6

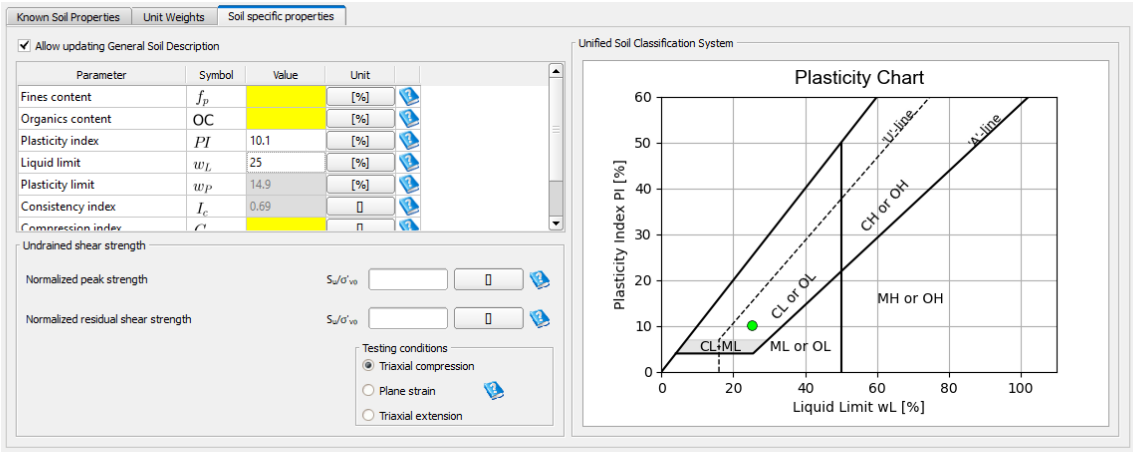
Degree of saturation	S	Measured or estimated degree of soil saturation at *in-situ* stress conditions. Introducing or changing the value of S updates the **State setup**. The value S is used to calculate dry unit weight from $\gamma_D = \gamma_S \cdot n_0 \cdot \gamma_W$.
Initial void ratio	e_0	Estimated void ratio at *in-situ* stress conditions. The number will be automatically updated once n_0 has been modified in the Physical Soil Properties table. Any change of e_0 will update γ_{SAT} if γ_D and γ are introduced be the user.
Initial porosity	n_0	Estimated porosity at *in-situ* stress conditions.
Weight of dry soil/ weight of saturated soil	γ_D / γ_{SAT}	γ_D corresponds to "dry" soil state when the degree of saturation is equal to 0 (in the *Deformation+flow* analysis type, γ_D is used to calculate total unit weight accounting for saturation degree), whereas γ_{SAT} is the weight of fully saturated soil ($S = 1$). The unit weight of a dry soil γ_D can computed based on the specified values of apparent unit weight γ and saturation degree S and voids ratio e_0 from: $\gamma = \gamma_D + nS\gamma_w$ where $n = e_0/(1+e_0)$. Moreover γ_{SAT} will be updated if e_0 or n_0 have been specified or modified. γ_D and γ_{SAT} are also the inputs for some correlations which estimate the compression index C_c.
Buoyant unit weight	γ_B	The buoyant unit weight (or effective unit weight) of soil is actually the saturated unit weight of soil minus the unit weight of water. It's value can be used to describe the effective soil weight below the ground water table when running the single-phase analysis considered as an effective stress analysis.

Physical soil properties can be used for calculating:

e_0	$= \gamma_s/\gamma_W \cdot w_n/S$ for $S > 0$	
γ_D	$= \gamma - n_0 S \gamma_W$	
e_0	$= n_0/(1 - n_0)$	

Window 2-7: Content of Soil specific properties for fine-grained soils

Z_Soil



Fine-grained soils		
Fines content	f_p	Content of particles smaller than 0.06 mm. If $f_p > 50\%$ then soil is classified as fine-grained (cohesive) otherwise as coarse-grained.
Organics content	OC	General classification in terms of organics content: - inorganic soil $\mathrm{OC} \leq 3\%$ - organic silt or clay $3 < \mathrm{OC} \leq 10\%$ - medium organic soils $10 < \mathrm{OC} < 30\%$ (not supported in Virtual Lab v2023) - highly organic soils $\mathrm{OC} \geq 30\%$ (not supported in Virtual Lab v2023)
Plasticity index	PI	$\mathrm{PI} = w_L - w_P$ is taken to estimate $\gamma_{0.7}$ and appears in some correlations for ϕ, m, K_0^{NC} and C_c.
Liquid limit	w_L	Introducing or modifying the value of w_L updates **Soil plasticity**: • Low plasticity $w_L \leq 35\%$ • Medium plasticity $35 < w_L \leq 50\%$ • High plasticity $50 < w_L \leq 70\%$ • Very high plasticity $70 < w_L \leq 90\%$ • Extremely high plasticity $w_L > 90\%$ The specified value appears in some correlations for the stiffness exponent m and the compression index C_c.
Plastic limit	w_P	Plastic limit is computed from: $w_P = w_L - \mathrm{PI}$ once both variables have been specified. The value of w_P can be used to correlate the small strain threshold $\gamma_{0.7}$ or the compression index C_c.
Consistency index	I_c	Consistency index helps to automatically update **Soil consistency**. Its value is computed from $I_c = (w_L - w_n)/\mathrm{PI}$ once w_n, w_L and PI have been specified.

Window 2-7

Unconfined compressive strength	q_u	Introducing or modifying the value of q_u updates **Soil consistency**: • very soft $q_u \leq 25$ kPa • soft $25 < q_u \leq 50$ kPa • medium $50 < q_u \leq 100$ kPa • stiff $100 < q_u \leq 200$ kPa • very stiff $200 < q_u \leq 400$ kPa • hard $q_u > 400$ kPa
Compression index	C_c	Compression index taken from primary loading branch in the oedometric test; it appears in correlations for $E_{\text{oed}}^{\text{ref}}$.
Normalized undrained shear strength	$s_{\text{u}}/\sigma'_{v0}$	$s_{\text{u}}/\sigma'_{v0}$ is used in correlations for E_s^{ref}, ϕ, OCR.

Window 2-8: Content of Soil specific properties for coarse-grained soils

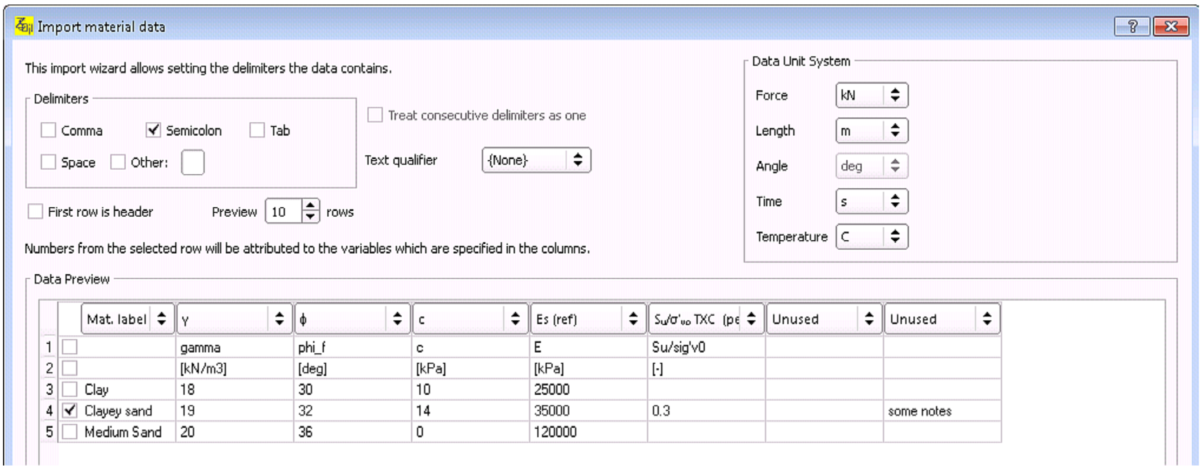
Z_Soil

Coarse-grained soils		
Fines content	f_p	Content of particles smaller than 0.06 mm. If $12\% < f_p < 50\%$ then coarse-grained soil may be classified as silty or clayey: - Silty if $PI < 4\%$ or Atterberg limits below "A" line in the plasticity chart - Clayey if $PI > 7\%$ or Atterberg limits above "A" line in the plasticity chart "A" line: $PI = 0.73(w_L - 20)$ If $f_p > 50\%$ then soil is classified as fine-grained (cohesive).
Coefficient of uniformity	C_u	$C_u = d_{60}/d_{10}$ is used to define **soil gradation**. Typical values of C_u for uniform (*poorly-graded*) materials: • Equal spheres 1.0 • Standard Ottawa sand 1.1 • Clean, uniform sand (fine or medium) 1.2 to 2.0 • Uniform, inorganic silt 1.2 to 2.0 • Poorly-graded sands ≤ 6 (and/or $C_k < 1$, $C_k > 3$) • Poorly-graded gravels ≤ 4 (and/or $C_k < 1$, $C_k > 3$) Typical values of C_u for *well-graded* materials: • Silty sand 5 to 10 • Silty sand and gravel 15 to 300 • Well-graded sands > 6 (and $1 \leq C_k \leq 3$) • Well-graded gravels > 4 (and $1 \leq C_k \leq 3$) C_u appears in a correlation estimating ranges of e for coarse-grained materials.
Coefficient of curvature	C_k	$C_k = d_{30}^2/(d_{10}d_{60})$ is used to define soil **gradation**. d_{10} - the maximum size of the smallest 10% of the sample d_{30} - the maximum size of the smallest 30% of the sample d_{60} - the maximum size of the smallest 60% of the sample • C_k between 1.0 and 3.0 indicates a well-graded soil • $C_k < 1$ or $C_k > 3.0$ indicates poorly-graded soil
Relative density	D_r	Introducing or changing the value of D_r updates the **relative density** setup. The specified value is used to estimate ϕ, ψ and e_0.

Window 2-8

Window 2-9: Importing data from ASCII file

Z_Soil



The values of soil characteristics can be prepared in advance for a number of geotechnical layers (rows) and imported from any ASCII file (*.csv, *.txt). The header in the import wizard table makes it possible to assign each column with the corresponding soil characteristic/parameter. Only the values in the selected layer/row (checked row) will be imported.

Window 2-9

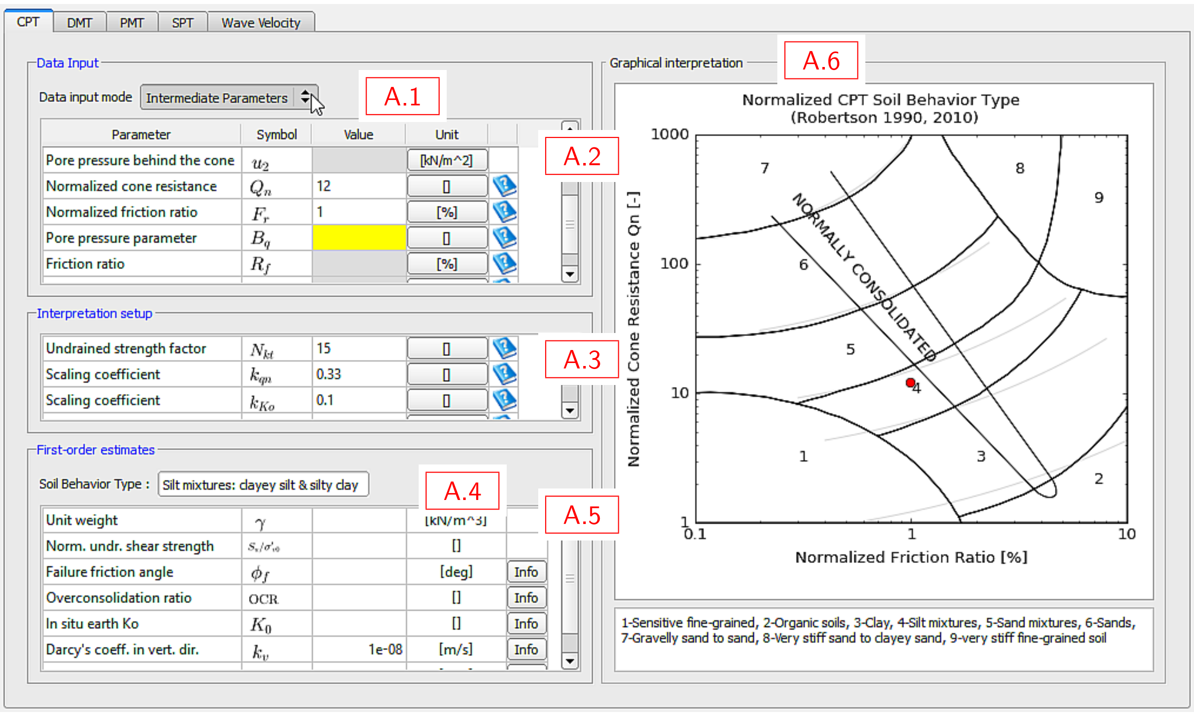
2.2 IN SITU TEST DATA

2.2.1 CONE PENETRATION TEST

The piezocone penetration test (CPTU) is an *in situ* testing method which is used to determine geotechnical engineering properties of soils and to assess site stratigraphy, relative density, strength characteristics and equilibrium groundwater pressures. The testing device consists of an instrumented steel cone with an usual apex angle of 60^o and cross-section area of 1000 mm^2, and additional pore water pressure transducer typically located behind the cone (u_2 position). The sleeve behind the cone is used to measure the sleeve friction resistance f_s. For further details see Lunne et al. (1997).

Window 2-10: Cone Penetration Test - data input and first-order estimates

Z_Soil



A.1 Selection of input parameters type:

- Direct parameters: q_t, f_s, u_2
- Indirect parameters (normalized direct parameters): Q_n, F_r, and B_q

A.2 Input parameters which are used to determine soil type and estimate soil parameters

A.3 Interpretation setup - empirical coefficients or auxiliary parameters which appear in empirical correlations or are used to transform the estimated stiffness moduli from the effective stress at the testing depth to the user-defined reference stress

A.4 Soil type based on the Robertson (1990) interpretation chart

A.5 First-order estimates computed based on provided field test results and interpretation setup. Note that the selection of the correlations which are applied for first-order parameter estimation is based on the soil type estimated with the Robertson (1990) interpretation chart

A.6 Graphical representation of field data interpretation

Window 2-10

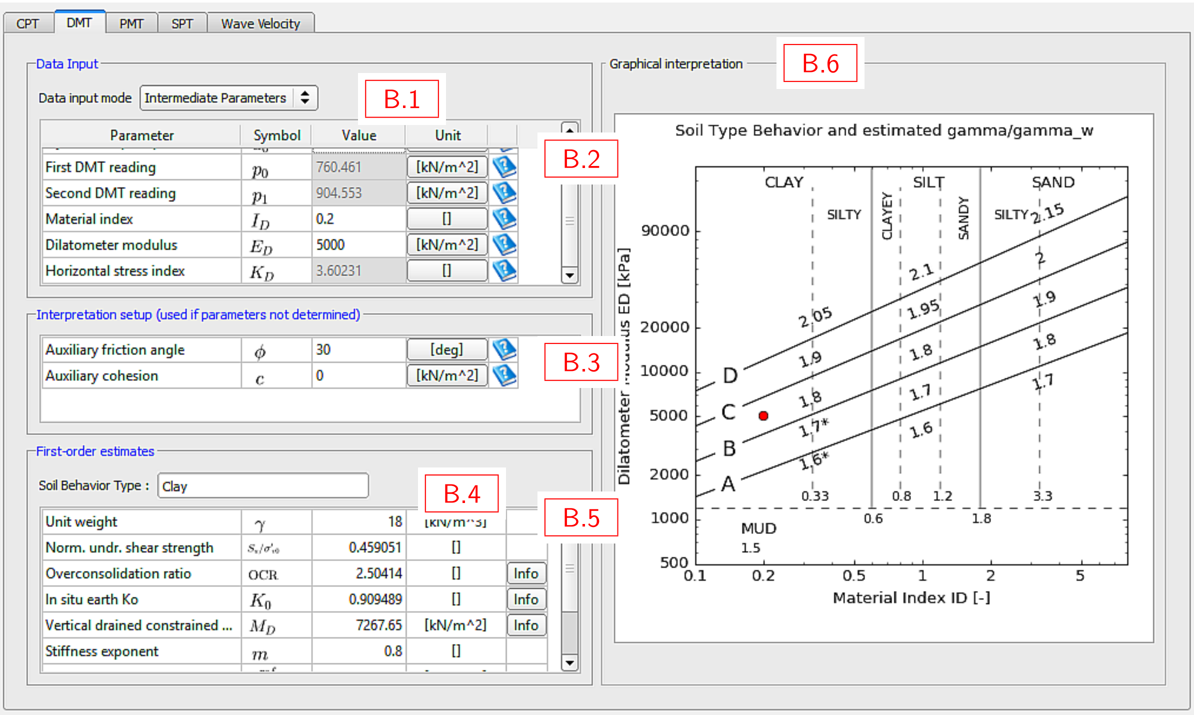
Cone Penetration Test (CPT/CPTU)		
Corrected cone resistance	q_t	The corrected cone tip resistance q_t is calculated as: $q_t = q_c + (1 - a_n)u_2$ where: q_c - measured cone resistance a_n - net area ratio of the cone (see Lunne et al., 1997) q_t, together with σ_{v0} and u_0, is used to automatically compute Q_t if the latter is not directly specified. q_t is also used to determine the soil behavior type and unit weight. q_t appears in correlations for E_0, V_s, E_{50}, ϕ in coarse-grained soil, and V_s, E_{oed}, ϕ, OCR, K_0 in fine-grained soils.
Pore pressure behind the cone	u_2	This number is used to calculate B_q. u_2 appears in correlations for OCR in fine-grained soils.
Friction sleeve resistance	f_s	Unit sleeve friction resistance. f_s, together with q_t and σ_{v0}, is used to automatically compute F_r if the latter is not directly specified. f_s is also used to determine the soil behavior type and unit weight. f_s appears in correlations for V_s
Total vertical stress	σ_{v0}	Estimated total vertical stress corresponding to the in situ stress level at which the CPT measurements have been taken. σ_{v0} appears in correlations estimating E_{oed}, OCR in fine-grained soils and is used to compute the effective vertical stress $\sigma'_{v0} = \sigma_{v0} - u_0$
Hydrostatic pore pressure	u_0	Hydrostatic pore pressure at testing level. This number is used to calculate B_q and effective vertical stress from $\sigma'_{v0} = \sigma_{v0} - u_0$
Effective vertical stress	σ'_{v0}	Calculated as $\sigma'_{v0} = \sigma_{v0} - u_0$. σ'_{v0} is needed to transform the estimated stiffness moduli to the reference modulus E^{ref} by accounting for the reference stress σ_{ref} and K_0 (cf. Win.2-15).
Dimensionless unit weight	γ_{CPT} $/\gamma_W$	Proposed using the relationship proposed by Robertson and Cabal (2010) based on q_t and f_s: $\gamma/\gamma_W = 0.27 \log Rf + 0.36 \log (q_t/p_a) + 1.236$, with $p_a = 100$ kPa being atmospheric pressure and $R_f = f_s/q_t \cdot 100\%$ is the friction ratio. This number can be used to estimate apparent unit weight: $\gamma = \gamma_{CPT}$ (γ_W = unit weight of water).
Normalized cone resistance	Q_t	$Q_t = (q_t - \sigma_{v0})/\sigma'_{v0}$ Q_t appears in correlations estimating ϕ, K_0 for for fine-grained soils.
Normalized pore pressure parameter	B_q	$B_q = (u_2 - u_0)/(q_t - \sigma_{v0})$ B_q appears in correlations estimating ϕ for for fine-grained soils.
Normalized friction ratio	F_r	$F_r = f_s/(q_t - \sigma_{v0})$
Soil type behavior		Determined based on Q_t and F_r numbers using the original chart by Robertson (1990)

2.2.2 MARCHETTI'S DILATOMETER TEST

The flat dilatometer, or DMT, is an in-situ device used to determine the soil in-situ lateral stress and soil lateral stiffness, and to estimate some other engineering properties of subsurface soils (Marchetti et al., 2001). A dilatometer test consists of pushing a flat blade located at the end of a series of rods. Once at the testing depth, a circular steel membrane located on one side of the blade is expanded horizontally into the soil. The pressure is recorded at specific moments during the test. The blade is then advanced to the next test depth.

Window 2-11: Marchetti's Dilatometer Test - data input and first-order estimates

Z_Soil



B.1 Selection of input parameters type:

- Direct parameters: p_0, p_1
- Indirect parameters (normalized direct parameters): E_D, I_D

B.2 Input parameters which are used to determine soil type and estimate soil parameters.

B.3 Interpretation setup - empirical coefficients or auxiliary parameters which appear in empirical correlations or are used to transform the estimated stiffness moduli from the effective stress at the testing depth to the user-defined reference stress by applying stress stiffness dependency law.

B.4 Soil type based on the material index I_D (Marchetti, 1980).

B.5 First-order estimates computed based on provided field test results and interpretation setup. Note that the selection of the correlations which are applied for first-order parameter estimation is based on the soil type estimated with the material index I_D (Marchetti, 1980).

B.6 Graphical representation of field data interpretation.

Window 2-11

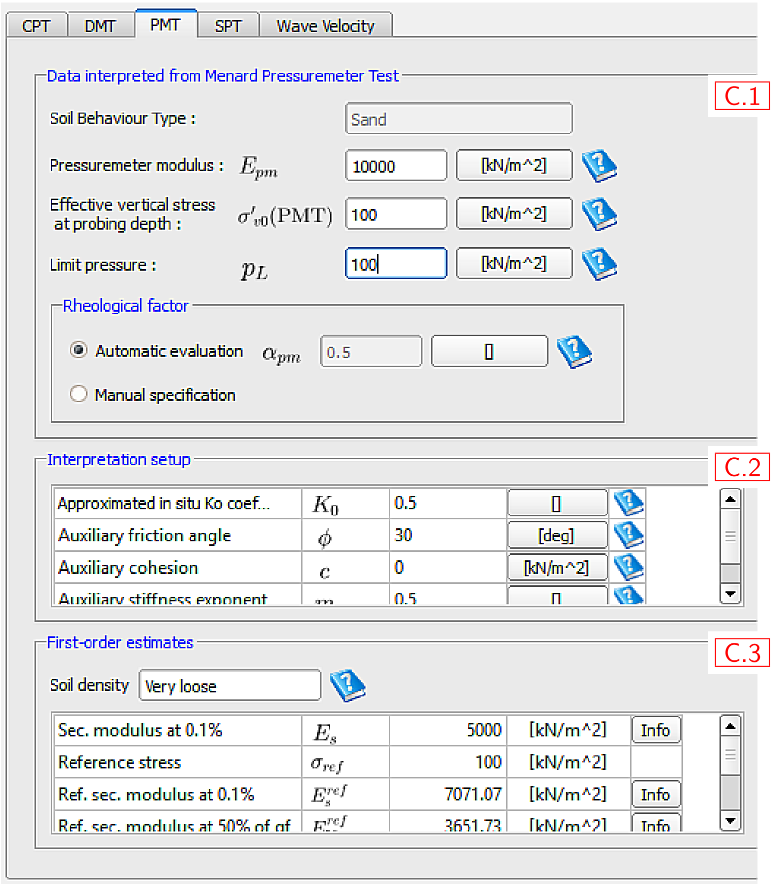
Marchetti's Dilatometer Test (DMT)		
First DMT reading	p_0	Corrected pressure which is required to start moving the membrane towards soil. The correction accounts for membrane stiffness. The value is used to calculate the dilatometer numbers I_D, K_D and E_D.
Second DMT reading	p_1	Corrected pressure which is required to move the center of the membrane 1.1 mm into soil. The value is used to calculate the dilatometer numbers I_D and E_D.
Hydrostatic pore pressure	u_0	Hydrostatic pore pressure at the testing depth. The value is used to calculate the dilatometer numbers I_D and K_D.
Effective in situ vertical stress	σ'_{v0}	Estimated effective vertical stress corresponding to the in situ stress level at which the DMT measurements have been taken. This number is needed to transform an estimated value of stiffness modulus to the reference modulus E^{ref} taking into account the reference stress σ_{ref}, K_0 and the power law (cf. Win.2-15).
Material index	I_D	$I_D = (p_1 - p_0)/(p_0 - u_0)$ used for determination of soil type behavior (Marchetti, 1980): • $I_D < 0.6$ - Clay • $0.6 \leq I_D < 1.8$ - Silt • $1.8 \leq I_D < 3.3$ - Silty sand • $3.3 \leq I_D < 8$ - Sand I_D is used to provide estimations of soil behavior type and unit weight. I_D appears in correlations estimating E_{oed} in normally-consolidated soils.
Horizontal stress index	K_D	$K_D = (p_0 - u_0)/\sigma'_{v0}$ K_D appears in correlations estimating E_{oed} in normally-consolidated soils, ϕ for coarse-grained soil, and OCR, K_0 for fine-grained soil.
Dilatometer modulus	E_D	$E_D = 34.7(p_1 - p_0)$ E_D is used to provide estimations of unit weight. E_D appears in correlations estimating $E_{\text{oed}}^{\text{ref}}$ in normally-consolidated soils, ϕ for coarse-grained soil.
Dimensionless unit weight	γ_{DMT} $/\gamma_W$	Estimated based on provided I_D and E_D numbers using the original chart for estimating soil type and unit weight by Marchetti and Crapps (1981). This number can be used to estimate apparent unit weight: $\gamma = \gamma_{DMT}$ (γ_W = unit weight of water).

2.2.3 MENARD'S PRESSUREMETER TEST

The pressuremeter test is an *in situ* testing method used to achieve a quick measure of the *in situ* stress-strain relationship of the soil (Mair and Wood, 1987). The principle is to introduce a cylindrical probe with a flexibl cover which can expand radially in a borehole. A pressure is applied by the probe on the sidewalls of the hole, and soil deformation is measured, through the acquisition of the hole volume increase.

Window 2-12: Menard's pressuremeter test - data input and first-order estimates

Z_Soil



C.1 Input parameters which are used to determine the stiffness modulus.

C.2 Interpretation setup - auxiliary parameters which are used to for transform the estimated stiffness modulus from the vertical effective stress at the testing depth to the user-defined reference stress by applying the stress stiffness dependency law.

C.3 First-order estimates computed based on provided input data and interpretation setup.

Window 2-12

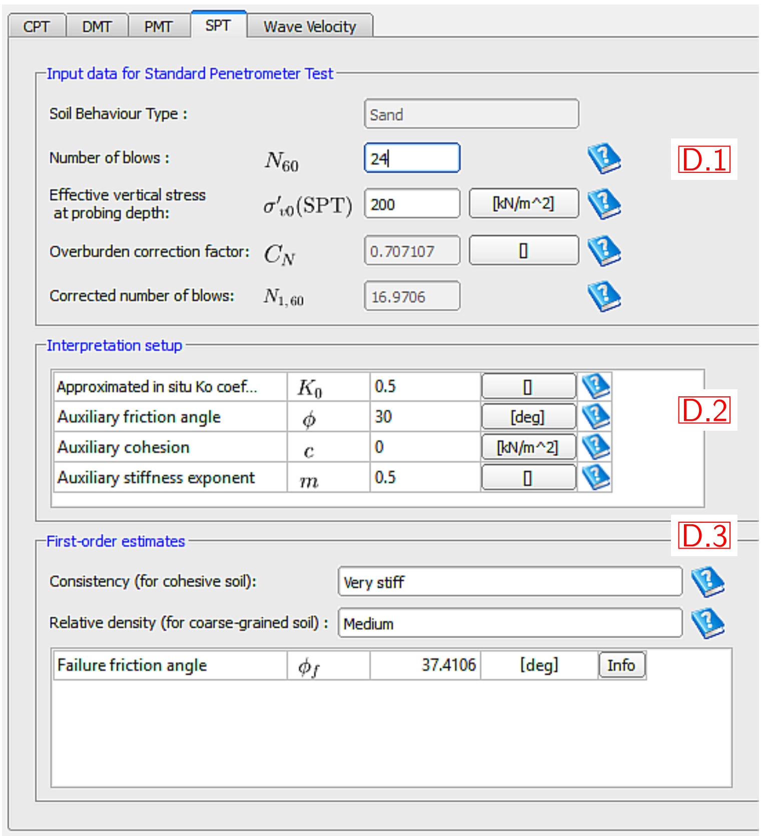
Menard's Pressuremeter Test (PMT)		
Pressuremeter modulus	E_{pm}	$E_{pm} = 2(1+\nu)\Delta p \cdot V/\Delta V$ with V denoting the initial volume of the pressuremeter cell plus an additional volume corresponding to the applied pressure p. E_{pm} appears in correlations estimating E_s.
Limit pressure	p_L	For the Menard's pressuremeter test, the limit pressure is defined as the pressure at which the change in probe volume equals the initial probe volume ($\Delta V/V = 1$). The limit pressure is usually not obtained by direct measurements during the test due to limitation in the probe expansion or excessively high pressure. It can be estimated by fitting the data points within the plastic deformation range. $p_L = \sigma_{h0} + S_u\left[1 + \ln\left(G/S_u\right)\right]$
Effective in situ vertical stress	σ'_{v0}	The estimated effective vertical stress corresponding to the depth at which the pressuremeter tests has been carried out. This number is needed to transform an estimated value of stiffness moduli to the reference modulus E^{ref} taking into account the reference stress σ_{ref} and K_0 (cf. Win.2-15).
Rheological coefficient	α	This number is used to evaluate "static" stiffness modulus from: $E_s = E_{pm}/\alpha$. If the automatic evaluation is selected, the coefficient α will be evaluated based on the soil type and E_{pm}/p_L ratio: *Peat* • Normally Consolidated for all E_{pm}/p_L: $\alpha = 1$ *Clay* • Overconsolidated: $E_{pm}/p_L > 16$: $\alpha = 1$ • Normally-consolidated: $E_{pm}/p_L = 9 \div 16$: $\alpha = 2/3$ *Silt* • Overconsolidated: $E_{pm}/p_L > 14$: $\alpha = 2/3$ • Normally-consolidated: $E_{pm}/p_L = 8 \div 14$: $\alpha = 1/2$ *Sand* • Overconsolidated: $E_{pm}/p_L > 12$: $\alpha = 1/2$ • Normally-consolidated: $E_{pm}/p_L = 7 \div 12$: $\alpha = 1/3$ *Sand and Gravel* • Overconsolidated: $E_{pm}/p_L > 10$: $\alpha = 1/3$ • Normally-consolidated: $E_{pm}/p_L = 6 \div 10$: $\alpha = 1/4$

2.2.4 STANDARD PENETRATION TEST

The standard penetration test (SPT) is an in-situ dynamic penetration sounding which is designed to provide information on the geotechnical engineering properties of soil. The test uses a thick-walled sample tube, with an outside diameter of 50.8 mm and an inside diameter of 35 mm, and a length of around 650 mm. This is driven into the ground at the bottom of a borehole by blows from a slide hammer with a mass of 63.5 kg (140 lb) falling through a distance of 760 mm (30 in). The sample tube is driven 150 mm into the ground and then the number of blows needed for the tube to penetrate each 150 mm (6 in) up to a depth of 450 mm (18 in) is recorded. The sum of the number of blows required for the second and third 6 in. of penetration is termed the "standard penetration resistance" or the "N-value". The blow count provides an indication of the relative density of the soil, approximation of shear strength and stiffness properties, and it is used in many empirical geotechnical engineering formulas.

Window 2-13: Standard Penetration Test - data input and first-order estimates

Z_Soil



D.1 Input parameters which are used to determine relative density or consistency of soil, and to estimate soil parameters.
D.2 Interpretation setup - empirical coefficients or auxiliary parameters which appear in empirical correlations or are used to transform the estimated stiffness moduli from the effective stress at the testing depth to the user-defined reference stress.
D.3 First-order estimates computed based on provided field test results and interpretation setup.

Window 2-13

Standard Penetration Test (SPT)		
Number of blows	N_{60}	Number of blows to drive the sampler the last two 150mm distances (300mm in total) to obtain the N number. N_{60} corresponds to the energy ratio $E_r = 60$. Since the energy $\times$ blow count should be a constant for any soil, the following equation can be applied $E_{r1} \times N_1 = E_{r2} \times N_2$ (Bowles, 1997). For example, $N_{55} = N_{60} \times 60/55$. Introducing or modifying N_{60} prompts the user to update *Relative density* group for coarse-grained soil or *Soil consistency* for fine-grained soil. • Relative soil density based on N_{60}: $0-4$ Very loose; $5-10$ Loose ; $11-30$ Medium; $31-50$ Dense; >50 Very dense • Soil consistency based on N_{60}: $0-2$ Very soft; $3-4$ Soft; $4-8$ Medium; $9-15$ Stiff; $16-30$ Very Stiff; >30 Hard N number appears in correlations for coarse-grained soils to estimate E_{ur}, ϕ, V_s.
Effective vertical stress	σ'_{v0}	The estimated effective vertical stress corresponding to the in situ stress level at which the number N_{60} has been measured. This number is needed to calculate stress overburden coefficient C_N and to transform the estimated stiffness moduli to the reference modulus E^{ref} by accounting for the reference stress σ_{ref} and K_0 (cf. Win.2-15).
Overburden correction factor	C_N	Overburden correction factor is calculated according to Liao and Whitman (1986) as $C_N = (p_a/\sigma'_{v0})^{0.5}$ ($C_N = 1.7$ if $C_N > 1.7$) with p_a - atmospheric pressure = 100 kPa once σ'_{v0} is provided for SPT.
Corrected N_{60}	$N_{60,1}$	Corrected SPT N value for overburden stress with respect to 100 kPa $N_{60,1} = N_{60} \times C_N$

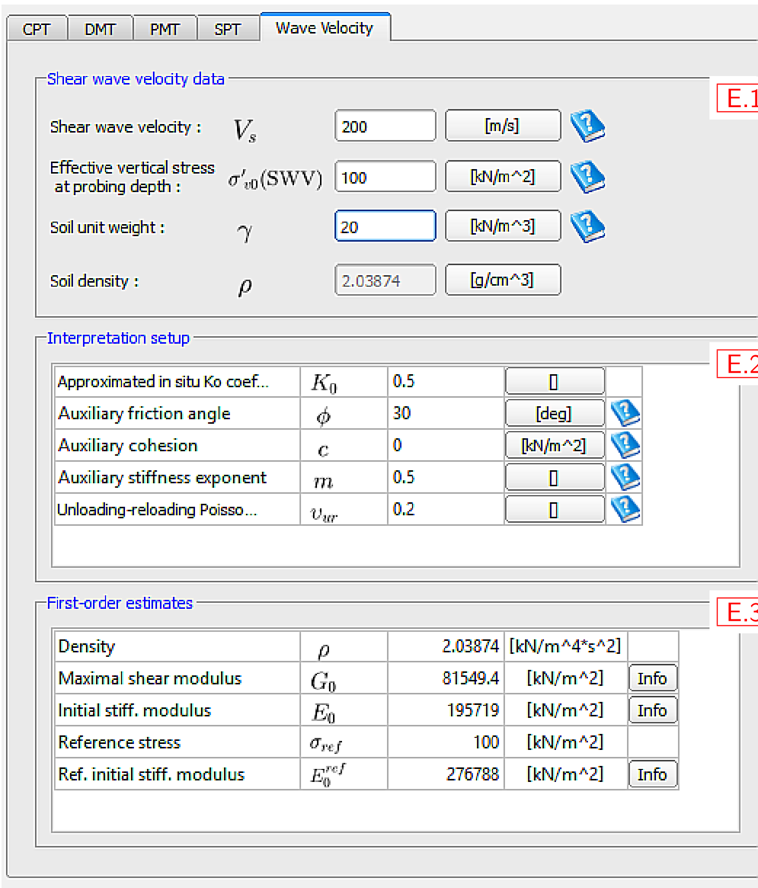
2.2.5 SHEAR WAVE VELOCITY

Characterization of the small-strain shear modulus and the shear wave velocity of soils and rocks is an integral component of various static and dynamic analyzes of soil-structure interaction. The shear wave velocity can be measured by a variety of testing methods:

- seismic piezocone testing (SCPTU) (Campanella et al., 1986)
- seismic flat dilatometer test (SDMT) (Marchetti et al., 2008)
- cross hole, down hole seismic tests
- geophysical tests (Long, 1998):
  - ⋆ continuous surface waves (CSW)
  - ⋆ spectral analysis of surface waves (SASW)
  - ⋆ multi-channel analysis of surface waves (MASW)
  - ⋆ frequency wave number (f-k) spectrum method

Window 2-14: Shear Wave Velocity - data input and first-order estimates

Z_Soil



E.1 Input parameters which are used to determine maximal shear modulus.

E.2 Interpretation setup - auxiliary parameters which are used to transform the estimated stiffness modulus from the vertical effective stress at the testing depth to the user-defined reference stress.

E.3 First-order estimates computed based on provided input data and interpretation setup.

Window 2-14

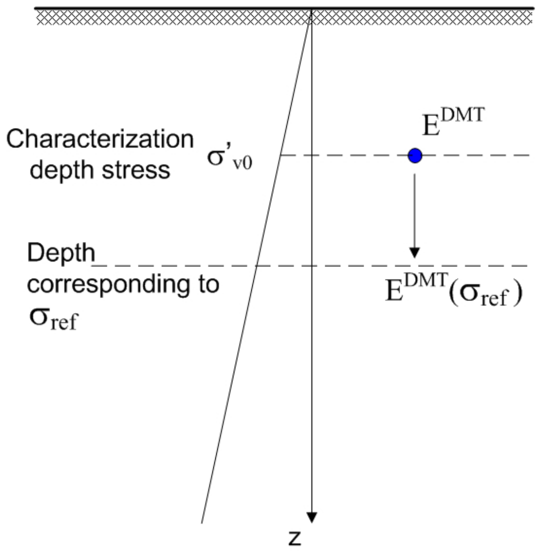
Shear wave velocity		
Shear wave velocity	V_s	If specified, the value is taken into account in *Automatic Parameter Selection* for estimation of $E_0 = 2G_0(1+\nu_{\text{ur}})$ by applying $G_0 = \rho V_s^2$.
Unit weight	γ	Unit weight of soil with natural moisture content
Effective in situ vertical stress	σ'_{v0}	Estimated effective vertical stress corresponding to the *in situ* stress level at which measurements of V_s have been taken. σ'_{v0} and auxiliary parameters are used to transform the computed E_0 value to the user-defined reference stress σ_{ref} according to the principle illustrated below Win.2-15).

2.2.6 STIFFNESS MODULI TRANSFORMATION

Window 2-15: Principle of transformation for stiffness moduli

Z_Soil

Stiffness moduli derived from *in situ* test data for a given charaterization depth are adjusted with respect to the depth that corresponds to σ_{ref} using stiffness stress dependency law, as illustrated below:



Transformation of stiffness moduli to the reference ones (i.e. those corresponding to the user-defined reference stress) is carried out by applying the following the power law for the standard Hardening-Soil model:

$$E^{\mathrm{ref}} = \frac{E}{\left(\dfrac{\sigma_3 \sin\phi + c\cos\phi}{\sigma^{\mathrm{ref}} \sin\phi + c\cos\phi}\right)^m} \tag{1}$$

where:
- E^{ref} is the target modulus corresponding to the user-defined reference stress σ^{ref}
- E: the modulus identified for a given minor stress state σ_3
- m: stiffness exponent (typically between 0.5 and 1.0)
- $\sigma_3 = \min(\sigma'_{v0}, \sigma'_{v0} \cdot K_0)$

Transformation to other available formulations of the power law, i.e.:

$$E = E^{\text{ref}} \left(\frac{\sigma_3}{\sigma^{\text{ref}}}\right)^m \quad \text{or} \quad E^p = E^{\text{ref,p}} \left(\frac{p^*}{\sigma^{\text{ref}}}\right)^{m_p} \tag{2}$$

is done automatically during automatic parameter selection or parameter identification.

The migration between different power laws can be carried out manually using the dedicated module described in Sec. 6.2.

Window 2-15

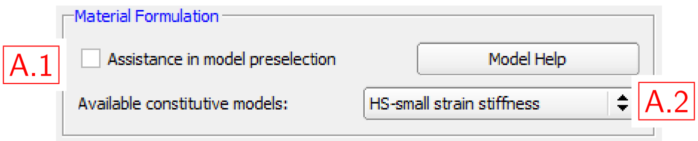
Chapter 3

MATERIAL FORMULATION SELECTION

An assistance in model preselection allows less experienced users to choose a suitable material formulation to describe the material behavior. By activating the model preselection assistance, the combobox will contain constitutive models which are considered to be adequate for the selected material behavior type and basic features. In the case of soils, the preconsolidation is the main criterion of model selection. For example, modeling of normally-consolidated and lightly over-consolidated deposits requires applying a model which accounts for volumetric plastic straining before reaching the ultimate state. In this case, only the models with the cap mechanism are suggested.
The suggested material formulation are arranged in the combobox list in order of adequacy.

Window 3-1: Material formulation

Z_Soil



A.1 Enable/disable the model preselection assistance
A.2 The combobox contains a list of available (or recommended, if assistance in preselection is enabled) constitutive models.

Window 3-1

Chapter 4

PARAMETER DETERMINATION

Parameter determination refers to an effective assessment of design soil properties which allow us to reproduce soil behavior by means of a numerical analysis assuming that an adequate constitutive model has been chosen.

The Virtual Lab offers the possibility of parameter determination including first-guess for model parameters for any incomplete or complete material data, as well as an automated parameter identification from laboratory curves.

Three general approaches can be applied to determine material model parameters:

- Automatic parameter selection
- Interactive parameter selection
- Parameter identification

The **automatic parameter selection** consists of applying a fully-automated algorithm to estimate model parameters based on a user-provided general soil description. In this case, parameter estimation refers to the evaluation of model parameters from reported typical ranges for parameter values which are extracted from an expert database. The module allows the user to have an insight into the correlations which have been used during automatic knowledge extraction.

The **interactive parameter selection** offers the possibility of a manual knowledge extraction. The user can manually browse the correlations database looking for best-working correlations for the analyzed "material sample". These correlations relate geotechnical characteristics or measurements with constitutive model parameters. The correlations database contains the following general groups of empirical correlations:

- those based on confidence limits for model parameters being the function of macroscopic soil features (general soil description),
- those obtained through statistical regression analyzes, which relates known numeric data (geotechnical properties or field test results) with constitutive model parameters,
- mixed approaches based on macroscopic soil description and numeric data.

Parameter identification refers to deterministic algorithms which are developed for given constitutive model and test geometry. These analytical solutions offer the direct identification of model parameters based on measured data from:

- triaxial cell test
- oedometer test

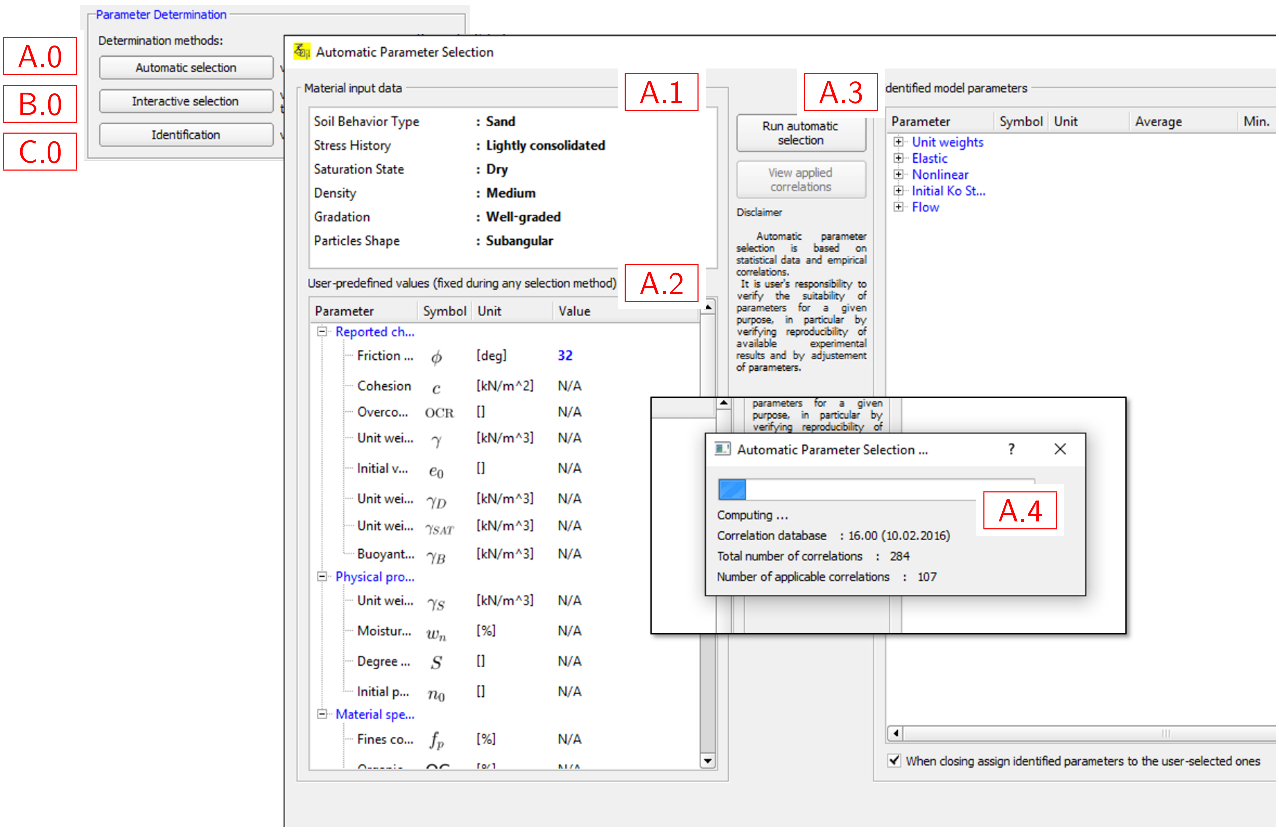
4.1 AUTOMATIC PARAMETER SELECTION

The Automatic Parameter Selection offers a fully-automated estimation of model parameters based on provided general soil description and numeric data.

Note that the automatic parameter selection relies on statistical data and empirical correlations. It is user's responsibility to verify the suitability of parameters for a given purpose, in particular by verifying reproducibility of available experimental results and by adjustment of parameters.

Window 4-1: Performing automatic parameter selection

Z_Soil



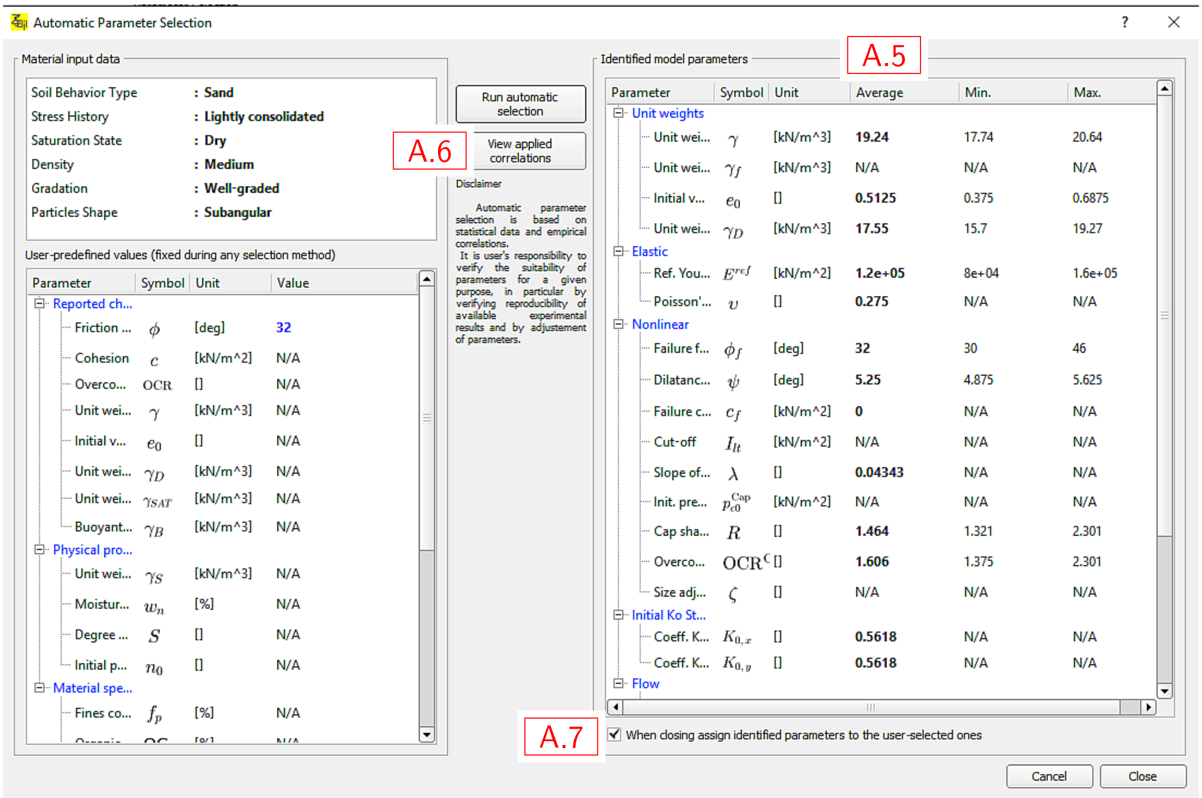
In order to run automatic parameter selection:

1. Specify a general soil description and given numeric data
2. Open the automatic parameter selection dialog A.0
3. Verify the general soil description A.1 and known numeric data A.2. Note that the user-predefined parameters will be highlighted in blue. They will be fixed and unchanged during the automatic parameter selection. The fixed parameter values will also be used by correlations for the inter-correlated parameters (parameters that are identified based on the fixed parameters).
4. Run the automatic selection with A.3. The window A.4 will inform the user about the progress of automatic selection, as well as, about the number of applicable correlations.

Window 4-1

Window 4-2: Viewing the results of automatic parameter selection

Z_Soil

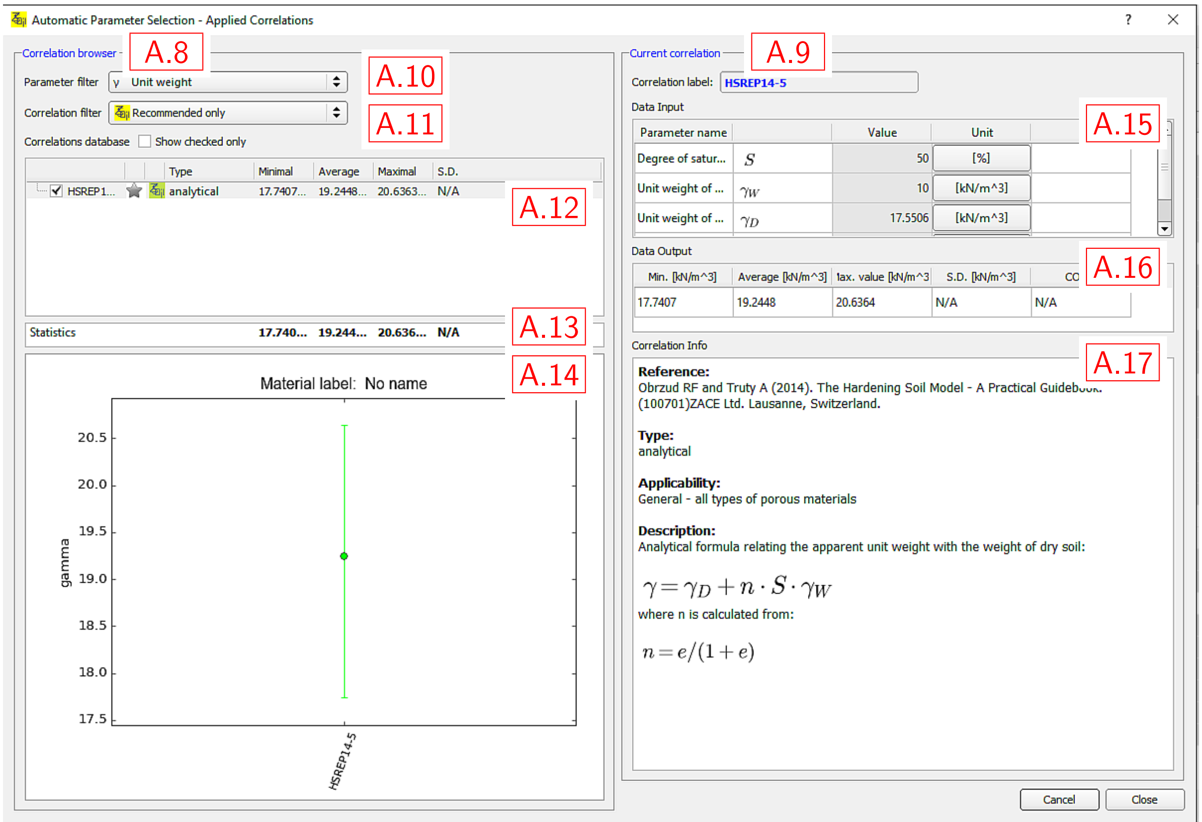


- The results of performed automatic selection are summarized in A.5
- The correlations which have been applied during automatic selection can be inspected by clicking on A.6
- A.7 simplifies attributing parameter estimations to model parameters (final user's selection in the main dialog of the Virtual Lab) after clicking "Accept" to close the dialog window. If disabled, the parameter estimations will appear in the column 'Automatic'; such a strategy makes it possible to manually pick the values for individual model parameters for the final "User's selection".

Window 4-2

Window 4-3: Correlations applied during parameter selection

Z_Soil



- The correlation browser makes possible to inspect correlations that have been applied during the automatic parameter selection. The left part of the dialog A.8 represents the assembly of correlations which is filtered by the analyzed parameter A.10. Moreover, the list of correlations A.12 shows the applied correlations, i.e. those set as default. Notice that in the automatic selection mode, the correlation filter A.11 is locked on Default only. The remaining correlations which would also be applicable for a considered general soil description setup, can be browsed in the interactive selection mode.
- The statistics for parameter estimation are given in A.13. The average and the standard deviation are computed based on the average values obtained with different correlations.
- The results are graphically represented in A.14.
- Algorithms for individual correlations can be viewed in the right part of the dialog window A.9 once one of the correlations has been selected in A.12 list.
- The current correlation view contains:
  - A.15 data input in the form of digits or material features; note that in the automatic selection mode, the data input is disabled and the numeric data can be modified in the material data,
  - A.16 results being the function of data input,
  - A.17 correlation information including a reference, correlation applicability, its description and working algorithm.

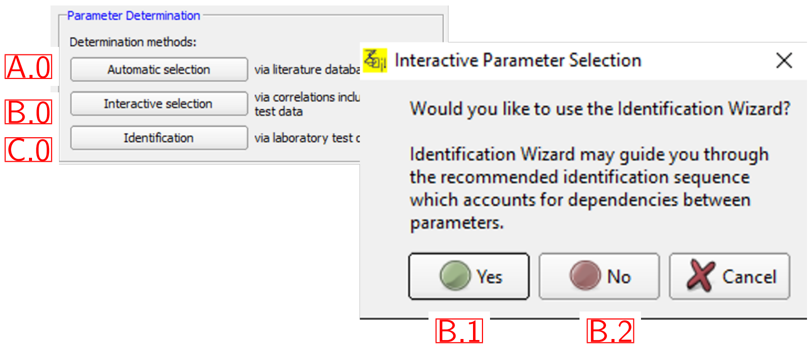
Window 4-3

4.2 INTERACTIVE PARAMETER SELECTION

The Interactive Parameter Selection offers the user with a manual knowledge extraction. The user can browse the database of correlations looking for the best-working correlations for the analyzed "soil sample". It is also possible to test correlations by modifying input data.

Window 4-4: Performing interactive parameter selection

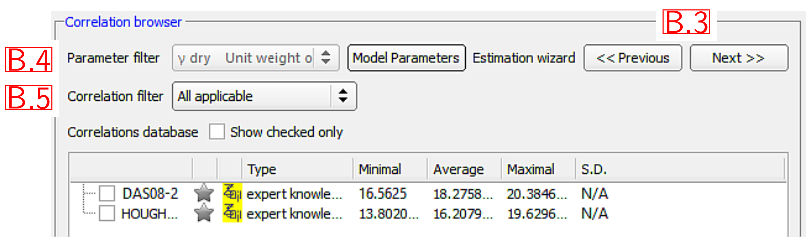
Z_Soil



In order to perform an interactive parameter selection:

1. Specify general soil description and known numeric data in Basic Material Properties dialog
2. Open the interactive parameter selection dialog B.0
3. Before opening the correlation browser, the user will be prompted to choose between:
   - B.1 guided parameter selection with the aid of the identification wizard; in this mode the algorithm follows the parameter identification sequence which accounts for dependencies between parameters (some parameters require prior identification of other parameters).
   - B.2 unconstrained exploring of correlation browser; in this mode the parameter filter is enabled B.4. The user can freely select the parameter to be determined.

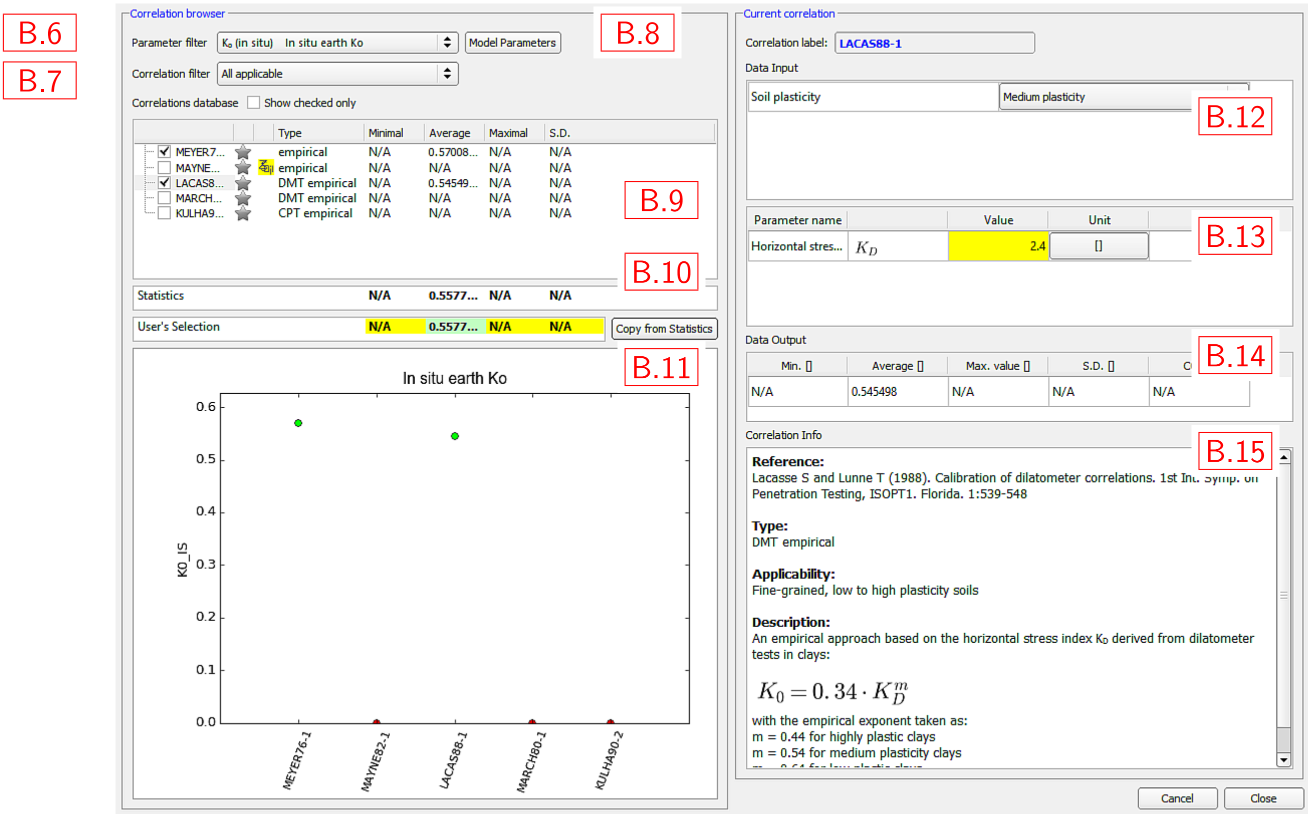
Note that in the interactive selection mode, the correlations can be filtered according to the following criteria B.5: *All applicable*, *Default* (those set as default ones) and *Favorite* (those preferred by the user and saved in the global configuration file).



Window 4-4

Window 4-5: Interactive parameter selection without estimation wizard

Z_Soil



4. During, the unconstrained interactive parameter selection the parameter filter B.6 remains unlocked.
5. Model parameters which are predefined in material data input can be controlled by pressing the button B.8
6. Suitable correlations can be selected in the correlations assembly B.9 by setting check-boxes active.
7. Resulting average value and confidence limits B.10 can be quickly copied to the "User's selection" using Copy from Statistics button.
8. The results are graphically represented in B.11.
9. The parameter values which from "User's selection" will appear in the column *Interactive* (in the main window of the Virtual Lab) once the correlation browser has been closed.

The current correlation view contains:

- data input in the form of digits B.13 or material feature B.12; parameters which are not pre-defined in advance can be introduced in input cells B.9, whereas the pre-defined ones remain locked and the input cells are gray
- results being function of data input B.14
- correlation information B.15 including the reference, correlation applicability, its description and the working algorithm

Window 4-5

4.3 PARAMETER IDENTIFICATION

Parameter Identification refers to deterministic algorithms which are developed for a given constitutive model and test boundary conditions. These analytical and numerical solutions allow model parameters to be identified directly from experimental test data. The methods and algorithms which are included in Parameter Identification module, are presented in the separated report on the Hardening-Soil model (Obrzud and Truty, 2018).

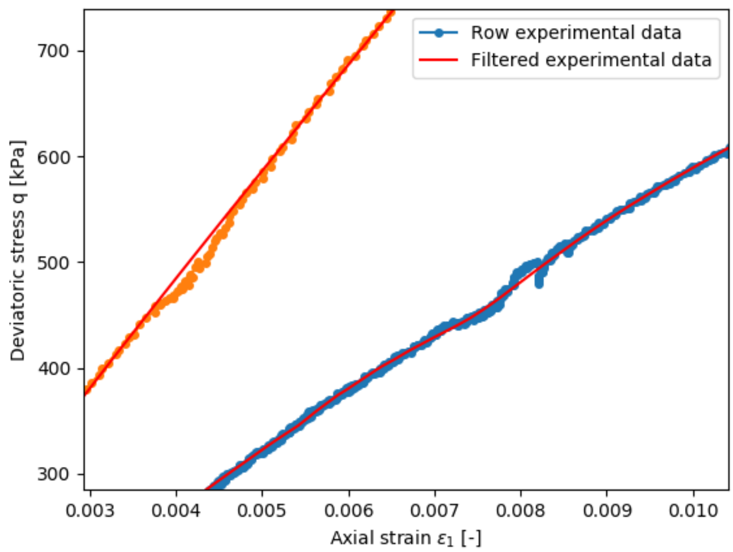
Parameter Identification module in ZSoil v2023 allows to interpret the following standard laboratory tests:

- triaxial drained compression (TX-CD)
- triaxial undrained compression (TX-CU)
- oedometric curves (OED)

With regard to the triaxial test, experimental curves can be imported as raw data (noisy and unfiltered) or smooth curves (treated data). Before the parameter identification, the identification algorithm automatically detects whether imported data are high resolution or not. The criterion of high resolution data is: for all the intervals of $\varepsilon = 1.0\%$, the mean increment of measurement, $\Delta\varepsilon$ is smaller than 0.1%.
Once high-resolution data have been detected, Savitzky-Golay smoothing filter applies (Savitzky and Golay, 1964).

Window 4-6: Filtering for high-resolution and noisy experimental data

Z_Soil

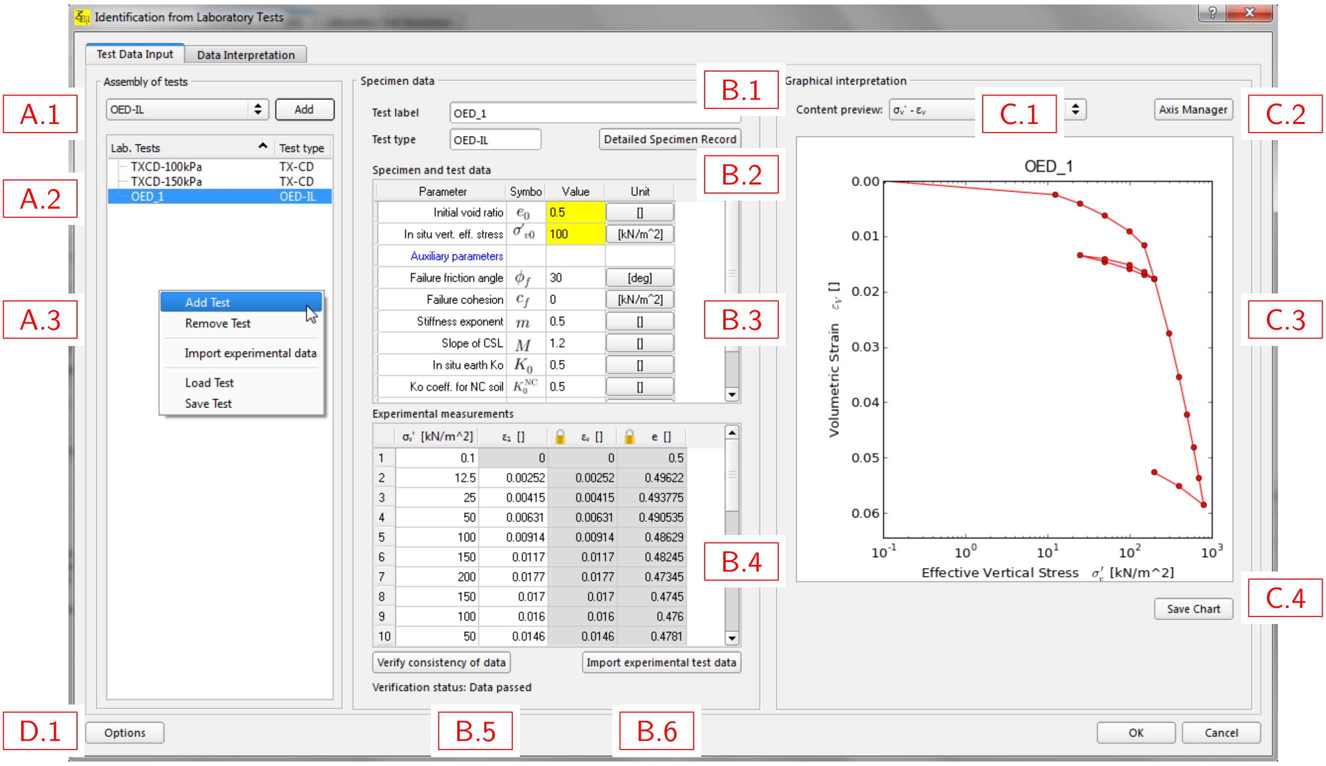


Application of smoothing algorithm to high-resolution and noisy triaxial test data.

Window 4-6

Window 4-7: Input of experimental data

Z_Soil



A.1 Add new test in assembly of tests tree (TX-CD - triaxial drained compression, TX-UD - triaxial undrained compression, OED-IL - oedometric test with incremental load)
A.2 Manage and browse different laboratory tests; selection of a given test updates the view in B.1, B.2 and B.3.
A.3 Context menu (right-button click) which makes it possible to 1) add new, empty test nodes, 2) remove existing test nodes, 3) import experimental measurements for selected test, 4) load previously saved test node, and finally, 5) save the selected test node to XML-formatted *[test-name].pit* file.

B.1 Modify test label
B.2 Define the detailed record of tested specimen
B.3 The table contains initial state variables which are evaluated for a given specimen, as well as auxiliary constants which may be used by the identification algorithm or during numerical optimization
B.4 Insert manually experimental data; copy-paste from a spread sheet is supported
B.5 Verify specified or imported data in terms of its completeness vis-a-vis the identification of some parameters
B.6 Import experimental data from an ASCII file

C.1 Contains a number of predefined data previews
C.2 Modifying axes limits (use right-click button context menu to invert axes)
C.3 Preview experimental data

C.4 Export current chart

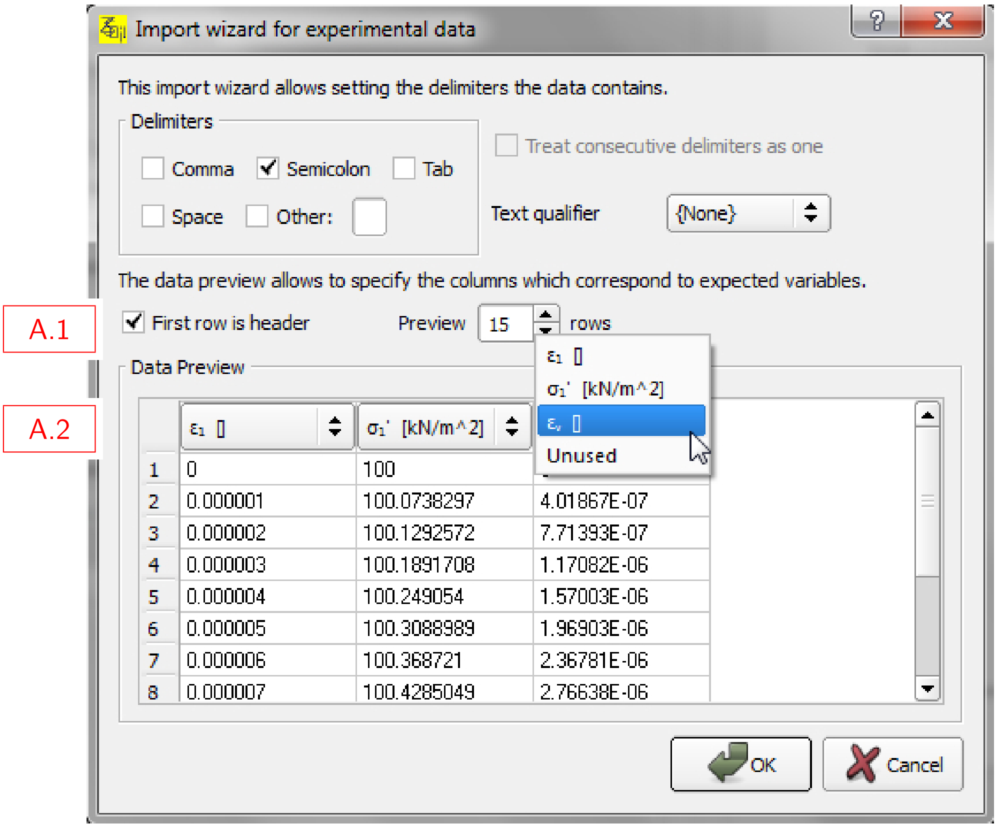
D.1 Configuring parameter identification algorithms.

Window 4-7

Window 4-8: Import wizard for experimental data

Z_Soil

Sign convention: The sign convention is the standard convention of soil mechanics, i.e. compression is assigned as positive.



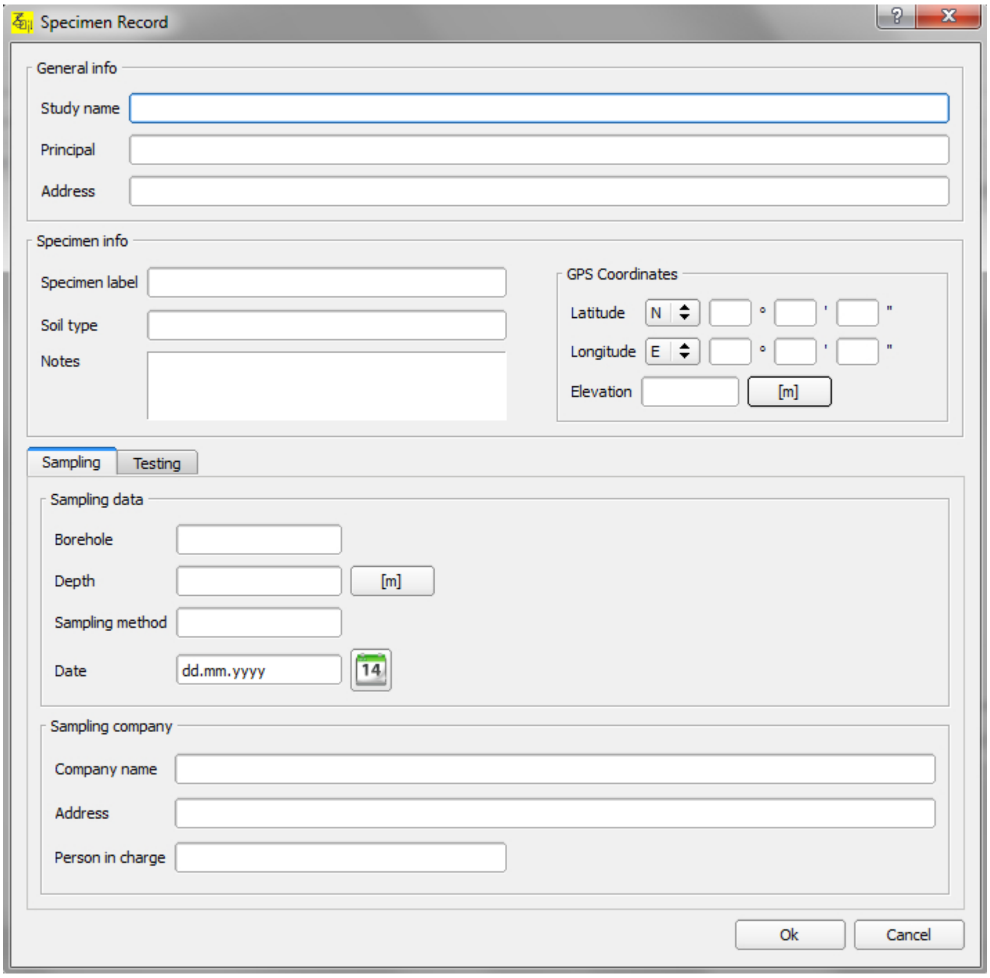
A.1 Hide/show the header row in ASCII file; note that any row containing string characters will be eliminated

A.2 Attribute data from an ASCII file to the corresponding experimental measurement

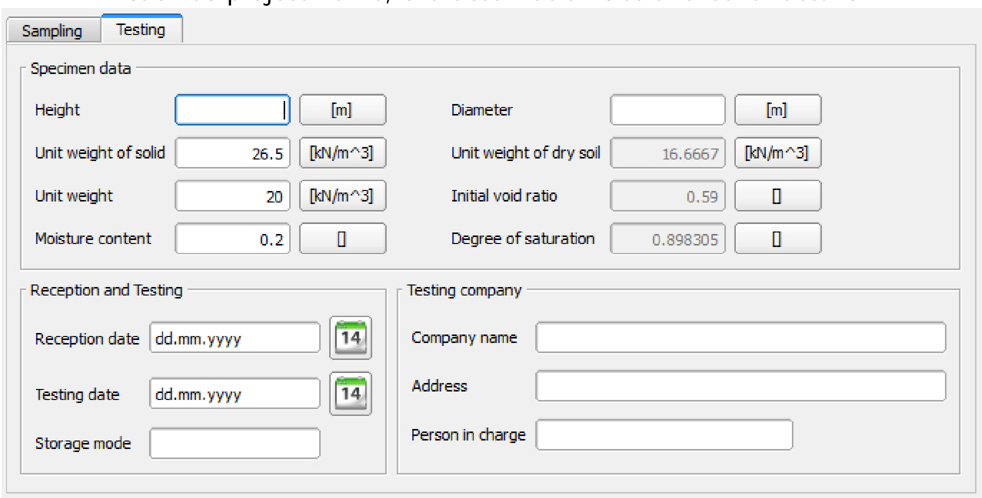
Window 4-8

Window 4-9: Specimen record dialog window

Z_Soil



The specimen record dialog makes it possible to store the information related to the specimen such as project name, characterization site and other details

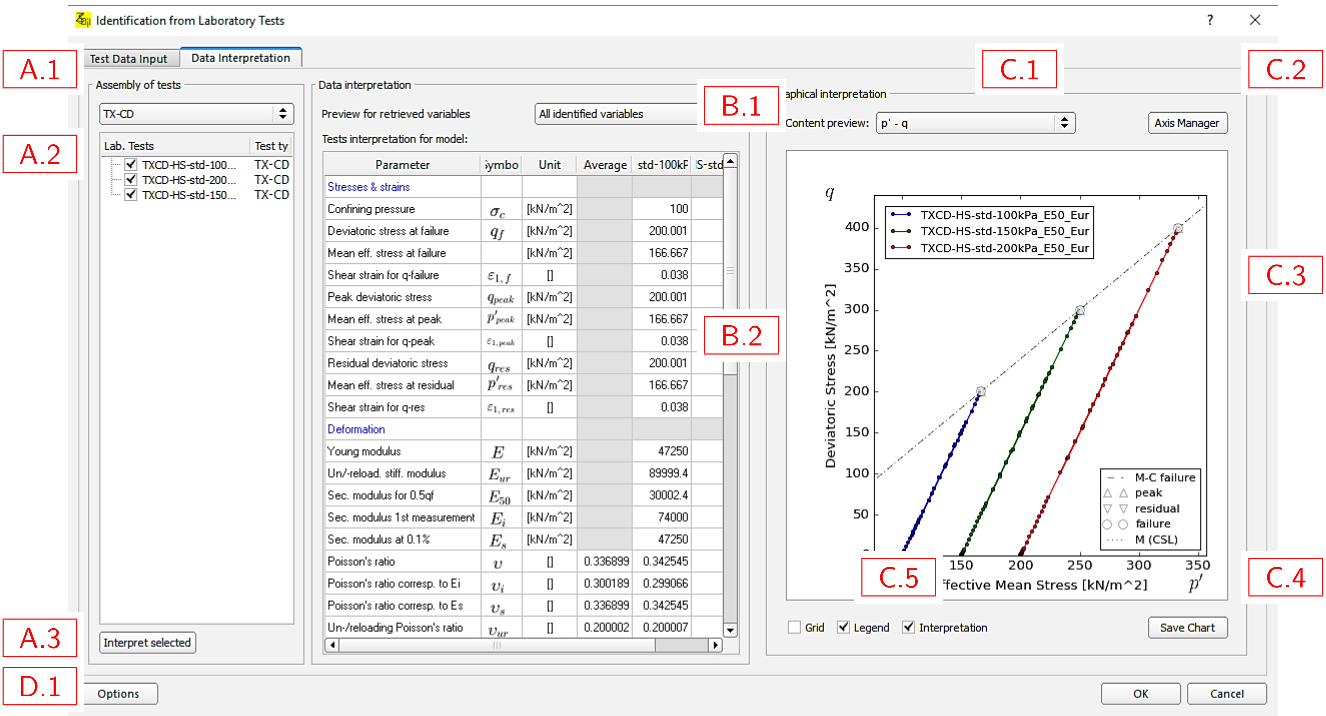


Moreover, it makes it possible to input the data related to the tested specimen

Window 4-9

Window 4-10: Data interpretation

Z_Soil



A.1 Filter tests by the test type; the following interpreting algorithms are available:

- TX-CD: only triaxial drained compression tests
- TX-CU: only triaxial undrained compression tests
- TX-C: both triaxial drained and undrained compression tests
- OED: only oedometric tests

A.2 Selection of tests to be interpreted

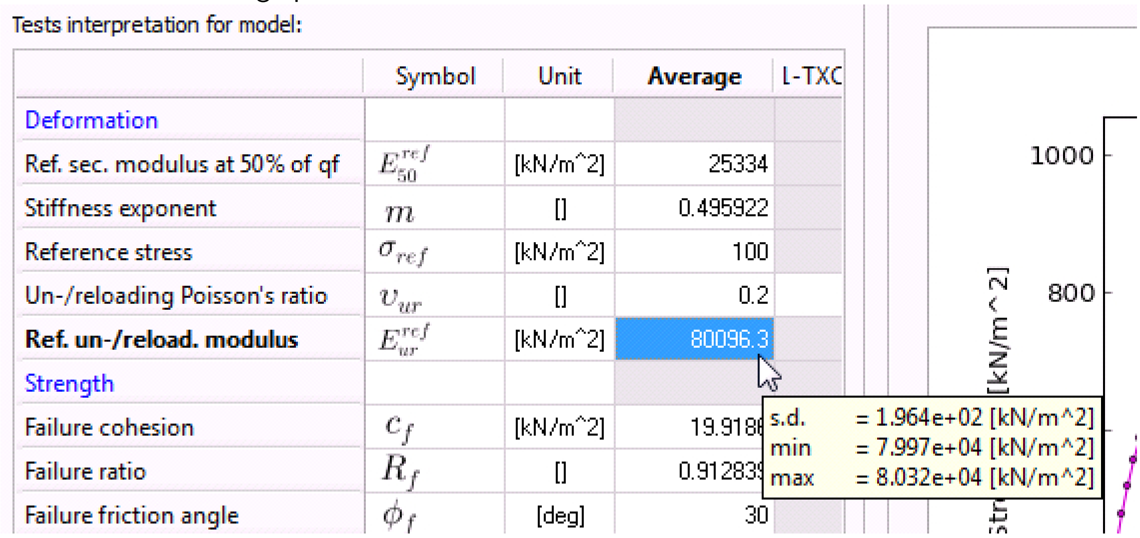
A.3 Run interpretation of the tests that have been selected in A.2; the results obtained by means of the automatic parameter identification are summarized in B.2

B.1 Modify the post-interpretation preview content. The following predefined groups of variables are available:

- model parameters: characteristics of currently chosen model only
- test variables + model parameters:
- all identified variables: includes test variables and typical geomechanical parameters which can be identified from a given laboratory test

NB. Note that the experimental curves are interpreted with the reference to all available information that experimental data may give. During an interpretation run, the algorithm identifies all possible parameters to be identified. i.e. those specific to the selected model, and other available constitutive laws, as well as other interpretable variables. Hence, any change of the constitutive model does not require and additional interpretation run for the previously analyzed experimental data.

B.2 Contains results of a parameter identification run. Note that minimal and maximal values of parameters, as well as the standard deviation can be viewed in the tooltip by holding the mouse cursor over the average parameter value as shown below



Tests interpretation for model:

	Symbol	Unit	Average	L-TXC
Deformation				
Ref. sec. modulus at 50% of qf	E_{50}^{ref}	[kN/m^2]	25334	
Stiffness exponent	m	[]	0.495922	
Reference stress	σ_{ref}	[kN/m^2]	100	
Un-/reloading Poisson's ratio	υ_{ur}	[]	0.2	
Ref. un-/reload. modulus	E_{ur}^{ref}	[kN/m^2]	80096.3	
Strength				
Failure cohesion	c_f	[kN/m^2]	19.918	
Failure ratio	R_f	[]	0.91283	
Failure friction angle	ϕ_f	[deg]	30	

C.1 Contains a number of predefined data previews

C.2 Modify axes limits (use right-click button context menu to invert axes)

C.3 Preview of the experimental data for the tests selected in A.2

C.4 Export/save the current chart view

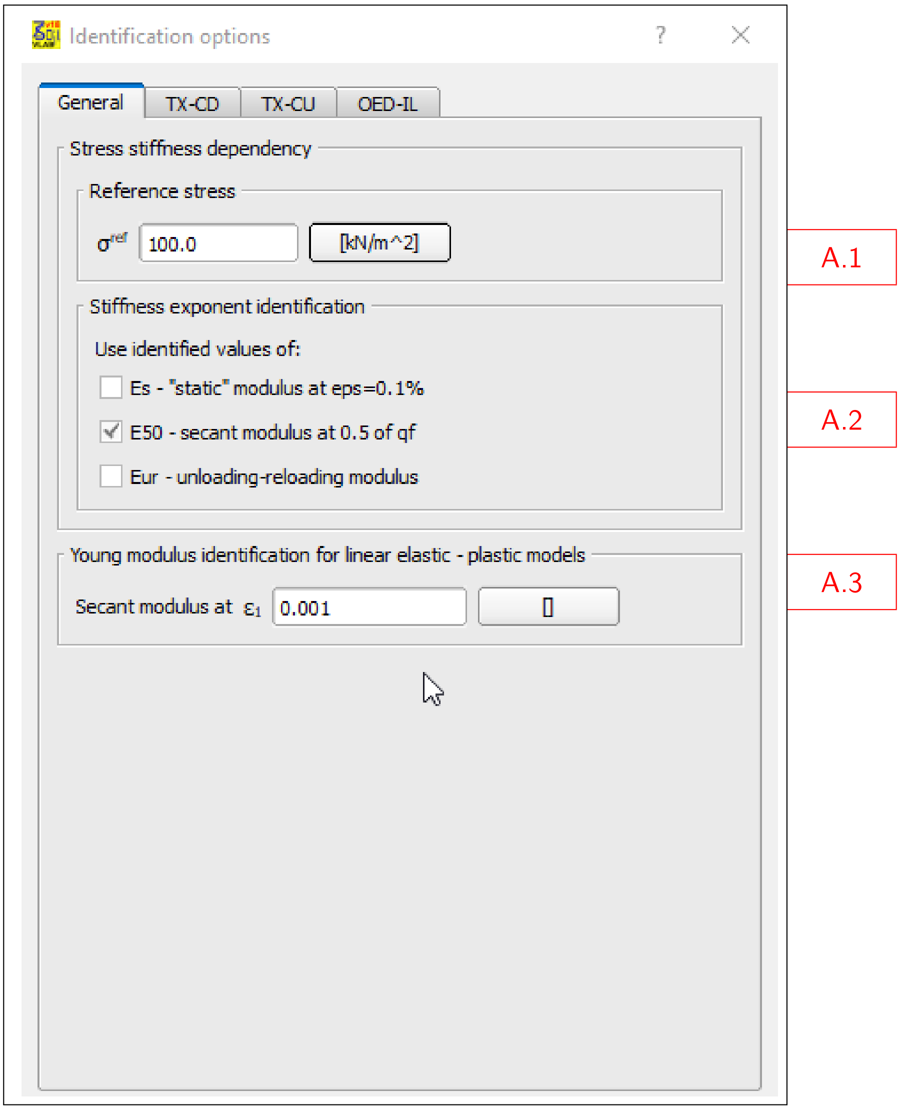
C.5 Show/hide the legend in C.3; the legend box is draggable

D.1 Configuring parameter identification algorithms.

Window 4-10

Window 4-11: Configure the parameter identification algorithm

Z_Soil



A.1 All identified stiffness characteristics will be scaled to the defined reference stress σ^{ref} using different power laws which describe the stress dependent stiffness:

$$E = E^{\text{ref}} \left(\frac{\sigma_3^* \sin\phi + c\cos\phi}{\sigma^{\text{ref}} \sin\phi + c\cos\phi} \right)^m \quad \text{or} \quad E^p = E^{\text{ref,p}} \left(\frac{p^*}{\sigma^{\text{ref}}} \right)^{m_p} \tag{1}$$

where σ_3^* is the minor stress and the corresponding power exponent m, whereas p^* is the mean stress ($=(\sigma_1+\sigma_2+\sigma_3)/3$) and the corresponding power exponent m_p. Note that the identification of stiffness exponents is first carried out for the σ_3-power law, then stiffness characteristics are automatically transformed to the p-power law (cf. Sec. 6.2).

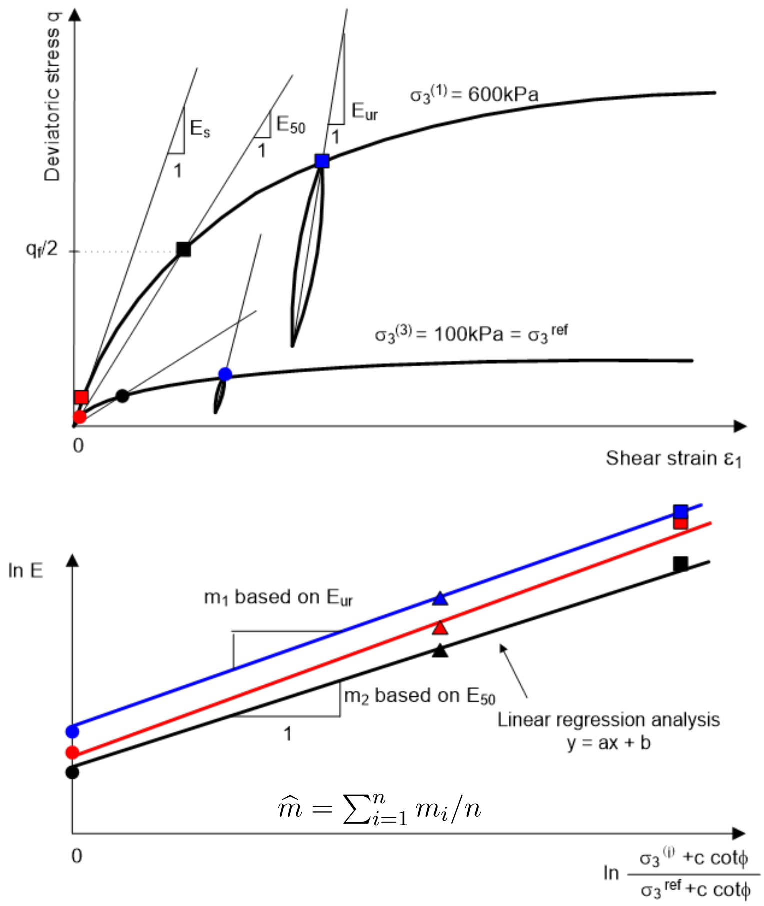
A.2 Stiffness exponent m can be interpreted from the triaxial test curves based on different identified moduli (E_s, E_{50}, and/or E_{ur}). Sometimes the m number identified based on one type of modulus may not be representative due to heterogeneity of tested specimens. Moreover, sometimes m may increase due to increasing amplitude of deformation (smaller values for elasticity and large for plasticity). The user may select more than one deformation modulus type based on which the stiffness exponent will be identified. Then the mean value will be assigned (see Win.4-12).

A.3 The Young's modulus defines the linear elastic domain in the models such as *Mohr-Coulomb* or *Cap*. Typically Young's modulus (also called the 'static' modulus) is identified through the triaxial test results for the axial strain equal to 0.1%. The user can modify the default value.

Window 4-11

Window 4-12: Identification of stiffness exponent m from E_s, E_{50}, and/or $E_{\mathbf{ur}}$ moduli

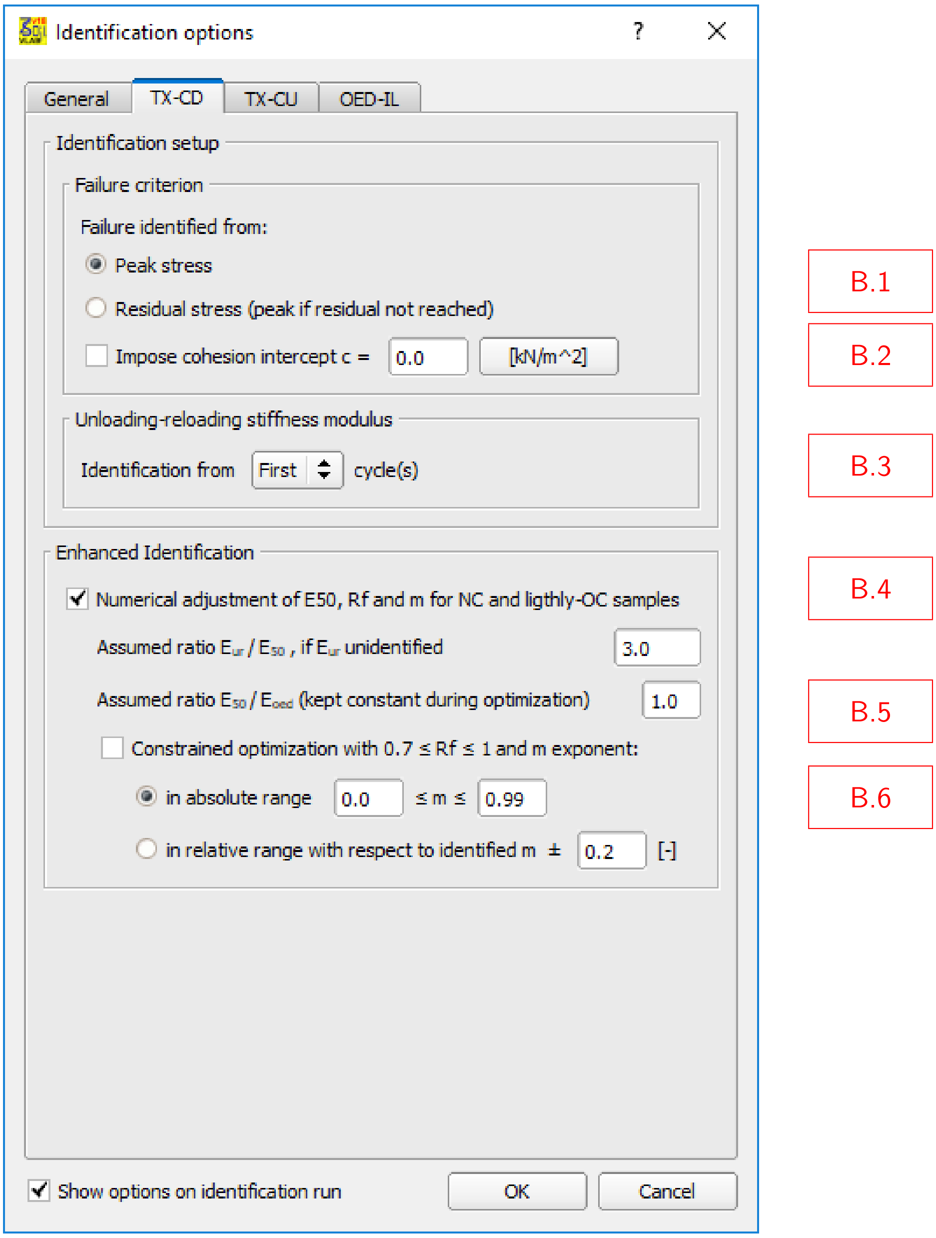
Z_Soil



Window 4-12

Window 4-13: Configuration for interpretation of drained triaxial tests

Z_Soil



B.1 This option allows users to decide which stress will be used to identify the failure criterion in the case of models without softening. The failure criterion is described by ϕ_f and c_f.

B.2 Users may impose the cohesion intercept for the regression analysis which identifies strength parameters ϕ and c.

B.3 User may specify the cycle from which the unloading-reloading modulus is identified. Typically, the first cycles are more relevant as the specimen is subject to smaller amplitudes of shear strain and a relatively smaller heterogeneity of stress distribution in the specimen.

B.4 Activates the optimization of E_{50}, R_f and the stiffness exponent m when running the parameter identification for drained compression test data. The algorithm applies the curve fitting to fit numerical curves to experimental data. **This option is strongly recommended for normally- and lightly overconsolidated specimens** (reconstituted specimens or confining stresses close to the *in situ* stress state with $\text{OCR}^{\text{test}} = 1$ to 2, but it can also be successfully applied to overconsolidated specimens. Note that the *in situ* overconsolidated ratio $\text{OCR} = \sigma_{vc}/\sigma'_{v0}$ of the soil can be different than OCR^{test} of the specimen in the triaxial cell conditions ($\text{OCR}^{\text{test}} = \sigma_{vc}/\sigma_c$, with σ_c denoting the effective confining pressure after consolidation).

Note that identification of these three parameters is affected by the activation of volumetric plastic strains due to mobilization of the isotropic hardening mechanism. In this case, the response of normally- and lightly consolidated specimens is softer than that of the overconsolidated specimen, and therefore will result in underestimation of the secant modulus - refer to Win. 4-14.

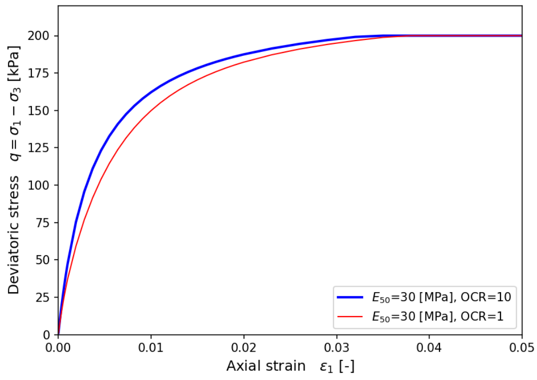
B.5 User can define a fixed ratio E_{50}/E_{ur} (if E_{ur} not identified) or E_{50}/E_{oed}. E_{ur} and E_{oed} will be updated during an iterative optimization with respect to the updated E_{50}.

B.6 Enables a constrained optimization when the numerical adjustment for m and R_f is applied. It can be used for non-standard experimental data for which the unconstrained optimization results in values of parameters which violate constitutive and numerical rules (e.g. $R_f < 0.7$ or $m > 1.0$). The stiffness exponent can be constrained to an absolute user-defined range or relatively to the analytically identified value of m.

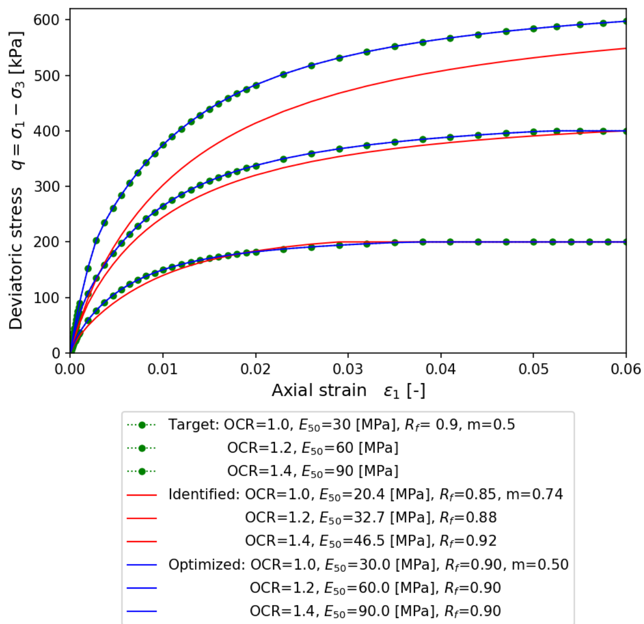
Window 4-13

Window 4-14: Isotropic mechanism mobilization during triaxial compression

Z_Soil



Effect of mobilization of the isotropic mechanism which affects the secant stiffness of normally-consolidated specimen OCR$=1$ (red) vs response of the material for in an overconsolidated state OCR$=10$ (blue); theoretical curves obtained for the same input parameter $E_{50}^{\text{ref}} = 30$MPa.



Example of optimization of E_{50}^{ref}, R_f and m for normally-consolidated and lightly overconsolidated specimens.

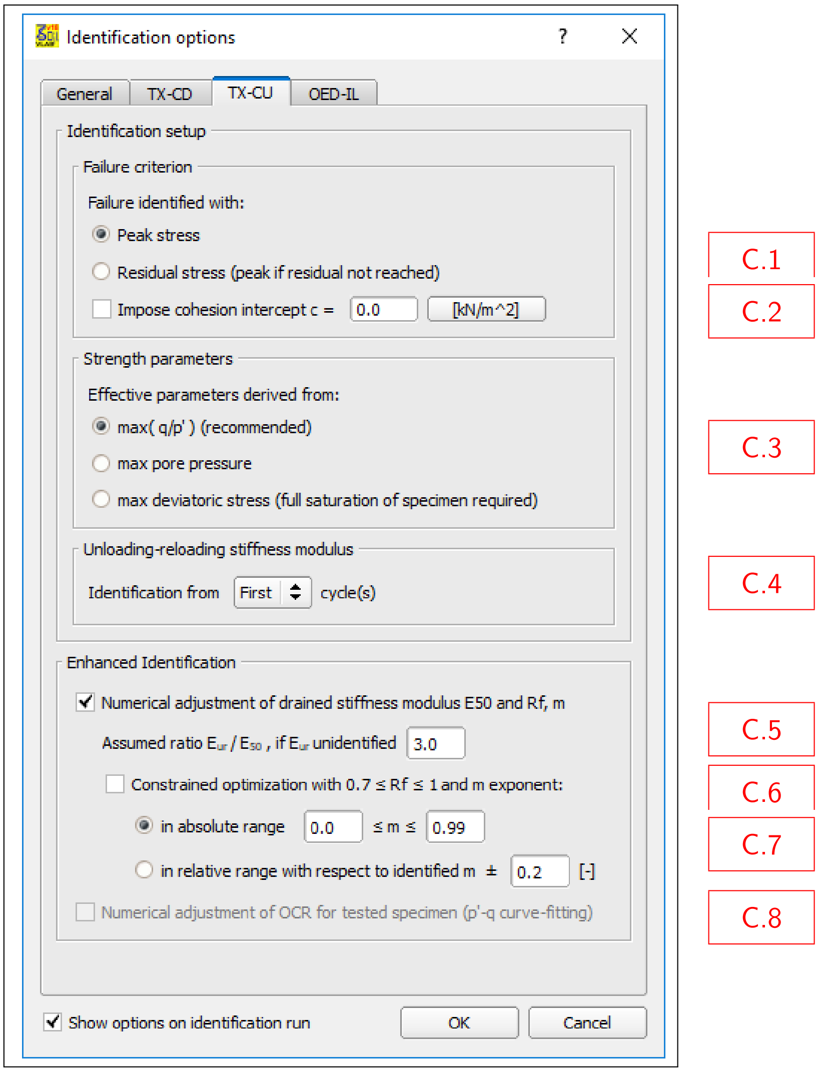
Theoretical curves obtained with:

- target parameters $E_{50}^{\text{ref}} = 30$MPa, $R_f = 0.9$ and $m = 0.5$ (green)
- parameters identified from theoretical curves obtained with target parameters and normally-consolidated specimens (red)
- numerically adjusted (optimized) parameters (blue)

Window 4-14

Window 4-15: Configuration for interpretation of undrained triaxial tests

Z_Soil



C.1 This option allows the user to decide which stresses will be used to define the failure criterion in case of models without softening. The failure criterion is described by ϕ_f and c_f.

C.2 The user may impose the cohesion intercept for the regression analysis which identifies strength parameters ϕ and c.

C.3 The option allows the user to define a criterion for identifying the effective strength parameters ϕ and c. The recommended option: $\max(q/p')$ - effective strength parameters determined based on maximal ratio between the deviatoric and mean effective stress. Pore pressure - parameters are determined based on the deviatoric stress corresponding to the strain for which the maximal pore pressure excess was recorded. Deviatoric stress - parameters are determined based on the maximal deviatoric stress $(\sigma_1 - \sigma_3)_{max}$. Note that the last option may lead to overestimation of cohesion (apparent cohesion) in the case of unsaturated specimens.

C.4 Users can specify the cycle from which the unloading-reloading modulus is identified. Typically, the first cycles are more relevant as the specimen is subject to smaller amplitudes of shear strain and smaller non-homogeneity of stress distribution in the specimen.

C.5 Activates optimization of E_{50}, R_f and the stiffness exponent m when running the parameter identification for undrained compression test data. **Note that identification of these three effective parameters is affected by undrained conditions and the numerical curve fitting is strongly recommended**. When using this option, the overconsolidation ratio of the sample, OCR^{test}, plays an important role in the identification as it defines the position of the cap mechanism.
Note that the *in situ* overconsolidated ratio OCR $= \sigma_{vc}/\sigma'_{v0}$ of the soil can be different to the OCR of the specimen in under triaxial cell conditions ($\text{OCR}^{\text{test}} = \sigma_{vc}/\sigma_c$, with σ_c denoting the effective confining pressure after consolidation).

C.6 Users can define a fixed ratio E_{50}/E_{ur} (if E_{ur} is not identified). E_{ur} will be updated during an iterative optimization with respect to the updated E_{50} value.

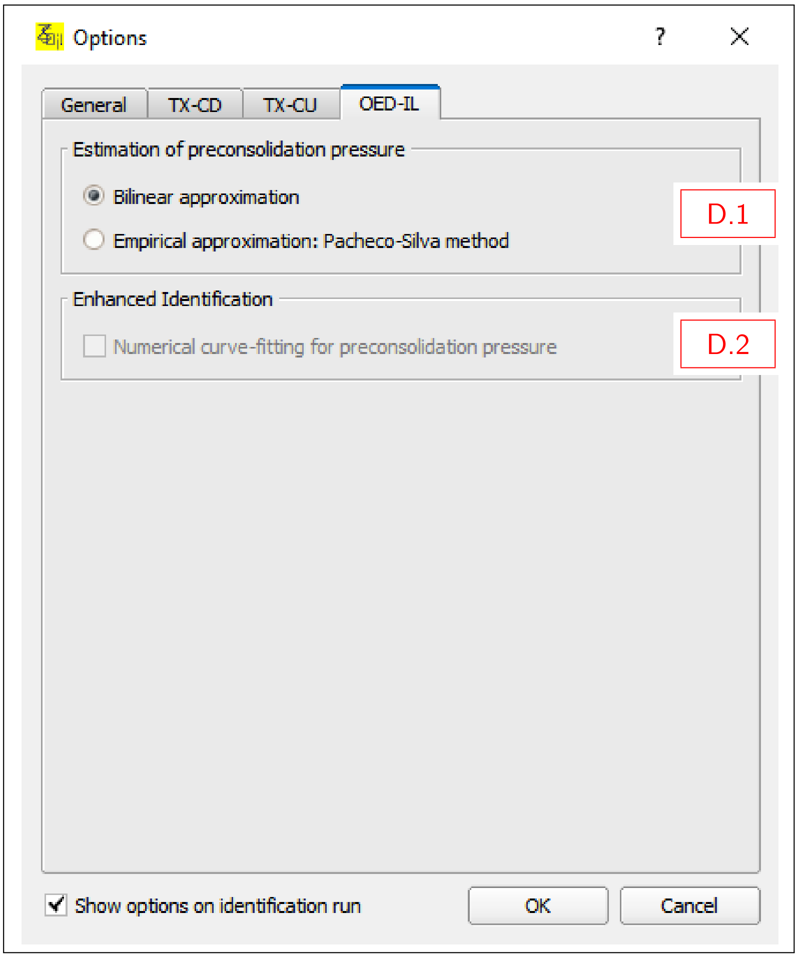
C.7 Enables a constrained optimization when the numerical adjustment for m and R_f is applied. It can be used for non-standard experimental data for which the unconstrained optimization results in values of parameters which violate constitutive and numerical rules(e.g. $R_f < 0.7$ or $m > 1.0$). The stiffness exponent can be constrained to an absolute user-defined range or relatively to the analytically identified value of m.

C.8 Activates optimization-based adjustment of specimen's OCR based on the $p' - q$ curve.

Window 4-15

Window 4-16: Configuration of oedometric test interpretation

Z_Soil



D.1 The preconsolidation pressure understood as a threshold point beyond which the important plastic straining occurs, is difficult to establish unambiguously. Among a number of methods proposed in literature for determining the preconsolidation pressure, the following ones are commonly used owing to their simplicity. The algorithms are provided in the report dedicated to the Hardening-Soil model.

D.2 Since the estimation of the preconsolidation pressure is based on empirical methods, the adjustment can be carried out for the Hardening Soil model with the aid of numerical curve-fitting.

Window 4-16

Chapter 5

PARAMETER VERIFICATION AND VALIDATION

The laboratory test simulator (Window 5-1) offers parameter verification and validation by running numerical simulations of elementary laboratory tests. Numerical simulations are carried out by means of ZSoil v2023 calculation module. This makes it possible to visualize a response of constitutive model for the user-defined or identified model parameters.

The constitutive model can be verified for the user-defined or estimated parameters by simulating one of the following elementary laboratory tests (Window 5-3):

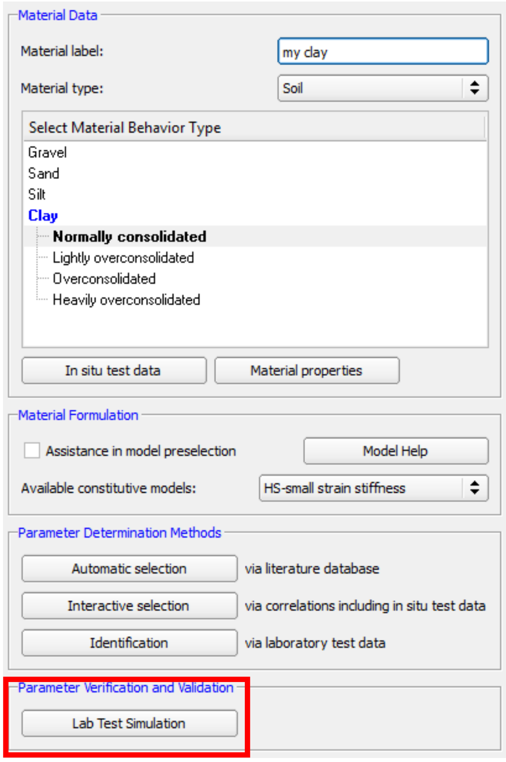
- triaxial drained compression (TX-CD)
- triaxial undrained compression (TX-CU)
- oedometric curves (OED)

Note that no parameter determination is required to run a numerical simulation to verify a model response for a given vector of parameters.

Model parameters which are identified based on laboratory curves can be validated by running numerical simulations and comparing numerical results with laboratory curves (Window 5-2). In order to compare laboratory curves with a model response, laboratory data must first be imported by means of the Parameter Identification module.

Window 5-1: Calling the Laboratory Test Simulator

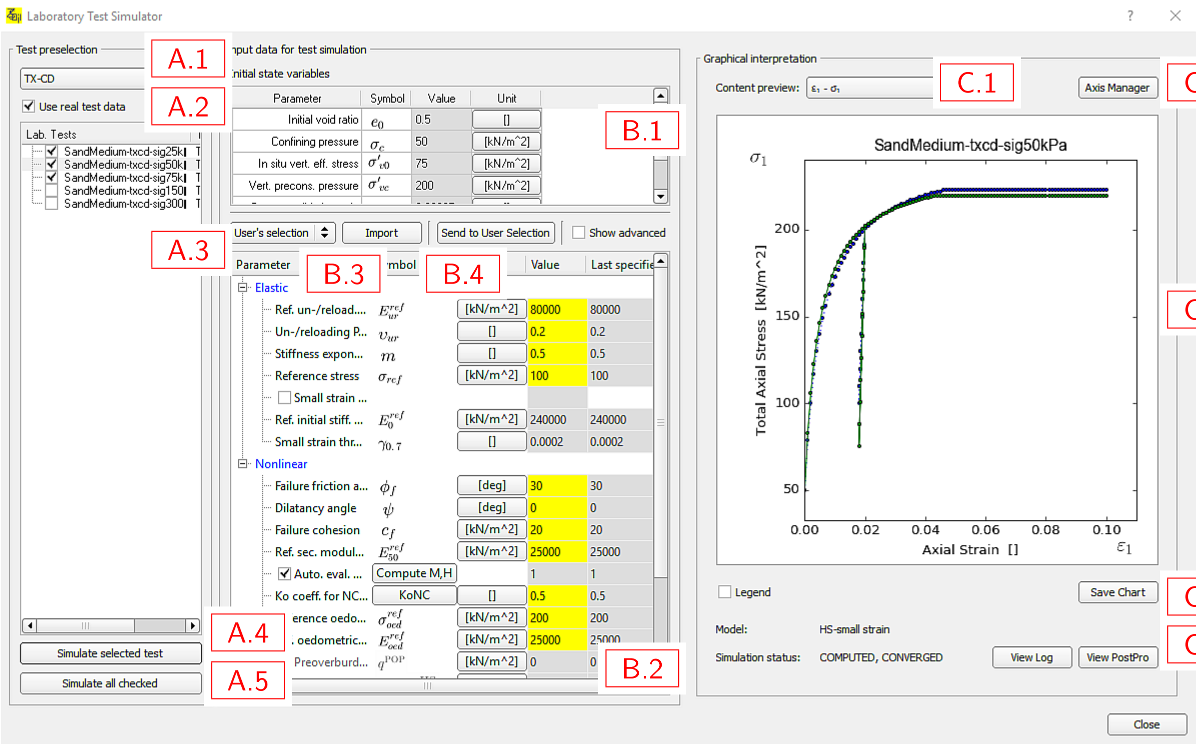
Z_Soil



Window 5-1

Window 5-2: Validation of model parameters

Z_Soil



A.1 Filtering tests according to the test type. The test simulation can be run in order to evaluate model behavior to the specified vector of parameters B.2 or to compare model response with experimental data. The following elementary laboratory tests can be simulated:

- TX-CD: strain-controlled, one-element triaxial drained compression; analysis type `Axisymmetry`, problem type `Deformation`, driver type `Driven Load`
- TX-CU: strain-controlled, one-element triaxial undrained compression; analysis type `Axisymmetry`, problem type `Deformation+Flow`, driver type `Driven Load (Undrained)`
- OED-IL: stress-controlled , one-element oedometric compression; analysis type `Axisymmetry`, problem type `Deformation+Flow`, driver type `Driven Load`

A.2 Show the assembly of real tests which have been specified in Test data input
A.3 Select tests which you want to simulate
A.4 Run a numerical simulation for the selected test using initial state variables from B.1 and vector of parameters B.2. The results will be presented in C.3
A.5 Run simulation of all checked tests. The results will be presented in C.3

B.1 Preview of initial state variables for currently selected test only. Since the initial state variables are specified in Test data input, the values are not editable
B.2 Specify model parameters. Note that these parameters can be automatically imported from parameter summary widget.
B.3 Import model parameters from the "User's selection" or those obtained by determination methods

B.4 Export the entire vector of modified parameter values to the "User's selection"

Sign convention: The sign convention is the standard convention of soil mechanics, i.e. compression is assigned as positive.

C.1 Predefined data previews

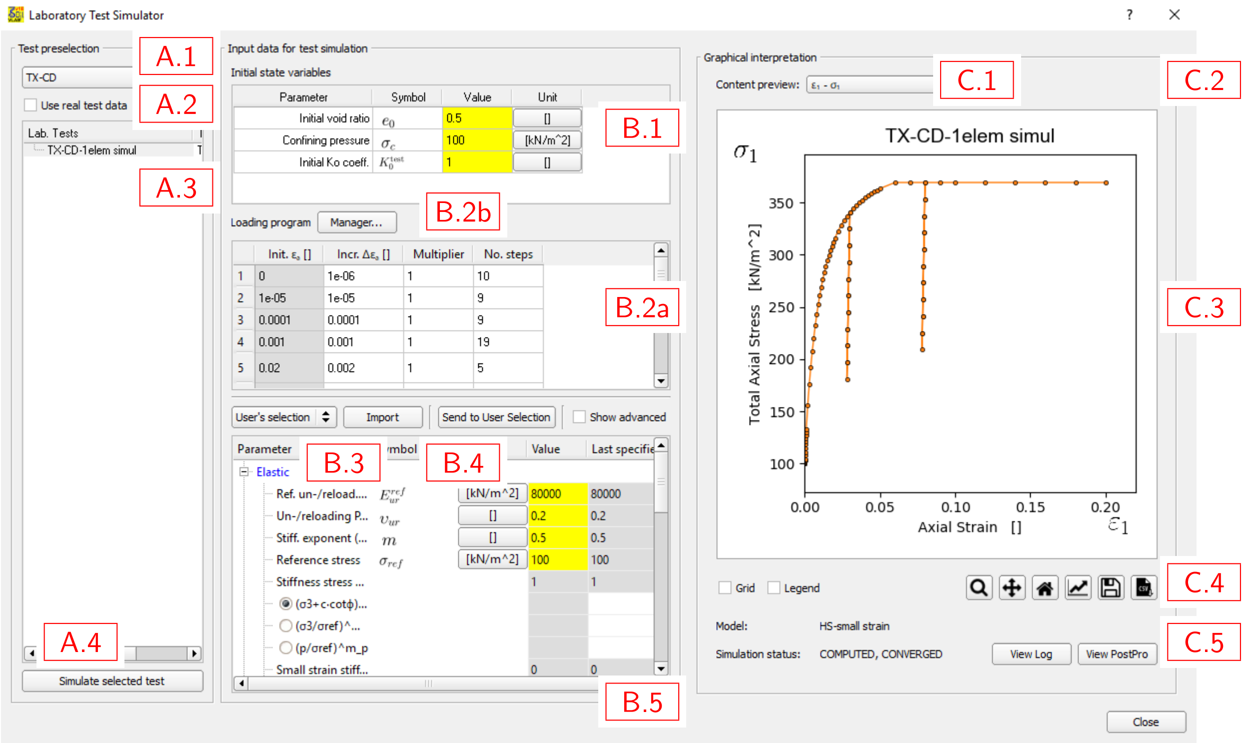
C.2 Modify axes limits (use right-click button context menu to invert axes)

C.3 Preview of experimental data and results obtained by means of a numerical simulation

C.4 Export/save the current chart to graphical file

C.5 Control the simulation status and the log of computations

Window 5-2



A.1 Cf. Window 5-2

A.2 Activate/deactivate the list of real test data (previously specified in Win.4-7)

A.3 Select tests which are meant to be simulated

A.4 Run a numerical simulation for the selected test using initial state variables from B.1 and vector of parameters B.5. The results will be presented in C.3

B.1 Specify initial state variables for currently selected test

B.3 Cf. Window 5-2

B.4 Cf. Window 5-2

B.2a Create the loading program using a dedicated manager Win. 5-4

B.2b Customize the loading program. Note that redundant rows in the loading program can be removed by the mouse right-click over the first column of the row to be removed

B.5 Define or modify model parameters

Sign convention: The sign convention is the standard convention of soil mechanics, i.e. compression is assigned as positive.

C.1 Cf. Window 5-2

C.2 Cf. Window 5-2

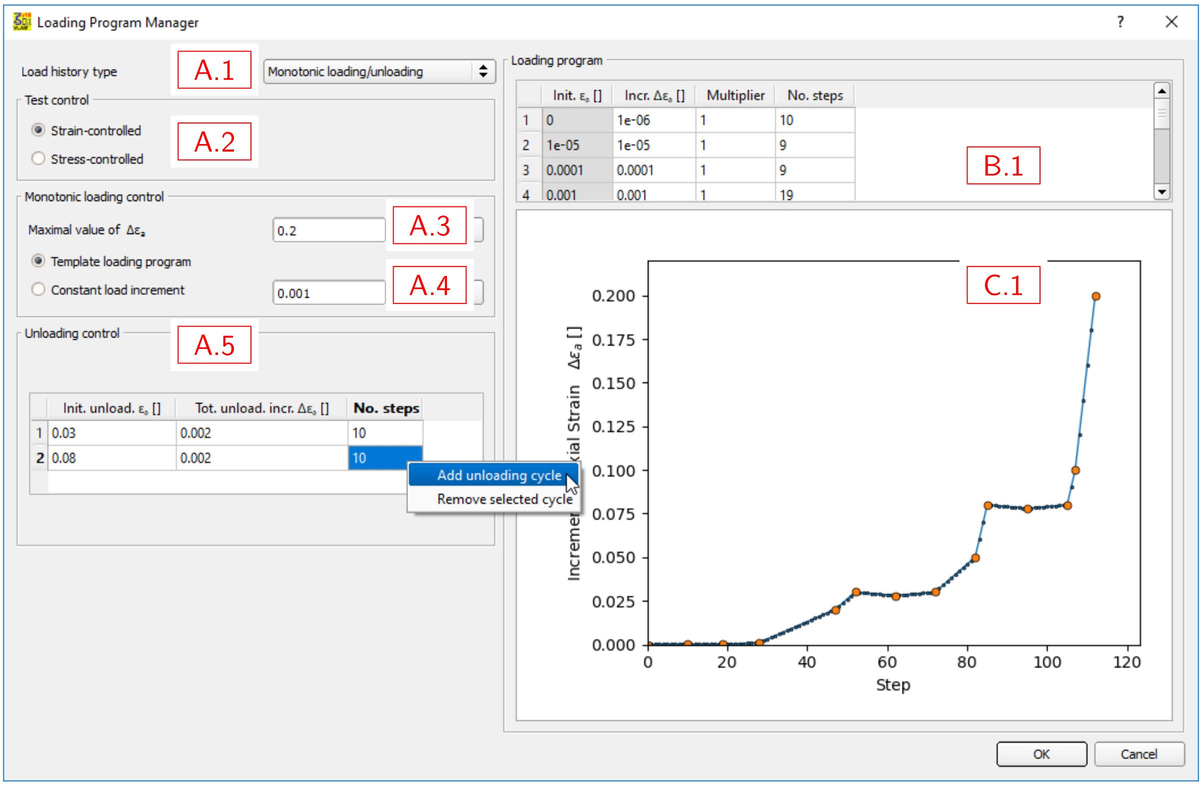
C.3 Cf. Window 5-2

C.4 Cf. Window 5-2

C.5 Cf. Window 5-2

Window 5-4: Loading program manager

Z_Soil



A.1 Define the load history type:

- Monotonic loading - defines an increase of strain or stress
- Monotonic loading/unloading - includes unloading cycles
- Cyclic loading - defines n-number of constant or constantly increasing amplitudes of strain or stress

A.2 Define the test control type:

- Strain-controlled - stress will be produced by displacement imposed at the top boundary conditions
- Stress-controlled - strain will be generated by load imposed at the top edge of element

A.3 Set up the maximal increment value of:

- axial strain $\Delta\varepsilon_a$
- dimensionless normalized deviatoric stress $\Delta q/\sigma_a, 0$ where $\sigma_{a,0}$ stands for the initial axial stress, whereas $\Delta q = (\sigma_a - \sigma_r)$ is the demanded maximal difference between the axial and radial stress

A.4

- Template loading program (recommended) - a generic algorithm proposes an increase in load increments with increasing load amplitudes, e.g. see B.1

- Constant load increment - the demanded load increment will be kept constant throughout the numerical simulation

A.5 Modify/add or remove unloading cycles:

- Init. unload - strain or normalized deviatoric stress level at which the unloading cycle is supposed to begin
- Tot. unload. incr. - total unloading increment (to be defined as positive value)
- No. steps - number of discrete computational increments per demi-cycle

Add or remove an unloading cycle by the mouse right-button click over the unloading control table.

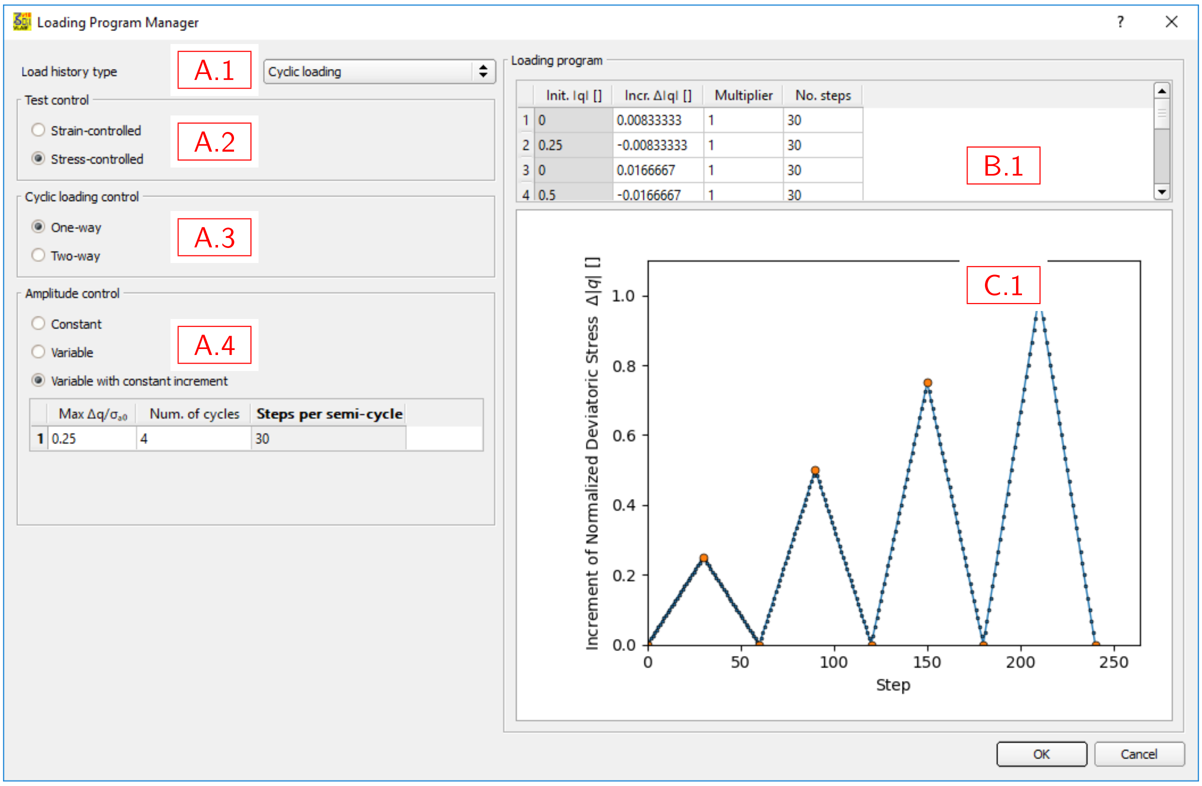
B.1 Preview of the automatic setup A.. The data in the table can by manually modified. Any change in A. modifies the content of B.1

C.1 Graphical visualization of the loading program B.1

Window 5-4

Window 5-5: Loading program manager

Z_Soil



A.1 cf. Win.5-4

A.2 cf. Win.5-4

A.3 Cyclic loading control:

- One-way - increments from 0 to max Δ without the sign reversal (as shown in the example C.1).
- Two-way - increments from 0 to max Δ, negative max Δ

A.4 Amplitude control:

- Constant - define n-number of cycles of constant amplitude
- Variable - set of m of n-uniform cycles of different amplitudes
- Variable with constant increment - amplitude of load increases constantly with each loading cycle (as shown in the example C.1)

B.1 cf. Win.5-4

C.1 cf. Win.5-4

Window 5-5

Chapter 6

TOOLS

6.1 INITIAL STATE PROFILE

The Initial State Profile tool allows the user to assess, in a simplified manner, the profiles of initial state variables. It makes it possible to test the influence of each parameter describing material behavior in terms of:

- Total stress (gravity analysis)
- Effective stress (Bishop's principle)
- Overconsolidation (preconsolidation state depending on mechanical constitutive model)
- Saturation (van Genuchten's model for the soil water retention curve)
- Permeability (Irmay or Mualem model for permeability of partially-saturated medium)

The profiles produced by the tool can be obtained with ZSoil when computing the initial state for a horizontal layer setup.

The tool allows the following profiles to be visualized:

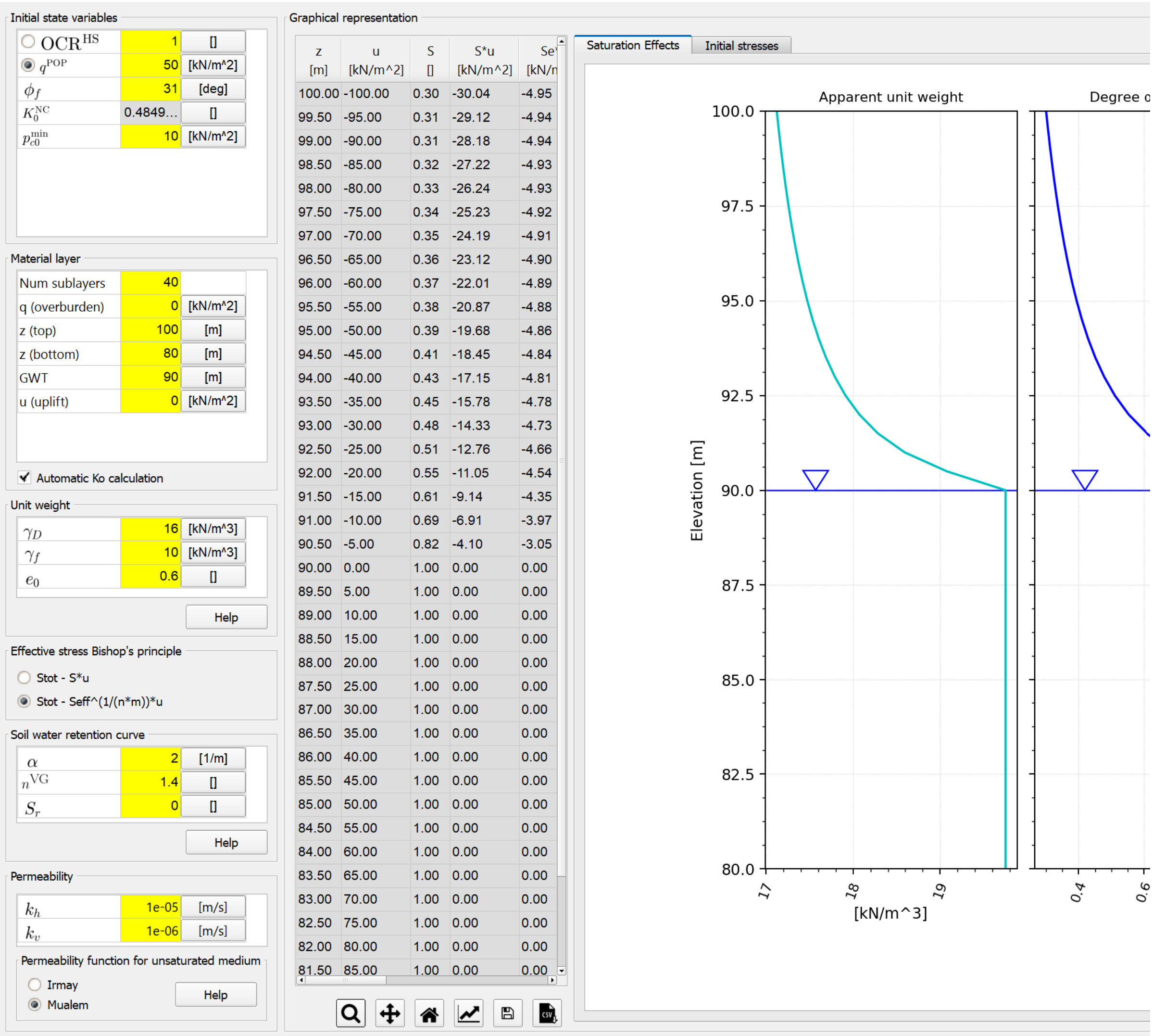
- Variation of the **apparent unit weight** between the fully-saturated and unsaturated medium
- Variation of the **degree of saturation** in the partially-saturated zone
- Magnitude of the ultimate **suction stress** (or apparent cohesion) in unsaturated soil for two different formulations of pore pressure weighting term (Bishop's effective stress principle Win.6-4)
- Profile of permeability which depends on the selected model describing the **permeability of the partially saturated medium**
- **Variation of initial K_0 state** as a function of preconsolidation state
- Profiles of **total and effective stresses**, as well as **preconsolidation pressure**
- **Variation of OCR** with respect to the preconsolidation stress and the vertical effective stress and the selected constitutive model (Hardening Soil, Cap, Modified Cam-Clay)

Note that all these variables and their profiles are highly transient (they vary with time and stress evolution) during any numerical analysis in ZSoil v2023 .

Window 6-3 describes input parameters which are used in profiling, Win.6-1.

Window 6-1: Definition of parameters in the initial state profile tool

Z_Soil

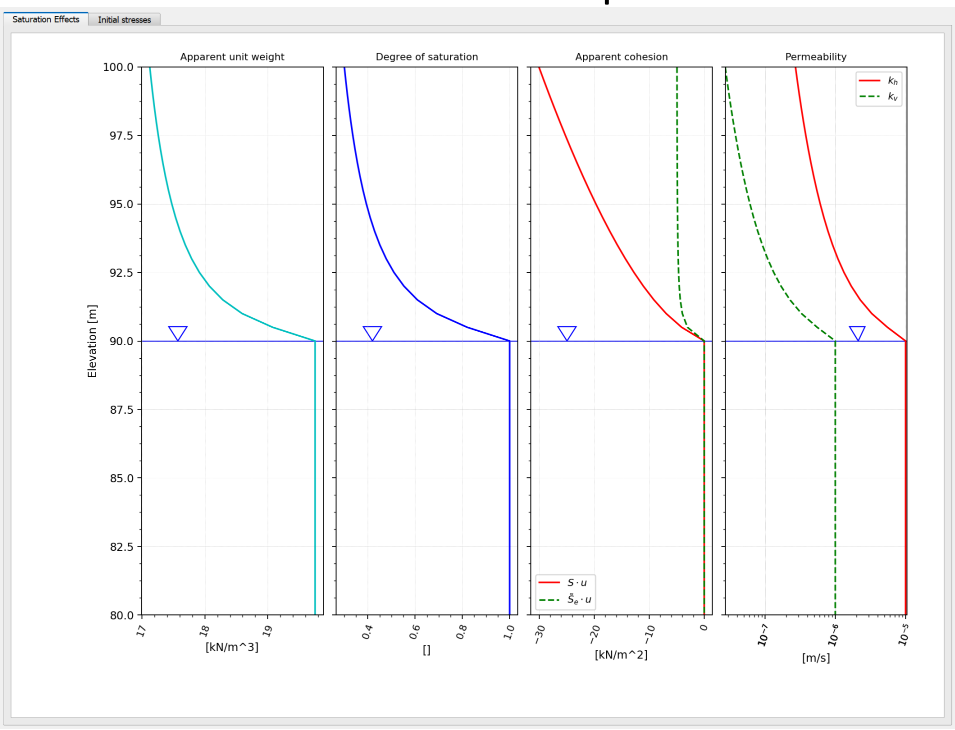


Window 6-1

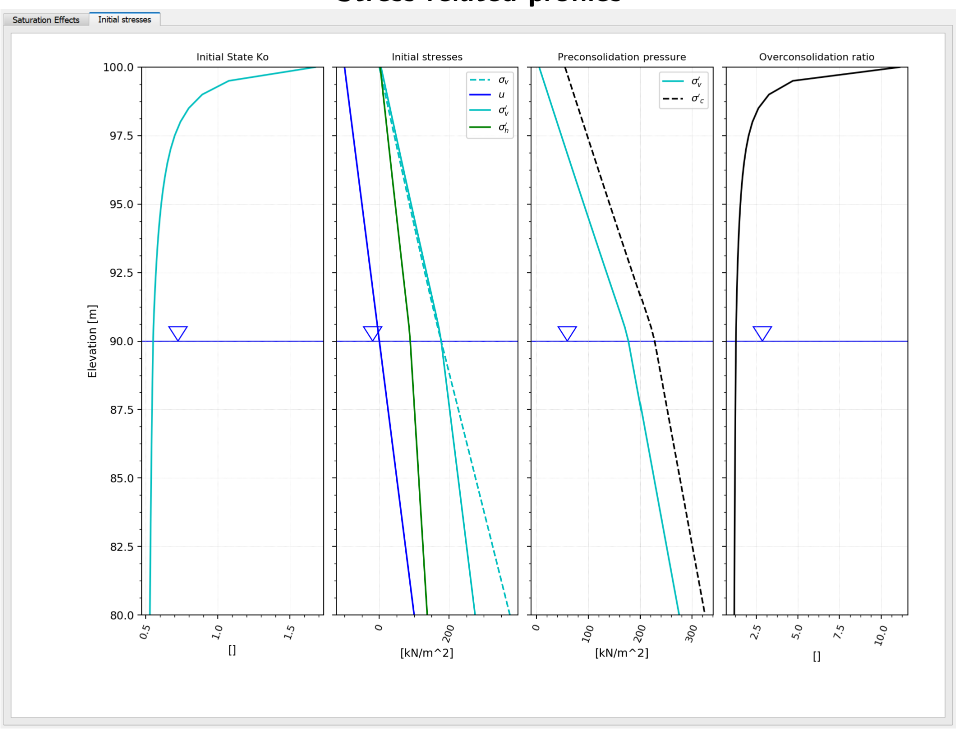
Window 6-2: Visualization of partial-saturation effects in the initial state profile tool

Z_Soil

Partial-saturation related profiles



Stress related profiles



Window 6-2

Window 6-3: Input parameters for the initial stress profile

Z_Soil

Input parameters			
Initial state variables	$\mathrm{OCR}^{\mathsf{HS}}$	$[-]$	Overconsolidation ratio in terms of vertical stress $(=\sigma'_c/\sigma'_{vo})$
	q^{POP}	$[\mathrm{kPa}]$	Preoverburden pressure (a historical pressure acting on soil layer)available; available only for the Hardening-Soil model (cf. stress history for the HS model)
	$\mathrm{OCR}^{\mathsf{MCC}}$	$[-]$	Overconsolidation ratio in terms of the mean effective stress $(=p_{c0}/p'_0)$; defines the initial preconsolidation state for the Modified Cam-Clay model
	$\mathrm{OCR}^{\mathsf{Cap}}$	$[-]$	Overconsolidation ratio in terms of the mean effective stress $(=p_{c0}/p'_0)$; defines the initial preconsolidation state for the Cap model
	ϕ	$[^{\mathrm{o}}]$	Friction angle
	K_0^{NC}	$[-]$	K_0 coefficient for normally-consolidated soil
	$p_{c0,\min}$	$[\mathrm{kPa}]$	Minimal mean preconsolidation stress; NB. overconsolidated state observed in the superficial soil layers can be obtained in MCC and Cap model by setting high values of $p_{c0,\min}$ (say from 30 to 100 kPa)
Material layer	Num sublayers		Number of discrete elements that are used to obtain variable profiles
	q (overburden)	$[\mathrm{kPa}]$	Total pressure acting at the top of the layer due to other layers and loads
	z (top)	$[\mathrm{m}]$	Elevation of top layer
	z (bottom)	$[\mathrm{m}]$	Elevation of bottom layer
	GWT	$[\mathrm{m}]$	Ground water level
	K_0 (top)	$[-]$	Estimated Ko coefficient at the top of the layer (meaningful for the cases where the initial stress is imposed through *Initial stresses* (at the Pre-Pro level) without running the Initial State analysis)
	K_0 (bottom)	$[-]$	Estimated Ko coefficient at the bottom of the layer (meaningful as above)
	u (uplift)	$[\mathrm{kPa}]$	Uplift pore pressure
	Auto K_0		Automatic evaluation of K_0 based on ϕ and OCR
Unit weight	γ_{D}	$[\mathrm{kN/m^3}]$	Unit weight of dry soil
	γ_f	$[\mathrm{kN/m^3}]$	Unit weight of fluid
	e_0	$[-]$	Initial void ratio
Flow constants	α	$[-]$	Soil water retention curve saturation constant which is a measure of the thickness of transition from full to residual saturation; it can be taken as the inverse of the capillary rise height
	n^{VG}	$[-]$	Measure of pore-size distribution $(n^{\mathrm{VG}} > 1.0)$
	S_r	$[-]$	Degree of residual saturation; note that for $S_r > 0.0$, $S \cdot u$ tends to infinity with increasing negative (capillary) pore pressure for the standard formulation of the saturation term (Bishop's parameter)

Window 6-3

6.1.1 Saturation effects

Win. 6-4 and 6-5 summarize the governing equations which are used to visualize stress profiles that account for the effects of partial saturation.

Window 6-4: Governing equations for the Bishop's effective stress principle

Z_Soil

Apparent unit weight	$\gamma = \gamma_{\text{D}} + n_0 S \gamma_f$ with: S - saturation degree obtained using the soil water retention curve by van Genuchten (1980) (Win.6-5) n_0 - initial porosity $= \dfrac{e_0}{1+e_0}$
Effective stress	$\sigma'_{ij} = \sigma_{ij} - \tilde{S} \cdot u \cdot \delta_{ij}$ For capillary pressures above the groundwater level, the suction stress $\tilde{S} \cdot u$ is the function of saturation degree S that depends on pore water pressure, u, according to Win.6-5. The pore pressure scaling term $\tilde{S}$ can be selected between: • $\tilde{S} = S$, saturation coefficient calculated according to Win.6-5 • $\tilde{S} = \tilde{S}_e = S_e^{\frac{1}{nm}} = \underbrace{\left(\dfrac{S - S_r}{1 - S_r}\right)}_{S_e}^{\frac{1}{nm}}$, corrected effective saturation The assumed form of the $\tilde{S}_e$ enforces monotonic and asymptotic behavior of the $\tilde{S} \cdot u$ when suction stress u tends to infinity above the groundwater level. For any n parameter value, $\tilde{S}u \rightarrow \gamma_w/\alpha$ for $u \rightarrow \infty$. In this way, the resulting apparent cohesion can be controlled in order to avoid unrealistic excessive numbers. δ_{ij} - Kronecker's delta

Window 6-4

Window 6-5: Governing equations for the partial-saturation effects

Z_Soil

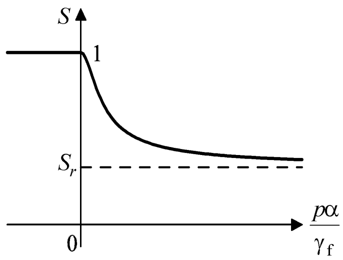
<table>
<tr><td>Saturation degree</td><td>

$$S = S(u) = \begin{cases} S_r + \dfrac{1 - S_r}{\left[1 + \left(\alpha \dfrac{u}{\gamma_f}\right)^n\right]^m} & \text{if} \quad u < 0 \\ 1 & \text{if} \quad u \leq 0 \end{cases}$$

with:

$m = 1 - \dfrac{1}{n}$

notice that by setting $n = 2$ and $m = 0.5$ the above equation reduces to the simplified version of van Genuchten's model offered in the ZSoil versions ¡ 23.50



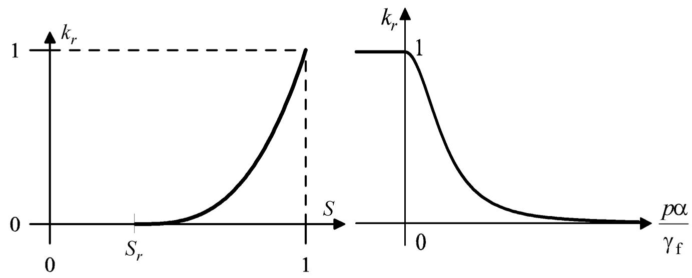
</td></tr>
<tr><td>Permeability</td><td>

The permeability tensor k^*_{ij} is obtained by scaling the k_{ij} tensor for fully saturated medium by scalar valued function k_r which depends on the saturation ratio.

$k^*_{ij} = k_r(S) k_{ij}$

ZSoil v2023 offers two different formulations for the scalar valued function k_r according to:
$k_r = S_e^3$ (Irmay)
or
$k_r = S_e^{1/2} \left(1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right)^2$ (Mualem)

with the effective saturation degree defined as:
$S_e = \dfrac{S - S_r}{1 - S_r}$



</td></tr>
</table>

Window 6-5

6.1.2 Initial stresses

Window 6-6 summarizes the governing equations which are used to visualize the variation of stresses and preconsolidation state.

Window 6-6: Governing equations for initial stress and preconsolidation profiles

Z_Soil

Initial State K_0	In the case of automatic evaluation, in situ K_0 profile is evaluated from a correlation by Mayne and Kulhawy (1982) : $K_0 = K_0^{\mathsf{NC}} \mathrm{OCR}^{\sin\phi'}$ where the coefficient K_0 for a normally-consolidated soil is evaluated from: $K_0^{\mathsf{NC}} = 1 - \sin\phi'$ The upper bound value for K_0 is limited to the passive lateral earth pressure coefficient: $K_p = \dfrac{1+\sin\phi}{1-\sin\phi}$
Initial stresses	The effective stresses are obtained obtained from the Bishop's effective stress definition for a single-phase model for fluid: $\sigma'_{ij} = \sigma_{ij} - \tilde{S} \cdot u \cdot \delta_{ij}$ with: u - pore water pressure δ_{ij} - Kronecker's delta The relationship between the effective vertical and horizontal stresses reads: $\sigma'_{h0} = K_0 \cdot \sigma'_{v0}$ The preconsolidation pressure is computed from: $\sigma_{vc} = \mathrm{OCR} \cdot \sigma'_{v0}$
Overconsolidation ratio	$\mathrm{OCR} = \max\left(\dfrac{\sigma_{vc}}{\sigma'_{v0}}, \dfrac{\sigma_{vc,\mathsf{min}}}{\sigma'_{v0}}\right)$ where: $\sigma_{vc,\mathsf{min}} = \dfrac{3p_{c0,\mathrm{min}}}{1+2K_0}$

Window 6-6

6.2 STRESS DEPENDENT STIFFNESS MIGRATION

Stress dependent stiffness in the Hardening Soil model in ZSoil v2023 can be described with the three different formulations of the power law (see The Hardening Soil model - a practical guidebook for a comprehensive discussion on the advantages and shortcomings of each formulation). In the first formulation, stiffness moduli depend on the evolution of the minor stress σ_3 following:

$$E = E^{\text{ref}} \left(\frac{\sigma_3' \sin\phi + c\cos\phi}{\sigma^{\text{ref}} \sin\phi + c\cos\phi} \right)^m \tag{6.1}$$

with:
E - standing for one of the deformation modulus, i.e. E_{50}, E_{ur} or E_0
ϕ - friction angle
c - cohesion
m - stiffness exponent

In the second formulation, the power law reduces to:

$$E^{\sigma_3} = E^{\sigma_3,\text{ref}} \left(\frac{\sigma'}{\sigma^{\text{ref}}} \right)^{m_\sigma} \tag{6.2}$$

neglecting the cohesion term.

In the third formulation, the power law takes more natural form where material stiffness depends on the mean stress (effective in the two-phase analysis):

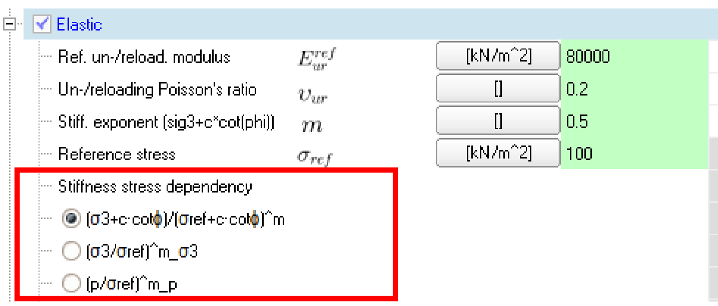
$$E^p = E^{p\text{ref}} \left(\frac{p'}{\sigma^{\text{ref}}} \right)^{m_p} \tag{6.3}$$

with E_p denoting any modulus which is scaled to the reference stress using a current mean stress p'.

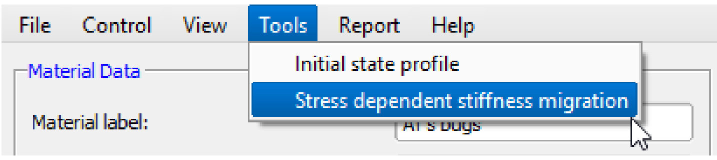
Notice that the stiffness exponents m, m_{σ_3} and m_p are equal to each other only if $c = 0$.

Moreover, compatibility for different stiffness moduli, i.e. E^{σ_3} or $E^p = E$, can be maintained only for the hydrostatic initial stress conditions $K_0 = 1$. In the other cases, deformation moduli should be transformed with the aid of special techniques which are described in the section Parameter migration between minor and mean stress formulations.

Virtual Lab v2023 offers an integrated tool to facilitate moduli migration which is illustrated in Figure 6-8. The toolbox can be initialized whenever the stress dependency formulation is changed in the elastic parameter window of the Hardening-Soil model:



and can be found in the ZSoil v2023 toolbar under *Tools*:



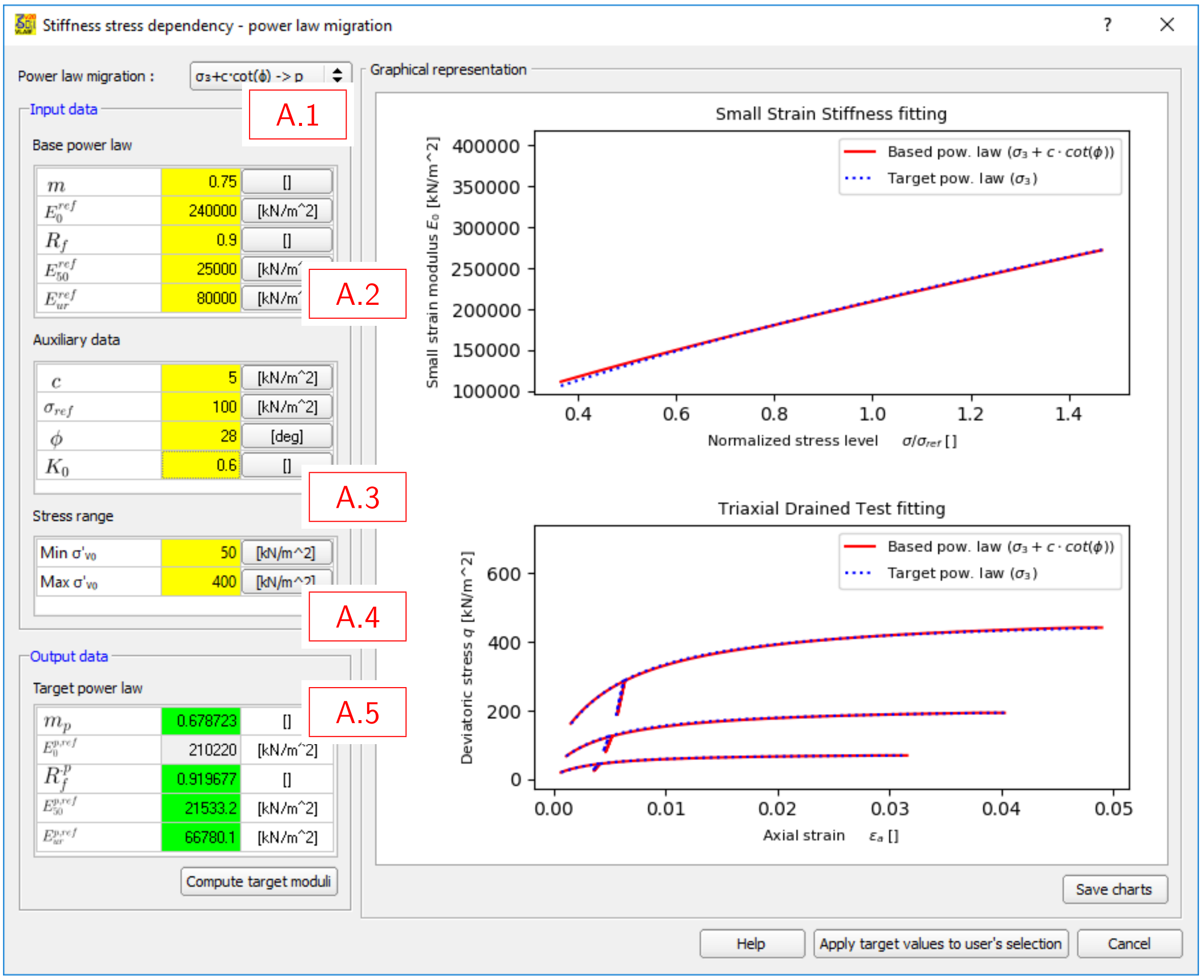
The tool (Win. 6-8) makes it possible to migrate parameters in each direction between the 3 different formulations:

- $\sigma_3 + c \cot \phi \rightarrow \sigma_3$ and $\sigma_3 \rightarrow \sigma_3 + c \cot \phi$
- $\sigma_3 + c \cot \phi \rightarrow p$ and $p \rightarrow \sigma_3 + c \cot \phi$
- $\sigma_3 \rightarrow p$ and $p \rightarrow \sigma_3$

the parameter migration requires setting the base parameters (stiffness moduli, power law exponent m and failure ration R_f) which will be transformed to the target parameters. This transformation involves fitting the target power law to the base power law in terms of the initial small strain stiffness and triaxial curves, in the best possible way (A.1).

Window 6-7: Parameter migration between stress dependent stiffness formulations

Z_Soil



A.1 - migration of parameters between two power laws, the base and the target one:
$\sigma_3 + c\cot\phi \rightarrow \sigma_3$ and $\sigma_3 \rightarrow \sigma_3 + c\cot\phi$
$\sigma_3 + c\cot\phi \rightarrow p$ and $p \rightarrow \sigma_3 + c\cot\phi$
$\sigma_3 \rightarrow p$ and $p \rightarrow \sigma_3$

A.2 - input moduli, stiffness exponent and failure ratio corresponding to the base power law

A.3 - auxiliary parameter required for power law migration

A.4 - range of vertical stresses for which the stiffness equivalency is sought

A.5 - output moduli, stiffness exponent and failure ratio corresponding to the target power law

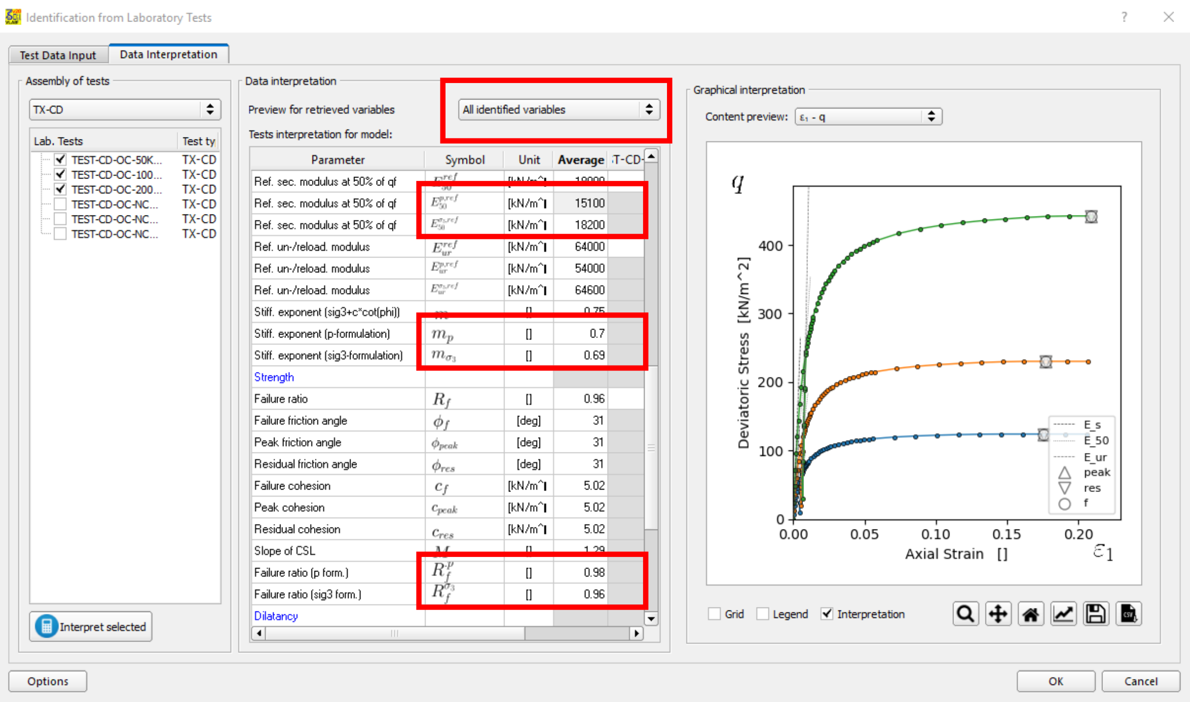
Window 6-7

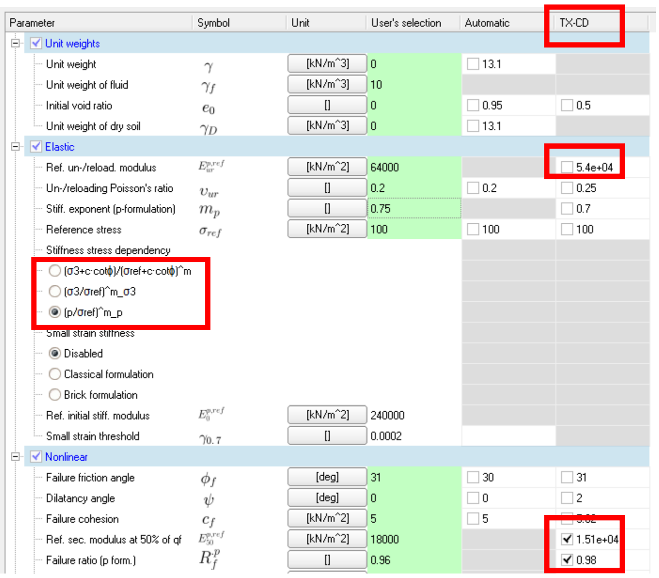
6.2.1 Automatic parameter migration for parameter identification from triaxial curves

For each parameter identification run from experimental triaxial curves, the algorithm identifies the parameters of "$\sigma_3 + c\cot\phi$" power law, and then it automatically determines the equivalent values of parameters which correspond to the σ_3 and p formulations. These parameters are optimized with respect to the initial stress conditions (i.e. σ_3 and K_0) of the interpreted tests and can be inspected by choosing *All identified variables* in the combobox as illustrated in Win. 6-8. The migrated parameters are collected and can be accepted as the user's selection in the main summary window. They are visible for a selected type of formulation as shown in Win. 6-8.

Window 6-8: Automatic parameter migration for identification from triaxial curves

Z_Soil





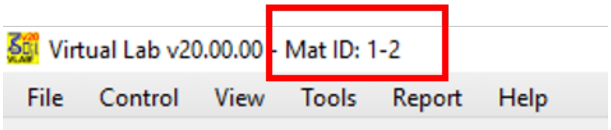
Chapter 7

PROJECT AND DATA MANAGEMENT

The data produced during a parameter identification session is saved and handled by the material database management system (refer to Section 1.2).

A default database is located in:
`c:/ProgramData/ZSoil v2023/Full/CFG/Materials/Soils.vldb`

Each material has an individual ID number which is displayed in the application's window title, as illustrated below:



Two copies of parameter session data are saved. The first one is saved to the currently connected database (by default `Soils.vldb`). The backup is stored in the database's root directory in the folder `[DatabaseName]-data` in a xml-formatted file `[material-ID].pid`, for example:
`../Soils/1-2.pid`. In the case of a problem encountered during a parameter identification session, users can send a `pid` file to the hotline attached to a detailed description of the problem.

Data for single laboratory tests are normally saved in the project data. However, they can also be exported to, or imported from *[test-name].pit* files.

Window 7-1: Format of saved data

Z_Soil

1-2.pid - Notepad

File Edit Format View Help

```
<?xml version='1.0' encoding='utf-8'?>
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  <version>20.00.00</version>
  <project_title></project_title>
  <author></author>
  <company></company>
  <unit_cfg>
    <unit_system>STANDARD</unit_system>
    <global_units>kN  m  deg  s  C</global_units>
  </unit_cfg>
  <precision_cfg>
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    <interval range="[1e-2,1e0)">2</interval>
    <interval range="[1e-4,1e-2)">2</interval>
    <interval range="[1e0,1e2)">3</interval>
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    <interval range="[1e4,inf)">3</interval>
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      </gravity>
      <p_atm unit="[kN/m^2]">
        <value>100.0</value>
      </p_atm>
    </parameters_collection>
  </environmental_constants>
  <material_sample label="Template 1">
    <material_type id="0">Soil</material_type>
    <behavior_type id="-1"/>
    <specific_feature id="-1"/>
    <inp_dat_setup>
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Window 7-1

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