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Evaluation of hydraulic boundary conditions in Plaxis 2D

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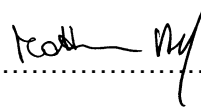
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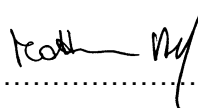


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Abstract

In the present master's thesis, the available hydraulic boundary conditions in Plaxis 2D have been evaluated. Thereby the application and effects of the conditions for the boundary value problems in accordance to the associated calculations have been investigated. Particularly, the numerical analysis of unsaturated and undrained material have been discussed. Hereof, the numerical method of unsaturated soil properties by means of the soil water characteristic curve is prescribed. The latter method and other numerical features have been elaborated on different geotechnical problems.

Keywords: Finite Element Method, hydraulic boundary conditions, undrained soil behaviour, unsaturated soil behaviour, precipitation, deep excavation

Kurzfassung

In der vorliegenden Diplomarbeit wurden die vorhandenen hydraulischen Randbedingungen in Plaxis 2D evaluiert. Dabei wurde die Anwendung und ihre Auswirkungen in Übereinstimmung mit den entsprechenden Berechnungsmethoden eruiert. Besonders die numerische Analyse von undrainierten und teilgesättigten Böden wurde eingehend untersucht. Diesbezüglich wird die numerische Methode von teilgesättigten Bodeneigenschaften in Hinsicht auf die Wasserretentionskurve genauer beschrieben. Diese und andere Methoden wurden letztendlich anhand von verschiedenen geotechnischen Problemstellungen ausgearbeitet.

Schlüsselwörter: Finite Elemente Methode, hydraulische Randwertbedingungen, undrainierte Böden, teilgesättigte Böden, Niederschlag, tiefe Baugruben

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List of symbols and abbreviations

Capital letters

A	[m ²]	Cross section area
\underline{B}	[-]	Strain interpolation matrix
\underline{C}	[-]	Coupling matrix for degree of saturation
D	[m]	Drainage path
E	[N/m ²]	Young's modulus
E'	[N/m ²]	Effective Young's modulus
E_{50}	[N/m ²]	Secant stiffness in standard drained triaxial test
E_{50}^{ref}	[N/m ²]	Reference value of secant stiffness in standard drained triaxial test
E_{oed}	[N/m ²]	Tangent stiffness for primary oedometer loading
E_{oed}^{ref}	[N/m ²]	Reference value of tangent stiffness for primary oedometer loading
E_{UR}	[N/m ²]	Unloading/ Reloading stiffness
E_{UR}^{ref}	[N/m ²]	Reference value of Unloading/ Reloading stiffness
\underline{G}	[m/s ²]	Gravity vector
G	[N/m ²]	Shear modulus
G_0	[N/m ²]	Shear modulus at very small strain
G_0^{ref}	[N/m ²]	Reference value of shear modulus at very small strain
G_{UR}^{ref}	[N/m ²]	Reference value of shear modulus at Unloading/ Reloading
\underline{H}	[m/s]	Permeability matrix
I	[m ⁴]	Moment of inertia
K_0	[-]	Coefficient of lateral earth pressure (initial stress state)
K_0^{nc}	[-]	Coefficient of lateral earth pressure for a normally consolidated stress
K_w	[N/m ²]	Bulk modulus of water
\underline{L}	[-]	Differential operator
M	[Nm]	Bending moment
\underline{M}	[N/m ²]	Material stiffness matrix
N	[N]	Normal force
\underline{N}	[-]	Matrix with shape function
OCR	[-]	Over consolidation ratio
POP	[N/m ²]	Pre-overburden pressure
Q	[N]	Shear force
\underline{Q}	[N/m ²]	Coupling matrix for stress components
R_{inter}	[-]	Strength reduction factor for interfaces
R_f	[-]	Failure ratio

\underline{S}	[N/m ²]	Compressibility matrix
S	[-]	Degree of saturation
S_{eff}	[-]	Effective or normalized degree of saturation
S_{res}	[-]	Residual degree of saturation
S_{sat}	[-]	Fully saturated degree of saturation
T_v	[-]	Dimensionless time factor according 1D-consolidation theory
V	[m ³]	Volume

Small letters

c	[N/m ²]	Cohesion
c_v	[1/s]	Consolidation coefficient according 1D-consolidation theory
d	[m]	Thickness
e	[-]	Void ratio
f	[-]	Yield function
\underline{f}_u	[N/m]	Vector of loads
g	[-]	Plastic potential function
g	[m/s ²]	Gravitational acceleration
g_a	[1/m]	Fitting parameter for van Genuchten-Mualem SWCC-approximation in in Plaxis 2D
g_c	[-]	Fitting parameter for van Genuchten-Mualem SWCC-approximation in in Plaxis 2D
g_n	[-]	Fitting parameter for van Genuchten-Mualem SWCC-approximation in in Plaxis 2D
h_{ref}	[m]	Reference head value
h_{inc}	[m/m]	Increment value of head
k_i	[m/s]	Coefficient of permeability
k_f	[m/s]	Hydraulic conductivity
m	[kg]	Mass
\underline{m}	[-]	Vector containing unity terms for normal and shear stress components
m_G	[-]	Fitting parameter for van Genuchten approximation
n	[-]	Coefficient of porosity
n_G	[-]	Fitting parameter for van Genuchten approximation
t	[s]	Time
p	[N/m ²]	Isotropic or mean stress
p_w	[N/m ²]	Pore water pressure
p_{active}	[N/m ²]	Active pore pressure in Plaxis 2D

p_{excess}	[N/m ²]	Excess pore pressure in Plaxis 2D
p_{ref}	[N/m ²]	Reference stress for stiffness (default value 100 kN/m ²)
p_{steady}	[N/m ²]	Steady state pore pressure in Plaxis 2D
p_{water}	[N/m ²]	Pore water pressure in Plaxis 2D
q	[N/m ²]	Equivalent shear stress or deviatoric stress
\underline{q}	[m ³ /s]	Flux matrix
u	[N/m ²]	Pore water pressure according to Terzaghi's stress theory
u	[m]	Displacements
\underline{v}	[m]	Vector with displacements component
w	[-]	Gravimetric water content
x_{ref}	[m]	Reference value in x-direction
y_{ref}	[m]	Reference value in y-direction

Greek letters

α	[1/m]	Fitting parameter for van Genuchten approximation
α	[-]	Integration coefficient
γ	[N/m ³]	Unit weight
γ_w	[N/m ³]	Unit weight of water
γ_{sat}	[N/m ³]	Saturated soil unit weight – mentioned for below phreatic level
γ_{unsat}	[N/m ³]	Unsaturated soil unit weight – mentioned for above phreatic level
$\gamma_{0.7}$	[-]	Shear strain at which $G_s = 0.722 G_0$
Δ	[-]	Mathematical operator: increment
ε	[-]	Strain
ε_q	[-]	Deviatoric strain
ε_v	[-]	Volumetric strain
θ_n	[-]	Normalized value of volumetric water content
θ_s	[-]	Saturated value of volumetric water content
θ_r	[-]	Residual value of volumetric water content
ν	[-]	Poisson's ratio
ν'	[-]	Effective Poisson's ratio
ν_u	[-]	Poisson's ratio of undrained state
ν_{UR}	[-]	Poisson's ratio of Unloading/ Reloading state
ρ	[kg/m ³]	Density
ρ_w	[kg/m ³]	Density of water
σ	[N/m ²]	Total stresses

σ'	[N/m ²]	Effective stresses
τ	[N/m ²]	Shear strength
φ	[°]	Angle of internal friction
ψ	[°]	Dilatancy angle

Abbreviations

BC	Boundary condition
BVP	Boundary value problem
CCP	Composition of pore water pressure
CT	Calculation type in Plaxis 2D (e.g. K0 procedure, Plastic, etc.)
FEM	Finite Element Method
FCFD	Fully coupled flow-deformation – calculation type in Plaxis 2D
GWFlowBaseBC	Groundwater flow base boundary condition
FOS	Factor of safety
HC	Hydraulic condition
HBC	Hydraulic boundary condition
HS	Hardening Soil – constitutive material model in Plaxis 2D
HSS	Hardening Soil small-strain Stiffness – constitutive material model in Plaxis 2D
LE	Linear-elastic – material model in Plaxis 2D
MC	Mohr-Coulomb – material model in Plaxis 2D
MX	Model explorer in Plaxis 2D – GUI
PDE	Partial differential equation
PHR	Phreatic
PPCT	Pore pressure calculation type in Plaxis 2D (e.g. Phreatic, etc.)
RM	Reference manual
SLS	Serviceability Limit State
SSGWF	Steady state groundwater flow
SWCC	Soil water characteristic curve
SX	Selection explorer in Plaxis 2D - GUI
TGWF	Transient groundwater flow
TM	Tutorial manual
ULS	Ultimate Limit State
UPPP	Use pressure from previous phase

1 Introduction

This master's thesis discusses the specific topic about numerical features with respect to hydraulic boundary conditions, unsaturated soil behaviour, pore pressure determination, drainage types, which are available in the finite element code of *Plaxis 2D v.2016* (Plaxis 2D Manual, 2016). Hereof, the definition of hydraulic boundary conditions should be investigated and evaluated. Furthermore the hydraulic properties for unsaturated soil behaviour should be discussed.

In the **second** chapter all available hydraulic boundary conditions in Plaxis 2D, particularly their applications and featured modifications in accordance of the associated calculations are described. The **third** chapter discusses the hydraulic properties of unsaturated soils. The hydraulic conductivity is determined by means of the soil water characteristic curve, which is implemented in Plaxis 2D. In chapter **four** the different types of analysis are described. In chapter **five** are finally assessed some of the aforementioned definitions and specifications by means of three different geotechnical models. The first model discusses the modelling of precipitation with respect to a partial saturated soil. The next model computes the bearing capacity concerning undrained and unsaturated soil behaviour. In the final model the analysis conditioning the ultimate state in accordance to undrained soil behaviour is computed. The chapter **six** concludes a summary of the shortcomings with respect to the assessed hydraulic boundary conditions. In the Appendix are given the conducted simplified models of various hydraulic boundary conditions.

2 Hydraulic boundary conditions in Plaxis 2D

The specification of initial and hydraulic boundary conditions (HBC) is an essential part of discretising and modelling a geotechnical problem with any form of water impact, e.g. phreatic level within the soil strata, precipitation onto the soil surface and seepage through a dam embankment. Hence by using a FEM software, e.g. the commercial available software Plaxis 2D Version 2016.01, the hydraulic conditions have to be considered carefully and appropriately chosen (Table 1). The computation of pore pressures involves the specified BVP conditions.

SOIL MODE	
Create borehole	
	Head - BoreholeWaterLevel
	Water
Show materials - Material sets	
	Drainage types
	Groundwater
MODEL EXPLORER	
Attributes library	
	Flow functions
	Water levels
GroundwaterFlow	
	Extremes Open
	Extremes Closed
Precipitation	
	Recharge
Water	
	GlobalWaterLevel
SELECTION EXPLORER	
GWFlowBaseBC	
	Seepage
	Closed
	Head
	Inflow
	Outflow
	Infiltration
WaterConditions	
	Global level
	Costum level
	Head
	User-defined
	Interpolate
	Dry
	Unsaturated

Table 1: Hydraulic boundary conditions in Plaxis 2D – Overview

2.1 Soil mode

When starting the software Plaxis 2D, after the setup of the project properties, the *Soil mode* (Figure 1) is the first graphical user interface (GUI), wherein the specification of soil stratigraphy by means of the command *Create borehole* is available. Furthermore the command *Show materials* obtains the *Material set*. Next to the *Soil mode*, the modes *Structure*, *Mesh*, *Flow conditions* and *Staged construction* are listed (Figure 2).

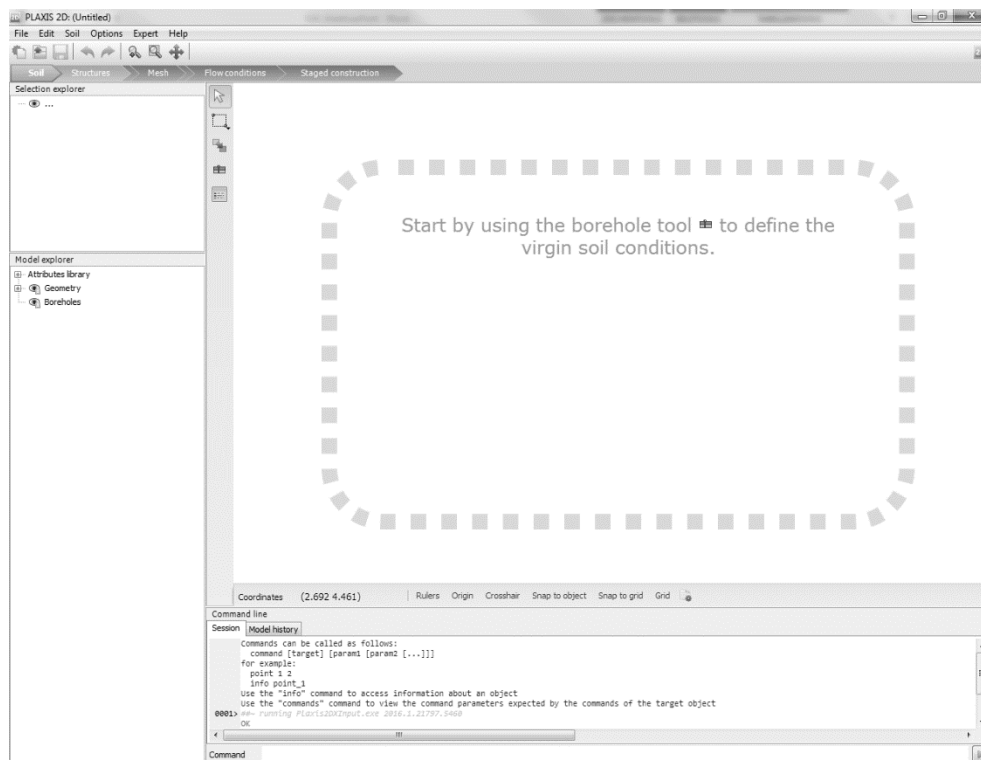


Figure 1: Plaxis 2D Version 2016.01 – GUI

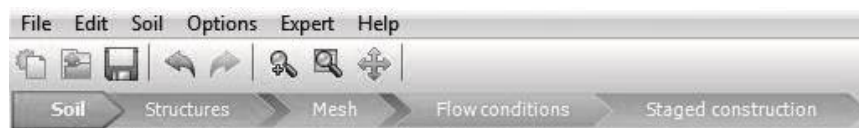


Figure 2: Plaxis 2D – Modes

2.1.1 Create borehole – tabsheet water

Keywords: BoreholeWaterLevel, tabsheet Water

Within the new prompting window, the user can define the *BoreholeWaterLevel* by means of the option *Head*. In the tabsheet *Water*, the phreatic conditions can be modified by the choices *Hydrostatic*, *Interpolate*, *Dry* or *User defined*. In contrast to *Head*, the user can adjust the linear distribution of water pressures explicitly (Figure 3). Consequently, the program creates automatically the associated hydraulic boundary condition, which is stated in the *Flow conditions* mode (Figure 4).

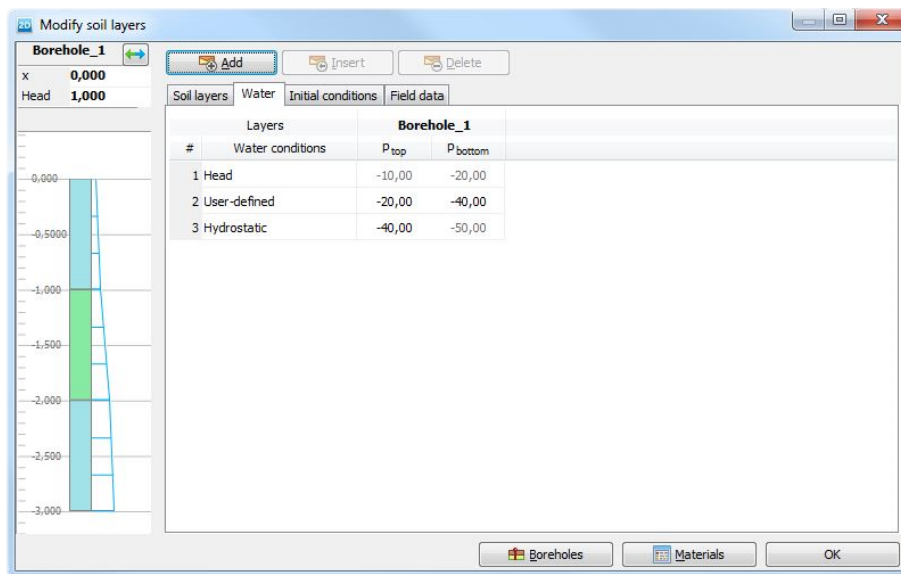


Figure 3: Plaxis 2D – Command *Create Borehole*: tabsheet *Water*

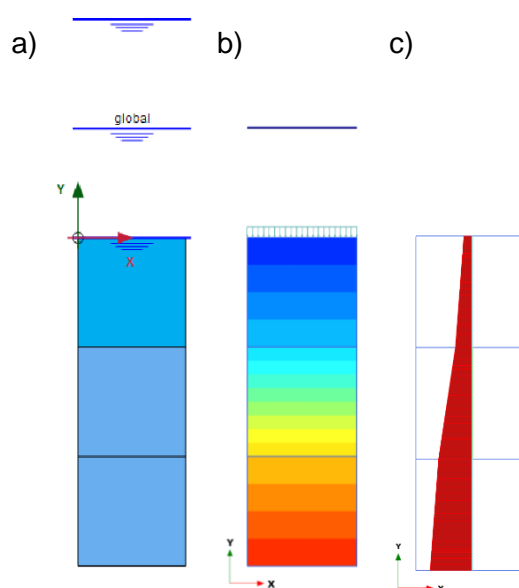


Figure 4: Plaxis 2D – Tabsheet *Water*: corresponding results

In Figure 4 (a), the associated specification of HBC in the *Flow conditions* mode is shown. Note that the specified water levels are *BoreholeWaterLevels*. The figures (b) and (c) are the result of an initial calculation phase with the corresponding pore pressure calculation type (PPCT), e.g. Initial Phase – PPCT Phreatic. This results can be computed by means of the command *Preview phase* in the *Flow conditions mode*.

2.1.2 Show materials – tabsheet Material sets

Keywords: Undrained (A, B), permeability, van Genuchten and SWCC

In the *Soil* mode, the user can define the material for the outlined soil strata by means of the command *Show materials*. Within the tabsheet (Figure 5), the soil material can be specified. Accordingly, two tabsheets are crucial with respect to the present topic. They are called *General* and *Groundwater*, wherein the drainage types and hydraulic behaviour are available.

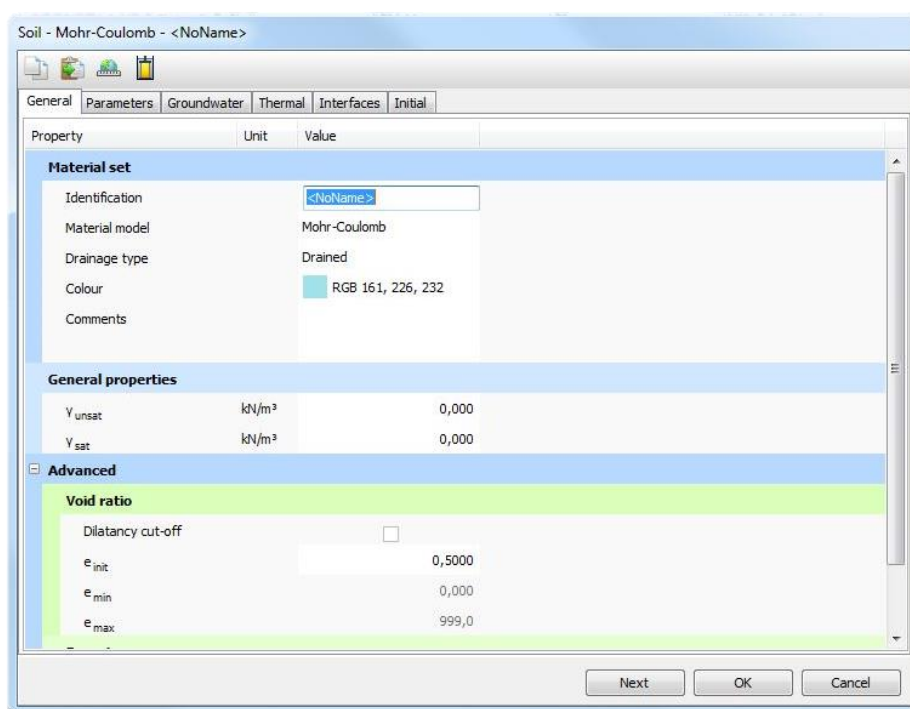


Figure 5: Plaxis 2D – Material data set

The term drainage has, with respect to geotechnical engineering, two different meanings. One refers to the drainage by means of dewatering systems. The other pertains to the drainage behaviour of a soil. Plaxis 2D provides a selection of different drainage types, which are considered for the calculation types *Plastic*, *Safety* and *Dynamic*. They are called *Drained*, *Undrained (A)*, *Undrained (B)* and *Undrained (C)* and *Non-porous*. In the tabsheet *Groundwater*, the hydraulic parameters associated with the soil classification by means of grain size distribution are stated.

2.1.3 Tabsheet General – drainage types

All of the aforementioned drainage types describe the water-soil skeleton interaction and is set for fully saturated soils. A material, which is specified as drained develops no excess pore pressures. Non-porous material compute either no pore water pressures. These two do not assist an associated calculation type. In comparison the undrained material *Undrained (A)*, *Undrained (B)* and *Undrained (C)* will only model undrained soil behaviour, if a plastic analyses is conducted. In contrast to the calculation types (CT) Consolidation and Fully coupled flow-deformation, which are not dealing with the drainage types but rather take into account the permeability, stiffness and time. However, an undrained analysis can be conducted by *Undrained (A)* and *Undrained (B)* with respect to computation of effective stresses. In contrast *Undrained (C)* will compute total stresses, hence no effective stresses and excess pore pressures are calculated.

2.1.4 Tabsheet Groundwater – hydraulic parameters

The hydraulic parameters in the tabsheet *Groundwater* are specified by means of the soil classifications and permeabilities (Figure 6). Within the soil classification, the so-called *Data set*, the user has a choice of various hydraulic models, which define the parameters for the approximation of the relationship between suction versus relative permeability and saturation respectively (Chapter 3.2).

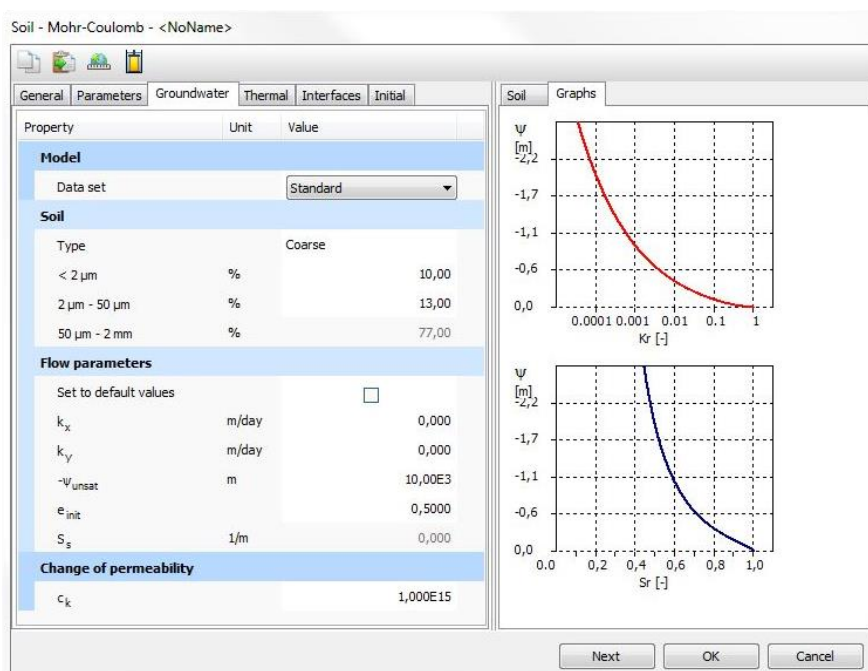


Figure 6: Plaxis 2D – Tabsheet *Groundwater*

The mentioned approximation is determined by means of a statistical regression analysis of laboratory data involving the associated function of van Genuchten-Mualem. The hydraulic models are listed as *Standard*, *Hypres* (Hydraulic Properties of European Soils), *USDA* (United States Department of Agriculture), *Staring* (H.C.W Staring, 1842) and *User-defined*. The data set *Standard* (Figure 7) is based on the data of *Hypres* and features *Topsoils*. The so-called *Topsoils* are within the first 100 centimetres below the ground surface and after this limit the so-called *Subsoils* are given. The parameters for *Hypres*, *USDA* and *Staring* are based on a collaborative database including the diversity and spatial variability of soils. Whenever possible the permeability should be obtained from field and laboratory testing and can be different in vertical and horizontal directions. Plaxis 2D provides also the possibility to specify a hydraulic model involving laboratory data by means of *User-defined*.

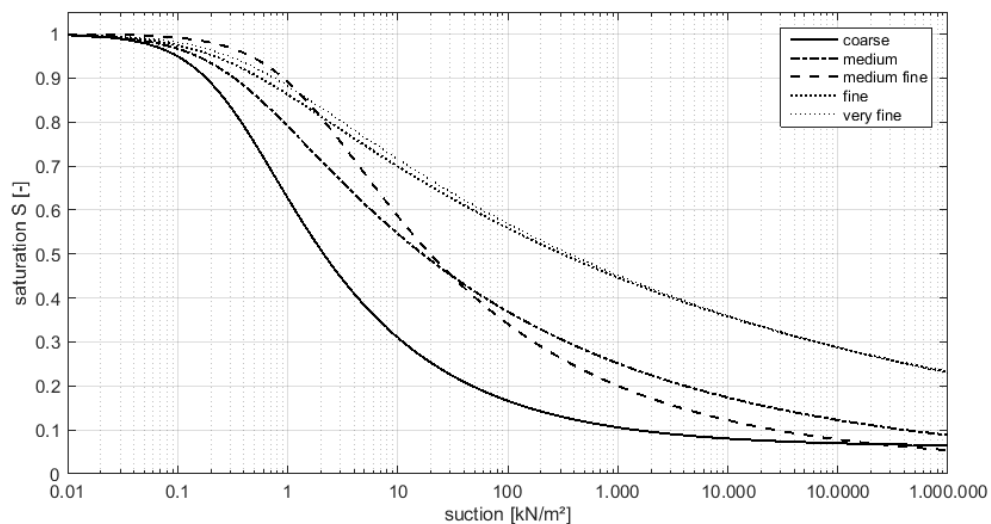


Figure 7: SWCC: *Standard* (Hypres, Topsoils)

2.2 Hydraulic boundary conditions

Plaxis 2D provides as many ways to determine the hydraulic boundary conditions. In the *Flow conditions* mode, the user can specify the hydraulic boundary conditions by selecting the desired elements, i.e. adjustment by the *Selection explorer*. Furthermore the HBC can be defined globally in the *Model explorer*.

2.2.1 Hydraulic model boundary conditions – Model explorer

Keywords: *Flow functions, Water levels, GroundwaterFlow, Precipitation, Water*

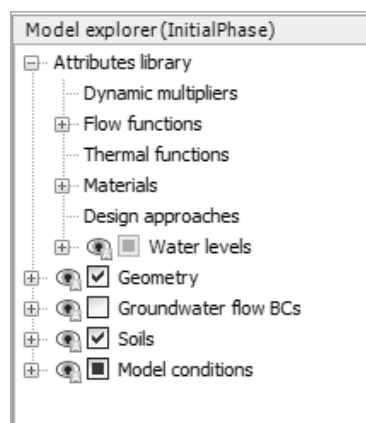


Figure 8: Plaxis 2D – *Model explorer*

The *Model explorer* (MX) is located on the left lower part of the GUI. The subtrees *Attributes library* with *Flow functions* and *Water levels* are relevant. Furthermore the subtree *Model conditions* including *GroundwaterFlow*, *Precipitation* and *Water* are of interest. The options of the *Model explorer* affect the numerical model globally. Thus, for example the specified precipitation is applied to the whole model surface.

In the subtree *Attributes library* (Figure 8), the user can define and edit the **Flow functions**. Two relevant functions are available, which are called *HeadFunction* and *DischargeFunction*. The *HeadFunction* can model a water level variation including a *UserWaterLevel* and *GWFlowBaseBC*, but not a *BoreholeWaterLevel*. Note that a *HeadFunction* on inclined elements is not admissible. The *DischargeFunction* defines a recharge on the associated surface, e.g. *GWFlowBaseBC*. Both functions are computed when the hydraulic boundary condition is stated as *Time dependent* and a flow calculation is conducted. In both functions, the user can model a linear or harmonic water head change. Furthermore a change of water head by means of table values is feasible (Figure 9).

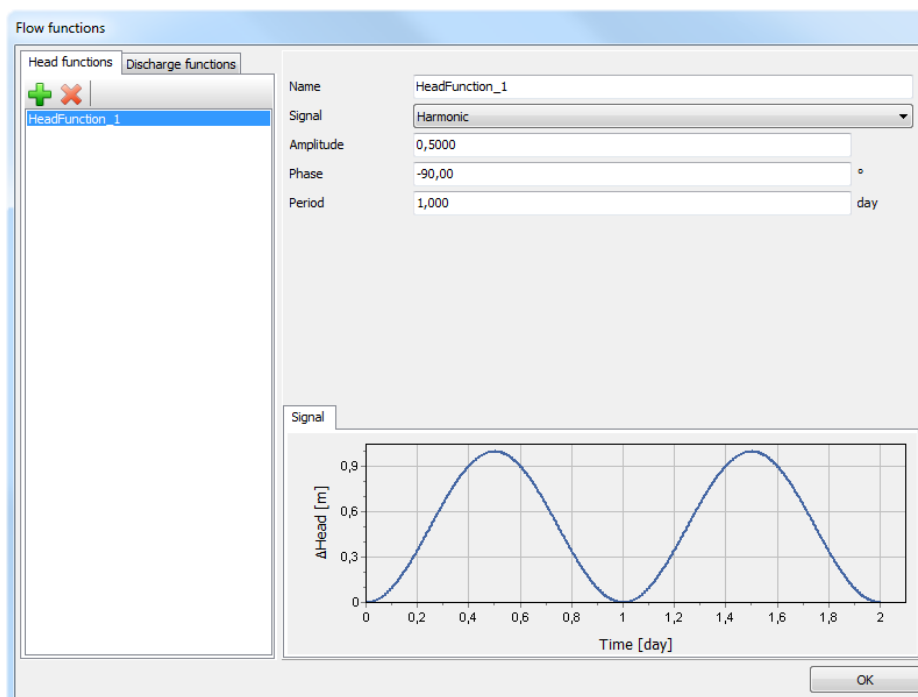


Figure 9: Plaxis 2D – Flow functions

The time value in the subtree *Signal* always refers to the cumulated time of a consecutive calculation. This means that in case of a complete flow analysis, e.g. precipitation, each calculation phase will only use the corresponding part of the flow function.

The subtree **Water levels** allows the user to navigate and adjust the specified phreatic levels more conveniently. The user can adjust two different water levels, the *BoreholeWaterLevel* and the *UserWaterLevel*. The *BoreholeWaterLevel* is assigned by the borehole *Head* specification and the *UserWaterLevel* is defined by means of the command *Create water level* in the *Flow conditions* mode. Note that a *BoreholeWaterLevel* cannot be modified by a *Flow functions*. In order to avoid the *BoreholeWaterLevel*, the soil stratigraphy can be modelled by means of soil polygons in the *Structure* mode and a *UserWaterLevel* can be alternatively applied. Corresponding definitions of hydraulic conditions in the soil polygons can be found in the chapter 2.2.2 in the section *Global level* and *Custom level*.

The subtree *Model conditions* (Figure 8), obtains the option **GroundwaterFlow**. Therein, the model extremes *XMin*, *XMax*, *YMin* and *YMax* are stated, which include the hydraulic boundary conditions *Open* and *Closed*. When modelling the soil stratigraphy the bottom boundary *YMin* is automatically set to *Closed*. In Figure 10, the difference between an opened and closed boundary is displayed. In this case, the left model extreme *XMin* should be closed in order to obtain the appropriate water head of an axisymmetric geotechnical model.

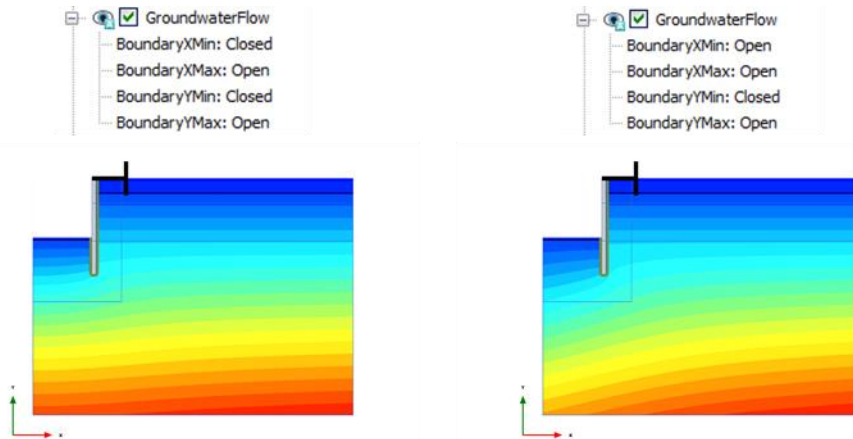


Figure 10: *GroundwaterFlow*: Closed versus Open

A further option to define a HBC in the subtree *Model Conditions* is the **Precipitation**. Likewise, this option is affecting all the associated model surfaces. Note that all boundaries, which represent the ground surface should not be specified with other HBC options, e.g. *Closed*, *Head*, etc. Otherwise, the precipitation in the associated ground surface will be not calculated. The precipitation is modelled on a horizontal and an inclined surface by means of defining the parameter recharge q and maximum and minimum water pressure referred to the affected boundary, which are stated as water head ψ_{max} and ψ_{min} . In the case of an inclined surface, the parameter q will be computed in the magnitude of $q \cdot \cos \alpha$, where α is the angle of the inclined surface. Accordingly, the term represents the recharge perpendicular to the model surface. The recharge q can be specified by means of a constant value or a time-dependent recharge. The latter option can be modelled by defining a *DischargeFunction* in the subtree *Flow functions*. Due to the periodic character of the meteorological incidence the function should be stated as intermittently step function. Thus the input by means of a table is the appropriate approach. Generally a meteorological phenomenon has a periodic character, because infiltration, stated as precipitation, and drying, encompassing evaporation and evapotranspiration, occur. In consequence, the recharge can be defined with a positive value for precipitation and a negative value for evapotranspiration. The variable ψ_{max} represents the height of the water head above the ground surface. Above this value ψ_{max} , a water run-off is simulated, when the initial water head due to the recharge increases until the associated head is reached. The parameter ψ_{min} defines the depth within the top soil. It is associated with a negative recharge, i.e. evaporation or evapotranspiration respectively. When the resulting minimum head is reached at the defined limit, the negative recharge is supposed to stop. The default value for the maximum water head is equal to 0.1 m and should describe the water storage capacity due to the uneven surface and plant cover. The minimum water head is specified by

default equal to minus 1.0 m and bounds the impact due to drying (Figure 11). The option *Infiltration* is discussed in chapter 2.2.2 in the corresponding section.

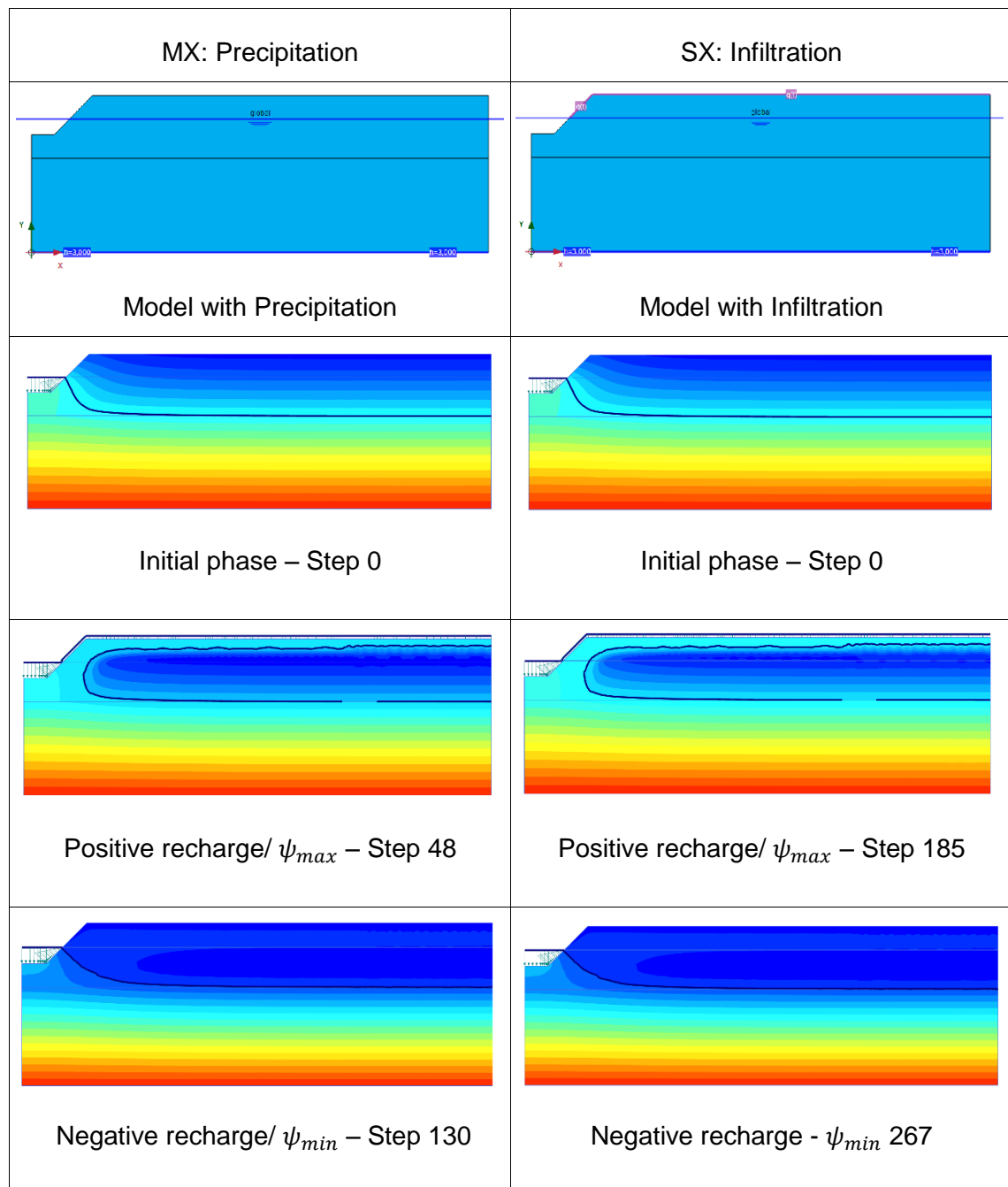


Figure 11: Comparison: *Precipitation and Infiltration*

2.2.2 Selective hydraulic boundary conditions – Selection explorer

Keywords: Seepage/ Closed, Head, Inflow/ Outflow, Infiltration, WaterConditions

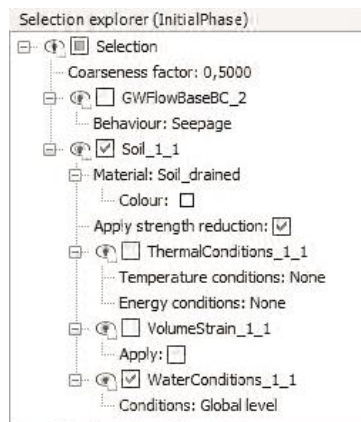


Figure 12: Plaxis 2D – *Selection explorer*

The *Selection explorer* (SX) is located on the left mid side of the GUI, above the *Model explorer*. The specification by means of SX prevails the corresponding options in the *Model explorer*. For instance the user sets the top boundary of a domain in the *Selection explorer* to *Closed*, that means no flux beyond the boundary is computed despite the same boundary is specified as *Open* in the *Model explorer*, also called *Seepage*. This adjustment is valid for other specification too, e.g. *Deformations*, *FieldStress* etc. The user can specify conditions on selected boundaries, known as groundwater flow base boundary conditions (GWFlowBaseBC), or on selected soil polygons by means of *WaterConditions* (Figure 12). The latter is an implicit specification of conditions for a boundary value problem. For example the option *WaterCondition Custom level* defines the relation between the soil polygon and the user defined phreatic level. The adjustment in the SX is convenient to specify local and explicit boundary conditions. The *GWFlowBaseBC*'s are only taken into account if a groundwater flow calculation, e.g. transient or steady-state groundwater flow, is conducted. For the subtree *GWFlowBaseBC*, there are *Seepage*, *Closed*, *Head*, *Inflow*, *Outflow*, *Infiltration* and few more additional options available. The aforementioned HBC are the most common ones. In the subtree *WaterConditions*, the user can choose between *Global level*, *Custom level*, *Head*, *User-defined*, *Interpolate*, *Dry* and *Unsaturated*. These options can be associated with the settings in the borehole tabsheet *Water* at the *Soil mode*. After activating a *GWFlowBaseBC* at the appropriate model boundary the user can select and specify the hydraulic condition. According to hydraulic boundary conditions, the internal report of Plaxis 2D (Galavi, 2010) is recommended, including many verifications with respect to *GWFlowBaseBC* and *WaterConditions*.

The options **Seepage** and **Closed** are similar to the *GroundwaterFlow* specifications in the MX (chapter 2.2.1). Consequently, any specification in the SX prevails the corresponding boundary conditions. *Seepage* means flux beyond the boundary and *Closed* avoids any flux.

The option **Head** can model a hydrostatic water head referred to its level, i.e. if the *GWFlowBaseBC* within the model is specified, then the pore pressure at the associated level is zero and the pore pressure below is not affected by any recharge (chapter 5.1.3). Within the option *Head*, several distributions, e.g. *Uniform*, *Vertical increment* etc. are available. The specifics will be not discussed here, but its application and results can be found the Appendix. The HBC can be used to directly generate a phreatic level, which confines a fully saturated soil layer without any flux beyond its surface.

The options **Inflow** and **Outflow** describe the same boundary conditions but have opposite effects. The *GWFlowBaseBC Inflow* or *Outflow* are strongly dependent on the hydraulic behaviour of the soil and the specification of flux. Accordingly, the user can define a local outflow in the tunnel wall by specifying uniform discharges involving field data.

The last mentioned *GWFlowBaseBC* is the **Infiltration**, which has the same specification of the HBC *Precipitation* in the *Model Explorer*. The application is differently. The user need to specify the infiltration by means of activating the *GWFlowBaseBC* at the boundary. Thereby, the corresponding ground surface should be determined and activated. (Figure 13, violet).



Figure 13: *GWFlowBaseBC: Infiltration*

The hydraulic boundary conditions, *Head*, *Inflow*, *Outflow* and *Infiltration* can be specified with a constant flux or a time-dependent recharge, hence the user needs to define time dependency and specify the recharge by means of a *HeadFunction* or *DischargeFunction* respectively.

The aforementioned *WaterConditions*, which are an implicitly modification of boundary conditions with respect to the soil polygon, can be defined by selecting the soil cluster and changing the options in the SX. The options ***Global level*** and ***Custom level*** encompass the same application, i.e. relates to the associated water level, but have different meanings. The soil polygon, which should be specified with the option *Global level*, computes the internal water pressures with respect to the corresponding water level (Figure 14, dark blue zone). The water level is marked as *global* and specified in the *Model explorer* in the subtree *Model conditions Water*. In contrast, the specification by means of *Custom level* defines the computation of internal water pressure with respect to the *UserWaterLevel*. A *UserWaterLevel* could be defined by the command *Create water level*. Consequently, the user can define many water levels but must take care in applying the corresponding soil polygons.

The phreatic level and the active model boundary require an intersection point. An intersection point means where the phreatic level and the activated model boundary coincide. For instance, a model boundary is active after an excavation step is conducted. Thus an intersection point must be always created in order to take into account the associated phreatic level for the pore water pressure calculation in the soil clusters (Figure 14, light blue zone).

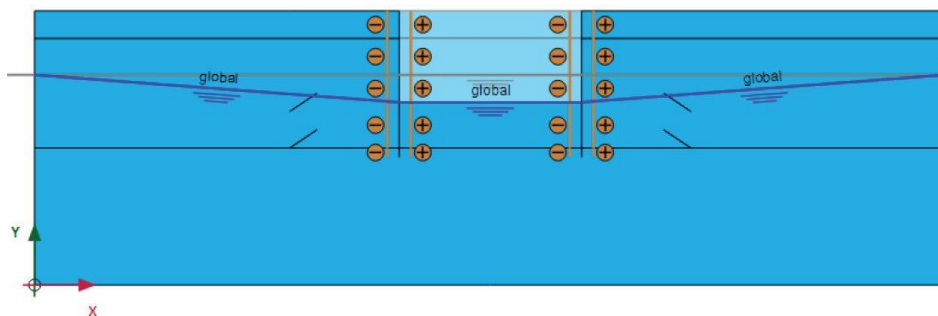


Figure 14: Active model boundary (TM Plaxis 2D, 2016)

The water condition **Head** specifies a phreatic level by means of a reference value y_{ref} in y-direction (Figure 15). The internal water pressure starts at zero and increase linearly with respect to the specified **Head** (Figure 16). This option and following conditions can be specified in the borehole tabsheet in the tab *Water* as well.

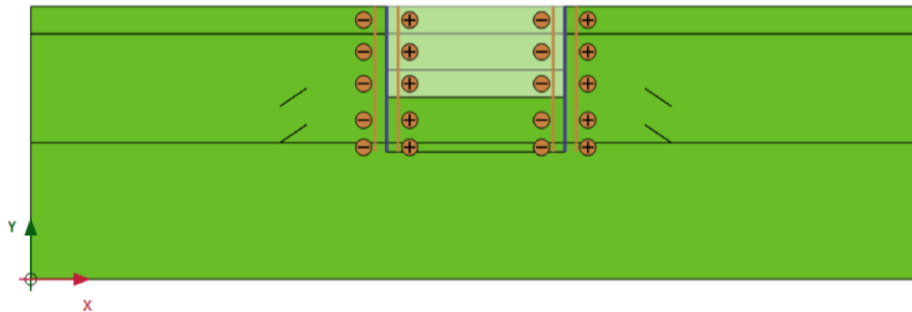


Figure 15: *WaterConditions: Head: 23.0m* (TM Plaxis 2D, 2016)

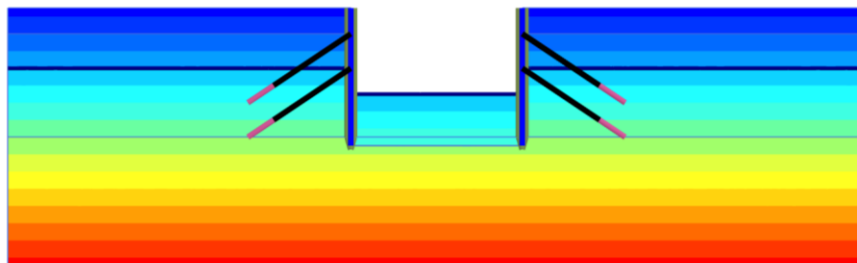


Figure 16: *WaterConditions: Head – Result p_{steady}* (TM Plaxis 2D, 2016)

The condition **User-defined** models a pore pressure distribution by means of the reference value y_{ref} , which specifies the level in y-direction. From this reference value, the reference water pressure p_{ref} starts and increases or decreases respectively with respect to a positive or negative value p_{inc} :

With the option **Interpolate** (Figure 17, orange), the adjacent pore water pressures are taken in to account and the distribution within the specified soil polygon changes linearly. This modification needs to be conducted at a dry excavation pit without computation of groundwater flow, e.g. PPCT Phreatic.

The option **Dry** (Figure 17, grey zone) will not compute any pore water pressure. Thus, it has the relevant behaviour of non-porous material. An application of this hydraulic condition in accordance to the PPCT Phreatic is following model. Further models are shown in the Appendix.

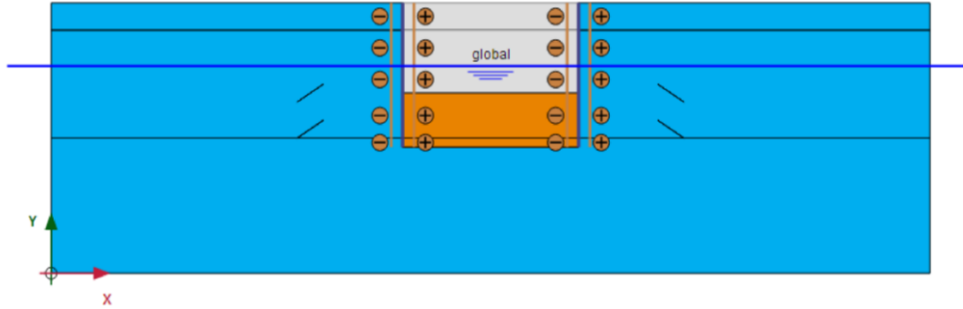


Figure 17: *WaterConditions: Dry* (TM Plaxis 2D, 2016)

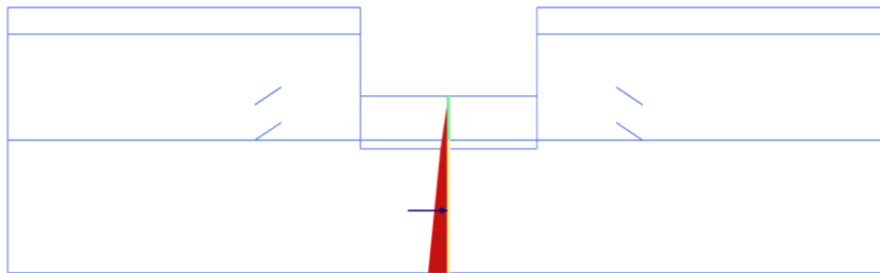


Figure 18: *WaterConditions: Dry – Result p_{steady}* (TM Plaxis 2D, 2016)

A partial saturation to the soil polygon is explicitly introduced by means of the water condition **Unsaturated**. The saturation throughout the soil clusters is uniform by the specified value. It is possible to deal with unsaturated soil cluster, if the option *Ignore suction* in the *Deformation control parameters* subtree is deselected. Hence the resulting pore water pressures involving suction will be computed according the water conditions and the specifications in the *Groundwater* tabsheet.

3 Soil water characteristic curve

The soil water characteristic curve (SWCC) is an empirical closed-form method to characterize unsaturated soil behaviour (Fredlund, 2012 et al.). The SWCC function depicts a correlation of tensile pore pressure, usually referred to suction, and gravimetric water content θ (Figure 19, Fredlund, 2012). The SWCC can be displayed with the degree of saturation S and the permeability k as ordinate as well.

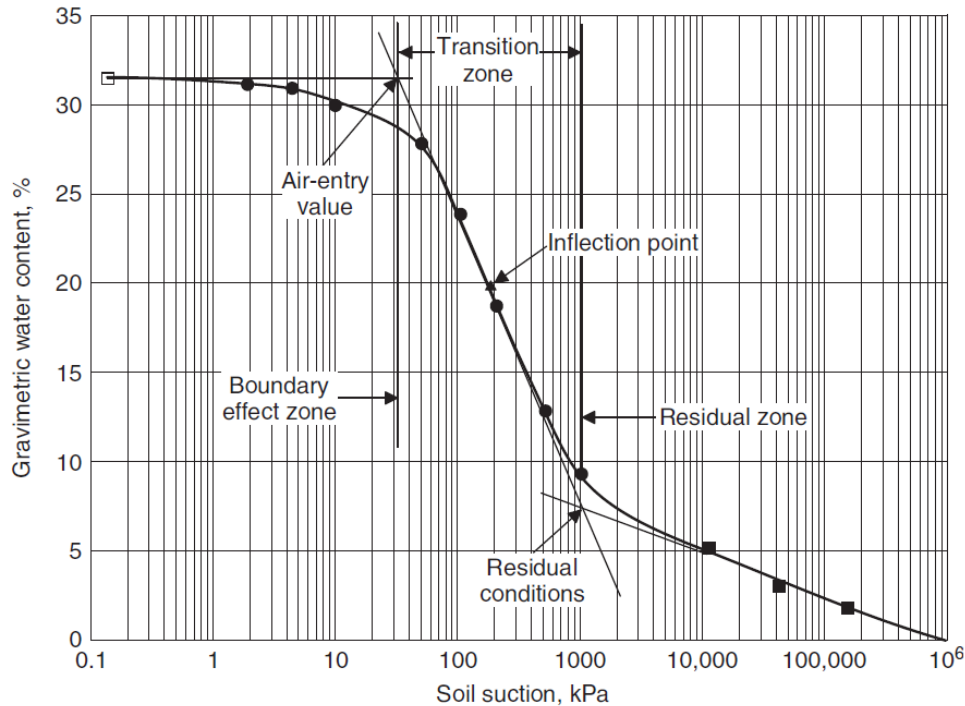


Figure 19: SWCC – Zones and Values

An increasing of suction in the partial saturated zone distinctively leads to a decreasing in saturation. Different approaches to determine the SWCC are available, which are described in the following chapters. The graph may be subdivided in three zones, which are dedicated first to the air-entry value, and second to the residual value. The zones describe the phases of a mechanically two-phase soil model and are called boundary effect zone, transition zone and residual zone. The boundary effect zone displays the saturated and capillary soil behaviour. The transition zone depicts the desaturation process, wherein the function decreases steeper. Thus, the degree of saturation reaches the residual value at a suction approx. equal to 1500 kPa (van Genuchten, 1980). After this value, the residual zone begins, wherein a soil is stated as dry.

3.1 Approximation of laboratory data

The relationship between suction and gravimetric water content can be measured by means of laboratory tests. Consequently, the experimental data cloud is fitted by means of the least square regression analysis in order to enhance an implementation of unsaturated soil properties in computational geotechnical models. Various researchers (Gardner 1958, Mualem 1976, van Genuchten 1980, Fredlund and Xing 1994, Pharm and Fredlund 2005 et al.) had carried out methods to best fit the experimental data (Figure 20, Fredlund 2012).

Gardner (1958b)	$\Theta_d = \frac{1}{1 + a_g \psi^{n_g}}$ <p>where</p> $\Theta_d = \frac{w(\psi)}{w_s}$	a_g = fitting parameter which is a function of air-entry value of the soil n_g = fitting parameter which is a function of rate of water extraction from soil once air-entry value of soil has been exceeded
van Genuchten (1980)	$\Theta_n = \frac{1}{[1 + (a_{vg} \psi)^{n_{vg}}]^{m_{vg}}}$ <p>where</p> $\Theta_n = \frac{w(\psi) - w_r}{w_s - w_r}$	a_{vg}, a_{vm}, a_{vb} = fitting parameters primarily related to inverse of air-entry value (units equal to 1/ kPa) n_{vg}, n_{vm}, n_{vb} = fitting parameters primarily related to rate of water extraction from soil once air-entry value has been exceeded
van Genuchten (1980)– Mualem (1976)	$\Theta_n = \frac{1}{[1 + (a_{vm} \psi)^{n_{vm}}]^{m_{vm}}}$ <p>where</p> $m_{vm} = 1 - \frac{1}{n_{vm}}$	m_{vg}, m_{vm}, m_{vb} = fitting parameters that are primarily related to residual water content conditions
Fredlund and Xing (1994)	$w(\psi) = C(\psi) \frac{w_s}{\{\ln [e + (\psi/a_f)^{n_f}]\}^{m_f}}$ <p>where</p> $C(\psi) = 1 - \frac{\ln(1 + \psi/\psi_r)}{\ln[1 + (10^6/\psi_r)]}$ $\Theta_d = \frac{w(\psi)}{w_s}$	a_f = fitting parameter which is primarily a function of air-entry value of soil n_f = fitting parameter which is primarily a function of rate of water extraction from soil once air-entry value has been exceeded m_f = fitting parameter which is primarily a function of residual water content $C(\psi)$ = correction factor which is primarily a function of suction corresponding to residual water content.
Pham and Fredlund (2005)	$\begin{cases} w_1(\psi) = w_u - S_1 \log(\psi) & 1 \leq \psi < \psi_{aev} \\ w_2(\psi) = w_{aev} - S_2 \log\left(\frac{\psi}{\psi_{aev}}\right) & \psi_{aev} \leq \psi < \psi_r \\ w_3(\psi) = S_3 \log\left(\frac{10^6}{\psi}\right) & \psi_r \leq \psi < 10^6 \text{ kPa} \end{cases}$	S_1, S_2, S_3 = slope of straight line portions of SWCC within each of three zones w_u = water content at 1 kPa w_{aev} = water content at air-entry value w_1, w_2, w_3 = water content in line segments 1, 2, and 3, respectively.

Figure 20: SWCC – Equations

Each equation is written in terms of the dimensionless water content θ_d , normalized water content θ_n or gravimetric water content $w(\psi)$ in relation to the soil suction ψ .

A SWCC can be mathematically described by two or three variables. The amount of variables, the so-called fitting parameters, provide a flexibility to best fit the experimental data. Consequently, each SWCC equations may represent either the drying (desorption) branch or the wetting (adsorption) branch of a SWCC (Figure 21, Fredlund 2012).

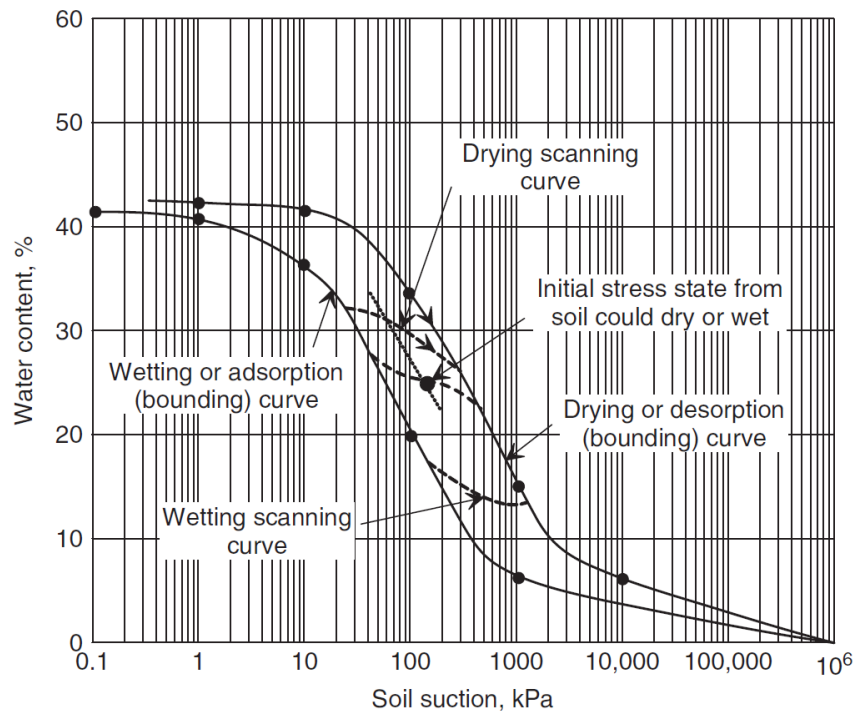


Figure 21: SWCC – Adsorption and desorption

The first variable a_i describes the air-entry value and the beginning of the transition zone. The second variable n_i governs how the soil saturation decreases in the transition zone. The third variable m_i influences the function in the high suction range, thus the unsaturated behaviour in the residual zone. In a few equations for the SWCC, the latter variable is substituted with a relation with respect to the variable n_i (van Genuchten, Mualem, 1980). The change in value of one variable effects the fitting curve according to Figure 22.

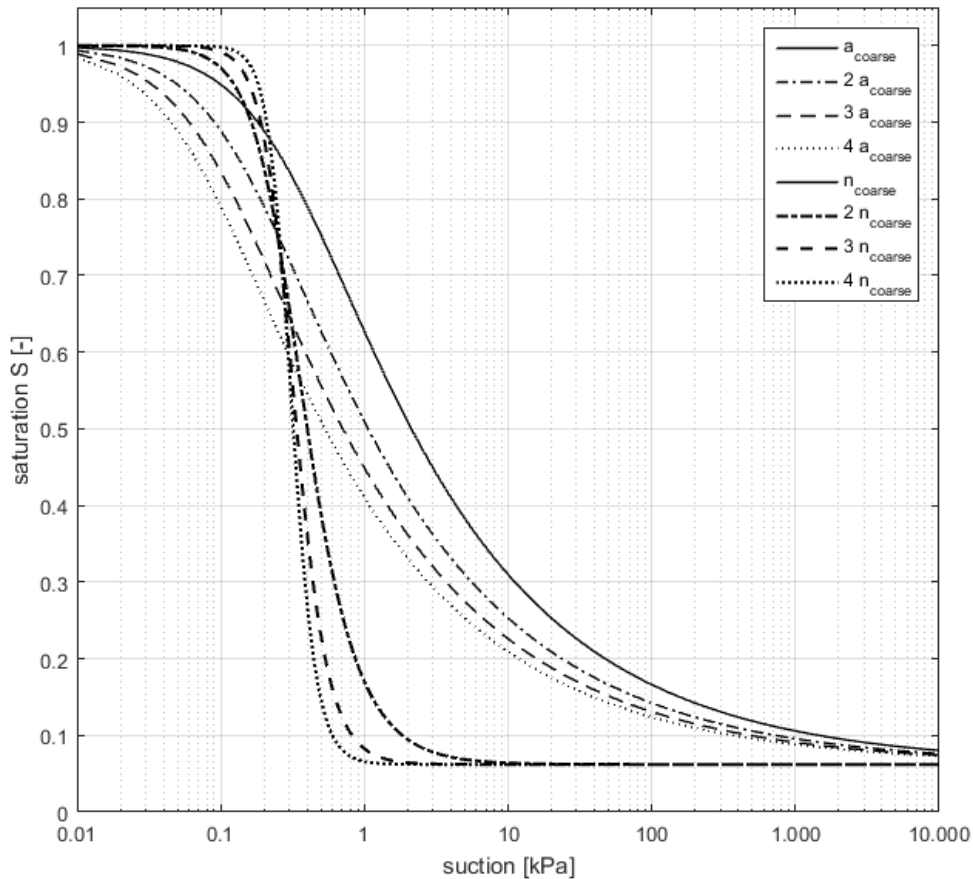


Figure 22: SWCC – Variable variation

3.2 Implementation in Plaxis 2D

In Plaxis 2D the SWCC is implemented by means of hydraulic models in the tabsheet *Groundwater* and is used to model unsaturated soil behaviour. Hereof, Bishop presented a theory to calculate effective stresses for unsaturated soils. The effective stresses are composed of total stresses and pore water pressures of all fluids in a three-phase model:

$$\sigma' = (\sigma - u_a) - \chi \cdot (u_a - u_w) \quad [1]$$

where σ is called the total stresses, u_a is the pore air pressure, χ is called matric suction coefficient and u_w is the pore water pressure. By using Bishop's Theory as basic calculation for effective stresses in Plaxis 2D, the distinction can still be made between fully saturated and partial saturated soil behaviour. In Plaxis it is assumed that the pore air pressure u_a is zero and the matric suction coefficient χ is specified with the relationship $\chi = S_{eff}$ (Figure 23, Nuth, 2007 et al.).

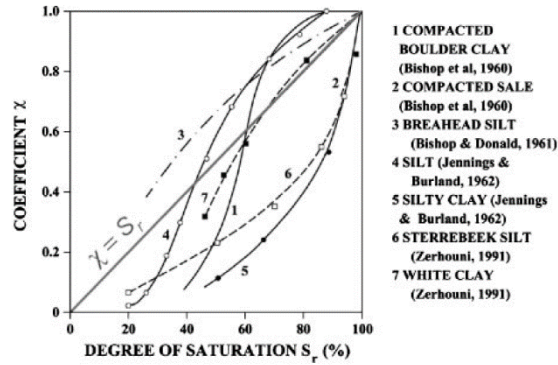


Figure 23: Matric suction coefficient and saturation trend

The equation [1], with the aforementioned preconditions and the denotation of pore water pressure p_{water} in Plaxis 2D for the term u_w , now reads:

$$\sigma' = \sigma - S_{eff} \cdot p_{water} \quad [2]$$

wherein the effective degree of saturation S_{eff} is written as an equation with the terms of an actual degree of saturation S , the residual value S_{res} and the saturated value S_{sat} :

$$S_{eff} = \frac{S - S_{res}}{S_{sat} - S_{res}} \quad [3]$$

The actual degree of saturation S is computed with the derivative (equation [4]), by means of the hydraulic model and the actual pore water pressures p_w in the geotechnical model. The computation of tensile pore pressures must be conducted by disabling the *Deformation control parameter Ignore Suction* in the tabsheet *Phases*.

$$\frac{\partial S(p_w)}{\partial p_w} = (S_{sat} - S_{res}) \left[\frac{1 - g_n}{g_n} \right] \left[g_n \left(\frac{g_a}{\gamma_w} \right)^{g_n} p_w^{(g_n-1)} \right] \left[1 + \left(g_a \frac{p_w}{\gamma_w} \right)^{g_n} \right]^{\left(\frac{1-g_n}{g_n} \right)} \quad [4]$$

The hydraulic model contains a framework of soil classes (Figure 24 – Source: Internet) and fitting parameters (Table 2, Plaxis 2D, 2016). The fitting parameters g_a , g_n are determined for the van Genuchten-Mualem approximation according to the soil classification, e.g. *Standard*, *Hypres*, *USDA*, *Staring* and *User-defined*.

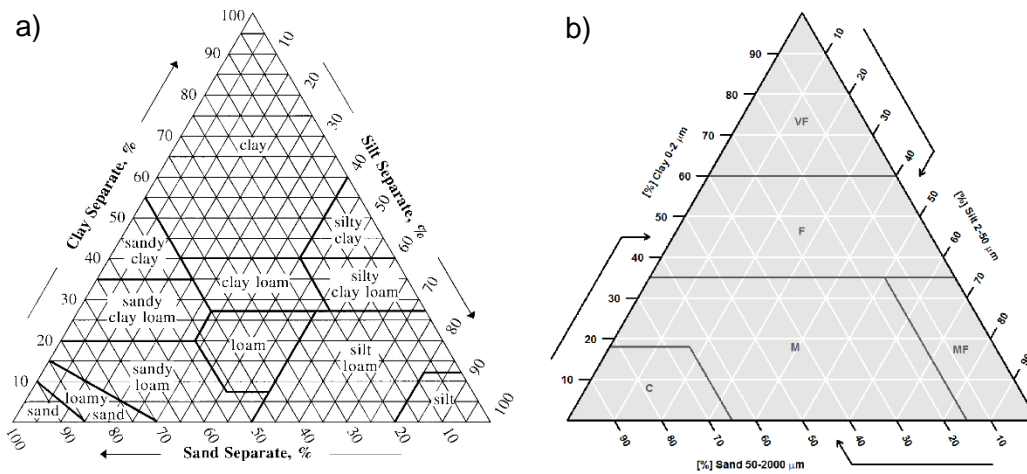


Figure 24: Soil classification: (a) USDA and (b) Hypry

	θ_r (-)	θ_s (-)	K_{sat} (m/day)	g_a (1/m)	g_l (-)	g_n (-)
<i>Topsoil:</i>						
coarse	0.025	0.403	0.600	3.83	1.2500	1.3774
medium	0.010	0.439	0.121	3.14	-2.3421	1.1804
medium fine	0.010	0.430	0.0227	0.83	-0.5884	1.2539
fine	0.010	0.520	0.248	3.67	-1.9772	1.1012
very fine	0.010	0.614	0.150	2.65	2.5000	1.1033
<i>Subsoil:</i>						
coarse	0.025	0.366	0.700	4.30	1.2500	1.5206
medium	0.010	0.392	0.108	2.49	-0.7437	1.1689
medium fine	0.010	0.412	0.0400	0.82	0.5000	1.2179
fine	0.010	0.481	0.0850	1.98	-3.7124	1.0861
very fine	0.010	0.538	0.0823	1.68	0.0001	1.0730
organic	0.010	0.766	0.0800	1.30	0.4000	1.2039

Table 2: Hypry series with van Genuchten parameters (RM Plaxis 2D, 2016)

4 Types of analyses and output

The numerical analysis can be divided into several calculation phases. One phase corresponds to a particular loading stage or construction sequence respectively. Hereof, Plaxis 2D provides different calculation types (CT) and pore pressure calculation types (PPCT) in order to compute deformations and pore water pressures. In consequence, the associated specifications of HBC are involved as well.

4.1 Calculation types

The calculation type relates to the geotechnical procedure, e.g. construction of a dam, excavation of a pit, lowering groundwater or dissipate excess pore pressures. At the beginning of every geotechnical model, the initial state must be defined by means of a parent phase. Additionally, the following calculation steps, also known as child phases, can carry out the geotechnical procedure. Table 3 shows an overview of all available calculation types and its possible applications. Furthermore the pore pressure calculation type with its abbreviations *Phreatic* (PHR), *Use pressure from previous phase* (UPPP), *Steady state groundwater flow* (SSGWF) and *Transient groundwater flow* (TGWF) is displayed. The PPCT pertains to the conducting *Calculation type* in a phase and is strongly dependent on the *Loading type Staged Construction*. The pore pressure calculation type UPPP adopts the pore water pressures from the previous phase, thus no pore water pressure calculation is conducted. Further this PPCT takes over the status quo of the activated and deactivated soil polygons from the previous phase although a new status quo in the present phase is considered. The TGWF is only available in the child phases, if the parent phase is specified with the calculation type *Flow only*. The CT Fully coupled flow-deformation has no PPCT.

Parent phase			
	Specification	Application	PPCT
<i>K0 procedure</i>	Direct generation of initial effective stresses, pore pressures and state parameters	Set up of geotechnical model	PHR, SSGWF
<i>Field stress</i>	Direct generation of initial effective stresses, pore pressures and state parameters	Set up of geotechnical model	PHR, SSGWF
<i>Gravity loading</i>	Initial stresses from finite element calculation	Set up of geotechnical model with inclined soil strata	PHR, SSGWF
<i>Flow only</i>	No effective stress calculation	Flow calculation for the geotechnical model	PHR, SSGWF, TGWF
Child phase			
<i>Plastic</i>	Elastoplastic drained or undrained analysis	e.g. failure load prediction, drained excavation sequence	PHR, UPPP, SSGWF
<i>Consolidation</i>	Time-dependent analysis of deformation and excess pore pressure	e.g. dissipation of excess pore pressure after a plastic analysis	PHR, UPPP, SSGWF
<i>Fully coupled flow-deformation</i>	Time-dependent analysis of deformation and pore water pressure	e.g. coupled analysis involving flow and deformation	-
<i>Safety</i>	Calculation of global factor of safety	Prediction of failure mechanism	UPPP
<i>Dynamic</i>	Dynamic analysis in the time domain	e.g. deformation analysis involving earthquake scenario	UPPP

Table 3: Calculation and pore pressure calculation type

4.2 Pore pressure calculation type

The pore water pressure is part of the total stresses and is denoted as active pore pressure p_{active} in Plaxis 2D. This pore pressure is a result of the effective degree of saturation multiplied by the pore water pressure p_{water} . In turn, p_{water} is composed of steady-state pore pressure and excess pore pressure. In Plaxis 2D four types of pore pressure calculations are available. They are called *Phreatic*, *Use pressure from previous phase*, *Steady-state groundwater flow* and *Transient groundwater flow*. The PPCT Phreatic generates directly steady-state pore pressure in consequence of the specified water levels and *WaterConditions* in the soil polygons. The pore pressure calculation type UPPP does not compute pore pressures, because it takes into account the already calculated pore pressures from the previous phase. The PPCT SSGWF and TGWF are actually computing pore pressures by means of groundwater flow involving the defined flow parameters and specified hydraulic boundary conditions.

4.3 Stress and pore pressure output

In the previous chapter the computation of stresses and pore pressures involving different calculation types have been discussed. Now the results and its specifications will be discussed.

The total stresses σ are composed of effective stresses σ' and the pore water pressures Δu according to Terzaghi (Terzaghi, 1925). Following equations show it clearly:

$$\sigma = \sigma' + u_w \quad \dots \text{total stresses} \quad [5]$$

$$\sigma' = \sigma - u_w \quad \dots \text{effective stresses} \quad [6]$$

Bishop introduced to pore water pressure the matric suction hence the formulation is described by the following equation:

$$\sigma' = (\sigma - u_a) - \chi \cdot (u_a - u_w) \quad \dots \text{effective stresses} \quad [7]$$

In Plaxis 2D two assumptions are postulated. The pore air pressure u_a is equal to zero and the matric suction coefficient is defined as $\chi = S_{eff}$. Thus, the equation [7] now reads:

$$\sigma' = \sigma - S_{eff} \cdot u_w \quad \dots \text{effective stresses} \quad [8]$$

Where the effective degree of saturation S_{eff} is a normalized factor containing the actual degree of saturation S in the soil, the residual degree of saturation S_{res} and the fully saturated degree S_{sat} (equation [9]).

$$S_{eff} = \frac{S - S_{res}}{S_{sat} - S_{res}} \quad \dots \text{effective degree of saturation} \quad [9]$$

In Plaxis 2D the pore pressure u_w in equation [8] is denoted as pore water pressure p_{water} (equation [10]).

$$\sigma' = \sigma - S_{eff} \cdot p_{water} \quad \dots \text{effective stresses} \quad [10]$$

Further the term of pore pressure including S_{eff} and p_{water} can be specified as active pore pressure p_{active} .

$$\sigma' = \sigma - p_{active} \quad \dots \text{effective stresses} \quad [11]$$

In case of $S = 1.0$, $S_{sat} = 1.0$ and $S_{res} = 0.0$, i.e. fully saturation of the soil, the effective degree of saturation S_{eff} is equal to 1.0, thus entail the active pore pressure correlates with the pore water pressure. Further the effective stresses according to Bishop coincide with Terzaghi's effective stresses.

In Plaxis 2D the pore water pressure p_{water} is composed of the steady-state pore water pressure p_{steady} and the excess pore water pressure p_{excess} . The steady-state pore pressure is directly generated by means of specified phreatic levels and associated pore pressure calculations types, e.g. Phreatic. The excess pore pressure is a result of undrained material behaviour, which can be computed by means of the drainage type Undrained (A, B). Accordingly, following table shows the available material models and the associated drainage types.

Material model	Drainage type
Linear elastic	Drained Undrained (A) Undrained (C) Non-porous
Mohr-Coulomb	Drained Undrained (A) Undrained (B) Undrained (C) Non-porous
Hardening soil	Drained Undrained (A) Undrained (B)
HS small	Drained Undrained (A) Undrained (B)
Soft soil	Drained Undrained (A)
Soft soil creep	Drained Undrained (A)
Modified Cam-Clay	Drained Undrained (A)
NGI-ADP	Drained Undrained (B) Undrained (C)
Sekiguchi-Ohta model	Drained Undrained (A)

Table 4: Drainage types – Overview

An undrained analysis can also be conducted by the calculation type *Fully coupled flow-deformation*. Hereof this CT takes only into account the time, the permeability and stiffness. Depending on the calculation type, the bulk modulus will be stated in the stiffness matrix (Table 5, Plaxis 2D, 2016)

Type of material	Plastic (drained)	Plastic (undrained)	Consolidation	Safety or dynamics (drained)	Safety or dynamics (undrained)
Undrained ($p_{water} \leq 0$)	$K_w = 0$	$\frac{K_w^{sat}}{n} = \frac{2 \cdot G}{3} \left(\frac{1 + \nu_u}{1 - 2\nu_u} - \frac{1 + \nu_l}{1 - 2\nu_l} \right)$	$\frac{K_w^{sat}}{n} = \frac{2 \cdot G}{3} \left(\frac{1 + \nu_u}{1 - 2\nu_u} - \frac{1 + \nu_l}{1 - 2\nu_l} \right)$	$K_w = 0$	$\frac{K_w^{sat}}{n} = \frac{2 \cdot G}{3} \left(\frac{1 + \nu_u}{1 - 2\nu_u} - \frac{1 + \nu_l}{1 - 2\nu_l} \right)$
Undrained ($p_{water} > 0$)	$K_w = 0$	$K_w^{unsat} = \frac{K_w^{sat} K_{air}}{SK_{air} + (1 - S)K_w^{sat}}$	$\frac{K_w^{sat}}{n} = \frac{2 \cdot G}{3} \left(\frac{1 + \nu_u}{1 - 2\nu_u} - \frac{1 + \nu_l}{1 - 2\nu_l} \right)$	$K_w = 0$	$K_w^{unsat} = \frac{K_w^{sat} K_{air}}{SK_{air} + (1 - S)K_w^{sat}}$
Drained ($p_{water} \leq 0$)	$K_w = 0$	$K_w = 0$	$\frac{K_w^{sat}}{n} = \frac{2 \cdot G}{3} \left(\frac{1 + \nu_u}{1 - 2\nu_u} - \frac{1 + \nu_l}{1 - 2\nu_l} \right)$	$K_w = 0$	$K_w = 0$
Drained ($p_{water} > 0$)	$K_w = 0$	$K_w = 0$	$\frac{K_w^{sat}}{n} = \frac{2 \cdot G}{3} \left(\frac{1 + \nu_u}{1 - 2\nu_u} - \frac{1 + \nu_l}{1 - 2\nu_l} \right)$	$K_w = 0$	$K_w = 0$
Cluster just been activated	$K_w = 0$	$K_w = 0$	$K_w = K_w^{sat} \cdot 10^{-8}$	Not relevant	Not relevant
Non-porous or dry cluster	$K_w = 0$	$K_w = 0$	$K_w = 0$	$K_w = 0$	$K_w = 0$

Table 5: Bulk modulus of water – Overview

The bulk modulus of water changes according to the degree of saturation. Generally the saturation of a soil coincides with the phreatic level. Above the phreatic level ($p_w > 0$) the saturation is equal to 0 % and below ($p_w < 0$) it is specified with 100 %. For fully saturated soils the phreatic level should be equal to the soil surface. In the undrained material, e.g. *Undrained (A)* or *Undrained (B)*, the saturation is automatically 100 %. Note that the saturation can be redefined by a numerical analysis involving suction in the unsaturated zone and the soil water characteristic curve. In the following table, the associated saturation in accordance to the drainage type and relation to the phreatic level are postulated.

Calculation type	Drainage type	Phreatic level	effective Satuarion S_{eff}	Notation
Plastic	Undrained (A,B)	above	1.0*	overruling specification
Consolidation	Undrained (A,B)	above	1.0*	overruling specification
FCFD	Undrained (A,B)	above	0.0*	

* Saturation could be modified by means of hydraulic model and enabled suction

Table 6: Specification of saturation

5 Application of hydraulic boundary conditions

In the previous chapters the hydraulic boundary conditions, soil water characteristic curve, undrained analysis and the type of analyses are prescribed. These features are now applied in the following chapter.

5.1 Precipitation

By using the *Model condition's Precipitation or Infiltration* it is possible to compute a moisture flux boundary condition on the model surface. It exist a distinction of two boundary conditions. One boundary condition (BC) is specified as hydraulic head (Dirichlet BC), the second BC is stated as infiltration respectively recharge (Neumann BC). The specifics are the water pressure head ψ_{max} and ψ_{min} and the recharge q . The quantification of moisture flux is related to hydro-meteorological and hydrogeological data survey. The evaluation of moisture flux involves infiltration rate, evaporation rate and evapotranspiration rate respectively.

5.1.1 Aim of geotechnical model

The scope of this simplified geotechnical model is the application of precipitation involving unsaturated soil layers (Figure 25, Kolymbas, 2011). In this assessment, it is necessary to model a partial saturated soil strata and a confined aquifer undergoing precipitation. The assumption for the precipitation recharge was a very heavy rain equal to 10 mm/h. The cumulative recharge for the presumed rain period of one day is therefore 240 mm/d that is equal to 0.24 m/d. The results emphasis are pore pressure distributions with respect to the soil water characteristic curve.

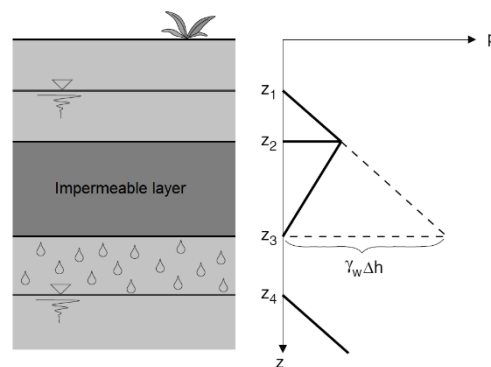


Figure 25: Precipitation: Model

5.1.2 Model configuration and material parameters

The model measures 1.0 m in width and 3.0 m in height and is subdivided into three uniform soil layers with different material behaviour (Figure 26). The soil clusters are modelled as soil polygons in the *Structure* mode. A plane-strain model with 15 – noded elements is utilized.

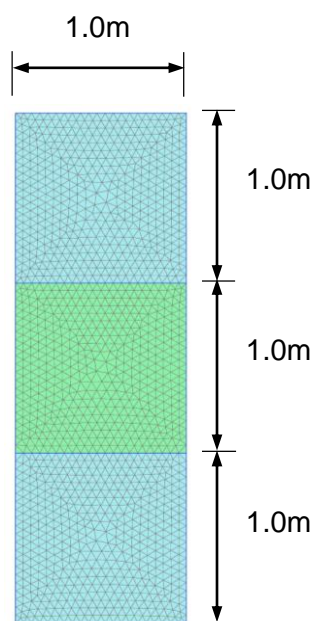


Figure 26: Precipitation: Model dimension

The top and bottom soil cluster behave drained (D) thus no excess pore pressure exist. The mid layer is specified as undrained (UD – Undrained A) due to very low permeability. Generally all soils are computed with a *Linear elastic* (LE) soil behaviour. The adopted material parameters are:

Soil:				
D	LE	$E' = 30000 \text{ kN/m}^2$	$\nu' = 0.3$	$\gamma = 20 \text{ kN/m}^3$
UD	LE	$E' = 30000 \text{ kN/m}^2$	$\nu' = 0.3$	$\gamma = 20 \text{ kN/m}^3$

Table 7: Precipitation: Soil parameters

Further both soil material parameters for unsaturated soil properties according to the hydraulic model *Standard* (Hypres Topsoils) are used. The adopted SWCC parameters are:

Soil: Data set <i>Standard</i> , soil types <i>coarse</i> (D), <i>fine</i> (UD)						
D	vGA	$k = 86. \text{ m/d}$	$\theta_r = 0.025$	$\theta_s = 0.403$	$g_a = 3.83.$	$g_n = 1.3774$
UD	vGA	$k = 0.0086 \text{ m/d}$	$\theta_r = 0.010$	$\theta_s = 0.520$	$g_a = 3.67$	$g_n = 1.1012$

Table 8: Precipitation: SWCC parameters

In the *Mesh mode* the *Very Fine* option is selected and a soil cluster refinement is used. The coarseness factor is equal to 0.5, thus the mesh quality is high (Figure 26).

In virtue of a one-dimensional flow, the top model boundary is specified with the model conditions *GroundwaterFlow Open* in the *Model explorer*; i.e. seepage is admissible. This specification is obligatory in order to allow a precipitation recharge. All other boundaries at the left, bottom and right of the model are closed. In consequence of a ground water flow calculation, this boundaries avoid flux, i.e. $q = 0$, beyond the model boundaries. Within the three soil cluster a water level by means of *UserWaterLevel* (model a) and *GWFlowBaseBC Head* (model b) respectively in the top and bottom layer is defined. Both phreatic levels occur in the middle of the soil layer. The soil cluster are designated to the water level by means of the associated specification *WaterCondition* in the *Selection explorer*. In addition the mid-layer interpolates the adjacent pore pressures (Figure 27).

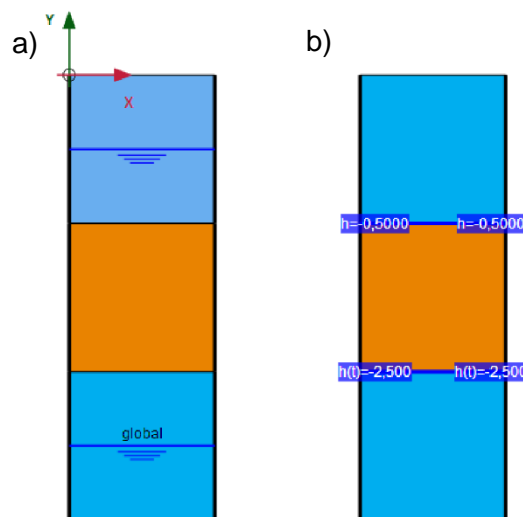


Figure 27: Precipitation: Model (a) *UserWaterLevel* and (b) *GWFlowBaseBC*

Both models (a) and (b) are computed in the same Plaxis 2D analysis in order to conduct the relevant precipitation calculation. Hereof, further specifications with respect to initial boundary state are defined (Figure 28).

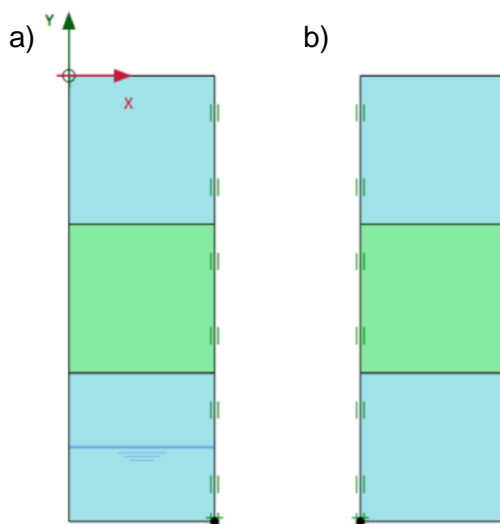


Figure 28: Precipitation: Fixities in model (a) and (b)

The initial state of geotechnical model is computed with the *CT K0 procedure* and the *PPCT Phreatic*. According to the selected pore pressure calculation type, the specified *GWFlowBaseBC's* in model (b) will be not computed. Hence the initial state is different in contrast to model (a) (FIGURE),

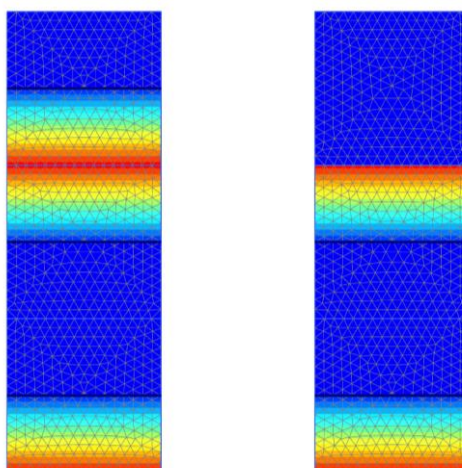


Figure 29: Precipitation: Active pore pressure in model (a) and (b)

Note that this setup for both models with respect to following computation is not relevant yet, because the output (5.1.3) of the model (b) will compute unexpected results.

The calculation type for the following phase is set to *Fully coupled flow–deformation*. In order to introduce the SWCC in the calculation, the option *Ignore suction* in the *Deformation control parameter* should be disabled.

The precipitation recharge cumulates 0.24 m/d by the end of a period equal to one day (Figure 30). The recharge is specified by means of a *DischargeFunction* in the *Model Explorer* (Figure 31).

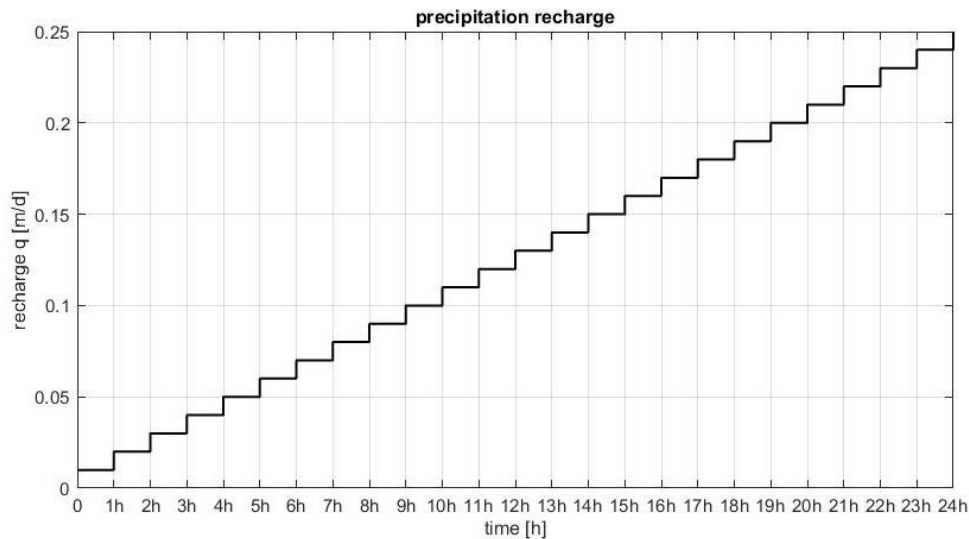


Figure 30: Precipitation: Recharge

A step function represent the alternate recharge within a precipitation incidence thus the recharge function cannot be modelled as linear function. Therefore a function with the *Signal Table* is defined.

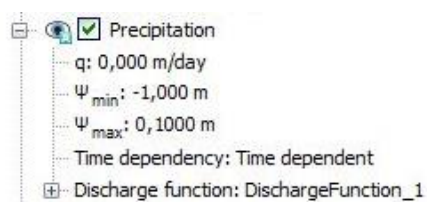


Figure 31: Precipitation: *DischargeFunction*

5.1.3 Output

In the Output of this simplified model, the active pore pressure distribution for two different hydraulic boundary configurations are shown. The first numerical model (a) with the *UserWaterLevel* and soil cluster interpolation. The second model (b) has the application of *GWFlowBaseBC* and soil cluster interpolation as well.

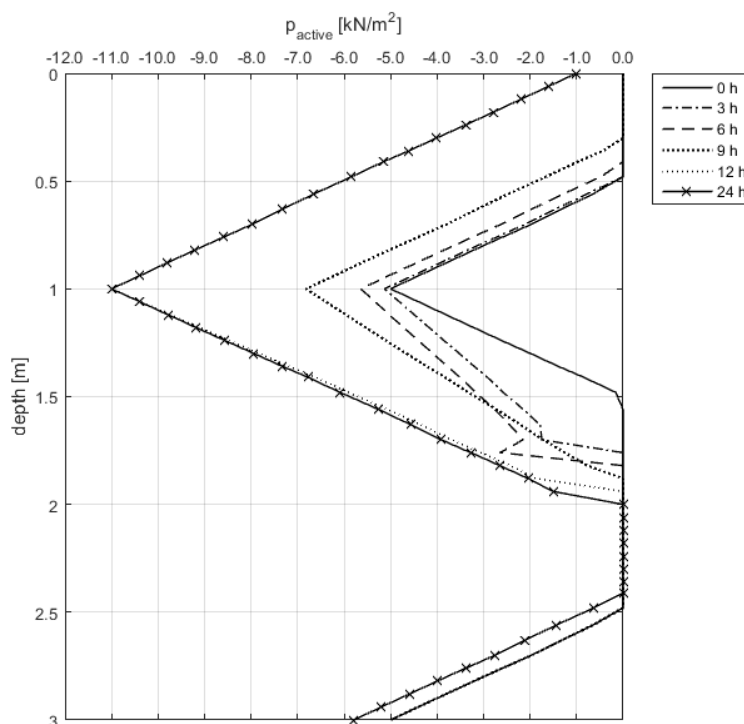


Figure 32: Result precipitation: Section – (a) *UserWaterLevel*

In Figure 32 the active pore pressure distribution along the centre line of the model is shown. The output of pore pressures is computed by means of section along the model height. Note that the p_{active} is equal to p_{water} , because the associated saturation S_{eff} is equal 100 %. The distributions displays the initial state, i.e. precipitation at 0 hour, and the next 12 hours of precipitation till 24 hours. The curves 3 h, 6 h, 9 h and 12 h show the development of pore pressures until the maximum water head ψ_{max} is reached, i.e. a run-off is simulated. Within the first metres the water level rises up to the maximum water head and draws down to approx. the level 2.0 m. In the bottom soil cluster, the water level does not increase significantly. A different development is observed in model with the *GWFlowBaseBC* (Figure 33).

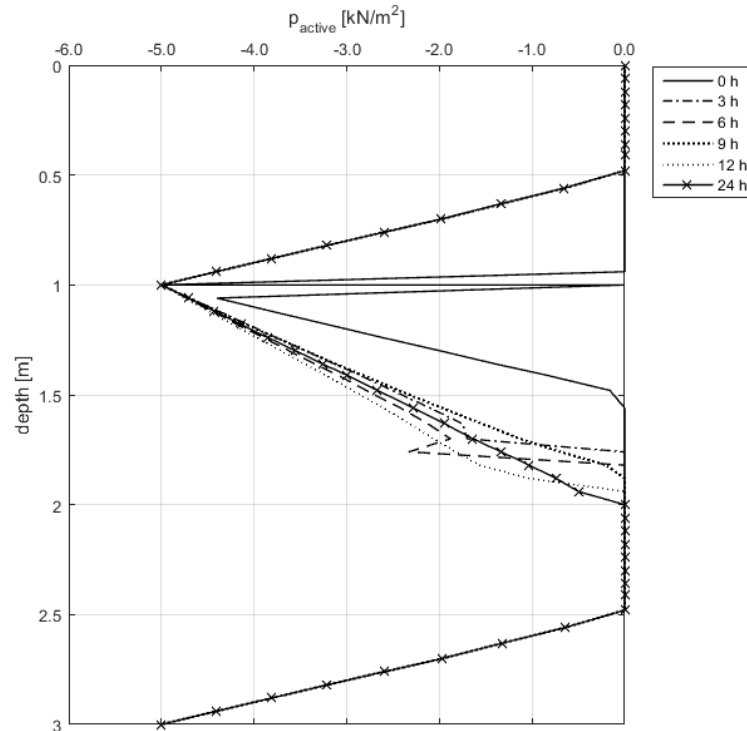


Figure 33: Result precipitation: Section – (b) *GWFlowBaseBC*

Within this model configuration, the active pore pressure distribution show unexpected results. As mentioned above, the initial hydraulic state for this model is not correct, but this has no crucial shortcomings so far. More of interest is that in the upper and lower soil polygon, i.e. between 0.0 m and 1.0 m or 2.0 m and 3.0 m, the pore pressure is equal to the hydrostatic state. No water level rises due to the precipitation recharge. Therefore, the modification by means of *GWFlowBaseBC* is not appropriate for modelling this simplified geotechnical model.

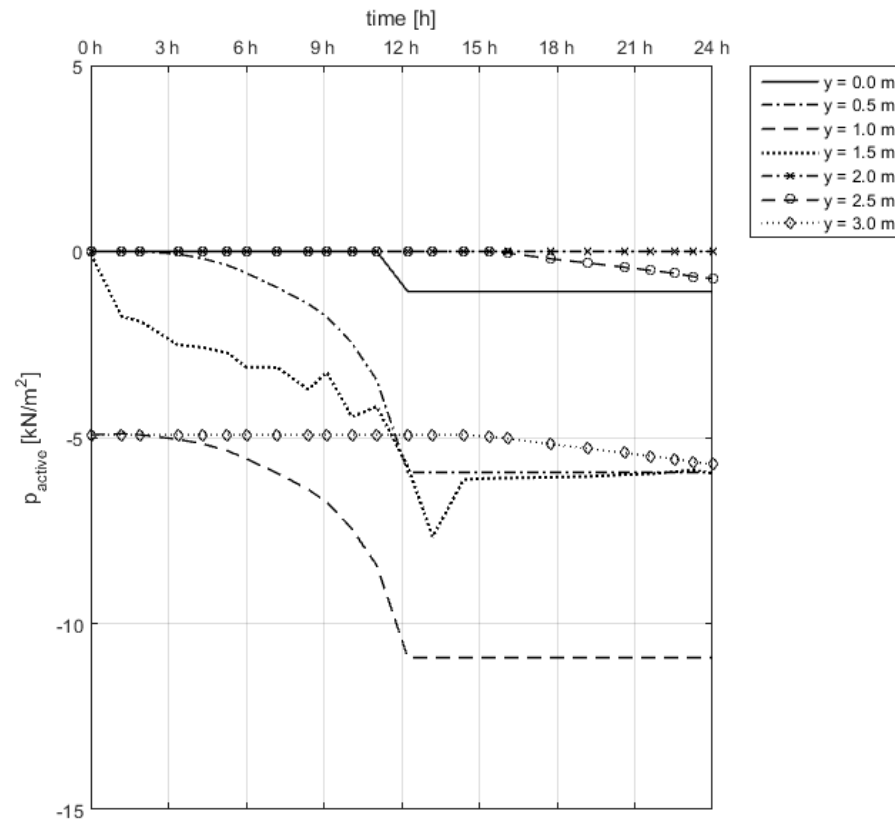


Figure 34: Result precipitation: Depth points – (a) *UserWaterLevel*

In Figure 34, the development of the active pore pressures within one day is shown. The results are computed by means of stress points at every depth of 0.5 m along the centre of the model. The run-off starts after 12.0 hour, i.e. at an amount of 0.12 m/d precipitation. Hereof, the pore pressure of level $y = 0.0$ m match with the maximum water head $\psi_{max} = 0.1$ m. For the depths y equal to 0.5 m, 1.0 m and 1.5 m the pore pressures shift about -6.0 kPa. The curve at the level 2.0 m displays zero pore pressures because no water pressure occur in this region. The last two curves, 2.5 m and 3.0 m increase within the last 12 hours, because the bottom water level rises up.

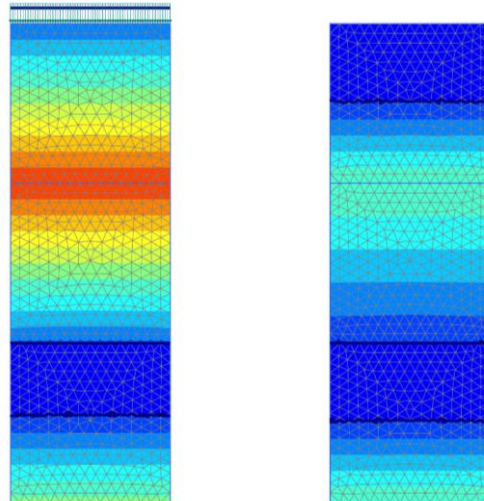


Figure 35: Result precipitation: (a) *UserWaterLevel* and (b) *GWFlowBaseBC*

In Figure 35 the active pore pressure distribution with the phreatic levels is shown. On the right is the model (a) with *UserWaterLevel* and on the left model (b) with *GWFlowBaseBC*.

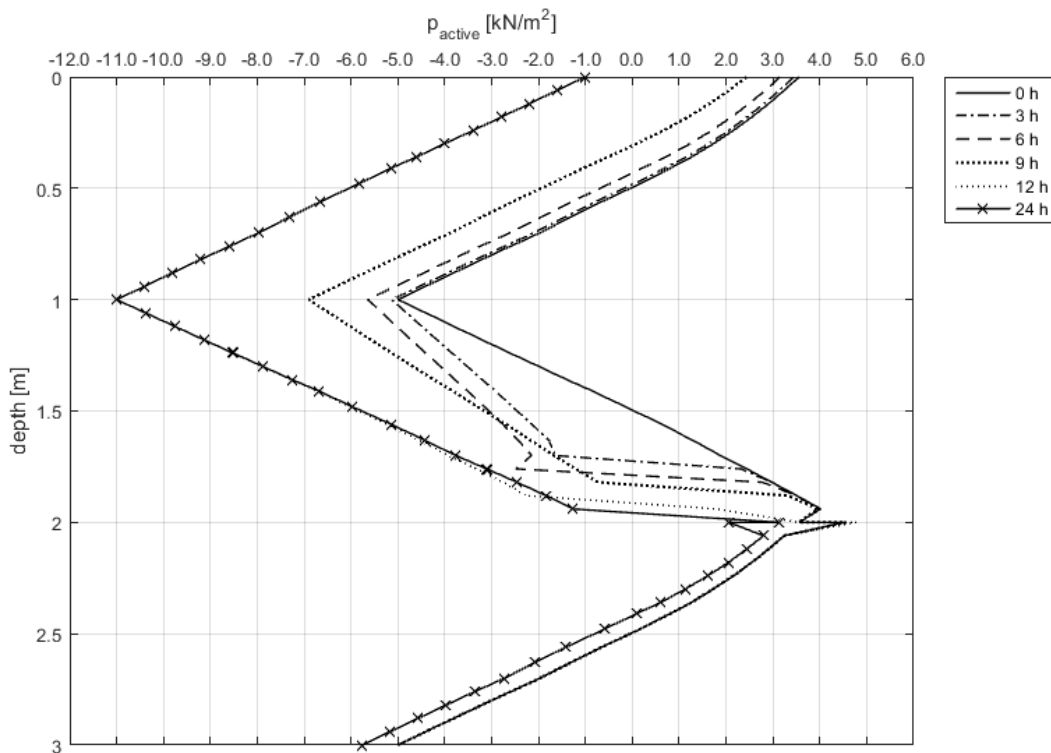


Figure 36: Result precipitation: Section suction – *UserWaterLevel*

As mentioned in the previous section, suction will be enabled and can be observed in Figure 36. The curves are plotted for every third hour starting from initial state 0 h and show the influence of the soil water characteristic curve within 0.0 m to 0.5 m and 2.0 m to 2.5 m, thus always above the phreatic level. In the coarse material the curves in the suction region, i.e. 0.0 m to 0.5 m and 2.0 m to 2.5 m incline distinctively. Within the fine

material, at 1.0 m to 2.0 m, the effect of the SWCC is hardly noticeable, because of the saturation of the pertained soil layer. At level 2.0 m, a numerical issue occur, because of the linking of nodal values from adjacent nodes.

5.1.4 Summary and concluding remarks

As mentioned before the model with the *GWFlowBaseBC* shows unexpected result. On one side the associated adjustment need to be considered for complete flow analysis thus the correct pore pressures are calculated. Then again the *GWFlowBaseBC HEAD* can be used to specify a constant water head within the geotechnical model, e.g. water level in fully coupled analysis according to the deep excavation in chapter 5.3.3. In consequence of computing many model configurations with respect to a recharge was observed that the difference between two different soil permeabilities should not exceed 10^{-3} . In the Plaxis 2D manual, for instance, was stated the value 10^{-5} , which can be obtained if groundwater flow is not computed (Appendix).

5.2 Bearing capacity

A simple geotechnical problem was chosen for demonstrating the consequences of different assumptions with respect to the drainage conditions. By using the appropriate drainage types in Plaxis 2D, the computation of excess pore pressures regarding to the corresponding calculation type entail different results. Furthermore the application of numerical methods for unsaturated soils influences the results significantly.

5.2.1 Aim of geotechnical model

A shallow foundation on a uniform soil layer was used to compute the available drainage types. Hereof, the soil water characteristic curve with respect to unsaturated soil behaviour was utilized as well. All calculations have been computed with the calculation type *Plastic* in consideration the material was set to *Undrained (A)*. Occasionally the suction was enabled. The bearing capacity involving undrained and unsaturated soil behaviour was determined.

5.2.2 Model configuration and material parameters

The concrete foundation slab lays on a 5.0 m thick soil strata (Figure 37). The foundation is 3.0 m x 3.0 m and has a thickness of 0.5 m. A plane-strain model with 15 – noded elements is utilized. A phreatic level exist at 2.0 m below the surface, hence a partial saturation is present. The applied load is depending on the bearing capacity of the underground.

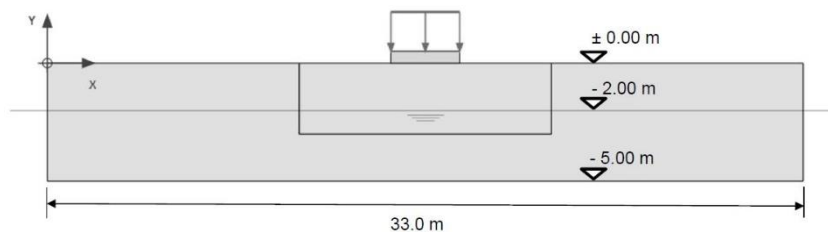


Figure 37: Bearing capacity: Model dimension

The strength parameters for concrete slab are equal to Eurocode 2 concrete strength class C25/30 and a linear elastic material model is adopted. For the soil material the linear elastic - perfectly plastic constitutive model *Mohr-Coulomb* (MC) is defined. The drainage type is specified with *Undrained (A)*. The dilatancy angle ψ is set to zero. The soil consists of coarse sand and heavy clay respectively. According to Staring's soil classification the sand is called O5 and the clay is specified as O12. Furthermore, within the soil classification, the fitting parameter for van Genuchten's approximation (vGA) of the SWCC are defined as well.

The strength and stiffness parameters are:

Material:					
Concrete	LE	$E = 31 \cdot 10^6 \text{ kN/m}^2$	$\nu = 0.2$		
O5	MC	$E' = 50000 \text{ kN/m}^2$	$\nu' = 0.3$	$c' = 0.0 \text{ kN/m}^3$	$\varphi' = 30.0^\circ$
O12	MC	$E' = 5000 \text{ kN/m}^2$	$\nu' = 0.3$	$c' = 1.0 \text{ kN/m}^3$	$\varphi' = 30.0^\circ$

Table 9: Bearing capacity: Soil parameters

The properties for unsaturated soils are:

Soil:						
O5	vGA	$k = 0.0102 \text{ m/d}$	$\theta_r = 0.01$	$\theta_s = 0.320$	$g_a = 5.210$	$g_n = 2.374$
O12	vGA	$k = 0.2497 \text{ m/d}$	$\theta_r = 0.01$	$\theta_s = 0.560$	$g_a = 0.950$	$g_n = 1.158$

Table 10: Bearing capacity: SWCC parameters

Unsaturated soils can be modelled with a soil water characteristic curve and Bishop's effective stresses, wherein suction is a stress component of pore water pressure.

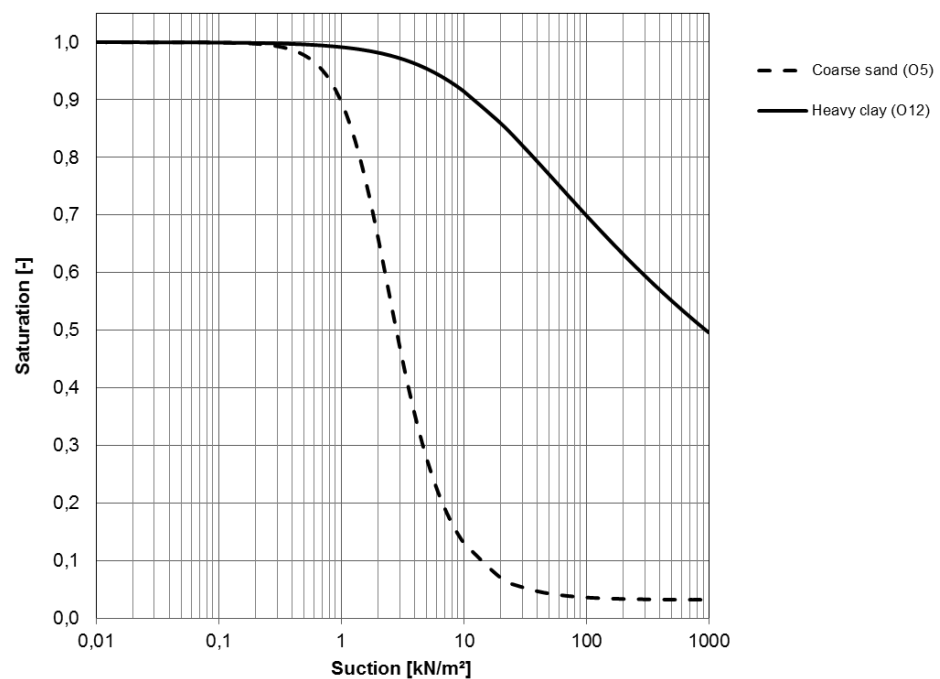


Figure 38: Bearing capacity: SWCC O5 and O12

In the *Mesh* mode, the shallow foundation and the surrounding zone with 11.0 m x 3.0 m is refined by a coarseness factor of 0.35 and the *Mesh option Fine* is used (Figure 39).

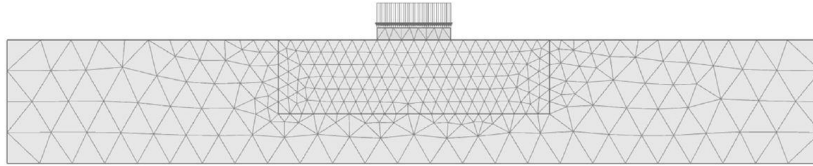


Figure 39: Bearing capacity: Connectivity plot

According to the drainage type *Undrained (A)*, the numerical analysis must be computed with the CT Plastic. The initial state is calculated by means of a parent phase with the CT *K0 Procedure*. The following child phases are plastic analysis, wherein the load will be applied. When dealing with suction in the numerical analysis, within the complete computation, the deformation control parameter *Ignore Suction* in the phase window should be disabled.

5.2.3 Output

In total this assessment includes 8 cases. The differences between the cases are the soil materials O5 and O12, drainage types *Drained* and *Undrained (A)* and the computation with or without suction in the unsaturated zone. In Table 11, the cases with the soil parameter O5 are shown. Accordingly, the specifications of the computation are presented. Here, the results of CASE 2 and 4 will be discussed. Furthermore, in both cases, the distinction between the states before loading and after loading are displayed.

	CASE 1	CASE2	CASE3	CASE 4
CASES	PL_NOS_D_O5	PL_NOS_UD_O5	PL_YESS_D_O5	PL_YESS_UD_O5
CALCULATION TYPE	Plastic	Plastic	Plastic	Plastic
SUCTION	NO	NO	YES	YES
DRAINAGE TYPE	Drained	Undrained [A]	Drained	Undrained [A]
SOIL MATERIAL	O5	O5	O5	O5

Table 11: Bearing capacity: Calculation cases

The pore pressure in a plastic analysis is composed of the steady-state pore pressure p_{steady} , the excess pore pressure p_{excess} , the pore water pressure p_{water} and the active pore pressure p_{active} . The relation between each component is following. The pore pressure p_{steady} is a direct generation of water pressure with respect to the existing hydraulic conditions, i.e. in this particular case the hydrostatic state is computed. The pore pressure p_{excess} , is a result of the undrained analysis in context of the material set *Undrained (A)* and CT *Plastic*. These two components reckon the pore pressure p_{water} . Furthermore, the pore pressure p_{active} is composed of p_{water} and the effective degree of saturation S_{eff} . The Figure 40 shows the simple composition of the active pore pressure.

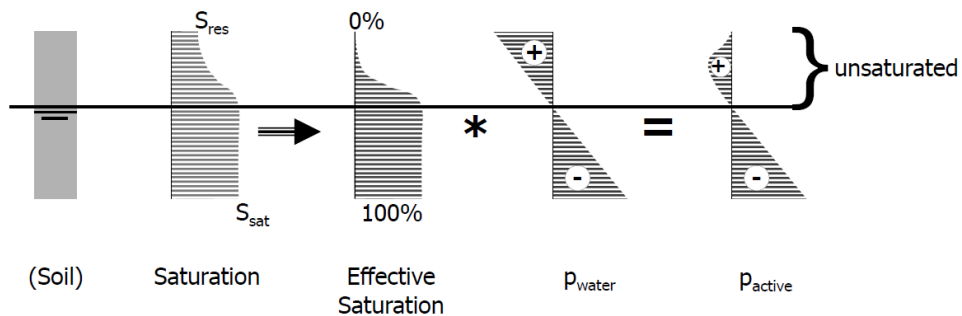


Figure 40: Bearing capacity: Composition of pore pressure (CPP)

The effective saturation is determined according to the equation [3] in chapter 3.2.

In case of the material set *Undrained (A)*, the saturation is uniform equal 100 % above the phreatic level. The degree of saturation can be redefined by means of the specified hydraulic model, if suction is enabled in the numerical analysis. In the following figures the composition of pore pressures with respect to undrained soil behaviour before loading are shown.

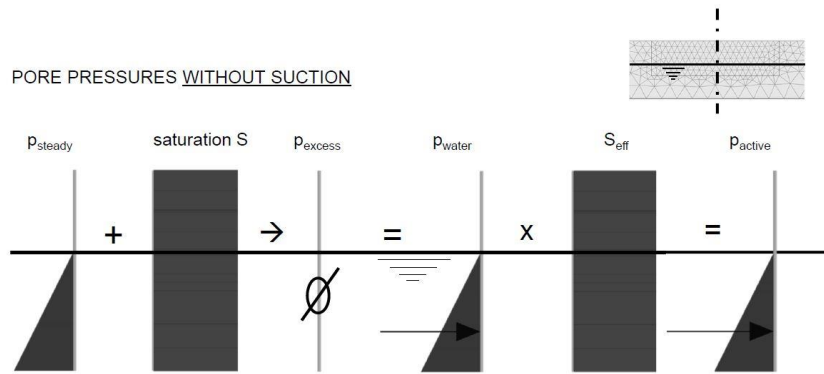


Figure 41: Results bearing capacity: CPP CASE 2 – before loading

In Figure 41, the associated pore pressures of CASE 2 without suction above the phreatic level are displayed. No excess pore pressure are computed, because no load is applied. The effective degree of saturation is equal to 100 %. Thus the steady-state pore pressure is equal to pore water pressure and likewise equal to the active pore pressure.

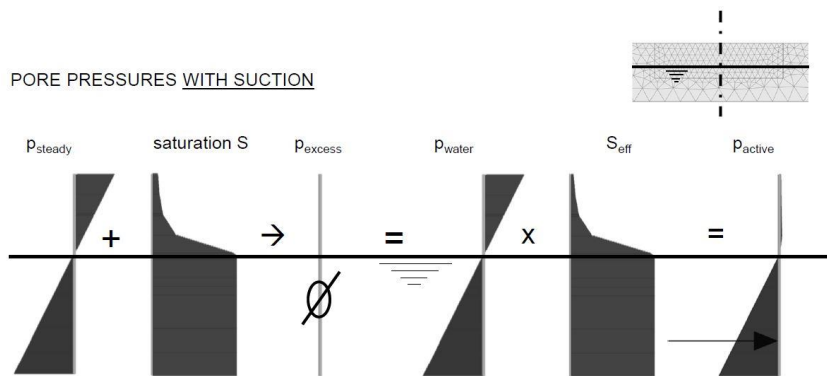


Figure 42: Results bearing capacity: CPP CASE 4 – before loading

Figure 42 shows the same pore pressure composition like in the figure above. The difference now is, the suction above the water level is computed (CASE 4). Hence, the saturation decrease with respect to the suction of the steady-state pore pressure and the SWCC of the soil material O5. Furthermore the effective degree of saturation is reduced as well. Thus the active pore pressure above the phreatic level is computed lower. The excess pore pressures are zero because no load is applied. Interestingly the saturation

is computed minor 100 % at the top although the numerical code for undrained material states 100 % saturation.

In the next figures the CASE 2 and 4 after loading are displayed. Thus the excess pore pressures occur due to undrained material behaviour and rapid loading. Consequently the pore water pressures are no longer equal to the steady state pore pressures.

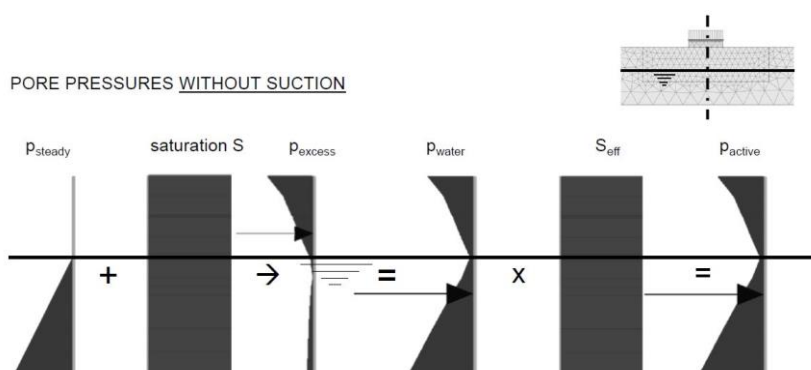


Figure 43: Results bearing capacity: CPP CASE 2 – after loading

In Figure 43, the composition of pore pressures without suction is shown (CASE 2). It can be observed that excess pore pressures are mainly computed above the phreatic level. The quantitative results for the CASE 2 are shown in Table 12.

CASE 2 - Failure load: 12.80 kN/m ²				
	TOP 0.00 m	PHREATIC LEVEL -2.00 m	BOTTOM -5.00 m	Unit [-]
p_{steady}	0.00	0.00	-30.00	[kN/m ²]
p_{excess}	-23.76	-2.42	-3.62	[kN/m ²]
p_{water}	-23.76	-2.42	-33.62	[kN/m ²]
S_{eff}	100.00	100.00	100.00	[%]
p_{active}	-23.76	-2.42	-33.62	[kN/m ²]

Table 12: Results bearing capacity: CPP CASE 2 – pore pressures

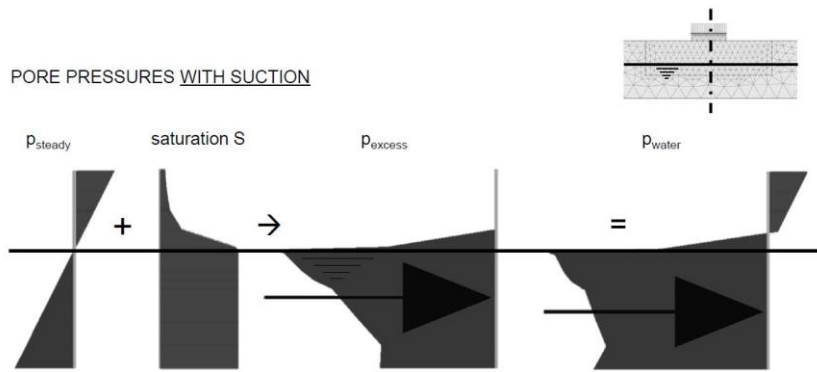


Figure 44: Results bearing capacity: CPP CASE 4 – after loading; Part 1

Figure 44 and Figure 45 display the results with suction. The saturation decrease with respect to the suction of the steady-state pore pressure and the SWCC of the soil material O5. In consequence, the excess pore pressure decrease from the top to the phreatic level.

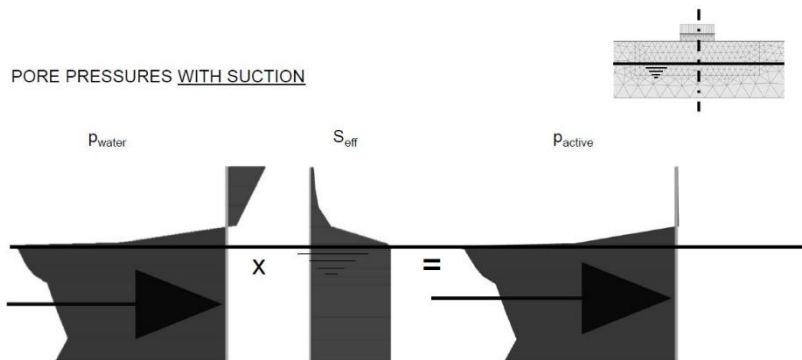


Figure 45: Results bearing capacity: CPP CASE 4 – after loading; Part 2

In Figure 44, the sequel of the results above is shown. In Table 13, the quantitative result of CASE 4 are shown.

CASE 4 - Failure load: 127.90 kN/m²				
	TOP 0.00 m	PHREATIC LEVEL -2.00 m	BOTTOM -5.00 m	Unit [-]
p_{steady}	20.00	0.00	-30.00	[kN/m ²]
p_{excess}	0.00	-125.96	-58.36	[kN/m ²]
p_{water}	20.00	-125.96	-88.36	[kN/m ²]
S_{eff}	3.96	100.00	100.00	[%]
p_{active}	0.79	-125.96	-88.36	[kN/m ²]

Table 13: Results bearing capacity: CPP CASE 4 – pore pressures

5.2.4 Summary and concluding remarks

In this assessment the primary focus was on the pore water pressure composition and its calculation. The assessed model concluded undrained and unsaturated soil behaviour. The steady state pore pressure p_{steady} is directly generated from the specified phreatic level. The excess pore pressures p_{excess} is a result of an undrained analysis. The sum of them both are denoted as pore water pressure p_{water} . Furthermore the active pore pressure p_{active} is composed of p_{water} and the effective saturation S_{eff} , which has a significant influence on the pore water pressure distribution. Hereof, the bulk modulus of water correlates with the effective degree of saturation. Plaxis 2D provides two options to define unsaturated material properties. One specification can be defined in the material data at the tabsheet *Parameter* in the subtree *Advanced undrained behaviour*. This calculation option directly specifies the bulk modulus as input parameter. The second option to modify the bulk modulus is the computation by means of the soil water characteristic curve and tensile pore pressure in the geotechnical model. Exact this procedure is taken into account at the present assessment. Depending on the calculation type the bulk modulus is specified in the stiffness matrix (Table 5). The following table shows the associated failure load with respect to the different configurations in accordance of drainage type and tensile pore pressure (suction).

Cases	Soil material	Drainage type	Suction	Bearing capacity
[-]	[-]	[-]	[-]	[kN/m ²]
CASE 1	O5	Drained	NO	128.90
CASE 2	O5	Undrained (A)	NO	12.80
CASE 3	O5	Drained	YES	292.30
CASE 4	O5	Undrained (A)	YES	127.90
CASE 5	O12	Drained	NO	277.00
CASE 6	O12	Undrained (A)	NO	21.70
CASE 7	O12	Drained	YES	544.20
CASE 8	O12	Undrained (A)	YES	143.10

Table 14: Results bearing capacity: Failure loads

5.3 Deep excavation

The geotechnical model is based on an already built structure in Vienna, the so-called underground parking Rudolfinerhaus. The geometry and strength parameter are given, but particularly the geometry have been modified. The missing stiffness parameters were adopted.

5.3.1 Aim of geotechnical model

The emphasis of this analyses were investigating the state conditioning the ultimate limit with respect to the time-dependent dissipation of excess pore pressure in undrained soils. Tensile excess pore pressures develop due to unloading and have a positive influence with respect to strength. Therefore the appropriate computation of pore pressures are important, particularly the specification of the hydraulic conditions regarding to the associated groundwater flow model. Hereof, an undrained analysis with the material data set *Undrained (A)* and the corresponding calculation type was conducted. Furthermore, a fully coupled flow-deformation with the associated hydraulic boundary conditions was computed in order to double-check the aforementioned analysis.

5.3.2 Model configuration and material parameters

The excavation pit is 24.0 m wide and 13.0 m deep. Due to the symmetric geometry only half of the excavation is modelled (Figure 46). The model has a dimension of 65.0 m in width and 48.0 m in depth. A plane-strain model with 15 noded-elements is utilized.

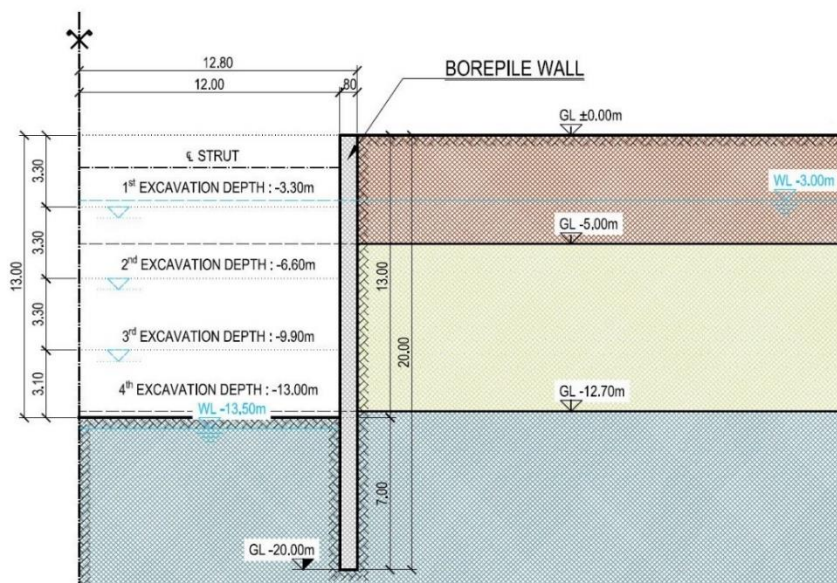


Figure 46: Deep excavation: Model

The soil stratigraphy consist of three horizontal layers. The top layer is called Fill and is 5.0 m thick. The middle soil layer is specified as Sand and is located between GL -5.0 m and GL -12.70 m. The last layer consist of Wiener Tegel, starts at GL -12.70 m and reaches the bottom model boundary at GL -48.0 m. Further at GL -3.0 m exist a phreatic level. All materials are assumed as undrained and specified with the constitutive model Hardening soil-small strain stiffness (HSS). The brace system is a bore pile wall with diameters of 0.80 m and embedded 7.0 m deep in the Wiener Tegel, thus the total length is 20.0 m. The bore pile wall is modelled by means of continuous elements. A strut at the level GL -1.50 is installed in order to minimize the top deflection. The whole brace system is specified as linear elastic. The material parameter are summarized in the following tables.

Identification		TEGEL	SAND	FILL	CONCRETE
Identification number		1	2	3	4
Material model		HS small	HS small	HS Small	Linear-elastic
Drainage type		Undrained (A)	Undrained (A)	Undrained (A)	Non-porous
Colour		RGB 120, 160, 170	RGB 230, 230, 160	RGB 170, 90, 50	RGB 200, 200, 200
γ_{unsat}	kN/m ³	21	21	20	24
γ_{sat}	kN/m ³	21	21	20	24
Dilatancy cut-off		No	No	No	No
e_{init}		0,78	0,5	0,5	0,5
e_{min}		0	0	0	0
e_{max}		999	999	999	999
Rayleigh α		0	0	0	0
Rayleigh β		0	0	0	0
E	kN/m ²	-	-	-	30000000,00
ν (nu)		-	-	-	0,20
G	kN/m ²	-	-	-	12950000,00
E_{oed}	kN/m ²	-	-	-	33330000,00
E_{50}^{ref}	kN/m ²	24000,00	50000,00	42000,00	-
E_{oed}^{ref}	kN/m ²	12500,00	50000,00	42000,00	-
E_{ur}^{ref}	kN/m ²	56000,00	150000,00	126000,00	-
power (m)		0,9	0,5	0,5	-
Use alternatives		No	No	No	-
C_c		0,0819	0,0069	0,0082	-
C_s		0,0165	0,0021	0,0025	-
e_{init}		0,78	0,5	0,5	-
c_{ref}	kN/m ²	25	0	0	-
ϕ (phi)	°	23	30	28	-
ψ (psi)	°	0	5	1	-
V_s	m/s	-	-	-	5537
V_p	m/s	-	-	-	9042
$\gamma_{0.7}$		0,0010	0,0010	0,0010	-
G_0^{ref}	kN/m ²	75000,00	120000,00	158000,00	-
Set to default values		No	Yes	Yes	Yes
ν_{ur}		0,2	0,2	0,2	-
p_{ref}	kN/m ²	250	100	100	-
K_0^{nc}		0,6093	0,5	0,5305	-
E_{inc}	kN/m ² /m	-	-	-	0
c_{inc}	kN/m ² /m	0	0	0	-
γ_{ref}	m	0	0	0	0
R_f		0,9	0,9	0,9	-
Tension cut-off		Yes	Yes	Yes	-
Tensile strength	kN/m ²	0	0	0	-
Undrained behaviour		Standard	Standard	Standard	-
Skempton-B		0,9866	0,9866	0,9866	-
ν_u		0,495	0,495	0,495	-
$K_w,ref/n$	kN/m ²	2294000,00	6146000,00	5162000,00	-
Failure criterion		Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	-
Strength		Manual	Manual	Manual	Manual
R_{inter}		0,7	0,7	0,7	0,7
Consider gap closure		Yes	Yes	Yes	Yes
δ_{inter}		0	0	0	0
R	m ² K/kW	0	0	0	0
K_0 determination		Automatic	Automatic	Automatic	Automatic
$K_{0,x} = K_{0,z}$		Yes	Yes	Yes	Yes
$K_{0,x}$		0,6093	0,5	0,5305	1
$K_{0,z}$		0,6093	0,5	0,5305	1
OCR		1	1	1	0
POP	kN/m ²	50	0	0	0
Data set		Hypres	Hypres	Hypres	-
Model		Van Genuchten	Van Genuchten	Van Genuchten	-
Subsoil/Topsoil		Subsoil	Subsoil	Subsoil	-
Type		Very fine	Medium	Coarse	-
< 2 μ m	%	74	19	10	-
2 μ m - 50 μ m	%	11	41	13	-
50 μ m - 2 mm	%	15	40	77	-
Set to default values		No	No	No	-
k_x	m/day	0,00	8,64	8,64	-
k_y	m/day	0,00	8,64	8,64	-
$-\psi_{unsat}$	m	10000,00	10000,00	10000,00	10000,00
e_{init}		0,78	0,50	0,50	0,50

Table 15: Deep excavation: Soil parameter

Identification		STRUT
Identification number		1
Comments		
Colour		RGB 0, 0, 0
Material type		Elastic
EA	kN	2000000,00
L_spacing	m	1

Table 16: Deep excavation: Strut parameter

The meshed model has three refined zones. The soil clusters of the brace system have a coarseness factor equal 0.05. Around the excavation a refinement zone with the dimension of 18.0 m to 31.0 m is modelled, which has coarseness factor equal 0.125. All other soil polygons are equal 0.5. In the *Mesh mode* the *Fine* option is selected.

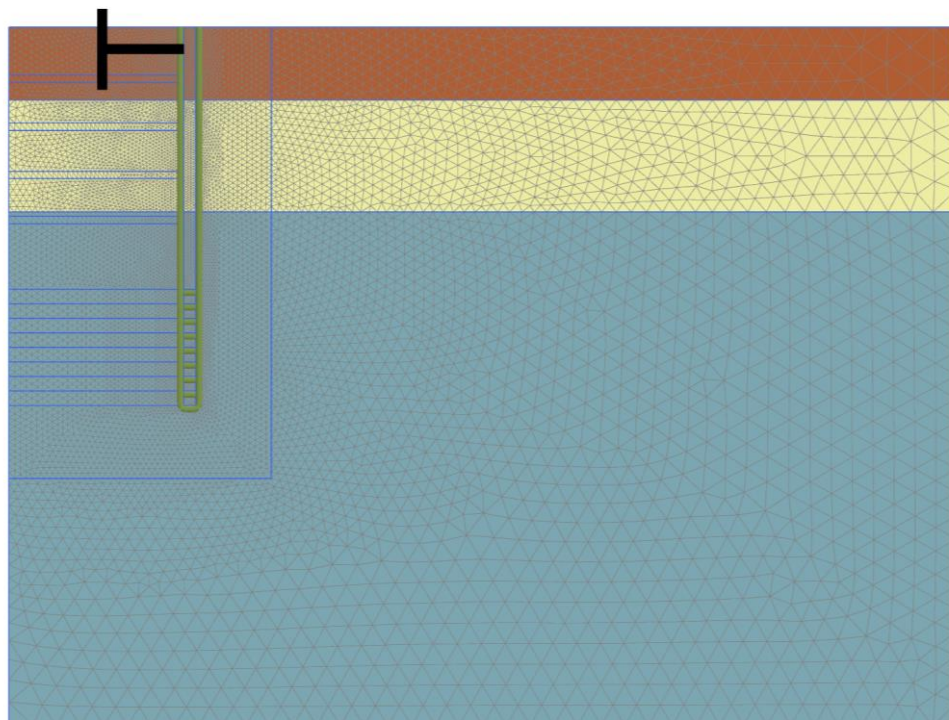


Figure 47: Deep excavation: Connectivity plot

The excavation work will be executed in four steps. Within the four steps the water level in the excavation zone is lowered always 0.5 m below the actual depth. Generally an undrained analysis will be computed by means of CT Plastic (Figure 48, green).

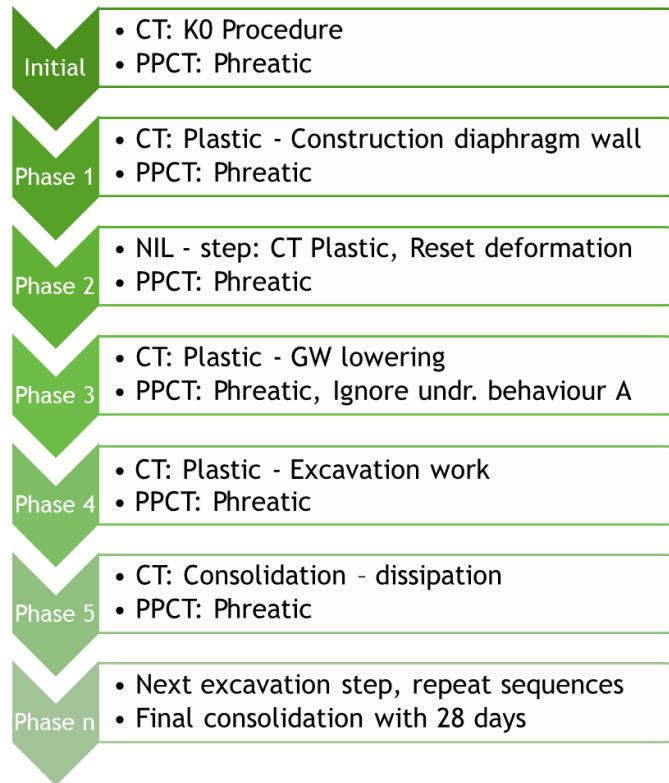


Figure 48: Deep excavation: Plastic – calculation phases

In order to double-check the results a fully coupled flow-deformation analysis with the same calculation procedure is conducted as well. The Table 17 shows an overview about the calculation types and the associated specifications.

ULS		
	CASE PL	CASE FCFD
Hydraulic conditions (HC)	2 water levels	1 inclined water level and GWFlowBase BC
	Symmetry boundary closed	Symmetry boundary closed
Phases	no time interval, interest of sequenced results	Concept of construction time with respect to soil behaviour
Calculation type (CT)	Plastic	FCFD
Undrained behaviour (UD)	Undrained [A]	Permeability, stiffness, time
Pore pressure calculation type (PPCT)	Phreatic	TGWF*

* Implicity transient flow calculation

Table 17: Deep excavation: Calculation types

The associated specifications are related to hydraulic conditions and to the pore pressure calculation type. The groundwater flow boundary at the centre line of axisymmetric model and the bottom boundary are closed by means of *XMin* and *YMin* in the *Model explorer*.

In the plastic analysis the PPCT Phreatic, which directly generates the pore water pressure in consequence of the specified phreatic levels, is chosen. Hence, there is no groundwater flow computed. In order to avoid a jump in the pore water distribution at the bottom of the brace system an interpolation of the soil polygon below the excavated depth is introduced. This adjustment is not required for the FCFD. For the implicit transient flow calculation, i.e. in the fully coupled flow-deformation analysis (Figure 49), the displayed definition of hydraulic boundary conditions is applied.

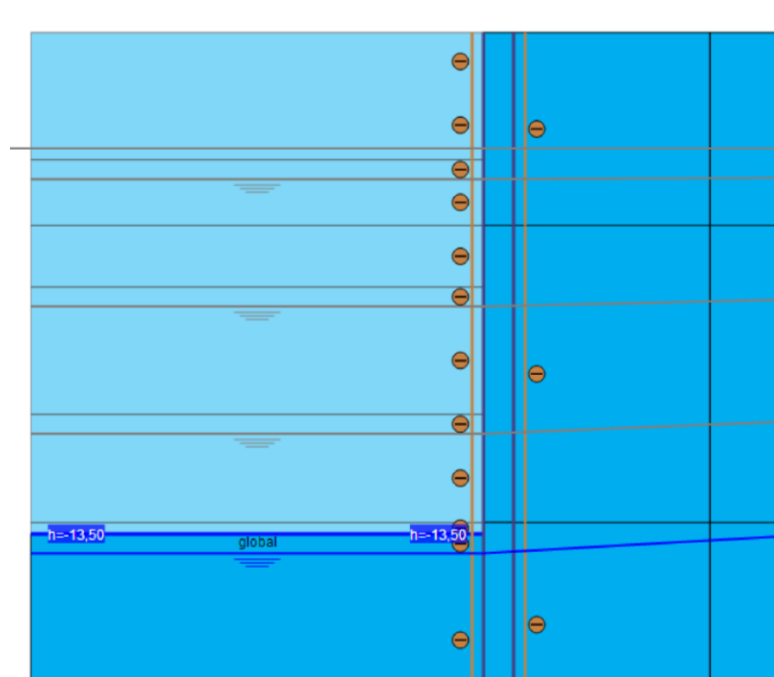


Figure 49: Deep excavation: Hydraulic boundary conditions for FCFD

In Figure 49, for instance, the specifics for the last excavation at GL -13.0 m are shown. The water level is modelled as polygon with intersections to the active boundary at the left model boundary and the right model boundary. A *GWFlowBaseBC* is specified in order to obtain a constant water level at GL -13.0 m. The flow calculation will compute a phreatic level behind the brace system at GL -3.0 m and in the excavation zone the phreatic level is at GL -13.0. Hereof, the right model was enlarged from 65.0 m to 200.0 m in order to compute the seepage curve and the steady state water level after.

In contrast to the plastic analysis the fully coupled analysis requires the definition of a time for the consecutive time-depending analysis. A construction time schedule was carried out (Table 18).

Construction time			
Notation	Unit	Value	
width	[m]		24,0
depth	[m]		13,0
length	[m]		50,0
excavation steps	[no.]		4,0
excavation depth	[m]	3,1	3,3
ratio volume per hour	[m ³ /h]		70,0
work time	[h/d]		8,0
excavation volume	[m ³]		15600,0
daily excavation volume	[m ³ /d]		560,0
excavation time	[d]		28,0
excavation sequence time	[d]		7,0

Table 18: Deep excavation: Construction time schedule

According to the time schedule the groundwater lowering takes 1/24 of daytime in consideration to compute steady state pore pressures with respect to hydraulic boundary conditions (Figure 49). The excavation time for 3.1 m to 3.3 m deep layer is specified with 7/50 d by means of the ratio excavation sequence time and an assumed length. Afterwards a consolidation with 7 days is conducted.

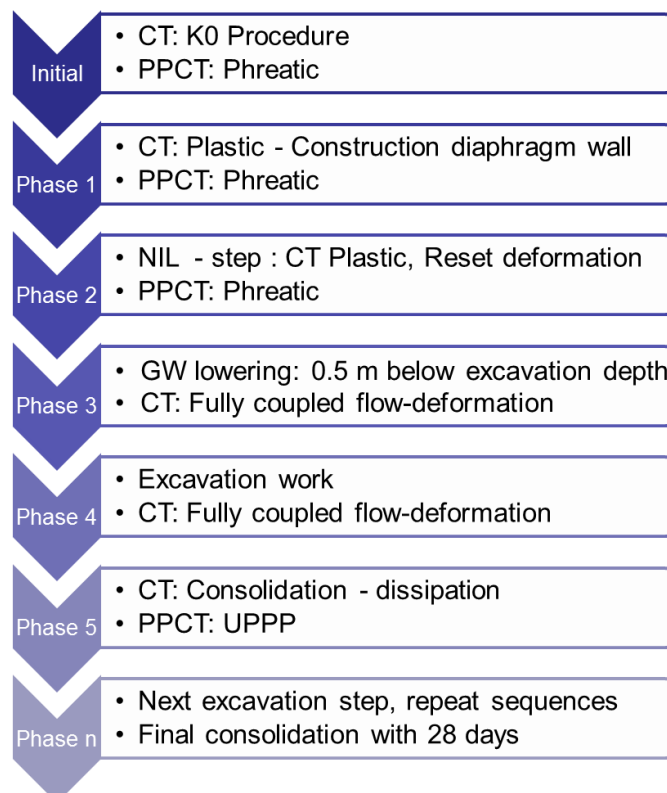


Figure 50: Deep excavation: FCFD – calculation phases

After all specifications for hydraulic conditions, pore pressure calculation and soil behaviour are defined, the results of this two different calculation are presented in the next chapter. Further informations about the excavation sequence can be found in the Appendix.

5.3.3 Output

First computations showed that the ultimate limit state for the current brace system was not given, hence the embedded depth was enlarged with 6.0 m. Thus the total length of the bore pile is equal to 26.0 m instead of 20.0 m in the initial model (Figure 51).

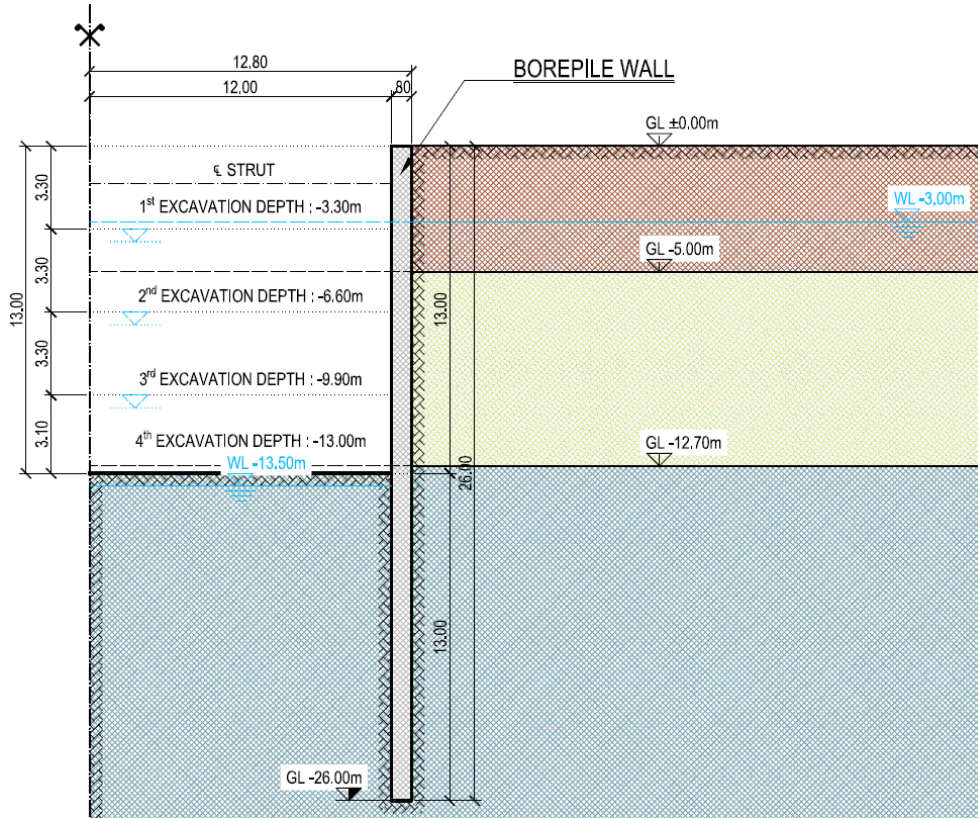


Figure 51: Deep excavation: Bore pile wall 26.0 m

Two cases of calculations with same geometry were carried out. The CASE 5 was a plastic analysis and CASE 7 was a fully coupled analysis (Table 19).

Ultimate Limit State analysis (ULS)						
	ΣM_{Stage}	Failure	Consolidation (28d)	Max. bending moments (28d)	Max. shear force (28d)	Max. displacements (28d)
	[-]	[-]	[kN/m ²]	[kNm/m]	[kN/m]	[m]
CASE 5	0.9998	NO 4th Excavation does not reach M_{Stage}	27.45	1977.4	612.50	0.037
CASE 7	1.0000	NO	17.63	1977.00	605.50	0.045

Table 19: Deep excavation: Calculations

In the table the results of the final consolidation after the last excavation are mentioned. The final consolidation was computed for 28 days with respect to the finished work of a future concrete slab.

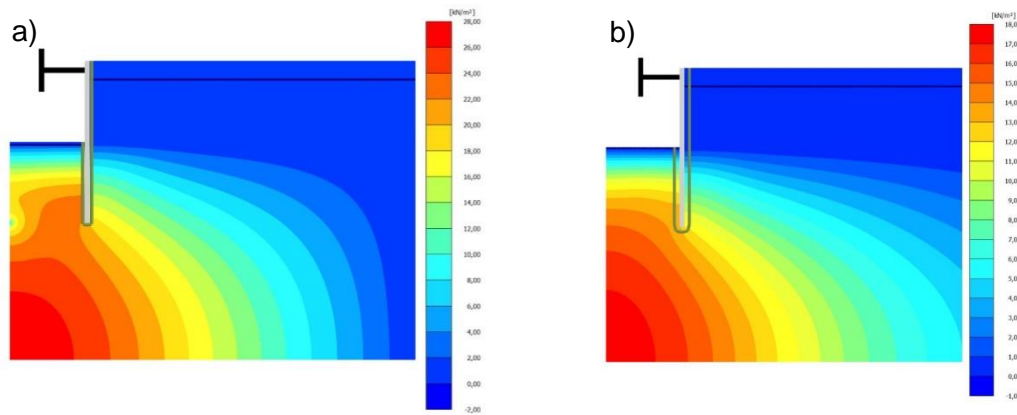


Figure 52: Results deep excavation: Excess pore pressure comparison

In Figure 52 the excess pore pressure for CASE 5 (a) and for CASE 7 (b) are displayed. The maximum value in figure (a) is 27.45 kN/m² in contrast to CASE 5 the maximum value is equal to 17.63 kN/m² for CASE 7. In consideration that the excess pore pressure show similar results, the pore water pressure should display similar results too, because p_{water} in the CT Consolidation is composed of p_{excess} and p_{steady} .

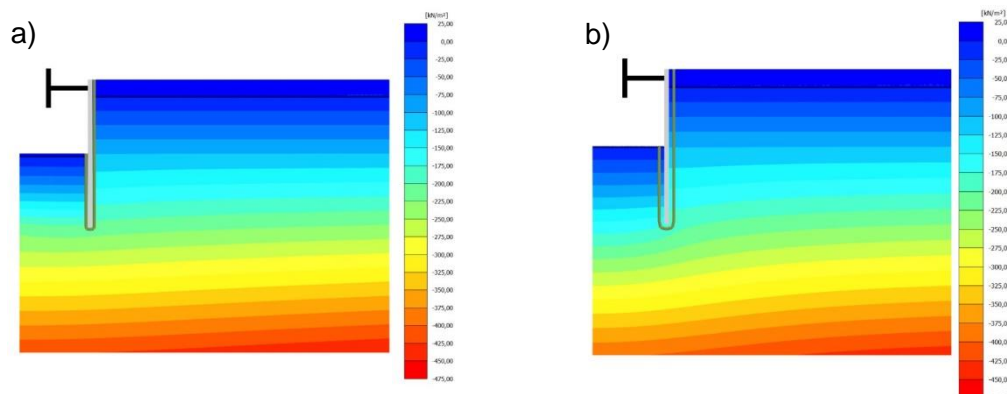


Figure 53: Results deep excavation: Pore water pressure comparison

In Figure 53 the pore water pressures of the plastic analysis (a) and of a fully coupled (b) analysis are displayed. Hereof, the next Figure 54 present a section at the centre of the excavation pit, i.e. at 6.0m in x-direction.

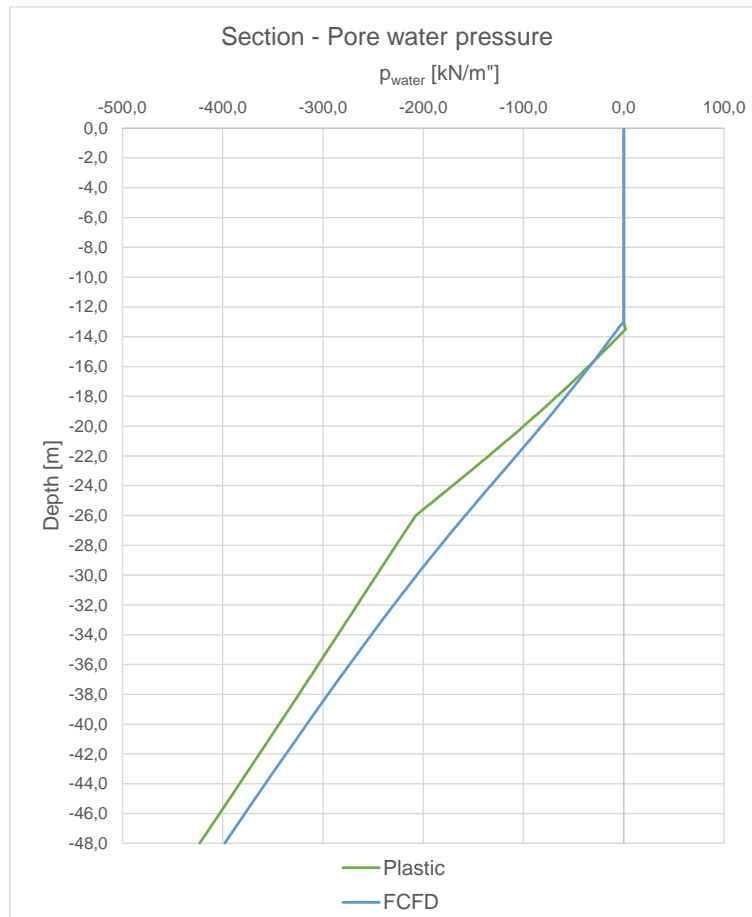


Figure 54: Results deep excavation: Section – Pore water pressure

Figure 54 shows the pore water distribution in the centre of the excavation pit with respect of steady-state pore pressure (Plastic) and a transient pore pressure (FCFD). Note that the pore water pressure in a FCFD analysis is the total pore pressure encompassing p_{excess} and p_{steady} . Significantly the kink of the curve Plastic at the last interpolation of adjacent pore pressures, at GL -26.0 m, is displayed. Hereof, the highest difference is equal to approx. 49.0 kPa.

In the next figures, the comparison between CASE 5 and CASE 7 with respect to displacements, structural forces and wall deflection are displayed. All results are computed by means of a section in Plaxis 2D.

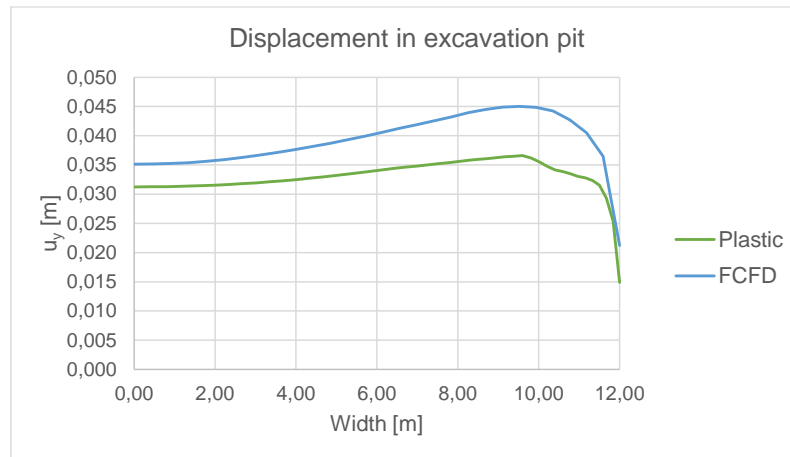


Figure 55: Results deep excavation: Section – Displacements in excavation pit

In Figure 55 the vertical displacement u_y along the excavation depth at GL -13.0 m after 28 days consolidation is shown. The displacements have the same qualitative shape but have maximum difference is equal to 8.4 mm though.

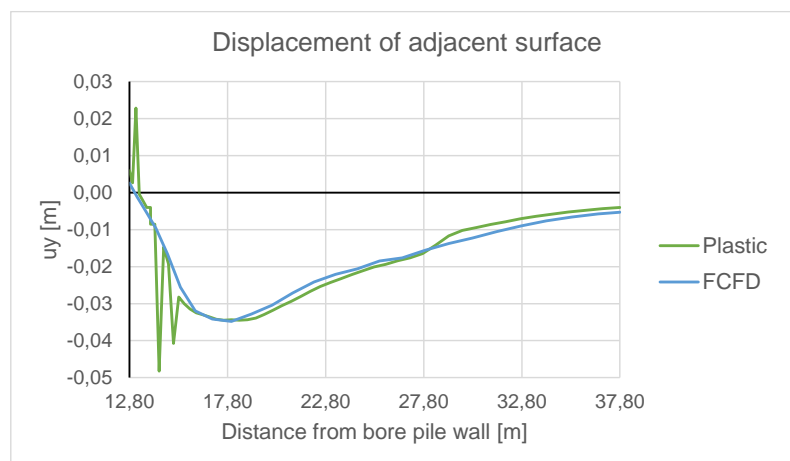


Figure 56: Results deep excavation: Section – Displacements of adjacent surface

In Figure 56 the vertical displacement u_y of the surface from the backside of the brace system till 25.0 m afterwards is displayed. In CASE 5 at the beginning are few aberrations, which can only be caused by the interpolation of nodal values. Generally both curves coincide and show a displacement equal to 3.48 cm at the distance approx. 5.0 m away from the brace system.

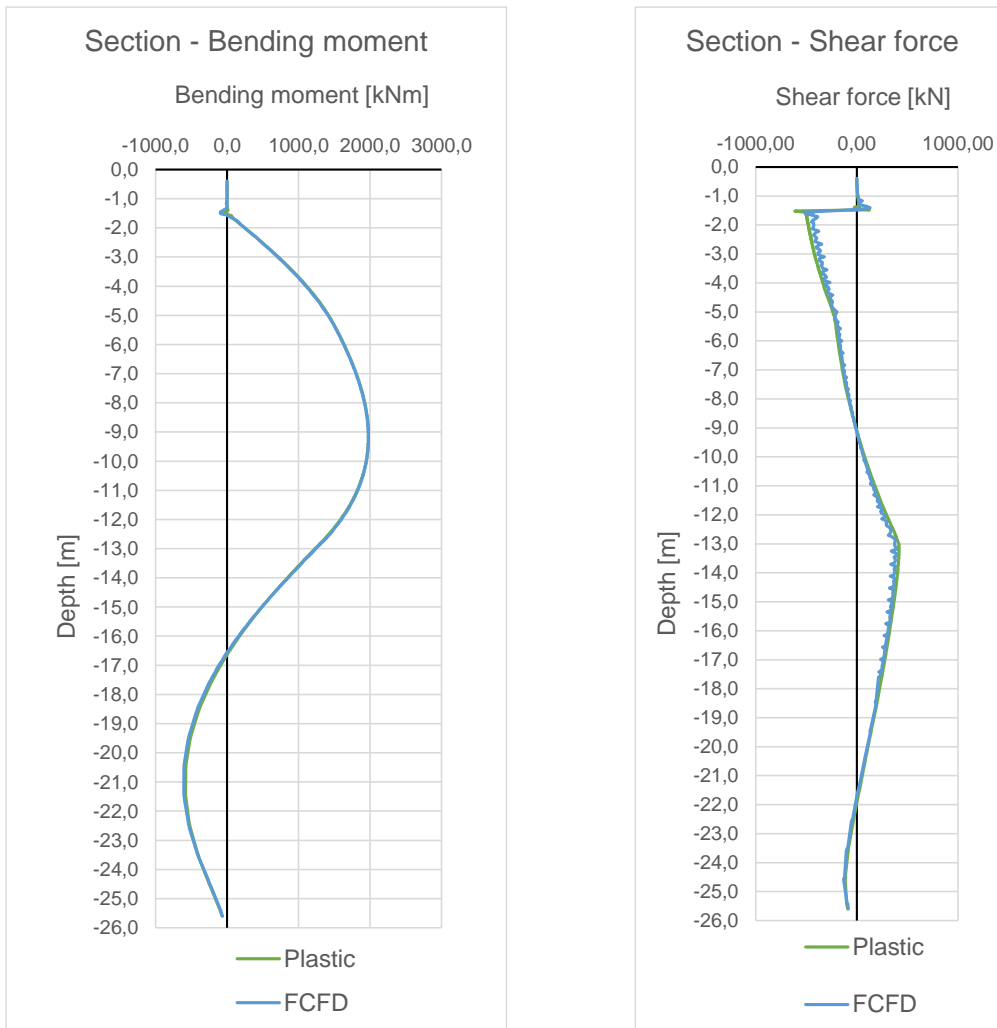


Figure 57: Results deep excavation: Section – Structural force

The figures above show the structural forces bending moment and shear force, which are computed by means of a section along the centre line of the bore pile wall. In both cases, the forces coincide perfectly. The maximum bending moment is equal to approx. 1977.00 kNm. The quantitative results of the shear forces are slightly different. The maximum value of CASE 5 is equal to 612.50 kN and in CASE 7 the shear force is 605.50 kN. A reason could be the output by means of a section, because it takes into account the adjacent nodal values and stress points.

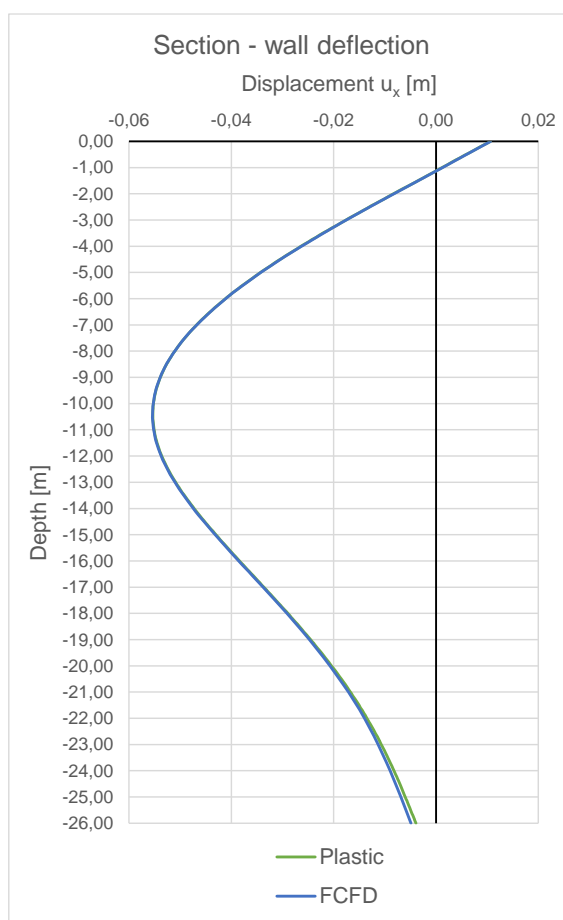


Figure 58: Results deep excavation: Section – Wall deflection

In Figure 58 the horizontal displacements of the bore pile wall are displayed. The results are computed by means of a section in the centre line. The maximum deflection is 5.50 cm, which is located at the depth of approx. 10.50 m below the surface.

Note that the present total length of the pore pile wall is equal to 26.0 m, thus the embedded length in the soil layer Tegel is equal to 13.0 m. In consequence of the influence of tensile pore pressures with respect to the strength, the strength of the associated soil layer decreases due to the dissipation of pore pressures to a minimum. Hereof, a final consolidation with a minimum excess pore pressure equal to 1.0 kPa instead of 28 days is computed. While performing this calculation, the state conditioning the ultimate limit may be reached with respect to the embedded length. Consequently, the embedded length could be modified. Accordingly these final calculations have been performed and show following results.

	Calculation type	Embedded length [m]	Failure	Reached total time [day]
CASE 5	Plastic	13.0 m	NO	189
CASE 12	Plastic	12.0 m	NO	241
CASE 13	Plastic	11.0 m	YES	0

Table 20: Deep excavation: Calculation cases

Table 20 shows the computed plastic analyses with respect to different embedded lengths. The embedded length was reduced by 1.0 m from the initial state of 13.0 m length. In CASE 12, the embedded length is the minimum length, because in CASE 13 the brace system fails and the surrounding soil collapses in phases before the final consolidation can be computed. Furthermore the reached time of dissipating excess pore pressure to the minimum equal to 1.0 kPa are displayed. The results concluding wall deflections, bending moments and factor of safety with respect to the fulfilled analyses conditioning limit state are shown in the following figures.

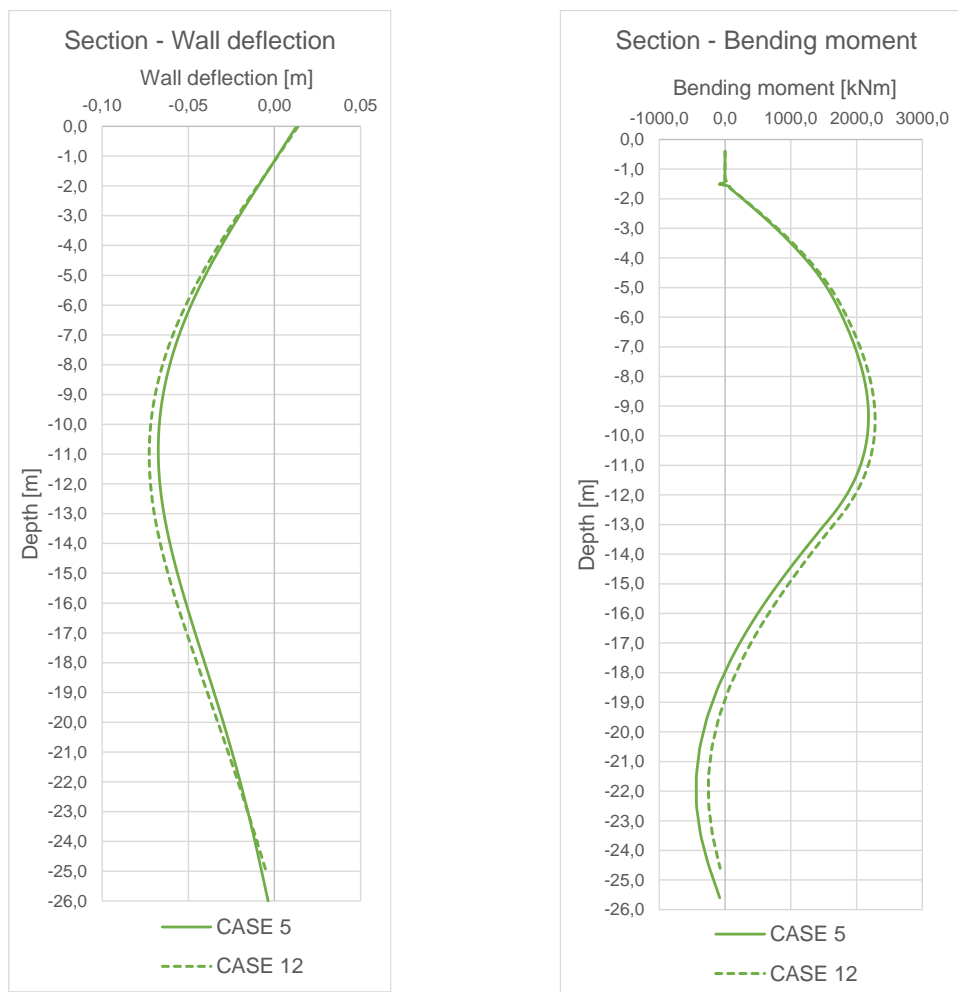


Figure 59: Results deep excavation: Sections – Embedded length

In Figure 59, the wall deflection and bending moments with respect to the CASE 5 and CASE 12 are displayed. The results are computed by means of a section in the centre line of the bore pile wall. The CASE 12 show slightly higher values in contrast to CASE 5, for instance, the maximum difference between the associated wall deflections is 5.0 mm. The difference between the bending moments is 102.40 kNm.

The next figures show the computations of global safety regarding to CASE 5 and CASE 12. The factor of safety (FOS) have been computed by means of a safety analysis, wherein the undrained behaviour was ignored in order to calculate a constant FOS.

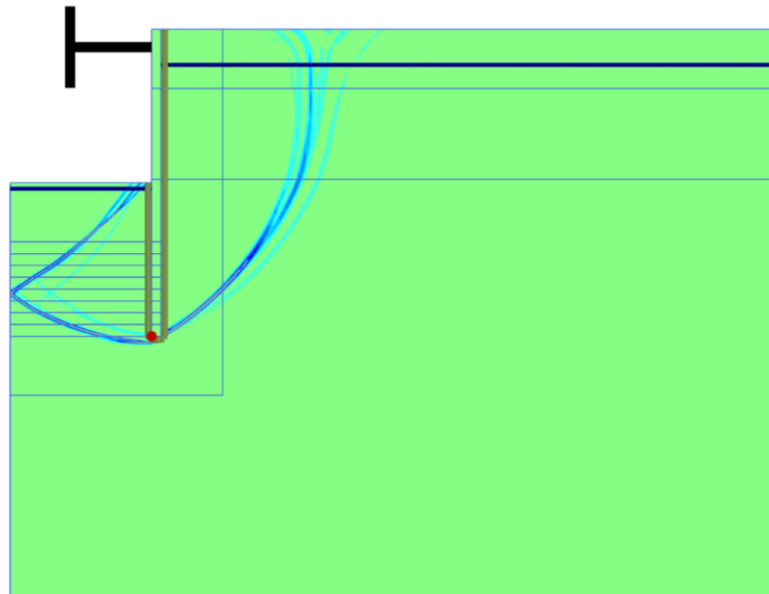


Figure 60: Results deep excavation: Incremental deviatoric strains – CASE 5

Figure 60 displays the incremental deviatoric strains with respect to CASE 5. Furthermore the associated point for the FOS analyses is depicted (red point).

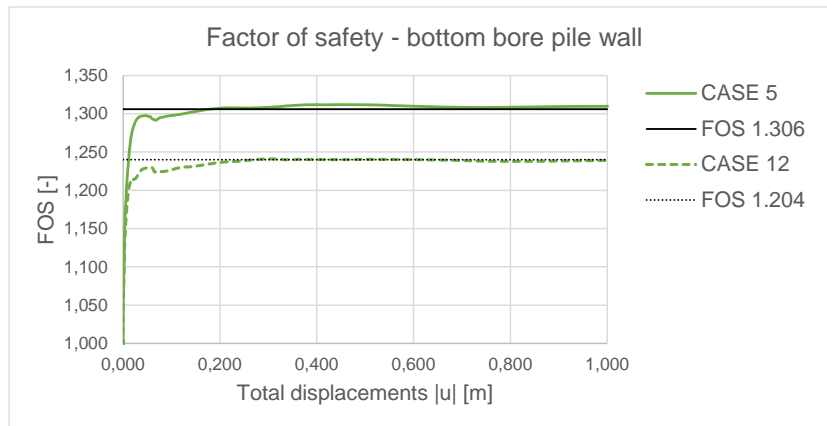


Figure 61: Results deep excavation: FOS – CASE 5 and CASE 12

Figure 61 shows the different FOS with respect to CASE 5 and CASE 12 at the bottom of the bore pile wall. For CASE 5 the FOS is equal to 1.306 and for CASE 7 the FOS is equal to 1.240.

5.3.4 Summary and concluding remarks

Generally can be mentioned both cases coincide exactly although different calculation types and different specifications of hydraulic boundary conditions are carried out. Hereof could be considered that the interpolation of pore pressures within the soil polygon from the excavated depth to the deepest point of the brace system coincide with the pore pressure of a groundwater flow calculation. Furthermore the brace system can be optimized in accordance of required time for construction work until the tensile pore pressures due to consolidation are dissipated.

6 Summary and conclusion

Generally the available hydraulic boundary condition in the borehole command, *Selection explorer*, the *Model explorer* and the material data tabsheet can be used to define the appropriate groundwater model in accordance with the geotechnical model. Thereby should be considered some specifications in context of the available hydraulic boundary conditions, which can cause shortcomings.

In the *Selection explorer*, the hydraulic model conditions, e.g. *GWFlowBaseBC* and *WaterConditions* are utilized, which can be enabled by selecting and specifying the hydraulic condition for the boundary value problem in the FEM analysis. For instance the *HBC Closed* or *Head* define the BVP condition by means of the specified value. This value is computed as a constant with possible numerical deviations due to a coarse mesh next to the associated boundary. Thus, when specifying a *GWFlowBaseBC* or phreatic level, a mesh refinement is advisable. By modelling a water reservoir with a dam structure the pertained water level within the dam structure will be not affected by the global precipitation, i.e. no rise of water level is computed. Likewise the pore pressure below the water level will not change in the soil polygons. In order to compute a water level rise the corresponding *HeadFunction* can be used. However, the specified *GWFlowBaseBC* will be only computed if a groundwater flow calculation is conducted. The option in the *WaterConditions* of a soil polygon correlates with the tabsheet *Water* in the command *Create borehole*. By using this modification for a soil stratigraphy the associated HBC will be automatically stated in the *Flow conditions mode*. Note that the specified water levels are *BoreholeWaterlevel's*, which cannot be modified anyway with the features *Flow functions*. The three most important water conditions for soil clusters are *Global level*, *Custom level* and *Interpolate*. They need to be specified if more than two water levels are defined in the geotechnical model. Particularly the option *Interpolate* must be used, if for instance an impermeable structure is present between two water levels and direct generation of pore pressures, e.g. *PPCT Phreatic* is utilized. Furthermore, the specified water levels, e.g. one *BoreholeWaterLevel* and one *UserWaterLevel* or two *UserWaterLevel* respectively, need an intersection with an active model boundary. The intersection must be specified in order to postulate the hydraulic condition in the BVP. Note for inclined water levels the model boundaries need to be extended in accordance of a flow calculation, because Plaxis 2D will compute an inflowing water table, which converge with the horizontal water level at larger distance from the structure.

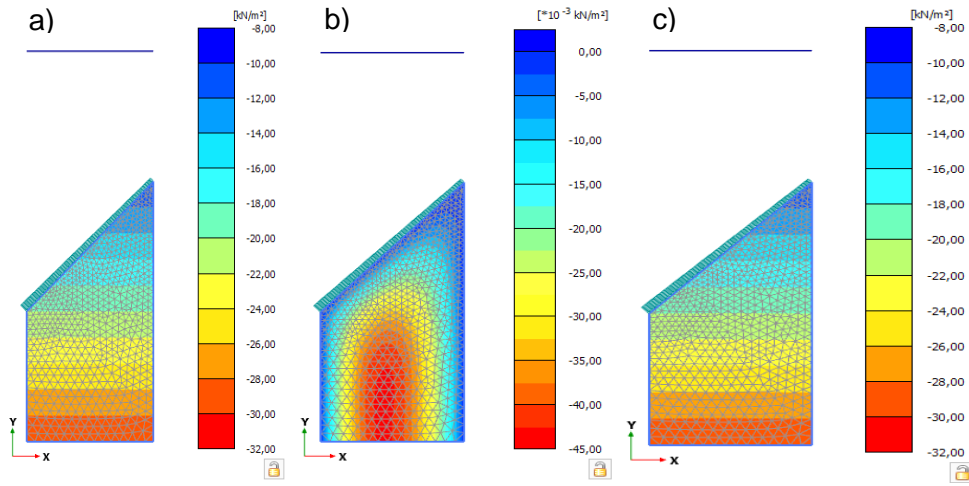
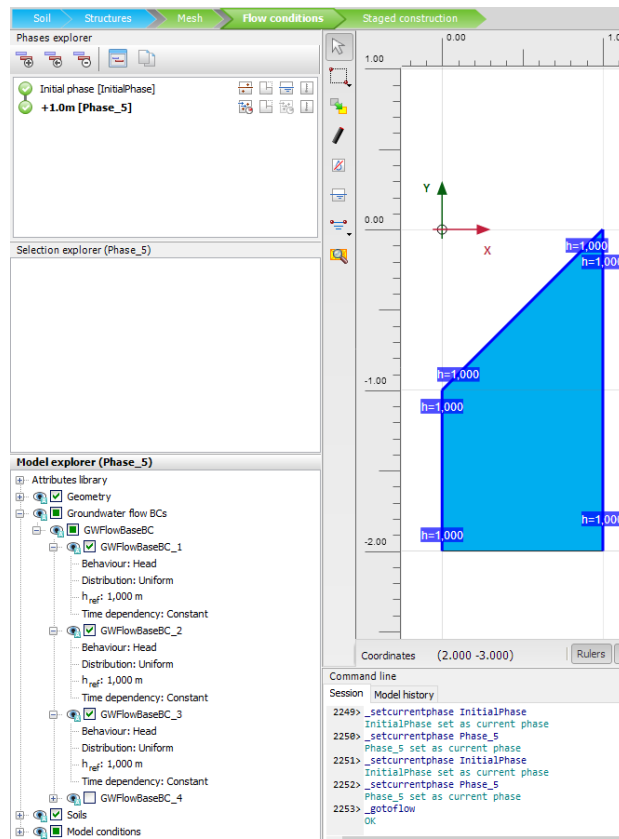
Generally an undrained analysis may be performed by means of the calculation type Plastic in consideration of the drainage types. Other calculation types is the fully coupled analysis by means of the CT FCFD. The latter does not compute undrained behaviour with respect to the drainage type but rather takes in to account the associated permeabilities, stiffness and time. The excess pore pressure will be calculated depending on the present soil saturation. The soil saturation for an undrained material, e.g. *Undrained (A)*, is a uniform value although the soil strata can be composed of a partial saturated soil layer and a fully saturated soil. Hereof, the computation of soil suction and the application of the associated soil water characteristic curve govern expecting results. This analysis is enabled by means of deselecting the *Deformation control parameter Ignore suction* in the phase window at the *Staged construction* mode. Consequently, the whole assembled computation must allow suction, i.e. from the parent phase till the child phase, thus the analysis takes into account the same method of effective stresses. Certainly the specification of the SWCC should be appropriately specified in the tabsheet Groundwater as well.

7 Literature

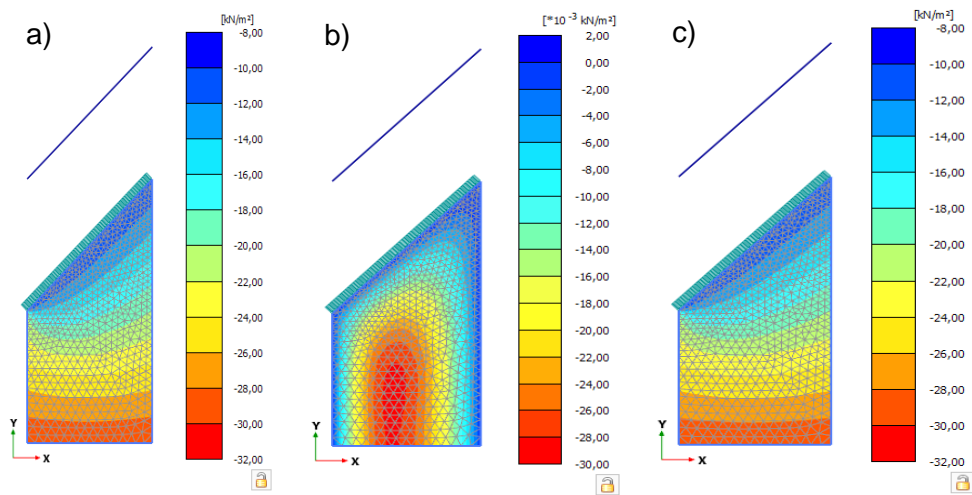
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Appendix

SX - GWFlowBaseBC: Head – Uniform and Start/End

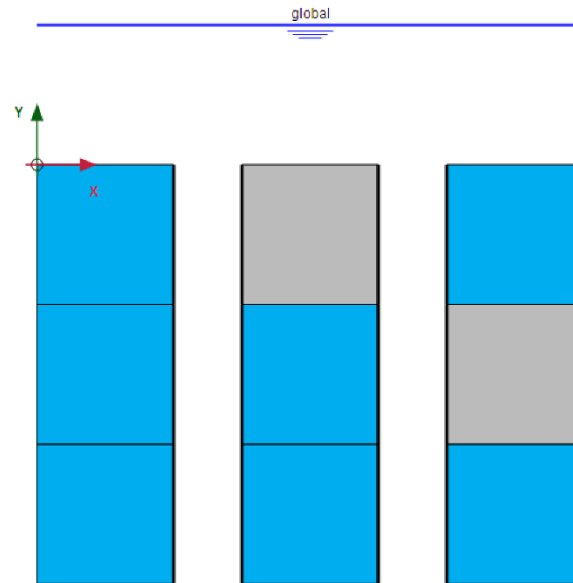


GWFlowBase BC Head: Uniform – a) p_{steady}, b) p_{excess}, c) p_{water}

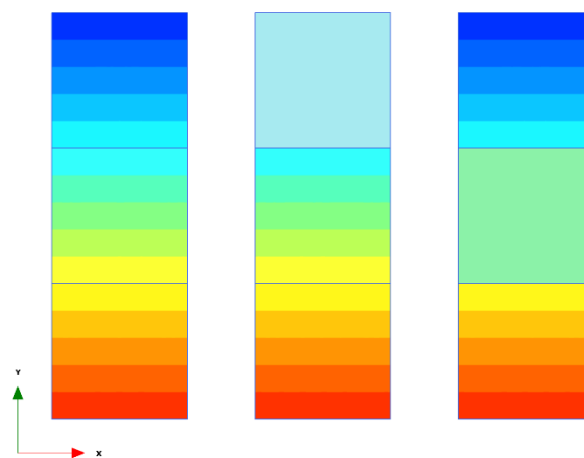


GWFlowBase BC Head: Start/ End – a) p_{steady} , b) p_{excess} , c) p_{water}

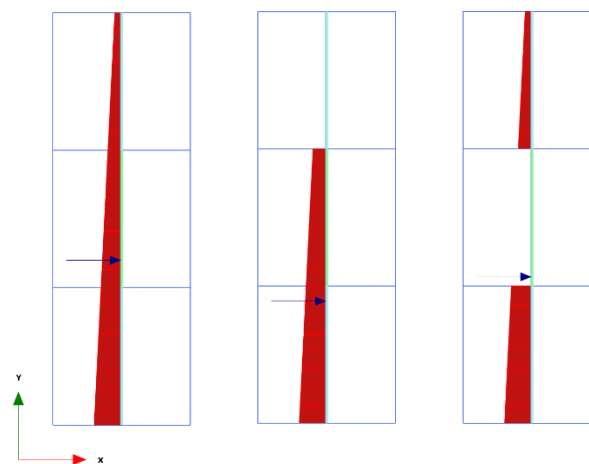
WaterConditions: Dry



Geotechnical model: dry cluster



Output : Pore water pressure p_{water}

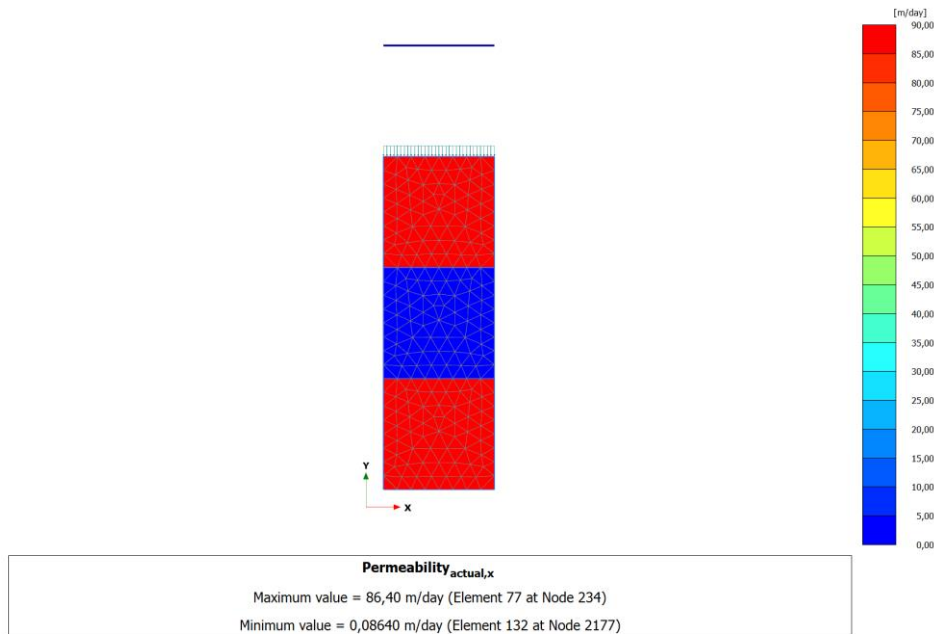


Section: Pore water pressure

Material data set: Permeability with respect to variation of water level:

Permeability [m/s]	Permeability [m/d]	Soil type [-]
10e-3	86,4	Coarse sand
10e-6	0,0864	Silt
10e-7	8,64e-3	Silty clay
10e-8	0,864e-3	Clay
10e-10	8,64e-6	Very fine clay

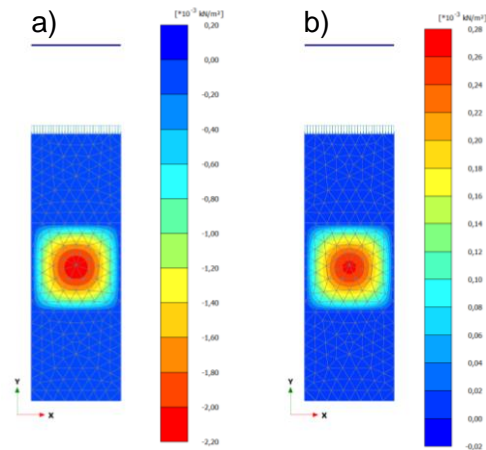
Investigated permeabilities



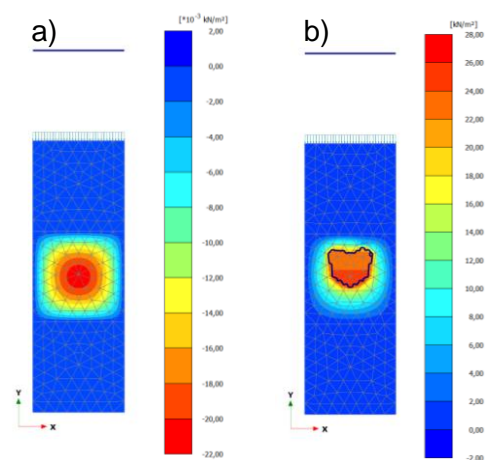
Geotechnical model: Plot of actual permeability (middle soil layer undrained)

ID	Calculation L...	Loading type...	Pore pressur...	Time interval	Estimated en...	Ignore undr...	Reset displa...	Updated me...	Max steps (D)	First step	Last step
Initial phase [InitialPhase]				0,000 day	0,000 day	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	1000	0	0
undrained_10e-7 [Phase_1]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	1	81
WLV_undrained_10e-7 [Phase_2]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	82	233
undrained_10e-8 [Phase_3]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	254	312
WLV_undrained_10e-8 [Phase_4]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	313	430
undrained_10e-10 [Phase_5]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	431	460
WLV_undrained_10e-10 [Phase_6]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	461	569
undrained_10e-6 [Phase_8]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	1070	1152
WLVundrained_10e-6 [Phase_9]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	1153	1322
dry [Phase_7]				1,000 day	1,000 day	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1000	570	1069

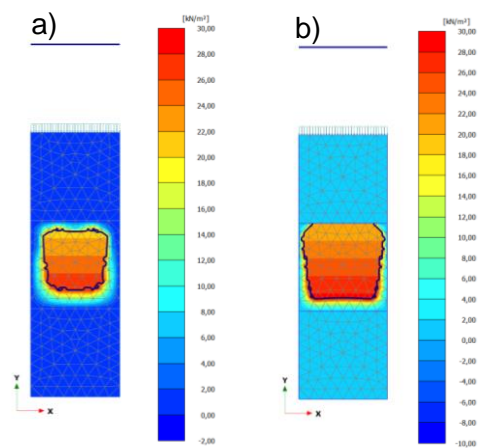
Overview of CT sequence: K0 procedure/ FCFD (1.0 day)



Actual permeability 10^{-6} vs excess pore pressure: a) constant WL, b) WL rise



Actual permeability 10^{-7} vs excess pore pressure: a) constant WL, b) WL rise



Actual permeability 10^{-8} vs excess pore pressure: a) constant WL, b) WL rise

Water level: Important specifications:

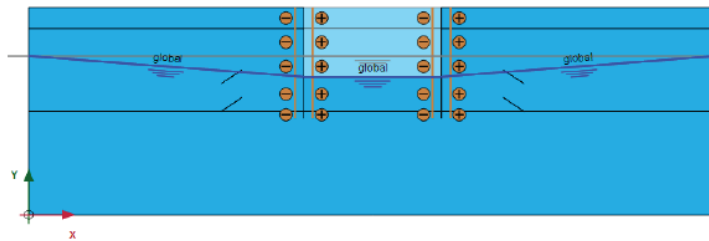
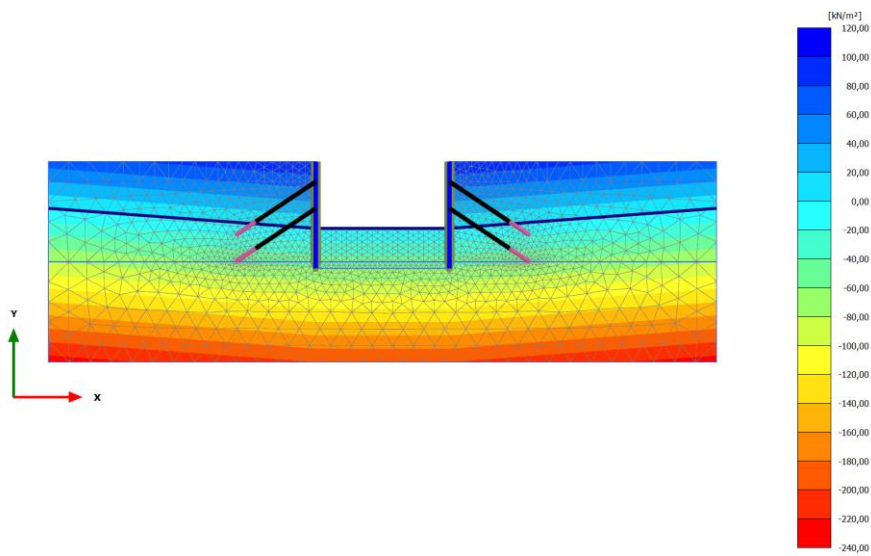


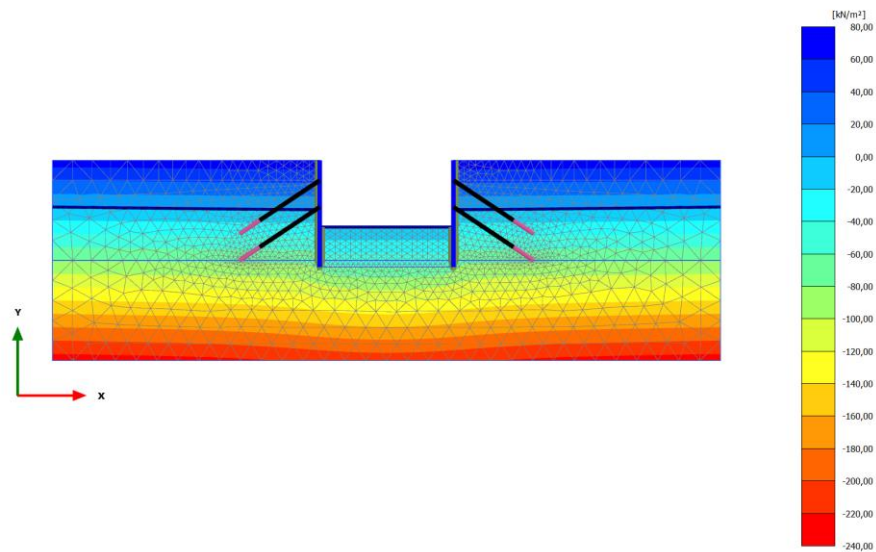
Figure 3.15 Configuration of Phase 6 in the *Flow conditions* mode

Hint: Note that for *Groundwater flow* (steady or transient) the intersection points of the water level with the active model boundaries are important. The program calculates flow boundary conditions in terms of a groundwater head corresponding to the water level. The 'internal' part of the water level is not used and will be replaced by the phreatic level resulting from the groundwater flow calculation. Hence, the water level tool is just a convenient tool to create boundary conditions for a flow calculation.

Plaxis 2D Tutorial: Dry excavation – Intersection point



Dry excavation: Incorrect PPCT - Phreatic

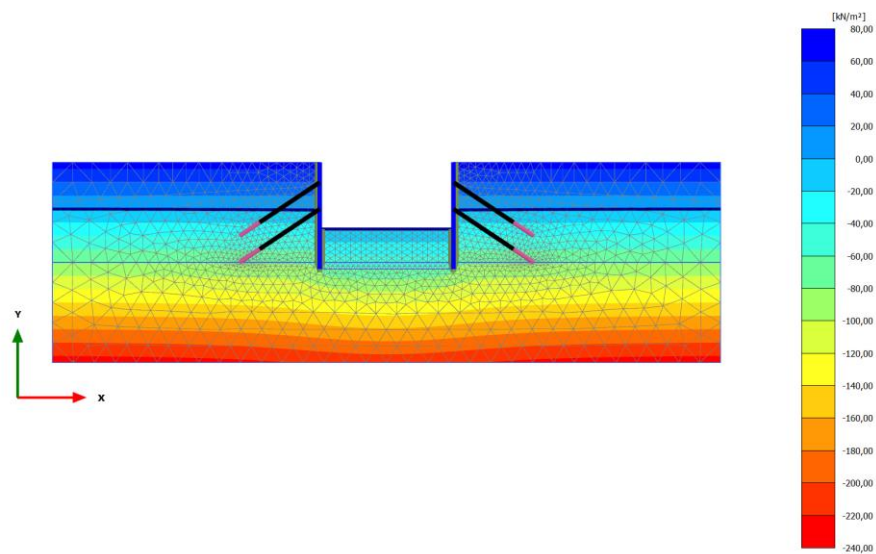


Pore water pressures p_{water} (Pressure = negative)

Maximum value = 73,71 kN/m² (Element 82 at Node 4627)

Minimum value = -230,0 kN/m² (Element 2526 at Node 18578)

Dry Excavation: PCCT Steady-State groundwater flow

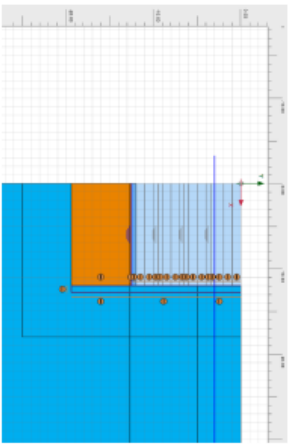
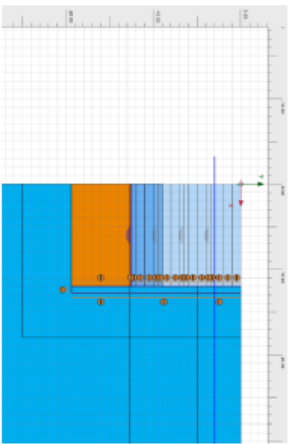
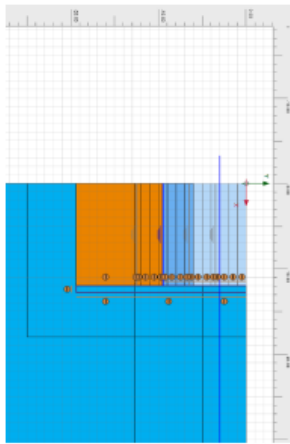
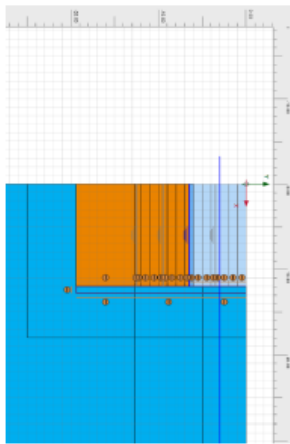
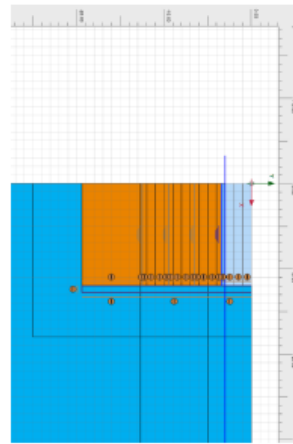
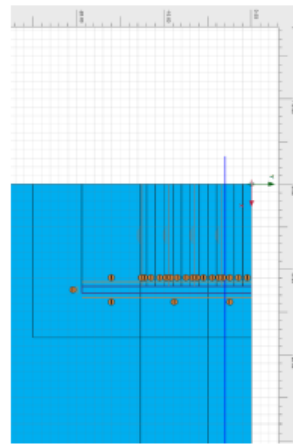


Pore water pressures p_{water} (Pressure = negative)

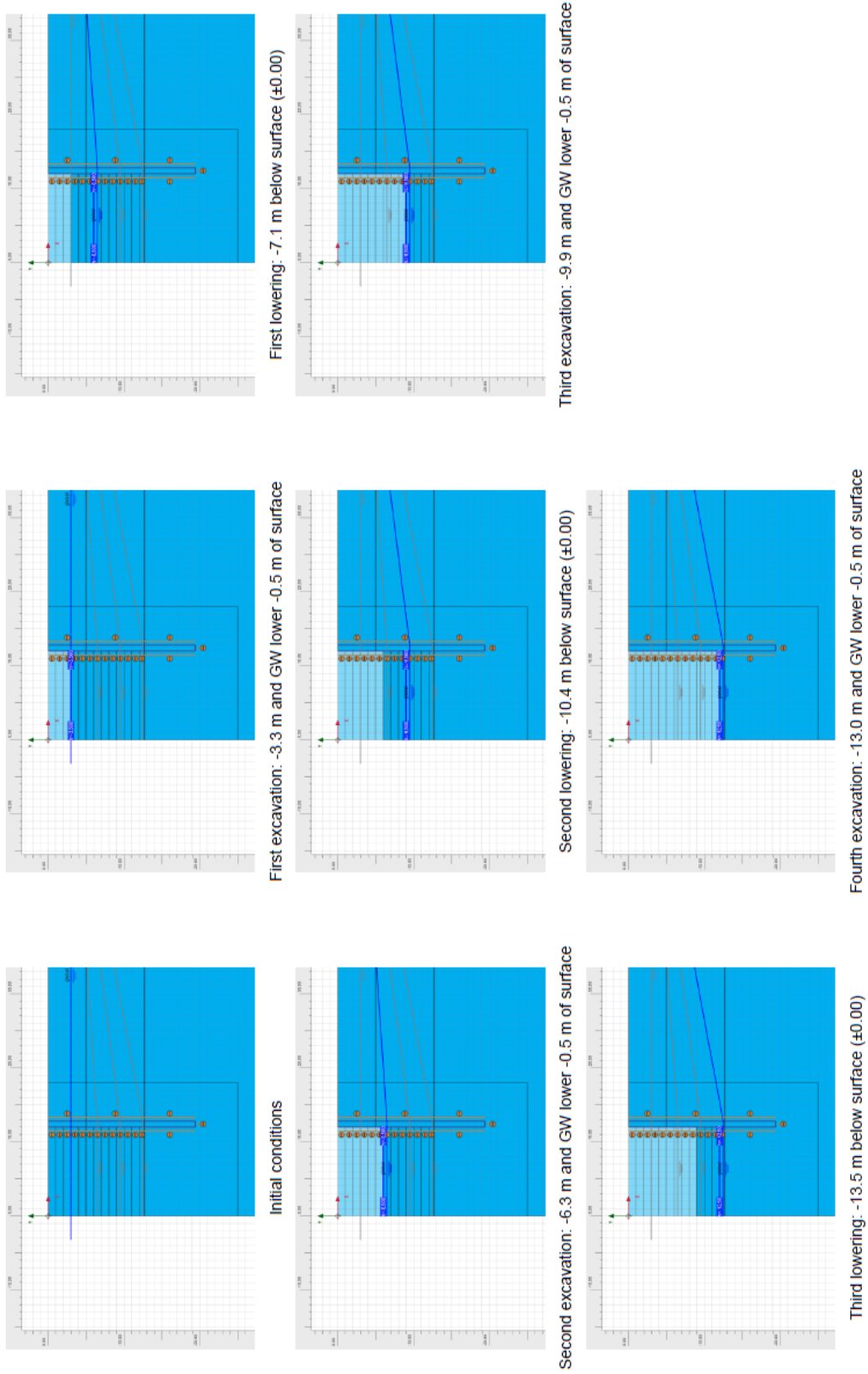
Maximum value = 70,00 kN/m² (Element 312 at Node 27329)

Minimum value = -230,0 kN/m² (Element 2523 at Node 3682)

Dry Excavation: PCCT Transient groundwater flow



Deep excavation: Sequence with respect to groundwater lowering



Deep excavation: Sequence with respect to groundwater lowering