Created in COMSOL Multiphysics 6.1

Wetting and Drying Paths for Partially Saturated Soil with the Extended Barcelona Basic Model

Introduction

Soil wetting and drying experiments under cyclic loading are performed to understand the behavior of partially saturated soils. Mechanical and hydraulic loads, or a combination of both, affect the behavior of partially saturated soils, making their study much more complex than that of fully saturated soils. The Barcelona Basic Model is one of the most popular models used to understand the complex behavior of partially saturated soils.

In this example, the Extended Barcelona Basic model (BBMx) is examined for the cases presented in Ref. 1 and Ref. 2. With a certain choice of material parameters, the BBMx model can predict the soil behavior that qualitatively matches the results presented in the references. The model can also predict the collapse of the soil sample during wetting processes, which is an important case for unsaturated sands and clays.

Model Definition

In this example, a 10 cm cubic soil sample is subjected to isotropic compression and suction. The soil specimen is modeled using the extended Barcelona Basic Model.

MATERIAL PROPERTIES

The material properties are based on Ref. 1, and are given in Table 1.

TABLE 1: MATERIAL PROPERTIES FOR THE SOIL MODEL.

Property	**Variable**	**Value**
Shear modulus	G	10 MPa
Density	ρ	2400 kg/m^3
Swelling index	κ	0.02
Swelling index for changes in suction	κ_s	0.008
Compression index at saturation	λ	0.2
Compression index for changes in suction	λ_s	0.08
Angle of internal friction	ϕ	25.4°
Weight parameter	w	0.75
Soil stiffness parameter	m	0.5 MPa
Plastic potential smoothing parameter	b_s	100
Tension to suction ratio	k_s	0.6
Initial yield value for suction	s_y	0.3 MPa
Void ratio at reference pressure and saturation	e_{ref0}	0.9

TABLE 1: MATERIAL PROPERTIES FOR THE SOIL MODEL.

Property	Variable	Value
Reference pressure	p_{ref}	0.1 MPa
Initial consolidation pressure	p_{c0}	0.2 MPa

CONSTRAINTS AND LOADS

- Roller conditions are applied on three perpendicular surfaces.
- For modeling isotropic compression, a normal displacement is applied on the three remaining mutually perpendicular surfaces using an interpolation function.
- The initial and current suction in the soil sample is parameterized using an interpolation function.

Results and Discussion

The results from the wetting (decreasing suction) experiment are given in Figure 1.

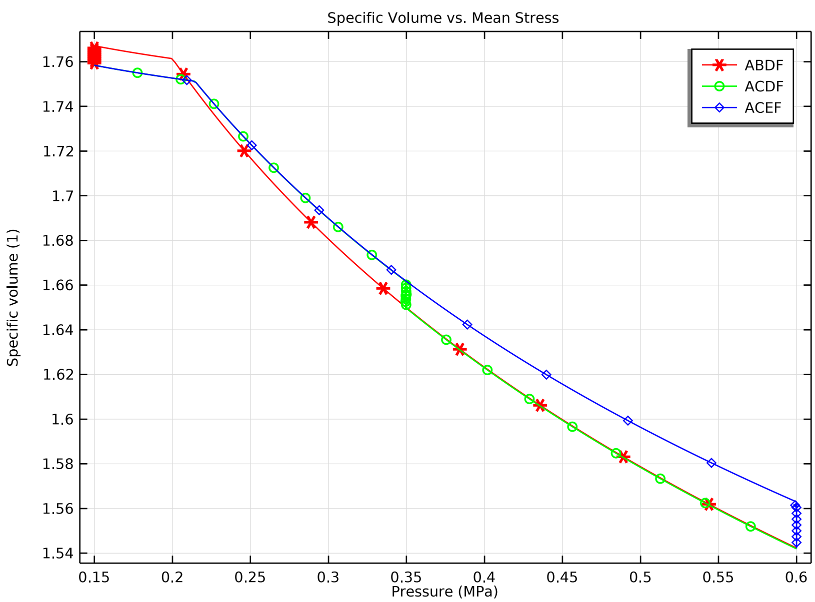

Figure 1: Wetting paths: Specific volume as a function of mean stress in an isotropic compression test.

For the wetting path ABDF, from A to B a volumetric elastic expansion happens because of the decrease in suction (0.2 MPa to 0) with constant mean stress. With zero suction, the soil reaches a fully saturated condition and the BBMx model becomes equivalent to a conventional critical state model. The predicted behavior along the path BDF (zero suction and increasing mean stress) is similar to the results predicted by the Modified Cam-Clay model. For the wetting path ACDF, the wetting path CD (reduction in suction) takes place after isotropic compression given by the path AC. At this point, the soil sample has undergone plastic deformations, which causes small net volumetric compression. The elastic volumetric expansion due to a decrease in suction is smaller than the plastic volumetric compression, which causes a net volumetric compression and the collapse of the soil. After collapse, the soil follows the unique path DF for saturated soils. For the wetting path ACEF, after isotropic compression ACE, the wetting path EF takes place at a larger confining mean stress, which causes a larger collapse.

The results from the drying (increasing suction) experiment are given in Figure 2.

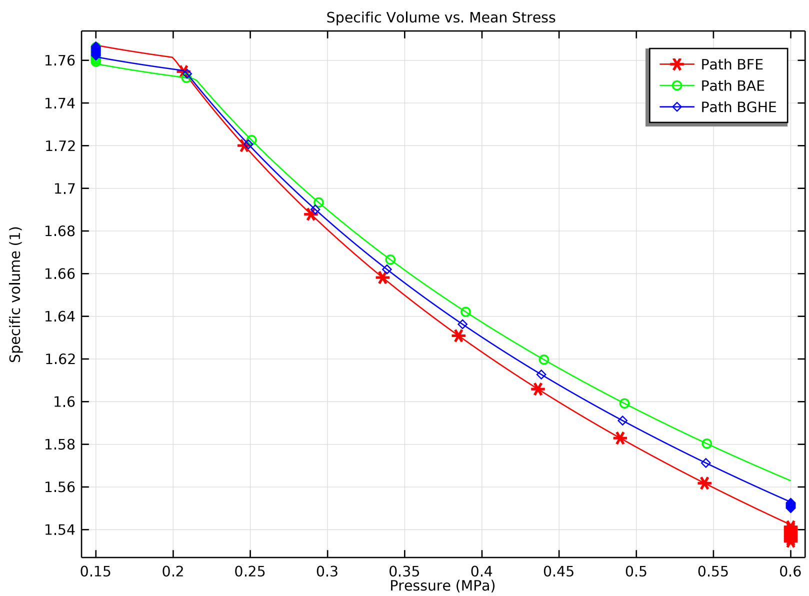

Figure 2: Drying paths: Specific volume as a function of mean stress in an isotropic compression test.

For the drying path BFE, from B to F the predicted behavior (zero suction and increasing mean stress) is similar to that predicted by the Modified Cam-Clay model. For the drying path FE (suction increases from 0 to 0.2 MPa) a slight volumetric compression takes place. For the drying path BAE, an initial increase in suction with a constant mean stress (path BA) in the elastic region gives a total volumetric compression. For the drying path BGHE, an initial increase in suction with a constant mean stress (path BG) in the elastic region gives a total volumetric compression. Path GH consists of isotropic compression with constant suction, followed by a drying path HE where the increase in suction while keeping the mean applied stress constant gives a slight volumetric compression (not visible in Figure 2, zoom the graph in the model).

The BBMx model is based on (although not identical to) the one presented in Ref. 2, and differs from the original BBM model in Ref. 1. The results presented here matches qualitatively well with the results presented in Ref. 1 and Ref. 2. The BBMx model is also able to predict soil behavior at cyclic loading including the collapse of the soil during wetting. The behavior of partially saturated soils is sensitive to the material parameters in the BBMx model. The weight parameter, w, and the soil stiffness parameter, m, are important material parameters, which govern the soil behavior in the plastic region. Also, note that the void ratio in the material model is not an initial void ratio but a void ratio at saturation ($s = 0$) and reference pressure ($p = p_{\mathrm{ref}}$).

The mechanical (mean stress) and hydraulic (suction) load paths are shown in Figure 3.

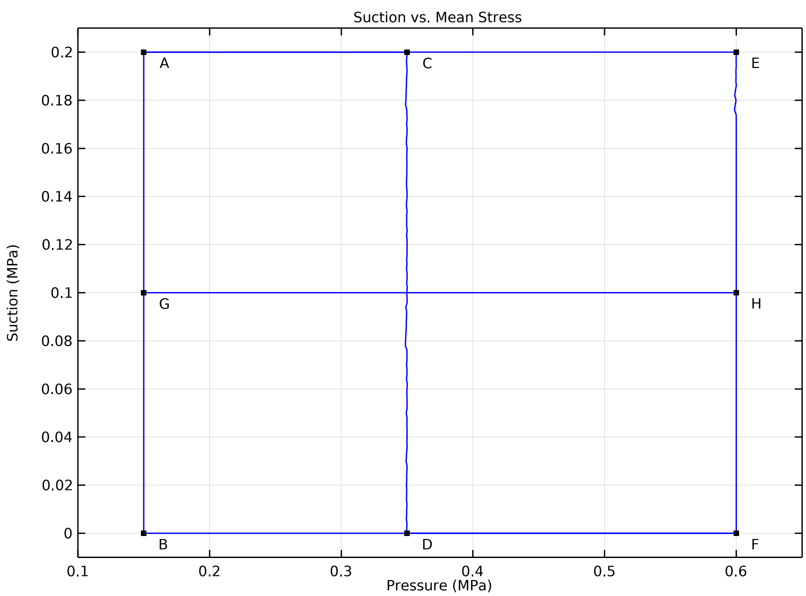

Figure 3: Load paths.

Notes About the COMSOL Implementation

For better convergence and a faster computation during isotropic compression, use a **Prescribed Displacement** instead of a **Boundary Load**. A parametric displacement in the normal direction is applied on three mutually perpendicular surfaces; this displacement is driven by the interpolation function `Pressure` through a **Global Equation** node.

In order to change the initial suction, current suction and the mean stress according to the load paths shown in Figure 3, different study steps are concatenated under the same study, where the initial values for the study step is taken from the previous step. The interpolation functions `InitSuction`, `Suction`, and `Pressure` are used with the parameter `para` to vary the initial suction, the current suction, and the mean stress. Table 2 indicates the range of the load parameter `para` for the corresponding load paths. For example, for the wetting path ACDF, `para` changes from 3 to 4 for the path AC; from 4 to 5 for the path CD, and from 5 to 6 for the path DF in separate stationary study steps.

TABLE 2: RANGE OF PARAMETER PARA FOR ALL LOAD PATHS.

Load paths	**Range of** `para`
ABDF	0–2
ACDF	3–6
ACEF	7–9
BFE	10–12
BAE	13–15
BGHE	16–19

References

1. E.E. Alonso, A. Gens, and A. Josa, “A constitutive model for partially saturated soils,” *Géotechnique*, vol. 40, no. 3, pp. 405–430, 1991.

2. D.M.Pedroso and M.M.Farias, “Extended Barcelona Basic Model for unsaturated soils under cyclic loadings,” *Comput. Geotech.*, vol. 38, pp. 731–740, 2011.

Application Library path: `Geomechanics_Module/Verification_Examples/wetting_and_drying_of_unsaturated_soil`

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 **3D**.

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

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

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 In the table, enter the following settings:

Name	Expression	Value	Description
para	0	0	Parameter

Create interpolation functions for the initial suction, the current suction, and the mean stress. Load the interpolation functions from a file.

Initial Suction Paths

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

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `InitSuction`.

4 In the **Label** text field, type `Initial Suction Paths`.

5 Locate the **Definition** section. Click **Load from File**.

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

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

Argument	Unit
t	1

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

Function	Unit
InitSuction	MPa

Note that to avoid numerical problems, instead of zero suction, a value of 1 Pa is used.

Suction Paths

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

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `Suction`.

4 In the **Label** text field, type `Suction Paths`.

5 Locate the **Definition** section. Click **Load from File**.

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

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

Argument	Unit
t	1

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

Function	Unit
Suction	MPa

Mean Stress Paths

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

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `Pressure`.

4 In the **Label** text field, type `Mean Stress Paths`.

5 Locate the **Definition** section. Click **Load from File**.

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

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

Argument	Unit
t	1

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

Function	Unit
Pressure	`MPa`

GEOMETRY 1

Block 1 (blk1)

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

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

3 In the **Width** text field, type `10[cm]`.

4 In the **Depth** text field, type `10[cm]`.

5 In the **Height** text field, type `10[cm]`.

6 Click **Build Selected**.

Create a nonlocal integration coupling with a point selection for use in the **Global Equation** interface that you will add shortly.

DEFINITIONS

Integration 1 (intop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 Click the **Go to Default View** button in the **Graphics** toolbar.

3 In the **Settings** window for **Integration**, locate the **Source Selection** section.

4 From the **Geometric entity level** list, choose **Point**.

5 Select Point 8 only.

This is the intersection point between the three perpendicular surfaces where the **Prescribed Displacement** is applied.

MATERIALS

Soil Material

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

2 In the **Settings** window for **Material**, type `Soil Material` in the **Label** text field.

SOLID MECHANICS (SOLID)

Elastoplastic Soil Material 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Solid Mechanics (solid)** and choose **Material Models>Elastoplastic Soil Material**.
2 Select Domain 1 only.
3 In the **Settings** window for **Elastoplastic Soil Material**, locate the **Elastoplastic Soil Material** section.
4 From the **Material model** list, choose **Extended Barcelona Basic**.
5 From the **Specify** list, choose **Shear modulus**.
6 In the s_0 text field, type `InitSuction(para)`.
7 In the s text field, type `Suction(para)`.
8 In the p_{ref} text field, type `0.1[MPa]`.
9 In the p_{c0} text field, type `0.2[MPa]`.

Enter the material data given in the model documentation.

MATERIALS

Soil Material (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Soil Material (mat1)**.
2 In the **Settings** window for **Material**, locate the **Material Contents** section.
3 In the table, enter the following settings:

Property	**Variable**	**Value**	**Unit**	**Property group**
Shear modulus	G	`10[MPa]`	N/m²	Bulk modulus and shear modulus
Angle of internal friction	internalphi	`25.4[deg]`	rad	Mohr-Coulomb
Swelling index	kappaSwelling	`0.02`	1	Barcelona Basic
Swelling index for changes in suction	kappaSwellings	`0.008`	1	Barcelona Basic
Compression index at saturation	lambdaComp0	`0.2`	1	Barcelona Basic

Property	**Variable**	**Value**	**Unit**	**Property group**
Compression index for changes in suction	lambdaCompss	0.08	1	Barcelona Basic
Weight parameter	wB	0.75	1	Barcelona Basic
Soil stiffness parameter	mB	0.5[MPa]	Pa	Barcelona Basic
Plastic potential smoothing parameter	bB	100	1	Barcelona Basic
Tension to suction ratio	kB	0.6	1	Barcelona Basic
Void ratio at reference pressure and saturation	evoidref0	0.9	1	Barcelona Basic
Initial yield value for suction	sy0	0.3[MPa]	Pa	Barcelona Basic
Density	rho	2400[kg/m^3]	kg/m³	Basic

SOLID MECHANICS (SOLID)

Roller 1

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

2 Select Boundaries 1–3 only.

Prescribed Displacement 1

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

2 Select Boundaries 4–6 only.

3 In the **Settings** window for **Prescribed Displacement**, locate the **Coordinate System Selection** section.

4 From the **Coordinate system** list, choose **Boundary System 1 (sys1)**.

5 Locate the **Prescribed Displacement** section. Select the **Prescribed in n direction** check box.

6 In the u_{0n} text field, type `-disp`.

Now add a **Global Equation** for the normal displacement, so that the mean stress equals the prescribed one. For that, you need to show advanced physics options.

7 Click the **Show More Options** button in the **Model Builder** toolbar.

8 In the **Show More Options** dialog box, in the tree, select the check box for the node **Physics>Equation-Based Contributions**.

9 Click **OK**.

Global Equations 1

1 In the **Physics** toolbar, click **Global** and choose **Global Equations**.

Multiply the equation by a suitable penalty factor in order to strictly satisfy this criterion. For the current model, `1e5` is an appropriate penalty factor.

2 In the **Settings** window for **Global Equations**, locate the **Global Equations** section.

3 In the table, enter the following settings:

Name	f(u,ut,utt,t) (1)	Initial value (u_0) (1)	Initial value (u_t0) (1/s)	Description
`disp`	`(intop1(solid.pm)-Pressure(para))*1e5`	`0`	`0`	

4 Locate the **Units** section. Click **Select Dependent Variable Quantity**.

5 In the **Physical Quantity** dialog box, type `disp` in the text field.

6 Click **Filter**.

7 In the tree, select **General>Displacement (m)**.

8 Click **OK**.

9 In the **Settings** window for **Global Equations**, locate the **Units** section.

10 Click **Select Source Term Quantity**.

11 In the **Physical Quantity** dialog box, type `pressure` in the text field.

12 Click **Filter**.

13 In the tree, select **General>Pressure (Pa)**.

14 Click **OK**.

MESH 1

Mapped 1

1 In the **Mesh** toolbar, click **Boundary** and choose **Mapped**.

2 Select Boundary 4 only.

Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.

2 In the **Settings** window for **Distribution**, locate the **Edge Selection** section.

3 From the **Selection** list, choose **All edges**.

4 Locate the **Distribution** section. In the **Number of elements** text field, type `2`.

Swept 1

In the **Mesh** toolbar, click **Swept**.

Distribution 1

1 Right-click **Swept 1** and choose **Distribution**.

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

3 In the **Number of elements** text field, type `2`.

4 Click **Build All**.

Add a separate **Study** node for each wetting and drying path. In order to change the suction and the mean stress according to the load path, different stationary study steps are used under the same study. The initial values for the subsequent study step is taken from the previous study step.

The interpolation functions **Suction** and **Pressure** are used with the `para` parameter to vary the suction and the mean stress. The appropriate parameter range for each study step is provided in Table 2.

STUDY: WETTING PATH ABDF

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

2 In the **Settings** window for **Study**, type `Study: Wetting Path ABDF` in the **Label** text field.

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

Stationary: Path AB

1 In the **Model Builder** window, under **Study: Wetting Path ABDF** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path AB` in the **Label** text field.

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

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(0,0.02,1)`	

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

Stationary: Path BDF

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path BDF` in the **Label** text field.

3 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**.

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

5 From the **Study** list, choose **Study: Wetting Path ABDF, Stationary: Path AB**.

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

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

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(1,0.005,2)`	

Step 2: Stationary: Path BDF

Right-click **Step 2: Stationary: Path BDF** and choose **Compute Selected Step**.

RESULTS

Cut Point 3D: Path AB

1 In the **Model Builder** window, expand the **Results** node.

2 Right-click **Results>Datasets** and choose **Cut Point 3D**.

3 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path AB` in the **Label** text field.

4 Locate the **Point Data** section. In the **X** text field, type `0.05`.

5 In the **Y** text field, type `0.05`.

6 In the **Z** text field, type `0.05`.

7 Locate the **Data** section. From the **Dataset** list, choose **Study: Wetting Path ABDF/ Solution Store 1 (sol2)**.

Cut Point 3D: Path BDF

1 Right-click **Cut Point 3D: Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path BDF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Wetting Path ABDF/ Solution 1 (sol1)**.

Load Paths

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

2 In the **Settings** window for **1D Plot Group**, type `Load Paths` in the **Label** text field.

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

4 In the **Title** text area, type `Suction vs. Mean Stress`.

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

6 In the **x minimum** text field, type `0.1`.

7 In the **x maximum** text field, type `0.65`.

8 In the **y minimum** text field, type `-0.01`.

9 In the **y maximum** text field, type `0.21`.

Path AB

1 Right-click **Load Paths** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, type `Path AB` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path AB**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Solid Mechanics>Soil material properties> Extended Barcelona Basic>solid.ss - Suction - Pa**.

5 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component 1 (comp1)>Solid Mechanics>Stress>solid.pm - Pressure - N/m²**.

6 Locate the **y-Axis Data** section. From the **Unit** list, choose **MPa**.

7 Locate the **x-Axis Data** section. From the **Unit** list, choose **MPa**.

8 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Blue**.

Path BDF

1 Right-click **Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path BDF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path BDF**.

Wetting Paths

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

2 In the **Settings** window for **1D Plot Group**, type `Wetting Paths` in the **Label** text field.

3 Locate the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Specific Volume vs. Mean Stress`.

Path AB

1 Right-click **Wetting Paths** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Cut Point 3D: Path AB**.

4 In the **Label** text field, type `Path AB`.

5 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Solid Mechanics>Soil material properties> Extended Barcelona Basic>solid.epsm1.v - Specific volume**.

6 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component 1 (comp1)>Solid Mechanics>Stress>solid.pm - Pressure - N/m²**.

7 Locate the **x-Axis Data** section. From the **Unit** list, choose **MPa**.

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

9 Find the **Line markers** subsection. From the **Marker** list, choose **Asterisk**.

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

Path BDF

1 Right-click **Path AB** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **Cut Point 3D: Path BDF**.

4 In the **Label** text field, type `Path BDF`.

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

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

7 In the table, enter the following settings:

Legends
ABDF

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>Stationary**.

4 Click **Add Study** in the window toolbar.

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

STUDY: WETTING PATH ACDF

1 In the **Model Builder** window, click **Study 2**.

2 In the **Settings** window for **Study**, type `Study: Wetting Path ACDF` in the **Label** text field.

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

Stationary: Path AC

1 In the **Model Builder** window, under **Study: Wetting Path ACDF** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path AC` in the **Label** text field.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(3,0.005,4)`	

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

Stationary: Path CD

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path CD` in the **Label** text field.

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

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

5 From the **Study** list, choose **Study: Wetting Path ACDF, Stationary: Path AC**.

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

7 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(4,0.01,5)`	

Step 2: Stationary: Path CD

Right-click **Step 2: Stationary: Path CD** and choose **Compute Selected Step**.

Stationary: Path DF

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path DF` in the **Label** text field.

3 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**.

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

5 From the **Study** list, choose **Study: Wetting Path ACDF, Stationary: Path CD**.

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

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

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(5,0.005,6)`	

Step 3: Stationary: Path DF

Right-click **Step 3: Stationary: Path DF** and choose **Compute Selected Step**.

RESULTS

Cut Point 3D: Path AC

1 In the **Model Builder** window, right-click **Cut Point 3D: Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path AC` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Wetting Path ACDF/ Solution Store 2 (sol4)**.

Cut Point 3D: Path CD

1 In the **Model Builder** window, right-click **Cut Point 3D: Path BDF** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path CD` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Wetting Path ACDF/ Solution Store 3 (sol5)**.

Cut Point 3D: Path DF

1 Right-click **Cut Point 3D: Path CD** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path DF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Wetting Path ACDF/ Solution 3 (sol3)**.

Path AC

1 In the **Model Builder** window, right-click **Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path AC` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path AC**.

Path CD

1 Right-click **Path AC** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path CD` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path CD**.

Path DF

1 Right-click **Path CD** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path DF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path DF**.

Path AC

1 In the **Model Builder** window, right-click **Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path AC` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path AC**.

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

5 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

Path CD

1 Right-click **Path AC** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path CD` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path CD**.

Path DF

1 Right-click **Path CD** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path DF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path DF**.

4 Click to collapse the **Coloring and Style** section. Locate the **Legends** section. Select the **Show legends** check box.

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

6 In the table, enter the following settings:

Legends
ACDF

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>Stationary**.

4 Click **Add Study** in the window toolbar.

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

STUDY: WETTING PATH ACEF

1 In the **Model Builder** window, click **Study 3**.

2 In the **Settings** window for **Study**, type `Study: Wetting Path ACEF` in the **Label** text field.

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

Stationary: Path ACE

1 In the **Model Builder** window, under **Study: Wetting Path ACEF** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path ACE` in the **Label** text field.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(7,0.005,8)`	

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

Stationary: Path EF

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path EF` in the **Label** text field.

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

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

5 From the **Study** list, choose **Study: Wetting Path ACEF, Stationary: Path ACE**.

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

7 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(8,0.01,9)`	

Step 2: Stationary: Path EF

Right-click **Step 2: Stationary: Path EF** and choose **Compute Selected Step**.

RESULTS

Cut Point 3D: Path ACE

1 In the **Model Builder** window, right-click **Cut Point 3D: Path AC** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path ACE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Wetting Path ACEF/ Solution Store 4 (sol7)**.

Cut Point 3D: Path EF

1 Right-click **Cut Point 3D: Path ACE** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path EF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Wetting Path ACEF/ Solution 6 (sol6)**.

Path ACE

1 In the **Model Builder** window, right-click **Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path ACE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path ACE**.

Path EF

1 Right-click **Path ACE** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path EF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path EF**.

Load Paths

In the **Model Builder** window, click **Load Paths**.

Table Annotation 1

1 In the **Load Paths** 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 In the table, enter the following settings:

x-coordinate	y-coordinate	Annotation
0.15	0.2	A
0.15	0	B
0.35	0.2	C
0.35	0	D
0.6	0.2	E
0.6	0	F
0.15	0.1	G
0.6	0.1	H

5 In the **Load Paths** toolbar, click **Plot**.

Path ACE

1 In the **Model Builder** window, right-click **Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path ACE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path ACE**.

4 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Blue**.

5 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.

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

Path EF

1 In the **Model Builder** window, right-click **Path BDF** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path EF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path EF**.

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

5 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.

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

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

Legends
ACEF

8 In the **Wetting Paths** toolbar, click **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>Stationary**.

4 Click **Add Study** in the window toolbar.

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

STUDY: DRYING PATH BFE

1 In the **Model Builder** window, click **Study 4**.

2 In the **Settings** window for **Study**, type `Study: Drying Path BFE` in the **Label** text field.

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

Stationary: Path BF

1 In the **Model Builder** window, under **Study: Drying Path BFE** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path BF` in the **Label** text field.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(10,0.005,11)`	

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

Stationary: Path FE

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path FE` in the **Label** text field.

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

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

5 From the **Study** list, choose **Study: Drying Path BFE, Stationary: Path BF**.

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

7 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(11,0.01,12)`	

Step 2: Stationary: Path FE

Right-click **Step 2: Stationary: Path FE** and choose **Compute Selected Step**.

RESULTS

Cut Point 3D: Path BF

1 In the **Model Builder** window, right-click **Cut Point 3D: Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path BF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Drying Path BFE/ Solution Store 5 (sol9)**.

Cut Point 3D: Path FE

1 In the **Model Builder** window, right-click **Cut Point 3D: Path BDF** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path FE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Drying Path BFE/ Solution 8 (sol8)**.

Drying Paths

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

2 In the **Settings** window for **1D Plot Group**, type `Drying Paths` in the **Label** text field.

3 Locate the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Specific Volume vs. Mean Stress`.

Path BF

1 Right-click **Drying Paths** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, type `Path BF` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path BF**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Solid Mechanics>Soil material properties> Extended Barcelona Basic>solid.epsm1.v - Specific volume**.

5 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component 1 (comp1)>Solid Mechanics>Stress>solid.pm - Pressure - N/m²**.

6 Locate the **x-Axis Data** section. From the **Unit** list, choose **MPa**.

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

8 Find the **Line markers** subsection. From the **Marker** list, choose **Asterisk**.

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

Path FE

1 Right-click **Path BF** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path FE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path FE**.

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

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

6 In the table, enter the following settings:

Legends
`Path BFE`

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>Stationary**.

4 Click **Add Study** in the window toolbar.

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

Study: Drying Path BAE

1 In the **Model Builder** window, click **Study 5**.

2 In the **Settings** window for **Study**, type `Study: Drying Path BAE` in the **Label** text field.

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

Stationary: Path BA

1 In the **Model Builder** window, under **Study: Drying Path BAE** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path BA` in the **Label** text field.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(13,0.01,14)`	

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

Stationary: Path AE

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path AE` in the **Label** text field.

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

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

5 From the **Study** list, choose **Study: Drying Path BAE, Stationary: Path BA**.

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

7 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(14,0.005,15)`	

Step 2: Stationary: Path AE

Right-click **Step 2: Stationary: Path AE** and choose **Compute Selected Step**.

RESULTS

Cut Point 3D: Path BA

1 In the **Model Builder** window, right-click **Cut Point 3D: Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path BA` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Drying Path BAE/ Solution Store 6 (sol11)**.

Cut Point 3D: Path AE

1 In the **Model Builder** window, right-click **Cut Point 3D: Path BDF** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path AE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Drying Path BAE/ Solution 10 (sol10)**.

Path BA

1 In the **Model Builder** window, right-click **Path BF** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path BA` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path BA**.

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

5 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

Path AE

1 In the **Model Builder** window, right-click **Path FE** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path AE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path AE**.

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

5 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

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

Legends
`Path BAE`

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>Stationary**.

4 Click **Add Study** in the window toolbar.

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

STUDY: DRYING PATH BGHE

1 In the **Model Builder** window, click **Study 6**.

2 In the **Settings** window for **Study**, type `Study: Drying Path BGHE` in the **Label** text field.

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

Stationary: Path BG

1 In the **Model Builder** window, under **Study: Drying Path BGHE** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path BG` in the **Label** text field.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	**Parameter value list**	**Parameter unit**
para (Parameter)	`range(16,0.01,17)`	

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

Stationary: Path GH

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path GH` in the **Label** text field.

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

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

5 From the **Study** list, choose **Study: Drying Path BGHE, Stationary: Path BG**.

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

7 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(17,0.005,18)`	

Step 2: Stationary: Path GH

Right-click **Step 2: Stationary: Path GH** and choose **Compute Selected Step**.

Stationary: Path HE

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, type `Stationary: Path HE` in the **Label** text field.

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

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

5 From the **Study** list, choose **Study: Drying Path BGHE, Stationary: Path GH**.

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

7 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Parameter)	`range(18,0.01,19)`	

Step 3: Stationary: Path HE

Right-click **Step 3: Stationary: Path HE** and choose **Compute Selected Step**.

RESULTS

Cut Point 3D: Path BG

1 In the **Model Builder** window, right-click **Cut Point 3D: Path AB** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path BG` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Drying Path BGHE/ Solution Store 7 (sol13)**.

Cut Point 3D: Path GH

1 In the **Model Builder** window, right-click **Cut Point 3D: Path BDF** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path GH` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Drying Path BGHE/ Solution Store 8 (sol14)**.

Cut Point 3D: Path HE

1 Right-click **Cut Point 3D: Path GH** and choose **Duplicate**.

2 In the **Settings** window for **Cut Point 3D**, type `Cut Point 3D: Path HE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: Drying Path BGHE/ Solution 12 (sol12)**.

Path BG

1 In the **Model Builder** window, right-click **Path BA** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path BG` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path BG**.

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

5 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.

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

Path GH

1 Right-click **Path BG** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path GH` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path GH**.

Path HE

1 In the **Model Builder** window, right-click **Path AE** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path HE` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path HE**.

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

5 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.

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

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

Legends
Path BGHE

8 In the **Drying Paths** toolbar, click **Plot**.

Path GH

1 In the **Model Builder** window, right-click **Path EF** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Path GH` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 3D: Path GH**.

4 Drag and drop below **Path EF**.

5 In the **Load Paths** toolbar, click **Plot**.