Created in COMSOL Multiphysics 6.1

Transient Response of a Shallow Foundation on Unsaturated Soil

Introduction

This example is an extension of the model Shallow Foundation on Unsaturated Soil. In the referred example, sudden changes in suction occur due to changes in the underground water level. In this example, the deformation of the clay stratum due to footing pressure and pore suction is analyzed after time-dependent changes in the boundary conditions. Two distinct natural events — a few days of rainfall and a few days of evaporation — are considered, after which the soil is subjected to a footing pressure.

The model is inspired by the example presented in Ref. 1. The Extended Barcelona Basic model (BBMx), which includes suction in its constitutive relationship, is used to demonstrate the behavior of a settlement on an unsaturated soil layer.

Model Definition

In this example, a 6 m wide and 3 m deep soil layer is studied. A 1 m wide footing is placed on top of the layer. The footing is modeled as a boundary load applied on the surface. The settlement analysis is carried out for an increasing footing pressure. Initially, in the first analysis, the ground water level is constant (3 m below the surface), and the footing pressure gradually increases to its final value. Once the final footing pressure is applied, a rainfall event with an infiltration rate of 10 cm/day is considered. The second scenario considers evaporation at a rate of 2 mm/day.

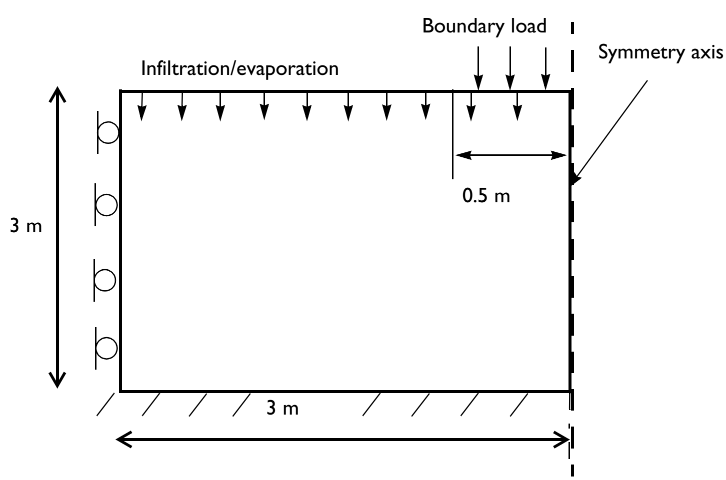

Figure 1: Dimensions, boundary conditions, pressure load, and flow rate for the unsaturated soil.

Soil Properties

The properties of the soil are given in Table 1.

TABLE 1: MATERIAL PROPERTIES

Property	Variable	Value
Poisson's ratio	ν	0.2
Soil density	ρ_s	1743 kg/m^3
Water density	ρ_w	1000 kg/m^3
Dynamic viscosity of water	μ_w	0.001 Pa.s
Swelling index	κ	0.006
Swelling index for changes in suction	κ_s	0.008
Compression index at saturation	λ	0.22
Compression index for changes in suction	λ_s	0.123
Slope of critical state line	M	1.24
Weight parameter	w	0.4
Soil stiffness parameter	m	50 kPa
Plastic potential smoothing parameter	b_s	10
Tension to suction ratio	k_s	0.6
Initial yield value for suction	s_y	100 kPa
Initial void ratio	e_0	0.666
Reference pressure	p_{ref}	10 kPa
Initial consolidation pressure	p_{c0}	50 kPa
Initial porosity	ϕ	0.4
Saturated hydraulic conductivity	k_{sat}	1 m/day
Fitting parameter	α	2 1/m
Residual degree of saturation	S_{res}	0.23
Degree of saturation at full saturation	S_{sat}	1

The Richards' Equation interface requires additional material properties, which are derived from Table 1 and based on data from Ref. 1.

Constraints and Loads

- The soil layer is supported by a rigid and perfectly rough base. Apply a fixed constraint on the lower horizontal boundary.
- Use a roller boundary condition on the left vertical boundary, symmetry on the right.

- A hydraulic head of 0 m is initially assigned to the lower horizontal boundary in the Richards' Equation interface.
- The infiltration and evaporation rates are applied in the Richards' Equation interface using the **Precipitation** node. Infiltration is represented by a positive quantity in the **Precipitation** node, and evaporation by a negative quantity.
- The gravity load is applied using the **Gravity** node. The pore pressure in the saturated region of the layer is applied using an **External Stress** node.
- A boundary load is applied on top of the soil layer to model the weight of the footing, see Figure 1.

Results and Discussion

Figure 2 shows the pressure head in the clay stratum after five days of rainfall (left) and five days of evaporation (right). The pressure head after five days of rainfall shows less variation across the layer due to the high infiltration rate. In contrast, with a low evaporation rate, the pressure head is almost linear with layer position and changes slightly at the top surface.

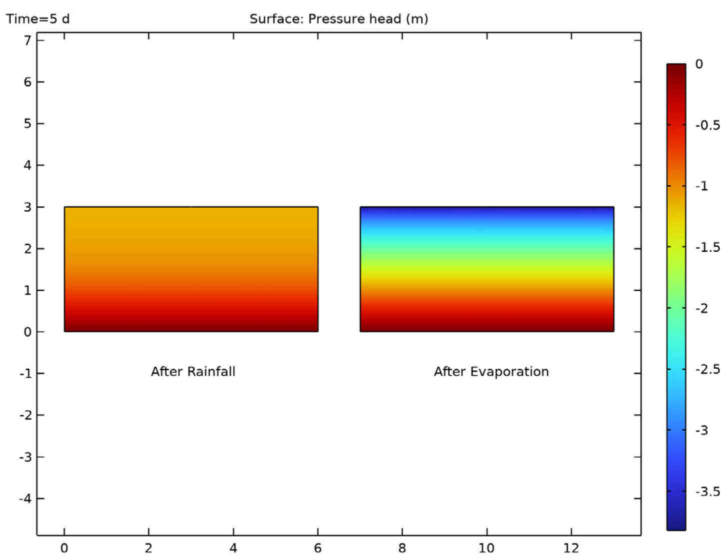

Figure 2: Pressure head after infiltration and evaporation.

The results presented in Figure 2 are emphasized in Figure 3 and Figure 4. With a high infiltration rate (Figure 3), the pressure head after 5 days of rainfall is within the range of 0–1 m instead of the initial range of 0–3 m. The pressure head after five days of rainfall matches the Gardener steady state solution quite well. Figure 4 shows changes in the pressure head with a low evaporation rate, with the opposite trend as compared to Figure 3. Evaporation decreases the water content, which lowers the pressure head. Due to the low evaporation rate, changes in the pressure head are much smaller as compared to the changes due to the rainfall event, and mostly affect the region near the top surface. Again, the pressure head after five days of evaporation matches the Gardener steady state solution.

The distribution of the von Mises stress due to footing pressure is shown in Figure 5. Five days of rainfall reduces the suction and increases the pore pressure. The water in the pores can bear more load, which reduces the stresses in the soil skeleton, see Figure 6. Vice versa, after five days of evaporation, the stress in the soil skeleton increases slightly due to the reduced amount of water in the pores, see Figure 7.

The footing pressure versus settlement after the rainfall and evaporation events is shown in Figure 8 and Figure 9, respectively. The collapse of the soil under the footing is expected with increasing infiltration. Collapse also occurs after evaporation (although barely visible in the figure). The vertical displacement of the top layer due to rainfall and evaporation is different (see Figure 10); with rainfall there is a large collapse under the footing, whereas the collapse due to evaporation is not that drastic.

The changes in pore suction due to rainfall and evaporation is shown in Figure 11. Pore suction decreases during rainfall event, which results in positive volumetric strains in the soil layer (expansion of pores). Pore suction increases when considering evaporation, which results in a negative volumetric strain in the soil (compression of pores).

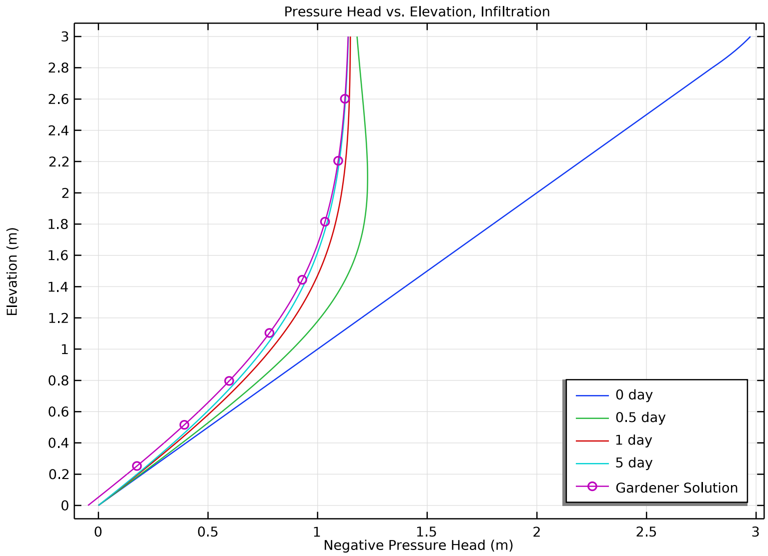

Figure 3: Pressure head versus elevation for rainfall event.

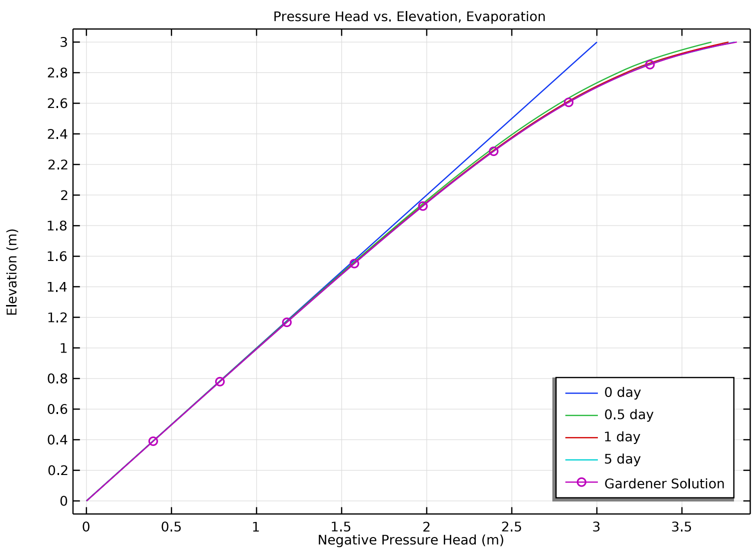

Figure 4: Pressure head versus elevation for evaporation event.

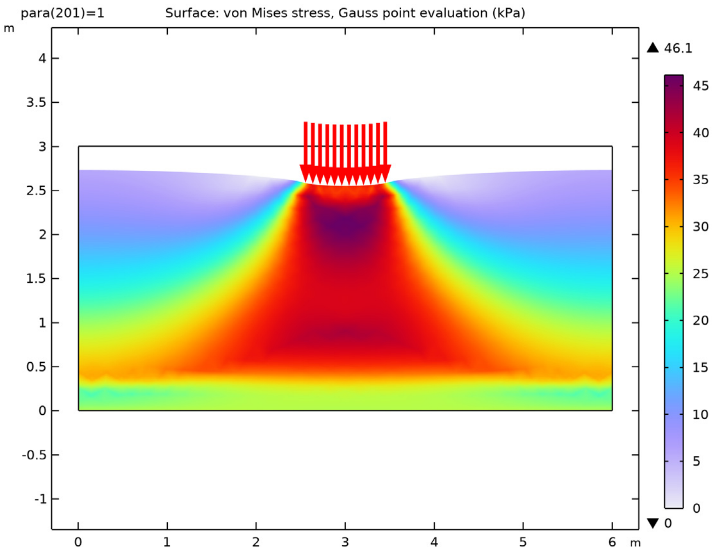

Figure 5: von Mises stress due to footing pressure.

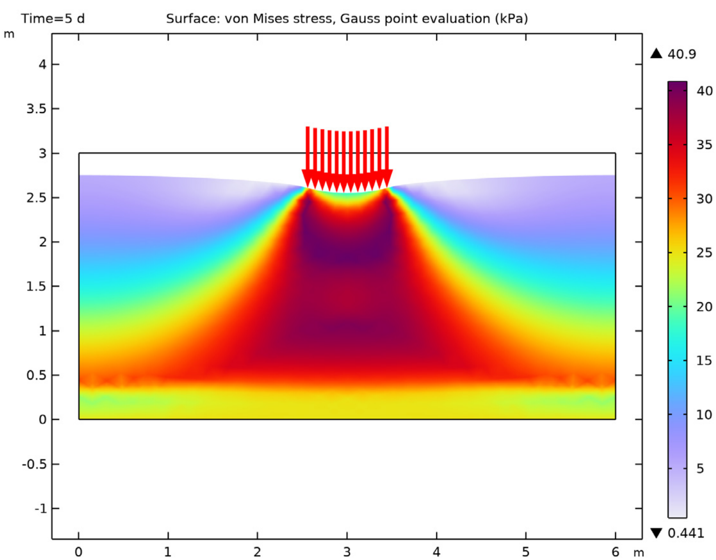

Figure 6: von Mises stress due to footing pressure after five days of rainfall.

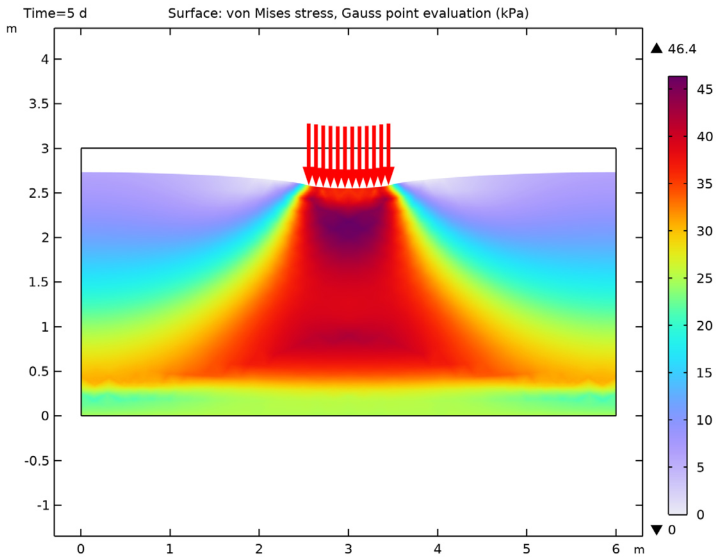

Figure 7: von Mises stress due to footing pressure after five days of evaporation.

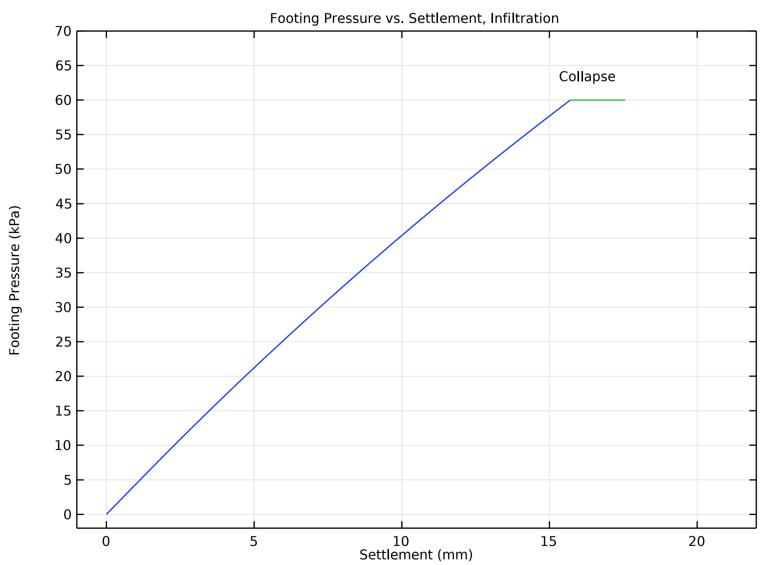

Figure 8: Footing pressure versus settlement after five days of rainfall.

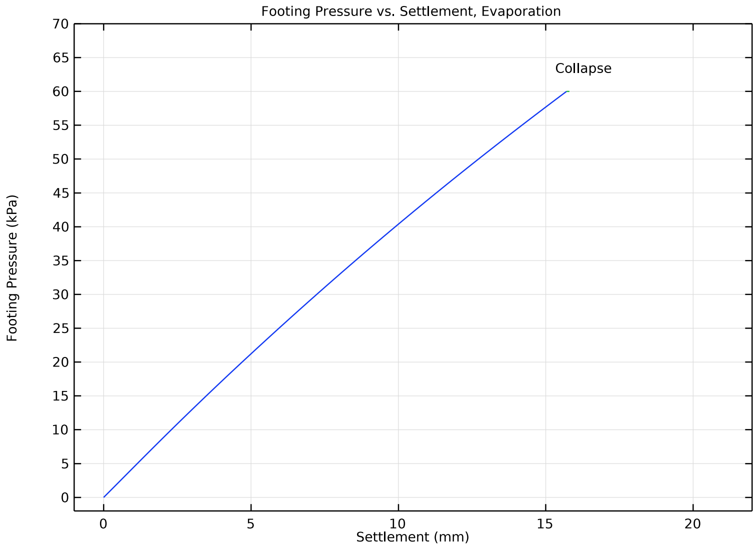

Figure 9: Footing pressure versus settlement after five days of evaporation.

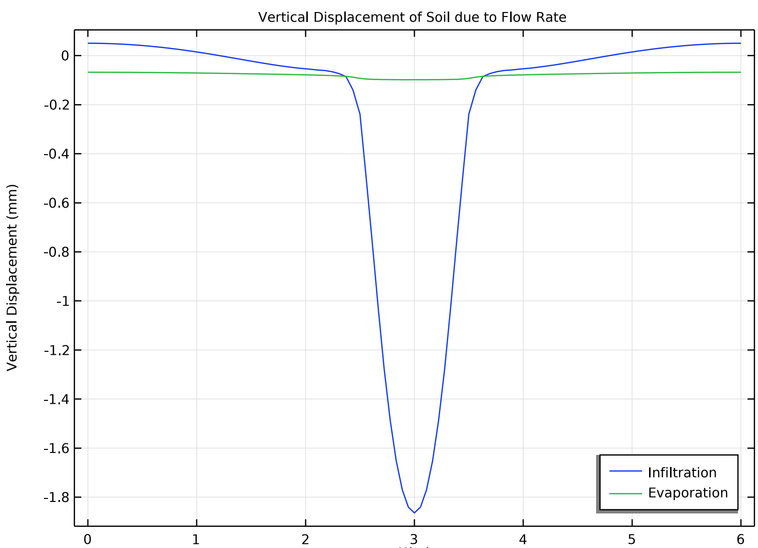

Figure 10: Vertical displacement of top layer of soil due to rainfall and evaporation.

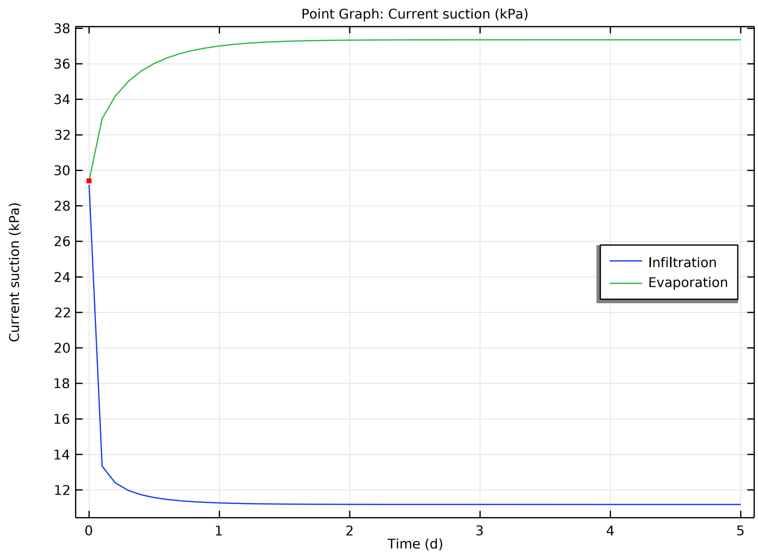

Figure 11: Changes in pore suction due to rainfall and evaporation.

Notes About the COMSOL Implementation

The model setup represents a unidirectional multiphysics coupling where changes in pore pressure affect the soil deformation, but changes in the deformation have no effect on the pore pressure.

The Cam–Clay family of soil models, like the MCC or BBMx models, do not define any stiffness at zero stress. To avoid numerical instabilities, prescribe an initial mean stress equal to the reference pressure at zero strain.

Reference

1. A.A. Abed and P.A. Vermeer, “Numerical Simulation of Unsaturated Soil Behavior,” *International Journal of Computer Applications in Technology*, vol. 34, no. 1, 2009.

Application Library path: `Geomechanics_Module/Soil/settlement_analysis_transient`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.

2 In the **Select Physics** tree, select **Fluid Flow>Porous Media and Subsurface Flow>Richards' Equation (dl)**.

3 Right-click and choose **Add Physics**.

4 In the **Select Physics** tree, select **Structural Mechanics>Solid Mechanics (solid)**.

5 Right-click and choose **Add Physics**.

6 Click **Study**.

7 In the **Select Study** tree, select **General Studies>Stationary**.

8 Click **Done**.

GEOMETRY 1

Model parameters are available in the appended text file.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `settlement_analysis_transient_parameters.txt`.

Footing Pressure

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, type `Footing Pressure` in the **Label** text field.

3 Locate the **Definition** section. In the **Function name** text field, type `F_P`.

4 In the table, enter the following settings:

t	f(t)
0	0
1	60

5 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	1

6 In the **Function** table, enter the following settings:

Function	Unit
F_P	kPa

DEFINITIONS

Variables 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

2 Right-click **Definitions** and choose **Variables**.

Model variables are available in the appended text file.

3 In the **Settings** window for **Variables**, locate the **Variables** section.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `settlement_analysis_transient_variables.txt`.

Create half of the geometry by exploiting symmetry.

GEOMETRY 1

Rectangle 1 (r1)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `3`.

4 In the **Height** text field, type `3`.

Add a line segment to represent the foundation.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.
2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.
3 From the **Specify** list, choose **Coordinates**.
4 In the **x** text field, type `2.5`.
5 In the **y** text field, type `3`.
6 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.
7 In the **x** text field, type `3`.
8 In the **y** text field, type `3`.
9 Click **Build Selected**.

MATERIALS

Add a **Porous Material** that contains information about the fluid and porous matrix properties together with the structural properties.

Porous Material 1 (pmat1)

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **More Materials>Porous Material**.

Continue with setting up the physics. After that, the software automatically detects which material properties are required.

RICHARDS' EQUATION (DL)

Unsaturated Porous Medium 1

1 In the **Settings** window for **Unsaturated Porous Medium**, locate the **Porous Medium** section.
2 From the **Storage model** list, choose **User defined**.

Porous Matrix 1

1 In the **Model Builder** window, click **Porous Matrix 1**.
2 In the **Settings** window for **Porous Matrix**, locate the **Retention Model** section.
3 From the **Retention model** list, choose **User defined**. In the S_e text field, type `Se`.
4 In the θ_l text field, type `S_res*phi0+Se*(phi0-S_res*phi0)`.
5 In the C_m text field, type `Cm`.
6 In the κ_r text field, type `k_rel`.
7 In the θ_r text field, type `S_res*phi0`.

Initial Values 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Richards' Equation (dl)** click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 Click the **Hydraulic head** button.

Hydraulic Head 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Hydraulic Head**.

2 Select Boundary 2 only.

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 Select Boundary 5 only.

Infiltration

1 In the **Physics** toolbar, click **Boundaries** and choose **Precipitation**.

2 In the **Settings** window for **Precipitation**, type `Infiltration` in the **Label** text field.

3 Select Boundaries 3 and 4 only.

4 Locate the **Precipitation** section. In the P_0 text field, type `U_in`.

Evaporation

1 Right-click **Infiltration** and choose **Duplicate**.

2 In the **Settings** window for **Precipitation**, type `Evaporation` in the **Label** text field.

3 Locate the **Precipitation** section. In the P_0 text field, type `-U_out`.

Continue with setting up the **Solid Mechanics** interface.

SOLID MECHANICS (SOLID)

In the **Model Builder** window, under **Component 1 (comp1)** click **Solid Mechanics (solid)**.

Extended Barcelona Basic Model (BBMx)

1 In the **Physics** toolbar, click **Domains** and choose **Elastoplastic Soil Material**.

2 In the **Settings** window for **Elastoplastic Soil Material**, type `Extended Barcelona Basic Model (BBMx)` in the **Label** text field.

3 Locate the **Elastoplastic Soil Material** section. From the **Material model** list, choose **Extended Barcelona Basic**.

4 From the M list, choose **From material**.

5 From the e_0 list, choose **From material**.

6 In the s_0 text field, type `InitSuction`.

7 In the s text field, type `Suction`.

8 In the p_{ref} text field, type `pref`.

9 In the p_{c0} text field, type `pc0`.

10 Select Domain 1 only.

External Stress 1

1 In the **Physics** toolbar, click **Attributes** and choose **External Stress**.

2 In the **Settings** window for **External Stress**, locate the **External Stress** section.

3 From the **Stress input** list, choose **Pore pressure**.

4 In the p_A text field, type `PorePressure`.

5 In the p_{ref} text field, type `0`.

6 From the α_B list, choose **User defined**. In the associated text field, type `1`.

Go to the material node and assign the required material properties.

MATERIALS

Porous Material 1 (pmat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Porous Material 1 (pmat1)**.

2 In the **Settings** window for **Porous Material**, locate the **Porosity** section.

3 In the ε_p text field, type `phi0`.

4 Locate the **Homogenized Properties** section. In the table, enter the following settings:

Property	**Variable**	**Value**	**Unit**	**Property group**
Plastic potential smoothing parameter	bB	`bb`	1	Barcelona Basic
Density	rho	`rhos`	kg/m³	Basic
Compression index at saturation	lambdaComp0	`lambda`	1	Barcelona Basic
Poisson's ratio	nu	`Nu`	1	Young's modulus and Poisson's ratio

Property	Variable	Value	Unit	Property group
Weight parameter	wB	wb	1	Barcelona Basic
Initial yield value for suction	sy0	sy	Pa	Barcelona Basic
Slope of critical state line	M	Mb	1	Barcelona Basic
Compression index for changes in suction	lambdaCompss	lambda_s	1	Barcelona Basic
Swelling index for changes in suction	kappaSwellings	kappa_s	1	Barcelona Basic
Soil stiffness parameter	mB	mb	Pa	Barcelona Basic
Tension to suction ratio	kB	kb	1	Barcelona Basic
Swelling index	kappaSwelling	kappa	1	Barcelona Basic
Initial void ratio	evoid0	e0	1	Barcelona Basic
Permeability	kappa_iso ; kappaii = kappa_iso, kappaij = 0	k	m^2	Basic

5 Locate the **Phase-Specific Properties** section. Click **Add Required Phase Nodes**.

Fluid 1 (pmat1.fluid1)

1 In the **Model Builder** window, click **Fluid 1 (pmat1.fluid1)**.

2 In the **Settings** window for **Fluid**, locate the **Material Contents** section.

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Density	rho	rhow	kg/m^3	Basic
Dynamic viscosity	mu	muw	Pa·s	Basic
Porosity	epsilon	phi0	1	Porous model

SOLID MECHANICS (SOLID)

Gravity 1

In the **Physics** toolbar, click **Global** and choose **Gravity**.

Fixed Constraint 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Fixed Constraint**.

2 Select Boundary 2 only.

Roller 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Roller**.

2 Select Boundary 1 only.

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 Select Boundary 5 only.

Boundary Load 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Boundary Load**.

2 Select Boundary 4 only.

3 In the **Settings** window for **Boundary Load**, locate the **Force** section.

4 Specify the $\mathbf{F}_A$ vector as

0	x
-F_P(para)	y

MESH 1

Free Triangular 1

1 In the **Mesh** toolbar, click **Free Triangular**.

2 In the **Settings** window for **Free Triangular**, click **Build All**.

STUDY: FOOTING PRESSURE

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, type `Study: Footing Pressure` in the **Label** text field.

Step 1: Stationary

1 In the **Model Builder** window, under **Study: Footing Pressure** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** check box.

4 In the tree, select **Component 1 (comp1)>Richards' Equation (dl)>Infiltration** and **Component 1 (comp1)>Richards' Equation (dl)>Evaporation**.

5 Right-click and choose **Disable**.

6 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

7 Click **Add**.

8 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(0,0.005,1)`	

9 In the **Home** toolbar, click **Compute**.

10 Click **Add Predefined Plot**.

ADD PREDEFINED PLOT

1 Go to the **Add Predefined Plot** window.

2 In the tree, select **Study: Footing Pressure/Solution 1 (sol1)>Solid Mechanics>Volumetric Plastic Strain (solid)**, **Study: Footing Pressure/Solution 1 (sol1)>Solid Mechanics>Current Void Volume Fraction (solid)**, and **Study: Footing Pressure/Solution 1 (sol1)>Solid Mechanics>Applied Loads (solid)**.

3 Click **Add Plot** in the window toolbar.

4 In the **Home** toolbar, click **Add Predefined Plot**.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Time Dependent**.

4 Right-click and choose **Add Study**.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY: INFILTRATION

1 In the **Settings** window for **Study**, type `Study: Infiltration` in the **Label** text field.

2 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study: Infiltration** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **d**.

4 In the **Output times** text field, type `range(0,0.1,5)`.

5 From the **Tolerance** list, choose **User controlled**.

6 In the **Relative tolerance** text field, type `0.0001`.

7 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

8 In the tree, select **Component 1 (comp1)>Richards' Equation (dl)>Evaporation**.

9 Right-click and choose **Disable**.

10 Click to expand the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

11 From the **Method** list, choose **Solution**.

12 From the **Study** list, choose **Study: Footing Pressure, Stationary**.

13 From the **Parameter value (para)** list, choose **Last**.

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node.

3 In the **Model Builder** window, expand the **Study: Infiltration>Solver Configurations>Solution 2 (sol2)>Time-Dependent Solver 1** node, then click **Fully Coupled 1**.

4 In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.

5 From the **Nonlinear method** list, choose **Automatic (Newton)**.

6 In the **Study** toolbar, click **Compute**.

ADD STUDY

1 In the **Study** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Time Dependent**.

4 Right-click and choose **Add Study**.

5 In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY: EVAPORATION

1 In the **Settings** window for **Study**, type `Study: Evaporation` in the **Label** text field.

2 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study: Evaporation** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **d**.

4 In the **Output times** text field, type `range(0,0.1,5)`.

5 From the **Tolerance** list, choose **User controlled**.

6 In the **Relative tolerance** text field, type `0.0001`.

7 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

8 In the tree, select **Component 1 (comp1)>Richards' Equation (dl)>Infiltration**.

9 Right-click and choose **Disable**.

10 Locate the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

11 From the **Method** list, choose **Solution**.

12 From the **Study** list, choose **Study: Footing Pressure, Stationary**.

13 From the **Parameter value (para)** list, choose **Last**.

Solution 3 (sol3)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 3 (sol3)** node.

3 In the **Model Builder** window, expand the **Study: Evaporation>Solver Configurations>Solution 3 (sol3)>Time-Dependent Solver 1** node, then click **Fully Coupled 1**.

4 In the **Settings** window for **Fully Coupled**, locate the **Method and Termination** section.

5 From the **Nonlinear method** list, choose **Automatic (Newton)**.

6 In the **Study** toolbar, click **Compute**.

RESULTS

Mirror 2D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Mirror 2D**.

2 In the **Settings** window for **Mirror 2D**, locate the **Axis Data** section.

3 In row **Point 1**, set **X** to `3`.

4 In row **Point 2**, set **X** to `3`.

5 Click to expand the **Advanced** section. Select the **Remove elements on the symmetry axis** check box.

Mirror 2D 2

1 Right-click **Mirror 2D 1** and choose **Duplicate**.

2 In the **Settings** window for **Mirror 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Study: Infiltration/Solution 2 (sol2)**.

Mirror 2D 3

1 Right-click **Mirror 2D 2** and choose **Duplicate**.

2 In the **Settings** window for **Mirror 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Study: Evaporation/Solution 3 (sol3)**.

Degree of Saturation, Infiltration

1 In the **Model Builder** window, under **Results** click **Flownet (dl)**.

2 In the **Settings** window for **2D Plot Group**, type `Degree of Saturation, Infiltration` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 2**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Degree of Saturation`.

6 In the **Model Builder** window, expand the **Degree of Saturation, Infiltration** node.

Contour 1, Streamline 1

1 In the **Model Builder** window, under **Results>Degree of Saturation, Infiltration**, Ctrl-click to select **Contour 1** and **Streamline 1**.

2 Right-click and choose **Delete**.

Surface 1

1 In the **Model Builder** window, right-click **Degree of Saturation, Infiltration** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 2**.

4 From the **Time (d)** list, choose **0**.

5 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Richards' Equation>Retention model>dl.Se - Effective saturation**.

Surface 2

1 Right-click **Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **From parent**.

4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Translation 1

1 Right-click **Surface 2** and choose **Translation**.

2 In the **Settings** window for **Translation**, locate the **Translation** section.

3 In the **x** text field, type 7.

4 In the **Degree of Saturation, Infiltration** toolbar, click **Plot**.

Degree of Saturation, Infiltration

In the **Model Builder** window, under **Results** click **Degree of Saturation, Infiltration**.

Table Annotation 1

1 In the **Degree of Saturation, Infiltration** toolbar, click **More Plots** and choose **Table Annotation**.

2 In the **Settings** window for **Table Annotation**, locate the **Coloring and Style** section.

3 Clear the **Show point** check box.

4 Locate the **Data** section. Select the **LaTeX markup** check box.

5 From the **Source** list, choose **Local table**.

6 In the table, enter the following settings:

x-coordinate	**y-coordinate**	**Annotation**
1.2	-0.7	Before Rainfall
8.5	-0.7	After 5 Days of \newline $\qquad$ Rainfall

Degree of Saturation, Infiltration

1 In the **Model Builder** window, click **Degree of Saturation, Infiltration**.

2 In the **Settings** window for **2D Plot Group**, locate the **Plot Settings** section.

3 From the **View** list, choose **View 2D 3**.

4 In the **Degree of Saturation, Infiltration** toolbar, click **Plot**.

Degree of Saturation, Evaporation

1 Right-click **Degree of Saturation, Infiltration** and choose **Duplicate**.

2 Drag and drop **Degree of Saturation, Infiltration 1** below **Degree of Saturation, Infiltration**.

3 In the **Settings** window for **2D Plot Group**, type `Degree of Saturation, Evaporation` in the **Label** text field.

4 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 3**.

Surface 1

1 In the **Model Builder** window, expand the **Degree of Saturation, Evaporation** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 3**.

4 In the **Degree of Saturation, Evaporation** toolbar, click **Plot**.

Table Annotation 1

1 In the **Model Builder** window, click **Table Annotation 1**.

2 In the **Settings** window for **Table Annotation**, locate the **Data** section.

3 In the table, enter the following settings:

x-coordinate	y-coordinate	Annotation
1.2	-0.7	Before Evaporation
8.5	-0.7	After 5 Days of \newline $\;\;$ Evaporation

4 In the **Degree of Saturation, Evaporation** toolbar, click **Plot**.

Pressure Head

1 In the **Model Builder** window, under **Results** click **Pressure (dl)**.

2 In the **Settings** window for **2D Plot Group**, type `Pressure Head` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 2**.

4 Locate the **Plot Settings** section. From the **View** list, choose **View 2D 3**.

Streamline 1

1 In the **Model Builder** window, expand the **Pressure Head** node.

2 Right-click **Results>Pressure Head>Streamline 1** and choose **Delete**.

Surface

1 In the **Model Builder** window, under **Results>Pressure Head** click **Surface**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `dl.Hp`.

Surface 2

1 Right-click **Surface** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 3**.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Inherit Style** section. From the **Plot** list, choose **Surface**.

Translation 1

1 Right-click **Surface 2** and choose **Translation**.

2 In the **Settings** window for **Translation**, locate the **Translation** section.

3 In the **x** text field, type `7`.

4 In the **Pressure Head** toolbar, click **Plot**.

Pressure Head

In the **Model Builder** window, under **Results** click **Pressure Head**.

Table Annotation 1

1 In the **Pressure Head** toolbar, click **More Plots** and choose **Table Annotation**.

2 In the **Settings** window for **Table Annotation**, locate the **Data** section.

3 From the **Source** list, choose **Local table**.

4 Locate the **Coloring and Style** section. Clear the **Show point** check box.

5 Locate the **Data** section. Select the **LaTeX markup** check box.

6 In the table, enter the following settings:

x-coordinate	**y-coordinate**	**Annotation**
`1.8`	`-0.7`	`After Rainfall`
`8.5`	`-0.7`	`After Evaporation`

Stress, Footing Pressure

1 In the **Model Builder** window, under **Results** click **Stress (solid)**.

2 In the **Settings** window for **2D Plot Group**, type `Stress, Footing Pressure` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 1**.

4 Locate the **Color Legend** section. Select the **Show maximum and minimum values** check box.

Surface 1

1 In the **Model Builder** window, expand the **Stress, Footing Pressure** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 From the **Unit** list, choose **kPa**.

4 Click to expand the **Quality** section. From the **Smoothing threshold** list, choose **None**.

Arrow Line 1

1 In the **Model Builder** window, right-click **Stress, Footing Pressure** and choose **Arrow Line**.

2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Solid Mechanics>Load>solid.F_Ax,solid.F_Ay - Load (spatial frame)**.

3 Click to expand the **Title** section. From the **Title type** list, choose **None**.

4 Locate the **Coloring and Style** section. From the **Arrow base** list, choose **Head**.

5 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

6 Clear the **Color** check box.

7 Clear the **Arrow scale factor** check box.

8 Clear the **Color and data range** check box.

Deformation 1

Right-click **Arrow Line 1** and choose **Deformation**.

Stress, Footing Pressure

1 In the **Settings** window for **2D Plot Group**, locate the **Plot Settings** section.

2 From the **View** list, choose **View 2D 4**.

3 In the **Stress, Footing Pressure** toolbar, click **Plot**.

Stress, Infiltration

1 Right-click **Stress, Footing Pressure** and choose **Duplicate**.

2 Drag and drop **Stress, Footing Pressure 1** below **Stress, Footing Pressure**.

3 In the **Settings** window for **2D Plot Group**, type `Stress, Infiltration` in the **Label** text field.

4 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 2**.

5 In the **Stress, Infiltration** toolbar, click **Plot**.

Stress, Evaporation

1 Right-click **Stress, Infiltration** and choose **Duplicate**.

2 Drag and drop **Stress, Infiltration 1** below **Stress, Infiltration**.

3 In the **Settings** window for **2D Plot Group**, type `Stress, Evaporation` in the **Label** text field.

4 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 3**.

5 In the **Stress, Evaporation** toolbar, click **Plot**.

Volumetric Plastic Strain (solid)

1 In the **Model Builder** window, click **Volumetric Plastic Strain (solid)**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 2**.

4 Locate the **Plot Settings** section. From the **View** list, choose **View 2D 3**.

Surface 2

1 In the **Model Builder** window, expand the **Volumetric Plastic Strain (solid)** node.

2 Right-click **Results>Volumetric Plastic Strain (solid)>Surface 1** and choose **Duplicate**.

3 In the **Settings** window for **Surface**, locate the **Data** section.

4 From the **Dataset** list, choose **Mirror 2D 3**.

5 Locate the **Title** section. From the **Title type** list, choose **None**.

6 Locate the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Translation 1

1 Right-click **Surface 2** and choose **Translation**.

2 In the **Settings** window for **Translation**, locate the **Translation** section.

3 In the **x** text field, type `7`.

Volumetric Plastic Strain (solid)

1 In the **Model Builder** window, under **Results** click **Volumetric Plastic Strain (solid)**.

2 In the **Volumetric Plastic Strain (solid)** toolbar, click **Plot**.

Table Annotation 1

1 In the **Volumetric Plastic Strain (solid)** toolbar, click **More Plots** and choose **Table Annotation**.

2 In the **Settings** window for **Table Annotation**, locate the **Data** section.

3 From the **Source** list, choose **Local table**.

4 Locate the **Coloring and Style** section. Clear the **Show point** check box.

5 Locate the **Data** section. Select the **LaTeX markup** check box.

6 In the table, enter the following settings:

x-coordinate	y-coordinate	Annotation
1.8	-0.7	After Rainfall
8.5	-0.7	After Evaporation

Current Void Volume Fraction (solid)

1 In the **Model Builder** window, under **Results** click **Current Void Volume Fraction (solid)**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 2**.

4 Locate the **Plot Settings** section. From the **View** list, choose **View 2D 3**.

Surface 1

1 In the **Model Builder** window, expand the **Current Void Volume Fraction (solid)** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `solid.evoid`.

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Traffic>Traffic** in the tree.

6 Click **OK**.

Surface 2

1 Right-click **Results>Current Void Volume Fraction (solid)>Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 3**.

4 Locate the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Translation 1

1 Right-click **Surface 2** and choose **Translation**.

2 In the **Settings** window for **Translation**, locate the **Translation** section.

3 In the **x** text field, type `7`.

4 In the **Current Void Volume Fraction (solid)** toolbar, click **Plot**.

Current Void Volume Fraction (solid)

1 In the **Model Builder** window, under **Results** click **Current Void Volume Fraction (solid)**.

2 Click **Plot**.

Table Annotation 1

1 In the **Current Void Volume Fraction (solid)** toolbar, click **More Plots** and choose **Table Annotation**.

2 In the **Settings** window for **Table Annotation**, locate the **Data** section.

3 From the **Source** list, choose **Local table**.

4 Locate the **Coloring and Style** section. Clear the **Show point** check box.

5 Locate the **Data** section. Select the **LaTeX markup** check box.

6 In the table, enter the following settings:

x-coordinate	y-coordinate	Annotation
1.8	-0.7	After Rainfall
8.5	-0.7	After Evaporation

Suction Changes

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 Drag and drop below **Current Void Volume Fraction (solid)**.

3 In the **Settings** window for **1D Plot Group**, type `Suction Changes` in the **Label** text field.

4 Locate the **Data** section. From the **Dataset** list, choose **Study: Infiltration/ Solution 2 (sol2)**.

5 Locate the **Legend** section. From the **Position** list, choose **Middle right**.

Point Graph 1

1 Right-click **Suction Changes** and choose **Point Graph**.

2 Select Point 5 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `Suction`.

5 From the **Unit** list, choose **kPa**.

6 Click to expand the **Legends** section. Select the **Show legends** check box.

7 From the **Legends** list, choose **Manual**.

8 In the table, enter the following settings:

Legends
`Infiltration`

Point Graph 2

1 Right-click **Point Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study: Evaporation/Solution 3 (sol3)**.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Evaporation`

Annotation 1

1 In the **Model Builder** window, right-click **Suction Changes** and choose **Annotation**.

2 In the **Settings** window for **Annotation**, locate the **Position** section.

3 In the **Y** text field, type `29.4`.

4 Locate the **Coloring and Style** section. From the **Color** list, choose **Red**.

5 In the **Suction Changes** toolbar, click **Plot**.

Volumetric Change due to Suction Changes

1 Right-click **Suction Changes** and choose **Duplicate**.

2 Drag and drop **Suction Changes 1** below **Suction Changes**.

3 In the **Settings** window for **1D Plot Group**, type `Volumetric Change due to Suction Changes` in the **Label** text field.

Point Graph 1

1 In the **Model Builder** window, expand the **Volumetric Change due to Suction Changes** node, then click **Point Graph 1**.

2 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `solid.epsm1.evols`.

Point Graph 2

1 In the **Model Builder** window, click **Point Graph 2**.

2 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `solid.epsm1.evols`.

Annotation 1

1 In the **Model Builder** window, click **Annotation 1**.

2 In the **Settings** window for **Annotation**, locate the **Position** section.

3 In the **Y** text field, type `0`.

4 In the **Volumetric Change due to Suction Changes** toolbar, click **Plot**.

Footing Pressure vs. Settlement, Infiltration

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 Drag and drop below **Volumetric Change due to Suction Changes**.

3 In the **Settings** window for **1D Plot Group**, type `Footing Pressure vs. Settlement, Infiltration` in the **Label** text field.

4 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** check box. In the associated text field, type `Settlement (mm)`.

7 Select the **y-axis label** check box. In the associated text field, type `Footing Pressure (kPa)`.

8 Locate the **Axis** section. Select the **Manual axis limits** check box.

9 In the **x maximum** text field, type `22`.

10 In the **y minimum** text field, type `-2`.

11 In the **y maximum** text field, type `70`.

12 Locate the **Legend** section. Clear the **Show legends** check box.

Point Graph 1

1 Right-click **Footing Pressure vs. Settlement, Infiltration** and choose **Point Graph**.

2 Select Point 5 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `F_P(para)`.

5 From the **Unit** list, choose **kPa**.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `abs(v-withsol('sol1',v,setval(para,0)))`.

8 From the **Unit** list, choose **mm**.

9 Click to expand the **Coloring and Style** section. From the **Width** list, choose **1**.

Point Graph 2

1 Right-click **Point Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study: Infiltration/Solution 2 (sol2)**.

Annotation 1

1 In the **Model Builder** window, right-click **Footing Pressure vs. Settlement, Infiltration** and choose **Annotation**.

2 In the **Settings** window for **Annotation**, locate the **Annotation** section.

3 In the **Text** text field, type `Collapse`.

4 Locate the **Position** section. In the **X** text field, type `15`.

5 In the **Y** text field, type `65`.

6 Locate the **Coloring and Style** section. Clear the **Show point** check box.

7 In the **Footing Pressure vs. Settlement, Infiltration** toolbar, click **Plot**.

Footing Pressure vs. Settlement, Evaporation

1 Right-click **Footing Pressure vs. Settlement, Infiltration** and choose **Duplicate**.

2 Drag and drop **Footing Pressure vs. Settlement, Infiltration 1** below **Footing Pressure vs. Settlement, Infiltration**.

3 In the **Settings** window for **1D Plot Group**, type `Footing Pressure vs. Settlement, Evaporation` in the **Label** text field.

Point Graph 2

1 In the **Model Builder** window, expand the **Footing Pressure vs. Settlement, Evaporation** node, then click **Point Graph 2**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study: Evaporation/Solution 3 (sol3)**.

4 In the **Footing Pressure vs. Settlement, Evaporation** toolbar, click **Plot**.

Cut Line 2D 1

1 In the **Results** toolbar, click **Cut Line 2D**.

2 In the **Settings** window for **Cut Line 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 2**.

4 Locate the **Line Data** section. In row **Point 2**, set **x** to `6`.

5 In row **Point 1**, set **y** to `3`.

6 In row **Point 2**, set **y** to `3`.

Cut Line 2D 2

1 Right-click **Cut Line 2D 1** and choose **Duplicate**.

2 In the **Settings** window for **Cut Line 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 3**.

Vertical Displacement of Soil due to Flow Rate

1 In the **Results** toolbar, click **1D Plot Group**.

2 Drag and drop below **Footing Pressure vs. Settlement, Evaporation**.

3 In the **Settings** window for **1D Plot Group**, type `Vertical Displacement of Soil due to Flow Rate` in the **Label** text field.

4 Locate the **Data** section. From the **Dataset** list, choose **Cut Line 2D 1**.

5 From the **Time selection** list, choose **Last**.

6 Locate the **Title** section. From the **Title type** list, choose **Label**.

7 Locate the **Plot Settings** section.

8 Select the **x-axis label** check box. In the associated text field, type `X(m)`.

9 Select the **y-axis label** check box. In the associated text field, type `Vertical Displacement (mm)`.

10 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

Line Graph 1

1 Right-click **Vertical Displacement of Soil due to Flow Rate** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `v-withsol('sol1',v,setval(para,1))`.

4 From the **Unit** list, choose **mm**.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `cln1x`.

7 Click to expand the **Legends** section. Select the **Show legends** check box.

8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends
Infiltration

Line Graph 2

1 Right-click **Line Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Cut Line 2D 2**.

4 From the **Time selection** list, choose **Last**.

5 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Evaporation`

6 In the **Vertical Displacement of Soil due to Flow Rate** toolbar, click **Plot**.

Pressure Head vs. Elevation, Infiltration

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 Drag and drop below **Vertical Displacement of Soil due to Flow Rate**.

3 In the **Settings** window for **1D Plot Group**, type `Pressure Head vs. Elevation, Infiltration` in the **Label** text field.

4 Locate the **Data** section. From the **Dataset** list, choose **Study: Infiltration/ Solution 2 (sol2)**.

5 From the **Time selection** list, choose **From list**.

6 In the **Times (d)** list, choose **0**, **0.5**, **1**, and **5**.

7 Locate the **Title** section. From the **Title type** list, choose **Label**.

8 Locate the **Plot Settings** section.

9 Select the **x-axis label** check box. In the associated text field, type `Negative Pressure Head (m)`.

10 Select the **y-axis label** check box. In the associated text field, type `Elevation (m)`.

11 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

Line Graph 1

1 Right-click **Pressure Head vs. Elevation, Infiltration** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Selection** section.

3 Click to select the **Activate Selection** toggle button.

4 Select Boundary 1 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `Y`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `-dl.Hp`.

8 In the **Pressure Head vs. Elevation, Infiltration** toolbar, click **Plot**.

9 Locate the **Legends** section. Select the **Show legends** check box.

10 From the **Legends** list, choose **Evaluated**.

11 In the **Legend** text field, type `eval(t, day) day`.

Line Graph 2

1 In the **Model Builder** window, right-click **Pressure Head vs. Elevation, Infiltration** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study: Infiltration/Solution 2 (sol2)**.

4 From the **Time selection** list, choose **Last**.

5 Select Boundary 1 only.

6 Locate the **y-Axis Data** section. In the **Expression** text field, type `Y`.

7 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

8 In the **Expression** text field, type `-Hp_in`.

9 Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

10 From the **Positioning** list, choose **Interpolated**.

11 Locate the **Legends** section. Select the **Show legends** check box.

12 From the **Legends** list, choose **Manual**.

13 In the table, enter the following settings:

Legends
Gardener Solution

14 In the **Pressure Head vs. Elevation, Infiltration** toolbar, click **Plot**.

Pressure Head vs. Elevation, Infiltration

1 In the **Model Builder** window, click **Pressure Head vs. Elevation, Infiltration**.

2 Click **Plot**.

Pressure Head vs. Elevation, Evaporation

1 Right-click **Pressure Head vs. Elevation, Infiltration** and choose **Duplicate**.

2 Drag and drop **Pressure Head vs. Elevation, Infiltration 1** below **Pressure Head vs. Elevation, Infiltration**.

3 In the **Settings** window for **1D Plot Group**, type `Pressure Head vs. Elevation, Evaporation` in the **Label** text field.

4 Locate the **Data** section. From the **Dataset** list, choose **Study: Evaporation/Solution 3 (sol3)**.

Line Graph 2

1 In the **Model Builder** window, expand the **Pressure Head vs. Elevation, Evaporation** node, then click **Line Graph 2**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study: Evaporation/Solution 3 (sol3)**.

4 Locate the **x-Axis Data** section. In the **Expression** text field, type `-Hp_out`.

5 In the **Pressure Head vs. Elevation, Evaporation** toolbar, click **Plot**.