Isotropic Compression with Modified Cam-Clay Material Model

Introduction

Isotropic compression is a common material test for soils. In this example, the Modified Cam-Clay (MCC) soil model is examined; in particular the relation between the void ratio and the logarithm of the hydrostatic pressure or mean stress is studied.

In COMSOL Multiphysics, several soil plasticity material models are implemented. With particular choices of parameters, some of these can be reduced to the MCC model. For example, the Extended Barcelona Basic model (BBMx) with zero suction reduces to the Modified Cam-Clay model. By setting the initial structural strength and the additional void ratio to zero and the plastic potential shape parameter to two, the Modified Structured Cam-Clay (MSCC) model reduces to the MCC model. With these choices of material parameters, we can verify that the BBMx and MSCC models replicate the behavior of the MCC model.

Model Definition

In this example, the test specimen is a cylindrical soil sample of 10 cm in diameter and 10 cm in height, see Figure 1. Due to the symmetry, the model is solved in 2D axisymmetry. A boundary load produces isotropic compression conditions.

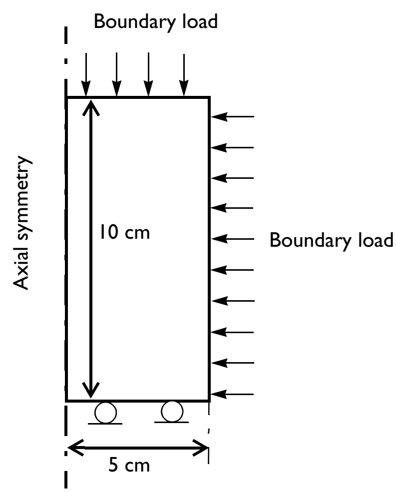

Figure 1: Dimensions, boundary conditions, and boundary loads for the isotropic compression test.

MODIFIED CAM-CLAY MATERIAL PROPERTIES

TABLE 1: MATERIAL PROPERTIES FOR THE MODIFIED CAM-CLAY MATERIAL MODEL.

Property	Variable	Value
Density	ρ	2400 kg/m^3
Shear Modulus	G	10 MPa
Angle of internal friction	ϕ	30°
Swelling index	κ	0.013
Compression index	λ	0.032
Void ratio at reference pressure	e_{ref}	0.7
Reference pressure	p_{ref}	100 kPa
Initial consolidation pressure	p_{c0}	300 kPa

EXTENDED BARCELONA BASIC MATERIAL PROPERTIES

Common material properties are the same as for the MCC model. Properties that are specific to the BBMx are listed in Table 2.

TABLE 2: MATERIAL PROPERTIES FOR THE EXTENDED BARCELONA BASIC MATERIAL MODEL.

Property	Variable	Value
Suction	σ	0
Swelling index for changes in suction	κ_{s}	0.0013
Compression index for changes in suction	λ_{s}	0.0032
Weight parameter	w	0.75
Soil stiffness parameter	m	10 kPa
Plastic potential smoothing parameter	b_{s}	100
Tension to suction ratio	k	0.6
Initial yield value for suction	s_{y0}	0.3 MPa

Note that material parameters related to the suction are chosen arbitrarily and does not affect the results since the suction is set to zero.

MODIFIED STRUCTURED CAM-CLAY MATERIAL PROPERTIES

The material parameters in common for the MSCC and MCC models are set identical.The properties that are specific to the MSCC model are listed in Table 3.

TABLE 3: MATERIAL PROPERTIES FOR THE MODIFIED STRUCTURED CAM-CLAY MATERIAL MODEL.

Property	Variable	Value
Initial structure strength	p_{bi}	0
Plastic potential shape parameter	ζ	2
Additional void ratio at initial yielding	Δe_{i}	0
Destructuring index for volumetric deformation	d_{v}	1
Destructuring index for shear deformation	d_{s}	1
Critical effective deviatoric plastic strain	$\varepsilon_{\mathrm{dc}}{}^{\mathrm{p}}$	0.02

Note that material parameters related to the structuring are chosen arbitrarily and does not affect the results since the structure strength will be set to zero in the Elastoplastic Soil feature.

CONSTRAINTS AND LOADS

- The left boundary of the computational domain is the axis of symmetry. A roller condition is applied at the lower boundary, and a boundary load is applied on the right and the top boundaries.
- The boundary load is applied in three steps: First the pressure increases from $0.5p_0$ to $3p_0$. Next, the pressure is reduced to $1.5p_0$, and finally the pressure increases again up to $4p_0$.

In order to reproduce the analytical results of Ref. 1, the load is controlled in a parametric analysis.

Results and Discussion

The relation between void ratio and pressure is shown in Figure 2. Note that the pressure is plotted on a logarithmic scale.

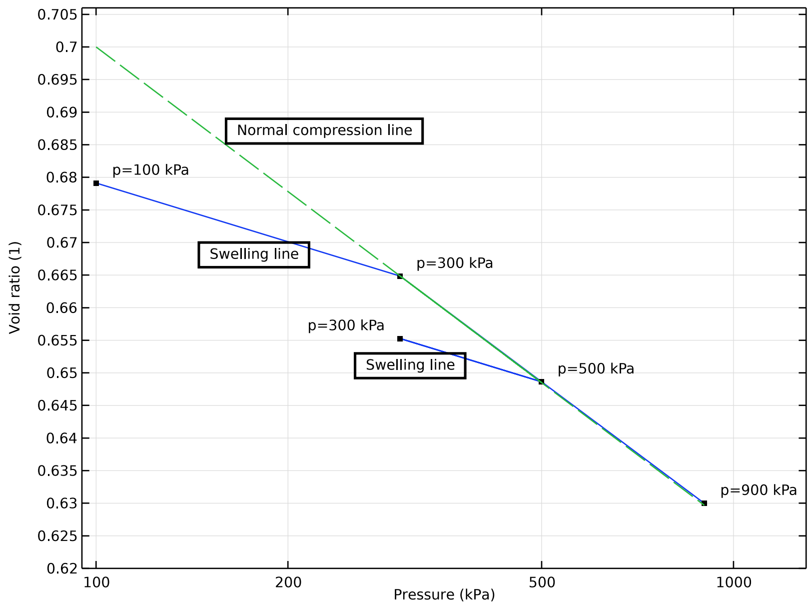

Figure 2: Void ratio as a function of the pressure in an isotropic compression test.

For the pressures from 100 kPa to 300 kPa, the curve follows the slope defined by the swelling index κ. Once the consolidation pressure is reached (p_{c0} = 300 kPa), the soil behaves plastically, and the curve follows the slope defined by the compression index λ. During the unloading and reloading of the soil (between the parameters 0.4 and 0.8), the curve in Figure 2 follows the elastic slope defined by the swelling index κ. Finally, the soil is compressed between the parameters 0.8 and 1, and it undergoes plastic deformation until it reaches its final stage at a void ratio e_0 = 0.630 at p = 900 kPa.

Figure 2 reproduces characteristic curves called the Normal Compression Line (NCL) and the Swelling Line (or Unloading/Reloading Line URL). The NCL has a slope defined by the compression index λ, and at $p = p_{ref}$ on the NCL the void ratio is $e = e_{ref}$.

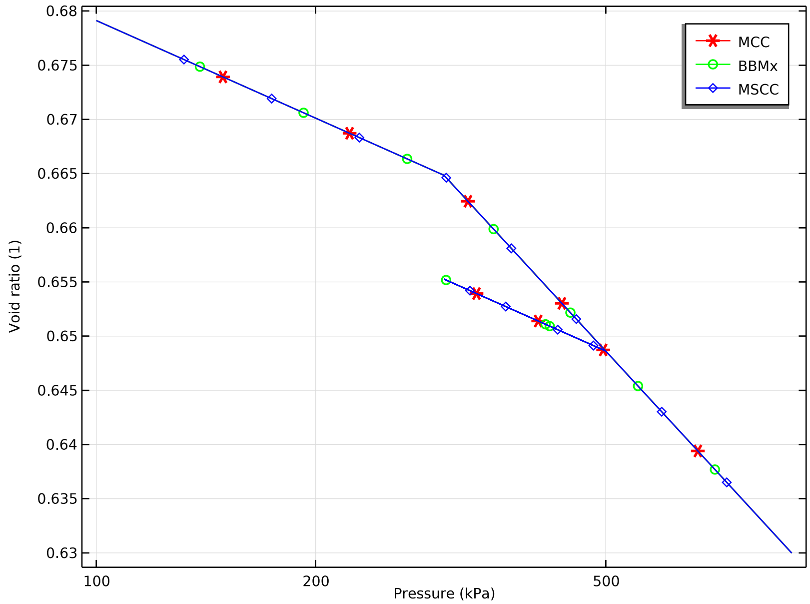

Figure 3: Void ratio versus pressure in the isotropic compression test for all three material models.

Figure 3 shows the variation in the void ratio with applied pressure for all three models. The behavior predicted is the same for all soil models, which verifies the correctness of the BBMx model for the case of saturated soils and that of the MSCC model for destructured soils.

Once the stress level reaches the MCC ellipse in stress space, ($p = p_{c0}$, parameter `para = 0.2`), the soil starts deforming plastically. Isotropic hardening expands the major semi-axis of the ellipse, with the expansion determined by the increase in consolidation pressure, see Figure 4. During the unloading–reloading steps (between parameter values 0.4 and 0.8), the consolidation pressure is kept constant.

The changes in consolidation pressure with respect to the boundary load is identical for all three material models, as expected.

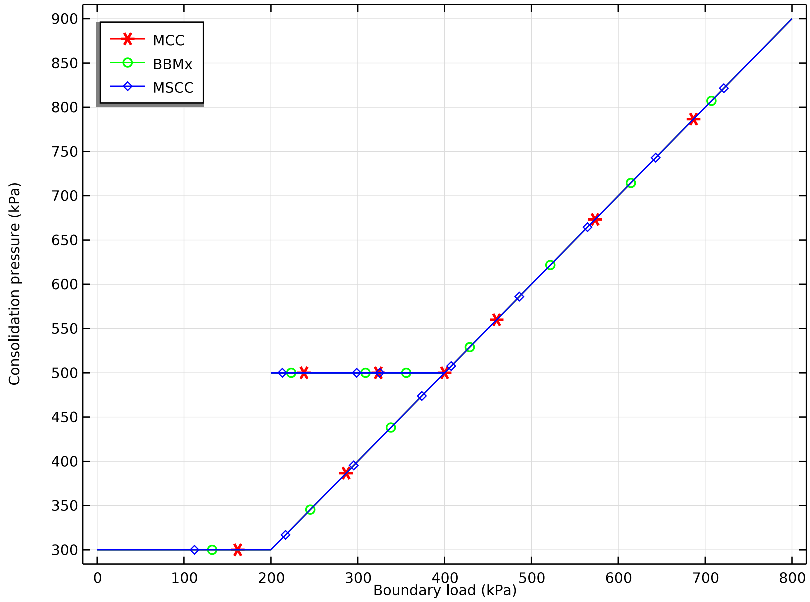

Figure 4: Increase in consolidation pressure due to isotropic hardening.

Reference

1. W.F. Chen and E. Mizuno, *Nonlinear Analysis in Soil Mechanics*, Elsevier, 1990.

Application Library path: `Geomechanics_Module/Verification_Examples/isotropic_compression`

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 Axisymmetric**.

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

3 Click **Add**.

4 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
p0	200[kPa]	2E5 Pa	Pressure

Boundary Load

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 `Boundary Load`.

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

t	f(t)
0	0
0.4	2*p0
0.6	1*p0
0.8	2*p0
1	4*p0

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

Argument	Unit
t	1

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

Function	Unit
Pressure	Pa

8 Click **Plot**.

An interpolation function is used to define the boundary load. First, a pressure of 2*p0 is applied. Next, the load is reduced to p0 followed by a reloading to 2*p0 and finally an increase up to 4*p0.

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 `5[cm]`.

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

Array 1 (arr1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

2 Select the object **r1** only.

3 In the **Settings** window for **Array**, locate the **Size** section.

4 In the **z size** text field, type `3`.

5 Locate the **Displacement** section. In the **z** text field, type `15[cm]`.

6 Click **Build All Objects**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar.

Add the three different **Elastoplastic Soil** material models. Start with the MCC model.

SOLID MECHANICS (SOLID)

Modified Cam-Clay Model (MCC)

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Solid Mechanics (solid)** and choose **Material Models>Elastoplastic Soil Material**.

2 In the **Settings** window for **Elastoplastic Soil Material**, type `Modified Cam-Clay Model (MCC)` in the **Label** text field.

3 Select Domain 1 only.

4 Locate the **Elastoplastic Soil Material** section. From the **Specify** list, choose **Shear modulus**.

5 From the M list, choose **Match to Mohr–Coulomb criterion**.

6 In the p_{c0} text field, type `300[kPa]`.

Next, add an BBMx model with zero suction in order to replicate the MCC behavior.

7 Right-click **Modified Cam-Clay Model (MCC)** and choose **Duplicate**.

Extended Barcelona Basic Model (BBMx)

1. In the **Model Builder** window, under **Component 1 (comp1)>Solid Mechanics (solid)** click **Modified Cam-Clay Model (MCC) 1**.
2. In the **Settings** window for **Elastoplastic Soil Material**, type `Extended Barcelona Basic Model (BBMx)` in the **Label** text field.
3. Locate the **Domain Selection** section. Click **Clear Selection**.
4. Select Domain 2 only.
5. Locate the **Elastoplastic Soil Material** section. From the **Material model** list, choose **Extended Barcelona Basic**.
6. In the s text field, type `0`.

Last, add a MSCC model. Set the initial structural strength and the additional void ratio to zero. Also, set the plastic potential shape parameter to 2.

Modified Cam-Clay Model (MCC)

In the **Model Builder** window, right-click **Modified Cam-Clay Model (MCC)** and choose **Duplicate**.

Modified Structured Cam-Clay Model (MSCC)

1. In the **Model Builder** window, under **Component 1 (comp1)>Solid Mechanics (solid)** click **Modified Cam-Clay Model (MCC) 1**.
2. In the **Settings** window for **Elastoplastic Soil Material**, type `Modified Structured Cam-Clay Model (MSCC)` in the **Label** text field.
3. Locate the **Domain Selection** section. Click **Clear Selection**.
4. Select Domain 3 only.
5. Locate the **Elastoplastic Soil Material** section. From the **Material model** list, choose **Modified Structured Cam-Clay**.
6. From the M list, choose **Match to Mohr–Coulomb criterion**.
7. From the p_{bi} list, choose **User defined**. From the ζ list, choose **User defined**. In the associated text field, type `2`.
8. From the Δe_{i} list, choose **User defined**.

Add one **Material** feature for each of the three models. Note that the material properties in common should be kept the same between all models. The parameters unique to the BBMx and MSCC models are set arbitrarily, as they have no influence on the solution because of the settings chosen in the corresponding **Elastoplastic Soil Material** nodes under **Solid Mechanics**.

MATERIALS

Modified Cam-Clay 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 `Modified Cam-Clay Material` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. Click **Clear Selection**.

4 Select Domain 1 only.

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

Property	Variable	Value	Unit	Property group
Shear modulus	G	`10[MPa]`	N/m^2	Bulk modulus and shear modulus
Swelling index	kappaSwelling	`0.013`	1	Cam-Clay
Compression index	lambdaComp	`0.032`	1	Cam-Clay
Void ratio at reference pressure	evoidref	`0.7`	1	Cam-Clay
Angle of internal friction	internalphi	`30[deg]`	rad	Mohr-Coulomb
Density	rho	`2400[kg/m^3]`	kg/m^3	Basic

6 Right-click **Modified Cam-Clay Material** and choose **Duplicate**.

Extended Barcelona Basic Material

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Modified Cam-Clay Material 1 (mat2)**.

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

3 Locate the **Geometric Entity Selection** section. Click **Clear Selection**.

4 Select Domain 2 only.

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

Property	**Variable**	**Value**	**Unit**	**Property group**
Swelling index	kappaSwelling	`0.013`	1	Barcelona Basic
Swelling index for changes in suction	kappaSwellings	`0.0013`	1	Barcelona Basic
Compression index at saturation	lambdaComp0	`0.032`	1	Barcelona Basic
Compression index for changes in suction	lambdaCompss	`0.0032`	1	Barcelona Basic
Weight parameter	wB	`0.75`	1	Barcelona Basic
Soil stiffness parameter	mB	`1e4`	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	`0.7`	1	Barcelona Basic
Initial yield value for suction	sy0	`0.3[MPa]`	Pa	Barcelona Basic

6 Right-click **Extended Barcelona Basic Material** and choose **Duplicate**.

Modified Structured Cam-Clay Material

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Extended Barcelona Basic Material 1 (mat3)**.

2 In the **Settings** window for **Material**, type `Modified Structured Cam-Clay Material` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. Click  **Clear Selection**.

4 Select Domain 3 only.

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

Property	**Variable**	**Value**	**Unit**	**Property group**
Swelling index for structured clay	kappaSwellingS	`0.013`	l	Structured Cam-Clay
Compression index for destructured clay	lambdaCompS	`0.032`	l	Structured Cam-Clay
Void ratio at reference pressure for destructured clay	evoidrefS	`0.7`	l	Structured Cam-Clay
Destructuring index for volumetric deformation	dvS	1	l	Structured Cam-Clay
Destructuring index for shear deformation	dsS	1	l	Structured Cam-Clay
Critical equivalent deviatoric plastic strain	epdevc	`0.02`	l	Structured Cam-Clay

Use the **Test Material** feature to carry out isotropic compression tests on the three different material models.

SOLID MECHANICS (SOLID)

Test Material [MCC]

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

2 In the **Settings** window for **Test Material**, type `Test Material [MCC]` in the **Label** text field.

3 Select Domain 1 only.

4 Locate the **Material Tests** section. In the N_{p} text field, type `100`.

5 From the **Test setup** list, choose **User defined**.

6 From the **Test control** list, choose **Force driven**.

7 Find the **Tests** subsection. Clear the **Uniaxial test** check box.

8 Select the **Isotropic test** check box.

9 In the p text field, type `Pressure(para)`.

10 Click **Automated Model Setup** in the upper-right corner of the **Material Tests** section. From the menu, choose **Set up Tests**.

11 Right-click **Test Material [MCC]** and choose **Duplicate**.

Test Material [BBMx]

1 In the **Model Builder** window, under **Component 1 (comp1)>Solid Mechanics (solid)** click **Test Material [MCC] 1**.

2 In the **Settings** window for **Test Material**, type `Test Material [BBMx]` in the **Label** text field.

3 Locate the **Domain Selection** section. Click **Clear Selection**.

4 Select Domain 2 only.

5 Click **Automated Model Setup** in the upper-right corner of the **Material Tests** section. From the menu, choose **Set up Tests**.

Test Material [MCC]

In the **Model Builder** window, right-click **Test Material [MCC]** and choose **Duplicate**.

Test Material [MSCC]

1 In the **Model Builder** window, under **Component 1 (comp1)>Solid Mechanics (solid)** click **Test Material [MCC] 1**.

2 In the **Settings** window for **Test Material**, type `Test Material [MSCC]` in the **Label** text field.

3 Locate the **Domain Selection** section. Click **Clear Selection**.

4 Select Domain 3 only.

5 Click **Automated Model Setup** in the upper-right corner of the **Material Tests** section. From the menu, choose **Set up Tests**.

RESULTS

In the **Model Builder** window, expand the **Results>Datasets** node.

Study: Test Material [BBMx]/Solution 1a (8) (solidtm2sol1), Study: Test Material [BBMx]/Solution 1a (9) (solidtm2sol1), Study: Test Material [BBMx]/Solution 2 (5) (solidtm2sol), Study: Test Material [BBMx]/Solution 2 (6) (solidtm2sol), Study: Test Material [BBMx]/Solution 2 (7) (solidtm2sol), Study: Test Material [MCC]/Solution (1) (solidtm1sol), Study: Test Material [MCC]/Solution (2) (solidtm1sol), Study: Test Material [MCC]/Solution 1 (3) (solidtm1sol1), Study: Test Material [MSCC]/Solution 1b (15) (solidtm3sol1), Study: Test Material [MSCC]/Solution 1b (16) (solidtm3sol1), Study: Test Material [MSCC]/Solution 1b (17) (solidtm3sol1), Study: Test Material [MSCC]/Solution 3 (11) (solidtm3sol), Study: Test Material [MSCC]/Solution 3 (12) *(solidtm3sol), Study: Test Material [MSCC]/Solution 3 (13) (solidtm3sol), Study: Test Material [MSCC]/Solution 3 (14) (solidtm3sol)*

1 In the **Model Builder** window, under **Results>Datasets**, Ctrl-click to select **Study: Test Material [MCC]/Solution (1) (solidtm1sol)**, **Study: Test Material [MCC]/Solution (2) (solidtm1sol)**, **Study: Test Material [MCC]/Solution 1 (3) (solidtm1sol1)**, **Study: Test Material [BBMx]/Solution 2 (5) (solidtm2sol)**, **Study: Test Material [BBMx]/Solution 2 (6) (solidtm2sol)**, **Study: Test Material [BBMx]/Solution 2 (7) (solidtm2sol)**, **Study: Test Material [BBMx]/Solution 1a (8) (solidtm2sol1)**, **Study: Test Material [BBMx]/Solution 1a (9) (solidtm2sol1)**, **Study: Test Material [MSCC]/Solution 3 (11) (solidtm3sol)**, **Study: Test Material [MSCC]/Solution 3 (12) (solidtm3sol)**, **Study: Test Material [MSCC]/Solution 3 (13) (solidtm3sol)**, **Study: Test Material [MSCC]/Solution 3 (14) (solidtm3sol)**, **Study: Test Material [MSCC]/Solution 1b (15) (solidtm3sol1)**, **Study: Test Material [MSCC]/Solution 1b (16) (solidtm3sol1)**, and **Study: Test Material [MSCC]/Solution 1b (17) (solidtm3sol1)**.

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

Void Ratio (MCC)

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

2 In the **Settings** window for **1D Plot Group**, type `Void Ratio (MCC)` in the **Label** text field.

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

4 Locate the **Plot Settings** section.

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

6 Select the **y-axis label** check box. In the associated text field, type `Void ratio (1)`.

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

8 In the **x minimum** text field, type `95`.

9 In the **x maximum** text field, type `1300`.

10 In the **y minimum** text field, type `0.62`.

11 In the **y maximum** text field, type `0.706`.

12 Set the x-axis in the e vs. p plot to logarithmic.

13 Select the **x-axis log scale** check box.

Point Graph 1

1 Right-click **Void Ratio (MCC)** and choose **Point Graph**.

2 Select Point 1 only.

3 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose

Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics>
Soil material properties>Modified Cam-Clay>solid1.epsm1.evoid - Void ratio - 1.

4 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics>Stress> solid1.pmGp - Pressure - N/m²**.

5 Locate the **x-Axis Data** section. From the **Unit** list, choose **kPa**.

6 In the **Void Ratio (MCC)** toolbar, click **Plot**.

Annotation 1

1 In the **Model Builder** window, right-click **Void Ratio (MCC)** and choose **Annotation**.

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

3 From the **Dataset** list, choose **Study: Test Material [MCC]/Solution 1 (solidtm1sol1)**.

4 From the **Parameter value (para)** list, choose **0**.

5 Locate the **Annotation** section. In the **Text** text field, type `p=eval(at3(0,0,0, solid1.pm), kPa) kPa`.

6 From the **Geometry level** list, choose **Global**.

7 Locate the **Position** section. In the **X** text field, type `at3(0,0,0,solid1.pm)/1000`.

8 In the **Y** text field, type `at3(0,0,0,solid1.epsm1.evoid)`.

9 Click to expand the **Advanced** section. In the **Expression precision** text field, type `3`.

10 Locate the **Coloring and Style** section. From the **Anchor point** list, choose **Lower left**.

11 Right-click **Annotation 1** and choose **Duplicate**.

Annotation 2

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

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

3 From the **Parameter value (para)** list, choose **0.2**.

4 Right-click **Annotation 2** and choose **Duplicate**.

Annotation 3

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

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

3 From the **Parameter value (para)** list, choose **0.4**.

4 Right-click **Annotation 3** and choose **Duplicate**.

Annotation 4

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

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

3 From the **Parameter value (para)** list, choose **0.6**.

4 Locate the **Coloring and Style** section. From the **Anchor point** list, choose **Lower right**.

5 Right-click **Annotation 4** and choose **Duplicate**.

Annotation 5

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

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

3 From the **Parameter value (para)** list, choose **1**.

4 Locate the **Coloring and Style** section. From the **Anchor point** list, choose **Lower left**.

Point Graph 1

In the **Model Builder** window, right-click **Point Graph 1** and choose **Duplicate**.

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 `solid1.epsm1.evoidref-solid1.epsm1.lambdaComp*log(solid1.epsm1.p/solid1.epsm1.pref)`.

4 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

Void Ratio (MCC)

In the **Model Builder** window, click **Void Ratio (MCC)**.

Table Annotation 1

1 In the **Void Ratio (MCC)** 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
160	0.689	Normal compression line
145	0.67	Swelling line
255	0.653	Swelling line

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

6 Select the **Show frame** check box.

7 In the **Void Ratio (MCC)** toolbar, click **Plot**.

Void Ratio (MCC), Numerical Vs. Analytical

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

2 In the **Settings** window for **1D Plot Group**, type `Void Ratio (MCC), Numerical Vs. Analytical` in the **Label** text field.

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

4 Locate the **Plot Settings** section.

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

6 Select the **y-axis label** check box. In the associated text field, type `Void ratio (1)`.

7 Locate the **Axis** section. Select the **x-axis log scale** check box.

Point Graph 1

1 Right-click **Void Ratio (MCC), Numerical Vs. Analytical** and choose **Point Graph**.

2 Select Point 1 only.

3 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics> Soil material properties>Modified Cam-Clay>solid1.epsm1.evoid - Void ratio - 1**.

4 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics>Stress> solid1.pmGp - Pressure - N/m²**.

5 Locate the **x-Axis Data** section. 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
`Numerical`

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

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 `solid1.epsm1.evoidref-(solid1.epsm1.lambdaComp-solid1.epsm1.kappaSwelling)*`

`log(solid1.epsm1.pc/solid1.epsm1.pref)-solid1.epsm1.kappaSwelling*`
`log(solid1.epsm1.p/solid1.epsm1.pref)`.

4 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

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

Legends
`Analytical`

6 In the **Void Ratio (MCC), Numerical Vs. Analytical** toolbar, click **Plot**.

Void Ratio

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

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

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

4 Locate the **Plot Settings** section.

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

6 Select the **y-axis label** check box. In the associated text field, type `Void ratio (1)`.

7 Locate the **Axis** section. Select the **x-axis log scale** check box.

Point Graph 1

1 Right-click **Void Ratio** and choose **Point Graph**.

2 Select Point 1 only.

3 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics>Soil material properties>Modified Cam-Clay>solid1.epsm1.evoid - Void ratio - 1**.

4 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics>Stress>solid1.pmGp - Pressure - N/m^2**.

5 Locate the **x-Axis Data** section. From the **Unit** list, choose **kPa**.

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

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

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

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

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

11 In the table, enter the following settings:

Legends
MCC

Point Graph 2

1 In the **Model Builder** window, right-click **Void Ratio** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study: Test Material [BBMx]/Solution 1a (solidtm2sol1)**.

4 Select Point 1 only.

5 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component: Test Material [BBMx] (solidtm2comp)>Solid Mechanics> Soil material properties>Extended Barcelona Basic>solid2.epsm2.evoid - Void ratio - 1**.

6 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component: Test Material [BBMx] (solidtm2comp)>Solid Mechanics>Stress> solid2.pmGp - Pressure - N/m²**.

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

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

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

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

11 In the **Number** text field, type 10.

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

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

14 In the table, enter the following settings:

Legends
BBMx

Point Graph 3

1 Right-click **Void Ratio** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study: Test Material [MSCC]/Solution 1b (solidtm3sol1)**.

4 Select Point 1 only.

5 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component: Test Material [MSCC] (solidtm3comp)>Solid Mechanics> Soil material properties>Modified Structured Cam-Clay>solid3.epsm3.evoid - Void ratio - 1**.

6 Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Component: Test Material [MSCC] (solidtm3comp)>Solid Mechanics>Stress> solid3.pmGp - Pressure - N/m²**.

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

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

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

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

11 In the **Number** text field, type `12`.

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

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

14 In the table, enter the following settings:

Legends
MSCC

15 In the **Void Ratio** toolbar, click **Plot**.

Consolidation Pressure vs. Boundary Load

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

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

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

4 Locate the **Plot Settings** section.

5 Select the **x-axis label** check box. In the associated text field, type `Boundary load (kPa)`.

6 Select the **y-axis label** check box. In the associated text field, type `Consolidation pressure (kPa)`.

Point Graph 1

1 Right-click **Consolidation Pressure vs. Boundary Load** and choose **Point Graph**.

2 Select Point 1 only.

3 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics> Soil material properties>Modified Cam-Clay>solid1.epsm1.pc - Consolidation pressure - Pa**.

4 Locate the **y-Axis Data** section. From the **Unit** list, choose **kPa**.

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

6 In the **Expression** text field, type `Pressure(para)`.

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

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**.

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
MCC

Point Graph 2

1 In the **Model Builder** window, right-click **Consolidation Pressure vs. Boundary Load** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study: Test Material [BBMx]/Solution 1a (solidtm2sol1)**.

4 Select Point 1 only.

5 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component: Test Material [BBMx] (solidtm2comp)>Solid Mechanics> Soil material properties>Extended Barcelona Basic>solid2.epsm2.pc - Consolidation pressure at saturation - Pa**.

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

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

8 In the **Expression** text field, type `Pressure(para)`.

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

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

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

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

13 In the **Number** text field, type `10`.

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

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

16 In the table, enter the following settings:

Legends
BBMx

Point Graph 3

1 Right-click **Consolidation Pressure vs. Boundary Load** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study: Test Material [MSCC]/Solution 1b (solidtm3sol1)**.

4 Select Point 1 only.

5 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component: Test Material [MSCC] (solidtm3comp)>Solid Mechanics> Soil material properties>Modified Structured Cam-Clay>solid3.epsm3.pc - Consolidation pressure - Pa**.

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

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

8 In the **Expression** text field, type `Pressure(para)`.

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

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

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

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

13 In the **Number** text field, type `12`.

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

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

16 In the table, enter the following settings:

Legends
MSCC

Consolidation Pressure vs. Boundary Load

1 In the **Model Builder** window, click **Consolidation Pressure vs. Boundary Load**.

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

3 From the **Position** list, choose **Upper left**.

4 In the **Consolidation Pressure vs. Boundary Load** toolbar, click **Plot**.

Evaluate the void ratio at the final state for all three soil models.

Final Void Ratio

1 In the **Results** toolbar, click **Evaluation Group**.

2 In the **Settings** window for **Evaluation Group**, type `Final Void Ratio` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter selection (para)** list, choose **Last**.

Point Evaluation 1

1 In the **Final Void Ratio** toolbar, click **Point Evaluation**.

2 Select Point 1 only.

3 In the **Settings** window for **Point Evaluation**, click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component: Test Material [MCC] (solidtm1comp)>Solid Mechanics> Soil material properties>Modified Cam-Clay>solid1.epsm1.evoid - Void ratio - 1**.

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

Expression	Unit	Description
`solid1.epsm1.evoid`	1	`Void ratio, MCC`

5 Right-click **Point Evaluation 1** and choose **Duplicate**.

Point Evaluation 2

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

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

3 From the **Dataset** list, choose **Study: Test Material [BBMx]/Solution 1a (solidtm2sol1)**.

4 From the **Parameter selection (para)** list, choose **Last**.

5 Select Point 1 only.

6 Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
`solid2.epsm2.evoid`	1	`Void ratio, BBMx`

7 Right-click **Point Evaluation 2** and choose **Duplicate**.

Point Evaluation 3

1 In the **Model Builder** window, click **Point Evaluation 3**.
2 In the **Settings** window for **Point Evaluation**, locate the **Data** section.
3 From the **Dataset** list, choose **Study: Test Material [MSCC]/Solution 1b (solidtm3sol1)**.
4 Select Point 1 only.
5 Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
`solid3.epsm3.evoid`	1	Void ratio, MSCC

Final Void Ratio

1 In the **Model Builder** window, click **Final Void Ratio**.
2 In the **Settings** window for **Evaluation Group**, click to expand the **Format** section.
3 From the **Include parameters** list, choose **Off**.
4 In the **Final Void Ratio** toolbar, click **Evaluate**.