VIRTUAL LAB
Z_Soil.PC 120201 report
revised 8.04.2018

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### 3 MATERIAL FORMULATION SELECTION

37
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.
Chapter 1

VIRTUAL LAB

1.1 OVERVIEW

Virtual Lab is a highly-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 tests data)
- ranges of parameter values which can be considered in parametric studies
- automated parameter identification from laboratory experimental data
- possibility of running numerical simulations of elementary laboratory tests in order to visualize the constitutive model response for the defined model parameters
- possibility of comparing numerical simulations of elementary laboratory tests with curves obtained in the laboratory

A parameter determination session corresponds to the analysis of a representative soil sample which can described by means of a general macroscopic behavior and available values of soil properties. Moreover, behavior of the material can be represented with the results derived from laboratory tests can be entered in the form of curves. All these 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 relying on default correlations)
- Interactive parameter selection (detailed statistical analysis based on a manual correlations database search)
• Parameter identification (based on laboratory curves, highly recommended for decisive soil layers)

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

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

- Mohr-Coulomb
- Hardening-Soil small strain
- Cam-Clay
- Cap model
The current version of the Virtual Lab v2016 is limited to the analysis of soils with the special reference to the aforementioned constitutive laws. Moreover, the automatic or interactive parameter determination algorithms allows parameters to be identified for the following groups of characteristics:

- Unit weight
- 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 flow of a fluid through a porous medium
  - van Genuchten’s model which defines the soil water retention curve (van Genuchten, 1980; Yang et al., 2004)

**Window 1-2: Initializing the Virtual Lab**

The *Open Virtual Lab* button is visible only if Mohr-Coulomb, Hardening-Soil Small Strain, Cam-Clay or Cap model is selected. It calls the main dialog window of the Virtual Lab module.
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 extracted knowledge is stored and used once the material model formulation has been changed. |
| §2 | The user-predefined 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 \( W_{in}^{2-15} \). It means that soil stiffness depends on the varying stress level and, in the \( in situ \) stress state, the stiffness increases with the raising depth. |
1.2 ARCHITECTURE

A Virtual Lab session 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.

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
- 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
CHAPTER 1. VIRTUAL LAB

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 the standard laboratory tests

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

- simulate standard elementary laboratory tests (triaxial drained and undrained compression and oedometric tests)
- compare the numerical model response with the laboratory curves based on which the parameters were identified

B.1 Parameter selection summary allows the user 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)
1.3 ELEMENTS

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

**A.0** defining 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 different determination approaches (automatic or interactive selection, parameter identification), running simulation of standard laboratory tests using user-defined parameter vectors.

**B.0** post-processing the model parameters which have been obtained by means of a variety determination methods (in columns on the right from “User’s selection”). The columns with
determination methods are hidden unless a parameter identification with a given method has been carried out. The parameters are arranged according to the groups of properties that define the selected constitutive model.
1.3. ELEMENTS

Window 1-5: Material setup and parameter determination methods

Z_Soil_PC

Material label as in main Material dialog of ZSoil

General family of the material. Only Soils are available in Virtual Lab v2018

Specification of Material Behavior Type and a specific 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 automatically selected parameter vectors.
CHAPTER 1. VIRTUAL LAB

Window 1-6: Post-processing - Parameter Summary

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 can exported to the main Material dialog of Z_Soil when closing the parameter determination session (see Win.7-1)
- **B.5** fast assigning individual parameters with the aid of the drag-and-drop technique
1.4 HOW TO PERFORM ... 

1.4.1 ... 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) that you would like to use

4. Perform parameter identification if complete laboratory experimental data are available

5. Perform Automatic Parameter Selection or/and Interactive Parameter Selection

6. Perform post-processing of identified results

7. Perform parameter verification or parameter validation by comparing numerical results with experimental data

1.4.2 ... 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

3. Perform parameter verification by running elementary laboratory tests

1.4.3 ... PARAMETER IDENTIFICATION

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

1.4.4 ... SIMULATION OF 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 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-delivered material data. These data can be specified by means of the two main dialog windows:

1. **Basic material properties** which enables specifying:
   - General soil description
   - Generic material properties
   - Material type specific properties

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 Pressuremeter Test (PMT)
   - Standard Penetration Test (SPT)
   - Shear wave velocity measurements (SWV)
CHAPTER 2. MATERIAL DATA INPUT FOR SOILS

2.1 BASIC MATERIAL PROPERTIES

The Basic Material Properties dialog boxes make possible to introduce all available data that are known for the considered real material.

Window 2-1: Basic material properties for soil

- **C.1** General soil description which best defines observed macroscopic material behavior
- **C.2** Group of known parameters, common for any type of soil
- **C.3** Group of parameters specific to the soil type, e.g. granular or cohesive soils
- **C.4** 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
- **C.5** Input of material characteristics typically reported in geotechnical documentations
- **C.6** Auxiliary data used to compute $e_0$, $\gamma_D$, $\gamma_{SAT}$, $\gamma_B$; they can also be used in many empirical correlations when performing interactive parameter selection
- **C.7** Simplified soil stiffness description; during parameter selection, the specified modulus

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2.1. BASIC MATERIAL PROPERTIES

will be kept unchanged, however its value will be transformed to the user defined reference stress $\sigma_{ref}$ by applying the stiffness power law and corresponding minor stress which is computed based on the provided value of the vertical stress $\sigma'_{v0}$ and evaluated in situ $K_0$ coefficient.

C.8 Importing tabular data collected in ASCII file.

2.1.1 QUICK HELP

Window 2-2: Quick help

A quick help is given when the mouse cursor rest 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**. The more precise soil description, the narrower the confidence limits for parameters.

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

<table>
<thead>
<tr>
<th>Soil Behavior Type</th>
<th>General soil type behavior according to the Unified Soil Classification System (USCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stress History</strong></td>
<td>Overconsolidation state according to geotechnical convention:</td>
</tr>
<tr>
<td></td>
<td>• 1.0 &lt; OCR &lt; 1.1 normally consolidated</td>
</tr>
<tr>
<td></td>
<td>• 1.1 &lt; OCR &lt; 2.5 lightly overconsolidated</td>
</tr>
<tr>
<td></td>
<td>• 2.5 &lt; OCR &lt; 5.0 overconsolidated</td>
</tr>
<tr>
<td></td>
<td>• OCR &gt; 5.0 heavily overconsolidated</td>
</tr>
<tr>
<td><strong>Relative density/Consistency</strong></td>
<td>Relative soil density or soil consistency depending on general soil type behavior</td>
</tr>
<tr>
<td></td>
<td>Coarse-grained soil classification in terms of <em>relative density</em> $D_r$:</td>
</tr>
<tr>
<td></td>
<td>• $D_r &lt; 15%$ - Very loose</td>
</tr>
<tr>
<td></td>
<td>• 15% &lt; $D_r$ &lt; 35% - Loose</td>
</tr>
<tr>
<td></td>
<td>• 35% &lt; $D_r$ &lt; 65% - Medium</td>
</tr>
<tr>
<td></td>
<td>• 65% &lt; $D_r$ &lt; 85% - Dense</td>
</tr>
<tr>
<td></td>
<td>• $D_r$ &gt; 85% - Very dense</td>
</tr>
<tr>
<td></td>
<td>Fine-grained soil classification in terms of <em>consistency</em> index $I_C$ ($= (w_L - w)/PI$):</td>
</tr>
<tr>
<td></td>
<td>• $I_C &lt; 0.05$ - Very soft</td>
</tr>
<tr>
<td></td>
<td>• 0.05 &lt; $I_C &lt; 0.25$ - Soft</td>
</tr>
<tr>
<td></td>
<td>• 0.25 &lt; $I_C &lt; 0.75$ - Medium</td>
</tr>
<tr>
<td></td>
<td>• 0.75 &lt; $I_C &lt; 1.00$ - Stiff</td>
</tr>
<tr>
<td></td>
<td>• $I_C &gt; 1.00$ and $w &gt; w_s$ - Very Stiff</td>
</tr>
<tr>
<td></td>
<td>• $I_C &gt; 1.00$ and $w &lt; w_s$ - Hard</td>
</tr>
</tbody>
</table>

with $w$ - moisture content, $w_s$ - shrinkage limit
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 $OC \leq 3\%$
- Organic silt or clay $3 < OC \leq 10\%$
- Medium organic soils $10 < OC < 30\%$ (not supported in v2016)
- Highly organic soils $OC > 30\%$ (not supported in v2016)

This classification affects the prediction of deformation characteristics

State

State of soil saturation

Automatic Parameter Selection estimates always two types of unit weight:
1. Dry unit weight $\gamma_D$ (used in *Deformation+Flow* analysis type)
2. Apparent unit weight $\gamma$ 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 current degree of saturation $S$ and porosity $n$:

$$\gamma = \gamma_D + nS\gamma_F$$

with $\gamma_F$ - fluid unit weight
2.1.3 AUXILIARY NUMERIC DATA

The dialog allows specifying known values for material characteristics typically reported in the 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. Note 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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction angle</td>
<td>Effective friction angle; if specified, it is used to estimate $K_0^{N_c}$ and $K_0$.</td>
</tr>
<tr>
<td>Cohesion</td>
<td>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 $a$ and $S_r$ which define the behavior of partially saturated medium).</td>
</tr>
<tr>
<td>Overconsolidation ratio</td>
<td>Value of OCR which corresponds to the provided representative parameters $E, \phi, c$ derived at corresponding characterization depth. Specifying or modifying OCR updates Stress History setup which is taken into account in estimation of $E_{sat}^{ref}$ for coarse-grained soils.</td>
</tr>
<tr>
<td>Unit weight</td>
<td>Total unit weight corresponding to the 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 $\gamma_D$. In the numerical analysis, $\gamma$ 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.</td>
</tr>
<tr>
<td>Initial void ratio</td>
<td>Estimated void ratio at <em>in situ</em> stress condition. 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 $\gamma_{SAT}$ if $\gamma_D$ and $\gamma$ are introduced by the user.</td>
</tr>
</tbody>
</table>
### 2.1. BASIC MATERIAL PROPERTIES

#### Weight of dry soil/weight of saturated soil

| $\gamma_D$ | $\gamma_{SAT}$ | $\gamma_D$ corresponds to “dry” soil state when the degree of saturation is equal to 0 (in the Deformation+flow analysis type, $\gamma_D$ is used to calculate total unit weight accounting for saturation degree), whereas $\gamma_{SAT}$ is the weight of fully saturated soil ($S = 1$). The unit weight of a dry soil $\gamma_D$ can be computed based on the specified values of apparent unit weight $\gamma$ and saturation degree $S$ and voids ratio $e_0$ from: $\gamma = \gamma_D + nS \gamma_w$ where $n = e_0/(1 + e_0)$. Moreover $\gamma_{SAT}$ will be updated if $e_0$ or $n_0$ have been specified or modified. $\gamma_D$ and $\gamma_{SAT}$ are also the inputs for some correlations which estimates the compression index $C_c$. |
| $\gamma_D$ | $\gamma_{SAT}$ |

#### Buoyant unit weight

| $\gamma_B$ | The buoyant unit weight (or effective unit weight) of soil is actually the saturated unit weight of soil minus the unit weight of water. Its value can be used to describe the effective soil weight of the soil below the ground water table when running the single-phase analysis considered as the effective stress analysis. |

#### 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 $\sigma'_v$ 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 estimate $E_{\text{ref}}$, $E_{50}$, $E_{\text{ur}}$ and $E_{\text{ref}}^{\text{50}}$. 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 $E_{50} < E_{\text{ref}} < E_{\text{ur}}$. 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. 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, such an approach is the least conservative. |

- “Static” modulus $E_s$  
- Unloading-reloading modulus $E_{ur}$  
- Secant modulus $E_{50}$ |

#### Vert. eff. stress at characterization depth or in the middle of soil layer

| $\sigma'_v$ | Estimated vertical effective stress at characterization depth; if not indicated $\sigma'_v$ 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 $\sigma_{\text{ref}}$ with respect to the minor effective stress estimated as $\sigma_3 = \min(\sigma'_v, \sigma'_v \cdot K_0)$. If $\sigma'_v$ is not specified, the minor stress will be taken equal to the user-defined reference $\sigma_3 = \sigma_{\text{ref}}$ kPa (no stiffness scaling applies). |

![INPUT DATA](image)

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## Physical soil properties and its description

Physical soil properties can be used for calculating:

<table>
<thead>
<tr>
<th>Property</th>
<th>Formula</th>
<th>Typical values of $G_s = \text{solid density} / \text{water density}$:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_0$</td>
<td>$e_0 = \frac{\gamma_s}{\gamma_W} \cdot \frac{w_n}{S}$ if $S &gt; 0$</td>
<td>- Gravel - quartz 2.65</td>
</tr>
<tr>
<td>$\gamma_D$</td>
<td>$\gamma_D = \gamma - n_0 S \gamma_W$</td>
<td>- Gravel - silty or clayey 2.66 – 2.68</td>
</tr>
<tr>
<td>$e_0$</td>
<td>$e_0 = \frac{n_0}{1 - n_0}$</td>
<td>- Sand - quartz 2.65</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>$\gamma_s = \gamma - n_0 S \gamma_W$</td>
<td>- Sand - silty or clayey 2.66 – 2.68</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>$\gamma_s = \gamma - n_0 S \gamma_W$</td>
<td>- Silt, inorganic 2.62 – 2.68</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>$\gamma_s = \gamma - n_0 S \gamma_W$</td>
<td>- Clay of low plasticity, inorganic 2.67 – 2.70</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>$\gamma_s = \gamma - n_0 S \gamma_W$</td>
<td>- Clay of medium plasticity, inorganic 2.69 – 2.72</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>$\gamma_s = \gamma - n_0 S \gamma_W$</td>
<td>- Clay of high plasticity, inorganic 2.71 – 2.78</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>$\gamma_s = \gamma - n_0 S \gamma_W$</td>
<td>- Clay, organic 2.58 – 2.65</td>
</tr>
</tbody>
</table>

$\gamma_s$ also appears in some correlations for $C_c$.

### Unit weight of material skeleton

- **$\gamma_s$**: Typical values of $G_s = \text{solid density} / \text{water density}$:
  - 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

### 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 $e_0$:

  $e_0 = \frac{\gamma_s}{\gamma_W} \cdot \frac{w_n}{S}$ if $S > 0$

  $w_n$ also appears in some correlations which estimates the compression index $C_c$.

### Degree of saturation

- **$S$**: Measured or estimated degree of soil saturation at *in situ* stress conditions.
  - Introducing or changing the value of $S$ updates State setup.
  - The value $S$ is used to calculate dry unit weight from
    $\gamma_D = \gamma_s \cdot n_0 \cdot \gamma_W$.

### Initial porosity

- **$n_0$**: Estimated porosity at *in situ* stress conditions.
## 2.1. BASIC MATERIAL PROPERTIES

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fines content</td>
<td>( f_p )</td>
<td>Content of particles smaller than 0.06 mm. If ( f_p &gt; 50% ) then soil is classified as fine-grained (cohesive) otherwise as coarse-grained.</td>
</tr>
</tbody>
</table>
| Organics content           | \( OC \) | General classification in terms of organics content:  
- inorganic soil \( OC \leq 3\% \)  
- organic silt or clay \( 3 < OC \leq 10\% \)  
- medium organic soils \( 10 < OC < 30\% \) (not supported in v2016)  
- highly organic soils \( OC \geq 30\% \) (not supported in v2016) |
| Plasticity index          | \( PI \) | \( PI = w_L - w_P \) is taken to estimate \( \gamma_{0.7} \) and appears in some correlations for \( \phi, m, K_0^{NC} \) 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 stiffness exponent \( m \) and compression index \( C_c \). |
| Plastic limit              | \( w_P \) | Plastic limit is computed from:  
\[ w_P = w_L - PI \]  
once both variables have been specified.  
The value of \( w_P \) can be used in some correlations to correlate the small strain threshold \( \gamma_{0.7} \) or compression index \( C_c \). |
| Consistency index          | \( I_c \) | Consistency index helps to automatically update Soil consistency.  
Its value is computed from \( I_c = (w_L - w_n)/PI \) once \( w_n, w_L \) and \( PI \) have been specified. |

---

Window 2-7

Z_Soil.FC 120201 report (revised 8.04.2018)
### CHAPTER 2. MATERIAL DATA INPUT FOR SOILS

#### 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 $E_{\text{ref}}^{\text{oed}}$. |

#### Normalized undrained shear strength

| $s_u/\sigma_{v0}'$ | $s_u/\sigma_{v0}'$ appears in correlations for $E_{\text{ref}}, \phi, \text{OCR}$. |
## 2.1. BASIC MATERIAL PROPERTIES

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

**Z_Soil.PC 120201 report (revised 8.04.2018)**

| Coarse-grained soils            | $f_p$ | 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 $\leq 6$ (and/or $C_k < 1$, $C_k > 3$)
- Poorly-graded gravels $\leq 4$ (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.
$\quad d_{10}$ - the maximum size of the smallest 10\% of the sample
$\quad d_{30}$ - the maximum size of the smallest 30\% of the sample
$\quad d_{60}$ - 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 relative density setup.
The specified value is used to estimate $\phi$, $\psi$ and $e_0$.  

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 allows attributing the soil characteristics to the corresponding parameters collected in columns. Only the values in the selected row (checked row) will be imported.
2.2 IN SITU TEST DATA

2.2.1 CONE PENETRATION TEST

The piezocone penetration test (CPTU) is an in situ testing method which 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° 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 allows measuring the friction resistance. For further detail see Lunne et al. (1997).

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

- **A.1** Selection of input parameters type:
  - Direct parameters: $q_t$, $f_s$, $u_2$
  - Indirect parameters (normalized direct parameters): $Q_u$, $F_r$, 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 for 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 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 is based on the soil type estimated with Robertson (1990) interpretation chart.

- **A.6** Graphical representation of field data interpretation.
**Cone Penetration Test (CPT/CPTU)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corrected cone resistance</strong></td>
<td>$q_t$ 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)</td>
</tr>
<tr>
<td></td>
<td>$q_t$ together with $\sigma_{v0}$ and $u_0$ is used to automatically compute $Q_q$ 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 $E_0$, $V_s$, $E_{50}$, $\phi$ in coarse-grained soil, and $V_s$, $E_{oed}$, $\phi$, OCR, $K_0$ in fine-grained soils.</td>
</tr>
<tr>
<td><strong>Pore pressure behind the cone</strong></td>
<td>$u_2$ This number is used to calculate $B_q$. $u_2$ appears in correlations for OCR in fine-grained soils.</td>
</tr>
<tr>
<td><strong>Friction sleeve resistance</strong></td>
<td>$f_s$ Unit sleeve friction resistance. $f_s$ together with $q_t$ and $\sigma_{v0}$ 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 $V_s$.</td>
</tr>
<tr>
<td><strong>Total vertical stress</strong></td>
<td>$\sigma_{v0}$ Estimated total vertical stress corresponding to the in situ stress level at which the CPT measurements have been taken. $\sigma_{v0}$ appears in correlations estimating $E_{oed}$, OCR in fine-grained soils and is used to compute the effective vertical stress $\sigma'<em>{v0} = \sigma</em>{v0} - u_0$</td>
</tr>
<tr>
<td><strong>Hydrostatic pore pressure</strong></td>
<td>$u_0$ Hydrostatic pore pressure at testing level. This number is used to calculate $B_q$ and effective vertical stress from $\sigma'<em>{v0} = \sigma</em>{v0} - u_0$.</td>
</tr>
<tr>
<td><strong>Effective vertical stress</strong></td>
<td>$\sigma'<em>{v0}$ Calculated as $\sigma'</em>{v0} = \sigma_{v0} - u_0$. $\sigma'<em>{v0}$ is needed to transform the estimated stiffness moduli to the reference modulus $E</em>{ref}$ by accounting for the reference stress $\sigma_{ref}$ and $K_0$ (cf. Win.2-15).</td>
</tr>
<tr>
<td><strong>Dimensionless unit weight</strong></td>
<td>$\gamma_{CPT} / \gamma_W$ 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 $Rf = f_s/q_t \cdot 100%$ is the friction ratio. This number can be used to estimate apparent unit weight: $\gamma = \gamma_{CPT} (\gamma_W = \text{unit weight of water})$.</td>
</tr>
<tr>
<td><strong>Normalized cone resistance</strong></td>
<td>$Q_t$ $Q_t = (q_t - \sigma_{v0}) / \sigma'_{v0}$ $Q_t$ appears in correlations estimating $\phi$, $K_0$ for for fine-grained soils.</td>
</tr>
<tr>
<td><strong>Normalized pore pressure parameter</strong></td>
<td>$B_q$ $B_q = (u_2 - u_0) / (q_t - \sigma_{v0})$ $B_q$ appears in correlations estimating $\phi$ for for fine-grained soils.</td>
</tr>
<tr>
<td><strong>Normalized friction ratio</strong></td>
<td>$F_r$ $F_r = f_s / (q_t - \sigma_{v0})$</td>
</tr>
<tr>
<td><strong>Soil type behavior</strong></td>
<td>Determined based on $Q_t$ and $F_r$ numbers using the original chart by Robertson (1990)</td>
</tr>
</tbody>
</table>
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

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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 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.
### Marchetti’s Dilatometer Test (DMT)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>First DMT reading</td>
<td>$p_0$ 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 $E_D$.</td>
</tr>
<tr>
<td>Second DMT reading</td>
<td>$p_1$ 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 $E_D$.</td>
</tr>
<tr>
<td>Hydrostatic pore pressure</td>
<td>$u_0$ Hydrostatic pore pressure at the testing depth. The value is used to calculate the dilatometer numbers $I_D$ and $K_D$.</td>
</tr>
<tr>
<td>Effective in situ vertical stress</td>
<td>$\sigma_{iv0}$ 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 $\sigma_{ref}$, $K_0$ and the power law (cf. Win.2-15).</td>
</tr>
</tbody>
</table>
| Material index                          | $I_D = (p_1 - p_0)/(p_0 - u_0)$ 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                 | $K_D = (p_0 - u_0)/\sigma_{iv0}$  
  $K_D$ appears in correlations estimating $E_{oed}$ in normally-consolidated soils, $\phi$ for coarse-grained soil, and OCR, $K_0$ for fine-grained soil. |
| Dilatometer modulus                     | $E_D = 34.7(p_1 - p_0)$  
  $E_D$ is used to provide estimations of unit weight. $E_D$ appears in correlations estimating $E_{ref}^{oed}$ in normally-consolidated soils, $\phi$ for coarse-grained soil. |
| Dimensionless unit weight               | $\gamma_{DMT}/\gamma_W$ 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: $\gamma = \gamma_{DMT} (\gamma_W = \text{unit weight of water})$. |
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 flexible 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

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<table>
<thead>
<tr>
<th>Soil Behaviour Type:</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressuremeter modulus:</td>
<td>$E_{pm}$</td>
</tr>
<tr>
<td>Effective vertical stress at probing depth:</td>
<td>$\sigma'_{vo}(PMT)$</td>
</tr>
<tr>
<td>Limit pressure:</td>
<td>$p_L$</td>
</tr>
<tr>
<td>Rheological factor:</td>
<td>$\alpha_{pm}$</td>
</tr>
</tbody>
</table>

Interpretation setup:
- Approximated in situ Ke coeff.: $K_p$ = 0.5 [deg]
- Auxiliary friction angle: $\phi$ = 20 [deg]
- Auxiliary cohesion: $c$ = 0 [kN/m$^2$]
- Auxiliary stiffness exponent: $m$ = 0.5 [1]

First-order estimates:
- Soil density: Very loose
- Sec. modulus at 0.1%: $E_{s}$ = 5000 [kN/m$^2$]
- Reference stress: $\sigma_{ref}$ = 100 [kN/m$^2$]
- Ref. sec. modulus at 0.1%: $E_{s}'$ = 7071.07 [kN/m$^2$]
- Ref. sec. modulus at 50% of $E_{s}$: $E_{s}''$ = 3653.73 [kN/m$^2$]

C.1 Input parameters which are used to determine stiffness modulus.
C.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 by applying the stress stiffness dependency law.
C.3 First-order estimates computed based on provided input data and interpretation setup.
### Menard’s Pressuremeter Test (PMT)

<table>
<thead>
<tr>
<th>Property</th>
<th>Formula/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressuremeter modulus</strong> $E_{pm}$</td>
<td>$E_{pm} = 2(1 + \nu)\Delta p \cdot V/\Delta V$ 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 $E_s$.</td>
</tr>
<tr>
<td><strong>Limit pressure</strong> $p_L$</td>
<td>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. $p_L = \sigma_{h0} + S_u [1 + \ln (G/S_u)]$</td>
</tr>
<tr>
<td><strong>Effective in situ vertical stress</strong> $\sigma'_{v0}$</td>
<td>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 $\sigma_{ref}$ and $K_0$ (cf. Win.2-15).</td>
</tr>
<tr>
<td><strong>Rheological coefficient</strong> $\alpha$</td>
<td>This number is used to evaluate &quot;static&quot; stiffness modulus from: $E_s = E_{pm}/\alpha$. If the automatic evaluation is selected, the coefficient $\alpha$ will be evaluated based on the soil type and $E_{pm}/p_L$ ratio:</td>
</tr>
<tr>
<td>Peat</td>
<td>Normally Consolidated for all $E_{pm}/p_L$: $\alpha = 1$</td>
</tr>
<tr>
<td>Clay</td>
<td>Overconsolidated: $E_{pm}/p_L &gt; 16$: $\alpha = 1$</td>
</tr>
<tr>
<td></td>
<td>Normally-consolidated: $E_{pm}/p_L = 9 \div 16$: $\alpha = 2/3$</td>
</tr>
<tr>
<td>Silt</td>
<td>Overconsolidated: $E_{pm}/p_L &gt; 14$: $\alpha = 2/3$</td>
</tr>
<tr>
<td></td>
<td>Normally-consolidated: $E_{pm}/p_L = 8 \div 14$: $\alpha = 1/2$</td>
</tr>
<tr>
<td>Sand</td>
<td>Overconsolidated: $E_{pm}/p_L &gt; 12$: $\alpha = 1/2$</td>
</tr>
<tr>
<td></td>
<td>Normally-consolidated: $E_{pm}/p_L = 7 \div 12$: $\alpha = 1/3$</td>
</tr>
<tr>
<td>Sand and Gravel</td>
<td>Overconsolidated: $E_{pm}/p_L &gt; 10$: $\alpha = 1/3$</td>
</tr>
<tr>
<td></td>
<td>Normally-consolidated: $E_{pm}/p_L = 6 \div 10$: $\alpha = 1/4$</td>
</tr>
</tbody>
</table>
2.2. STANDARD PENETRATION TEST

The standard penetration test (SPT) is an in-situ dynamic penetration test 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

[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 for 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.
### Standard Penetration Test (SPT)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
</table>
| 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 |
| Effective vertical stress        | $\sigma'_{e0}$ | 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 $\sigma_{ref}$ and $K_0$ (cf. Win.2-15). |
| Overburden correction factor     | $C_N$ | Overburden correction factor is calculated according to Liao and Whitman (1986) as $C_N = (p_a/\sigma'_{e0})^{0.5}$ ($C_N = 1.7$ if $C_N > 1.7$) with $p_a$ - atmospheric pressure = 100 kPa once $\sigma'_{e0}$ 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. IN SITU TEST DATA

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

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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.
### Shear wave velocity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear wave velocity</td>
<td>$V_s$</td>
<td>If specified, the value is taken into account in Automatic Parameter Selection for estimation of $E_0 = 2G_0(1 + \nu_{ur})$ by applying $G_0 = \rho V_s^2$.</td>
</tr>
<tr>
<td>Unit weight</td>
<td>$\gamma$</td>
<td>Total unit weight.</td>
</tr>
<tr>
<td>Effective in situ vertical stress</td>
<td>$\sigma'_{v0}$</td>
<td>Estimated effective vertical stress corresponding to the in situ stress level at which measurements of $V_s$ have been taken. $\sigma'<em>{v0}$ and auxiliary parameters are used to transform the computed $E_0$ value to the user-defined reference stress $\sigma</em>{ref}$ according to the principle illustrated below Win.2-15.</td>
</tr>
</tbody>
</table>
2.2.6 STIFFNESS MODULI TRANSFORMATION

Stiffness moduli derived from in situ test data for a given characterization depth are adjusted with respect to the depth that corresponds to \( \sigma_{\text{ref}} \) using stiffness stress dependency law, as illustrated below:

\[
E_{\text{ref}} = E \left( \frac{\sigma_3 + a}{a + \sigma_{\text{ref}}} \right)^m
\]

where:
- \( E_{\text{ref}} \) is the target modulus corresponding to the user-defined reference stress \( \sigma_{\text{ref}} \)
- \( E \): the modulus identified for a given minor stress state \( \sigma_3 \)
- \( m \): stiffness exponent (typically between 0.5 and 1.0)
- \( \sigma_3 = \min(\sigma'_{v0}, \sigma'_{v0} \cdot K_0) \)
- \( a = c \cdot \cot(\phi) \)
Chapter 3

MATERIAL FORMULATION SELECTION

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

Window 3-1: Material formulation

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A.1 Input parameters which are used to determine maximal shear modulus.
A.2 The combobox contains a list of available (or suggested, if assistance in preselection enabled) constitutive models.
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 provided general soil description. In this case, parameter estimation refers here to the evaluation of model parameters from observed limits 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 consciously browse the correlations database looking for best-working correlations for the analyzed “material sample”. These correlations relate geotechnical properties 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 from test measurements.
4.1 AUTOMATIC PARAMETER SELECTION

The Automatic Parameter Selection offers the possibility of 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.

In order to run automatic parameter selection:
1. Specify 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 about the progress of automatic selection, as well as, about the number of applicable correlations.
CHAPTER 4. PARAMETER DETERMINATION

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

- The results of performed automatic selection are summarized in A.5.
- The correlations which have been applied during automatic selection can be viewed 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 closing the dialog window. If disabled, the parameter estimations will appear in the column 'Automatic'; such a strategy makes it possible to consciously choose the values for individual model parameters in the final “user’s selection”.

Window 4-2
4.1. AUTOMATIC PARAMETER SELECTION

Window 4-3: Correlations applied during parameter selection

- The correlation browser makes possible to have an insight into 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 the correlation filter A.11 is locked on Default in the automatic selection mode. All correlations which are applicable for the 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 feature; 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 info including the reference, correlation applicability, its description and the working algorithm.
4.2 INTERACTIVE PARAMETER SELECTION

The Interactive Parameter Selection offers the possibility of a manual knowledge extraction. The user can consciously browse the correlations database looking for best-working correlations for the analyzed “soil sample” and testing correlations by modifying input data.

Window 4-4: Performing interactive parameter selection

In order to perform an interactive parameter selection:
1. Specify general soil description and known numeric data
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].

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
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 checkboxes 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 parameters values which from "User’s selection" will appear in the column ‘Interactive’ (in the main window of the Virtual Lab ) after closing the correlation browser.

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.16.
- correlation info B.15 including the reference, correlation applicability, its description and the working algorithm.
4.3 PARAMETER IDENTIFICATION

Parameter Identification refers to deterministic algorithms which are developed for a given constitutive model and test boundary conditions. These analytical solutions allow to directly identify model parameters from experimental test measurements. 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 v2016 allows to interpret the following standard laboratory tests:

- triaxial drained compression (TX-CD)
- triaxial undrained compression (TX-CU)
- oedometric curves (OED)
4.3. PARAMETER IDENTIFICATION

**Window 4-6: Test data input**

A.1  Allow adding new test nodes in assembly of tests tree (TX-CD - triaxial drained compression, TX-UD - triaxial undrained compression, OED-IL - oedometric test with incremental load).

A.2  Tree allowing managing and browsing 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), allows adding new, empty test nodes, removing existing test nodes, importing experimental measurements for selected test, loading previously saved test node, and finally, saving selected test node to XML-formatted [test-name].pit file.

B.1  Allows changing test label.

B.2  Allows documenting the detailed record of tested specimen.

B.3  Contains initial state variables which are evaluated for a given specimen, as well as auxiliary constants which may be used by an identification algorithm or during a numerical optimization run.

B.4  Allows manual insertion of experimental data.

B.5  Allows verification of specified or imported data in terms of its completeness vis-à-vis the identification of particular parameters.

B.6  Allows importing experimental data from an ASCII file.

C.1  Contains a number of predefined data previews.

C.2  Allows modifying axes limits (use right-click button context menu to invert axes).
CHAPTER 4. PARAMETER DETERMINATION

C.3 Preview of experimental data.
C.4 Allows exporting current chart.

D.1 Configuring parameter identification algorithms.

Window 4-6
4.3. PARAMETER IDENTIFICATION

Window 4-7: Import wizard for experimental data

Z_Soil.FC

**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 Allows attributing the data from ASCII file to the expected experimental measurements.
Specimen record dialog allows storing information on project, characterization site and specimen sampling details.

Moreover, it allows specifying the data related to the tested specimen.

Window 4-8
4.3. PARAMETER IDENTIFICATION

Window 4-9: Data interpretation

A.1 Allows filtering tests according to a 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 Tree allowing a selection of tests which are meant to be interpreted.

A.3 Runs 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 Allows modifying 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.
CHAPTER 4. PARAMETER DETERMINATION

NB. Note that the experimental curves tests are interpreted with the reference to all available information that experimental data may contain. Hence, any change of the constitutive model does not require additional reinterpretation of 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 resting the mouse cursor over the average parameter value.

<table>
<thead>
<tr>
<th>Tests interpretation for model:</th>
<th>Symbol</th>
<th>Unit</th>
<th>Average</th>
<th>l-TXC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ref. sec. modulus at 50% of qf</td>
<td>$E_{30}^r$</td>
<td>[kN/m$^2$]</td>
<td>25334</td>
<td></td>
</tr>
<tr>
<td>Stiffness exponent</td>
<td>$m$</td>
<td>[]</td>
<td>0.495522</td>
<td></td>
</tr>
<tr>
<td>Reference stress</td>
<td>$\sigma_{ref}$</td>
<td>[kN/m$^2$]</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Un-/reloading Poisson's ratio</td>
<td>$v_{ur}$</td>
<td>[]</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Ref. un-/reload. modulus</td>
<td>$E_{ur}^r$</td>
<td>[kN/m$^2$]</td>
<td>0.00953</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure cohesion</td>
<td>$c_f$</td>
<td>[kN/m$^2$]</td>
<td>19.918</td>
<td>1.964e-02 [kN/m$^2$]</td>
</tr>
<tr>
<td>Failure ratio</td>
<td>$R_f$</td>
<td>[]</td>
<td>0.91263</td>
<td>7.997e-04 [kN/m$^2$]</td>
</tr>
<tr>
<td>Failure friction angle</td>
<td>$\phi_f$</td>
<td>[deg]</td>
<td>30</td>
<td>8.632e-04 [kN/m$^2$]</td>
</tr>
</tbody>
</table>

C.1 Contains a number of predefined data previews.
C.2 Allows modifying 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 Allows exporting current chart.
C.5 Show/hide the legend in C.3. The legend box is draggable.

D.1 Configuring parameter identification algorithms.

Window 4-9
4.3. PARAMETER IDENTIFICATION

Window 4-10: Configuring parameter identification

A.1 All identified stiffness characteristics will be scaled to the defined reference stress using the power stiffness dependency law.

A.2 In general, different values of stiffness exponent $m$ can be obtained in laboratory test. The user can specify stiffness characteristics based on which the stiffness exponent will be identified.

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.
CHAPTER 4. PARAMETER DETERMINATION

Window 4-11: Configuration drained triaxial test interpretation

B.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 $\phi_f$ and $c_f$.

B.2 Allows the user to 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.

B.3 Activates optimization of $E_{50}$, $R_f$ and the stiffness exponent $m$ when running the parameter identification for drained compression test data. Note that identification of these three parameters can be affected by the mobilization of the volumetric plastic strains (softening) for the tests on normally- and lightly consolidated specimens - refer to Win.4-12.
4.3. PARAMETER IDENTIFICATION

Window 4-12: Effect of softening

Effect of strain softening on the stiffness of normally-consolidated specimen OCR = 1 (red) vs overconsolidated one OCR = 10 (blue); theoretical curves obtained for $E_{50}^{\text{ref}} = 30\text{MPa}$

Theoretical curves obtained with:
- target parameters $E_{50}^{\text{ref}} = 30\text{MPa}$, $R_f = 0.9$ and $m = 0.5$ (green),
- parameters identified from the theoretical curves with target parameters (red),
- numerically adjusted (optimized) parameters (blue)
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 $\phi_f$ and $c_f$.

C.2 Allows specifying the criterion for identification of effective strength parameters. $\max(q/p)$ - 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 strain for which the maximal pore pressure excess was observed. Deviatoric stress - parameters are determined based on the maximal deviatoric stress $(\sigma_1 - \sigma_3)_{\text{max}}$. Note that the last option may lead to overestimation of cohesion (apparent cohesion) in the case of an unsaturated specimen.

C.3 Allows the user to 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.4 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.

C.5 Activates optimization-based adjustment of specimen’s OCR based on the $p' - q$ curve.
4.3. PARAMETER IDENTIFICATION

Window 4-14: Configuration of oedometric test interpretation

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.

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.
Chapter 5

PARAMETER VERIFICATION AND VALIDATION

The laboratory test simulator offers a possibility of parameter verification and validation by running numerical simulations of elementary laboratory tests in order to visualize the constitutive model response 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 test (verify) a vector of parameters for the constitutive model.

Model parameters which are identified based on laboratory curves can be validated by running numerical simulations and comparing numerical results with the laboratory curves (Window 5-2). In order to compare laboratory curves with the model response, the laboratory results has to be imported by means of the Parameter Identification module.
The Laboratory test simulator can be called by pressing Lab Test Simulation.
A.1 Allows 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 Allows a selection of 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.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 for the selected tests.

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 Allows specifying model parameters. Note that these parameters can be automatically
imported from parameter summary widget.

B.3 Allows importing model parameters from the "User’s selection" or those obtained by determination methods.

B.4 Allows sending the whole 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 Contains a number of predefined data previews.

C.2 Allows modifying 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 Allows exporting current chart.

C.5 Control the simulation status and the log of computations.
Window 5-3: Verification of model parameters

A.1  Cf. Window 5-2.
A.2  Deactivation of real test data.
A.3  Allows a selection of 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  Allows specifying initial state variables for currently selected test.
B.2  Allows defining/modifying model parameters.
B.3  Cf. Window 5-2.
B.4  Cf. Window 5-2.
B.5  Allows customizing the loading program. Note that unwanted rows in the loading program can me removed by clicking the right-click button over the first column of the unwanted row.

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
Chapter 6

TOOLS

6.1 INITIAL STATE PROFILE

The Initial State Profile tool allows the user to assess in a simple manner the effect of selected material parameters on the results which would be obtained from the initial state analysis assuming 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 in unsaturated soil
- Variation of initial $K_0$ state in the 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

Note that all these variables and their profiles are highly transient (varies with time and stress evolution) in the numerical analysis.

Window 6-1 describes input parameters which are used in profiling.
Figure 6.1: Visualization of saturation related effects with initial state profile tool.

Figure 6.2: Visualization of initial profiles of stresses and preconsolidation.
### 6.1. INITIAL STATE PROFILE

#### Window 6-1: Input parameters for the initial stress profile

##### Z.Soil.PC

<table>
<thead>
<tr>
<th><strong>Input parameters</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial state variables</strong></td>
<td></td>
</tr>
<tr>
<td>OCR\textsubscript{HS}</td>
<td>Overconsolidation ratio</td>
</tr>
<tr>
<td>(q\textsubscript{POP})</td>
<td>Preoverburden pressure (a historical pressure acting on soil layer) available; available only for the Hardening-Soil model (cf. stress history for the HS model)</td>
</tr>
<tr>
<td>OCR\textsubscript{MCC}</td>
<td>Overconsolidation ratio in terms of the mean effective stress ((= p_{\text{a}}/p'_0)); defines the initial preconsolidation state for the Modified Cam-Clay model</td>
</tr>
<tr>
<td>OCR\textsubscript{Cap}</td>
<td>Overconsolidation ratio in terms of the mean effective stress ((= p_{\text{a}}/p'_0)); defines the initial preconsolidation state for the Cap model</td>
</tr>
<tr>
<td>(\phi\textsubscript{NC})</td>
<td>Friction angle</td>
</tr>
<tr>
<td>(K_0\textsubscript{NC})</td>
<td>(K_0) coefficient for normally-consolidated soil</td>
</tr>
<tr>
<td>(p_{c0,\text{min}})</td>
<td>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,\text{min}}) (say from 30 to 100 kPa)</td>
</tr>
<tr>
<td><strong>Material layer</strong></td>
<td></td>
</tr>
<tr>
<td>Num sublayers</td>
<td>Number of discrete elements that are used to obtain variable profiles</td>
</tr>
<tr>
<td>(q) (overburden)</td>
<td>Total pressure acting at the top of the layer due to other layers and loads</td>
</tr>
<tr>
<td>(z) (top)</td>
<td>Top layer elevation</td>
</tr>
<tr>
<td>(z) (bottom)</td>
<td>Bottom layer elevation</td>
</tr>
<tr>
<td>GWT</td>
<td>Ground water level</td>
</tr>
<tr>
<td>(K_0) (top)</td>
<td>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)</td>
</tr>
<tr>
<td>(K_0) (bottom)</td>
<td>Estimated Ko coefficient at the top of the layer (meaningful as above)</td>
</tr>
<tr>
<td>(u) (uplift)</td>
<td>Uplift pore pressure</td>
</tr>
<tr>
<td>Auto (K_0)</td>
<td>Automatic evaluation of (K_0) based on (\phi) and OCR</td>
</tr>
<tr>
<td><strong>Unit weight</strong></td>
<td></td>
</tr>
<tr>
<td>(\gamma_D)</td>
<td>Unit weight of dry soil</td>
</tr>
<tr>
<td>(\gamma_f)</td>
<td>Unit weight of fluid</td>
</tr>
<tr>
<td>(\epsilon_0)</td>
<td>Initial void ratio</td>
</tr>
<tr>
<td><strong>Flow constants</strong></td>
<td></td>
</tr>
<tr>
<td>(\alpha)</td>
<td>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 raise height</td>
</tr>
<tr>
<td>(S_r)</td>
<td>Degree of residual saturation; note that for (S_r &gt; 0.0), (s \cdot u) tends to infinity with increasing negative pore pressure</td>
</tr>
</tbody>
</table>
6.1.1 Saturation effects

Window 6-2 summarizes the governing equations which are used to visualize the effects of partial saturation.

**Window 6-2: Governing equations for the saturation effects profile**

### Apparent unit weight

\[ \gamma = \gamma_D + n_0 S \gamma_f \]

with:

- \( S \) - saturation degree obtained using a simplified soil water retention curve by van Genuchten (1980)
- \( n_0 \) - initial porosity \( = \frac{e_0}{1 + e_0} \)

### Saturation degree

\[
S = S(u) = \begin{cases} 
S_r + \left( \frac{1 - S_r}{1 + (\alpha \frac{u}{\gamma_f})^2} \right)^{1/2} & \text{if } u < 0 \\
1 & \text{if } u \leq 0 
\end{cases}
\]

### Suction

\[ S \cdot u \] suction stress above the ground water table being a function of the saturation degree that depends on pore water pressure, \( u \), obtained from the Bishop’s effective stress definition for a single-phase model for fluid:

\[ \sigma_{ij}^{\text{tot}} = \sigma_{ij}' + S \cdot u \cdot \delta_{ij}, \]

\( \delta_{ij} \) - Kronecker’s delta.
6.1.2 Initial stresses

Window 6-3 summarizes the governing equations which are used to visualize the variation of stresses, preconsolidation state.

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

The stress dependent stiffness for the Hardening Soil model in ZSoil v2018 can be described by two different formulations for the power law (see The Hardening Soil model - a practical guidebook for a comprehensive discussion on the advantages and shortcomings of both formulations). In the first formulation, stiffness moduli depends on the evolution of the minor stress $\sigma_3$ according to:

$$E = E_{ref} \left( \frac{\sigma_3 + c \cdot \cot \phi}{\sigma_{ref} + c \cdot \cot \phi} \right)^m$$  \hspace{1cm} (6.1)

with:
- $E$ - stands for any modulus ($E_{50}$, $E_{ur}$, $E_0$)
- $\phi$ - friction angle
- $c$ - cohesion
- $m$ - stiffness exponent

In the second formulation, the power law takes more natural form where material stiffness depends on the mean (effective) stress:

$$E_p = E_{p_{ref}} \left( \frac{p}{\sigma_{ref}} \right)^{m_p}$$  \hspace{1cm} (6.2)

with $E_p$ standing for any modulus which gives an equivalent stiffness $E$ obtained for any stress level using the original power law given in Eq. 6.1. However, notice that the stiffness exponents $m$ and $m_p$ are equal to each other only if $c = 0$. Moreover, the condition $E_p = E$ can be satisfied only if and $K_0 = 1$. In the other cases, the moduli should be transformed by means of the migration approaches which are described in the section Parameter migration between minor and mean stress formulations.

Virtual Lab v2018 offers and an integrated toolbox for moduli migration which is presented in Figure 6-4. The tool can be initialized whenever stress dependency is changed in the elastic group:

The tool (Fig. 6-4) makes it possible to migrate parameters in two directions: from $\sigma_3$ to $p$ formulation and vice versa ([A.1]).
6.2. STRESS DEPENDENT STIFFNESS MIGRATION

Window 6-4: Parameter migration between stress dependent stiffness formulations

- migration of parameters in two directions $\sigma_3 \rightarrow p$ and $p \rightarrow \sigma_3$
- input moduli and stiffness exponent for the base power law
- auxiliary parameter required for power law migration
- range of vertical stresses for which the stiffness equivalency is sought
- output moduli and stiffness exponent for the target power law
Chapter 7

PROJECT AND DATA MANAGEMENT

Window 7-1: Dialog on the toolbox exit

A.1 All inserted or modified data will be saved in a file [current-project-name].pid
A.2 All cells will be updated in main Material dialog
The project is saved in the easily accessible xml data format.

- **project**: `[current-project-name].pid`
- **single laboratory test**: `[test-name].pit`
REFERENCES


