Created in COMSOL Multiphysics 6.0

Isotropic Compression with Modified Cam-Clay Material Model

Introduction

Isotropic compression is a common exercise in soil testing. 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.

The Extended Barcelona Basic (BBMx) model with zero suction reduces to the Modified Cam-Clay model. While, setting initial structural strength and additional void ratio to zero, and plastic potential shape parameter to two, the Modified Structured Cam-Clay (MSCC) model reduces to the Modified Cam-Clay model. With these choice of material parameters, we verify that the Extended Barcelona Basic and Modified Structured Cam-Clay material models replicate the behavior shown by the Modified Cam-Clay material model.

Model Definition

In this example, a soil sample is placed inside a cylinder 10 cm in diameter and 10 cm in height, see Figure 1. Due to the symmetry, the model is solved in 2D axial symmetry. A boundary load produces isotropic compression conditions.

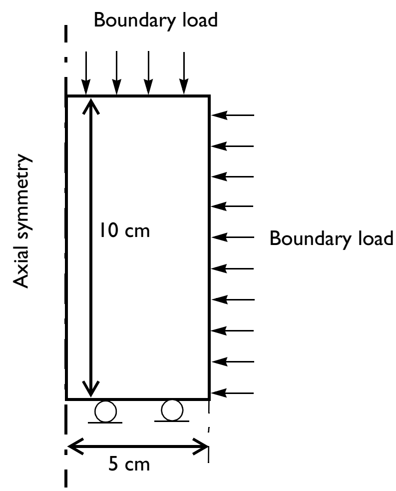

Figure 1: Dimensions, boundary conditions, and boundary load for the isotropic compression test.

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 intex	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 Extended Barcelona Basic model 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	10^4
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

Common material properties are same as for the MCC model. Properties that are specific to the Modified Structured Cam-Clay 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

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

Property	Variable	Value
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 soil is not structured.

CONSTRAINTS AND LOADS

- The left boundary is the axis of symmetry, a roller condition is applied at the lower boundary, and a boundary load is applied on the right and upper boundaries.
- The boundary load is applied in three steps: First the pressure increases from $0.5p_0$ to $3p_0$, then the sample is unloaded until the pressure reaches $1.5p_0$, and finally the pressure increases again until it reaches $4p_0$.

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

Results and Discussion

The produced void ratio versus pressure is shown in Figure 2. Note that the `log` operator is implemented in base “`e`” and not in base “10”.

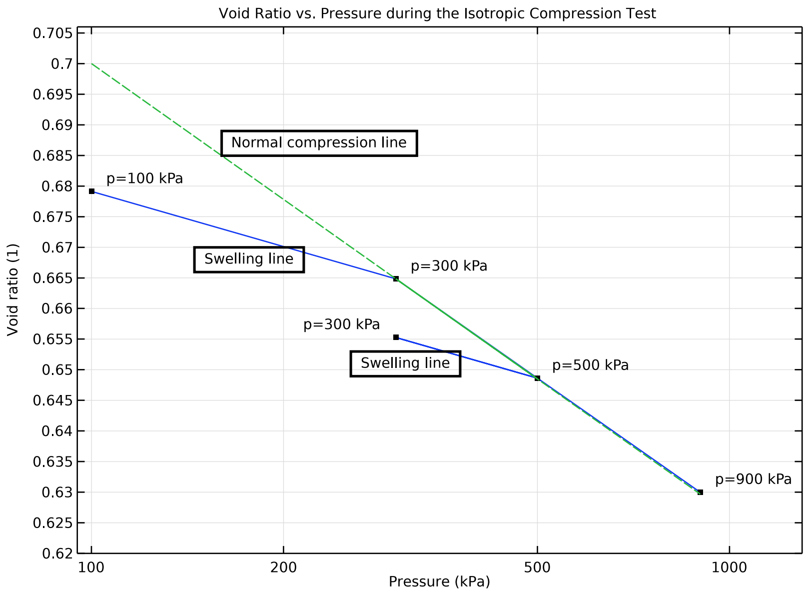

Figure 2: Void ratio as a function of the logarithm of the pressure in an isotropic compression test.

For the parametric sweep between 0 and 0.2 (the boundary load ranges from 100 kPa to 300 kPa), the curve follows the slope defined by the swelling index κ.

Once the user-defined consolidation pressure is reached (p_{c0} = 300 kPa), the sample of 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 pressure p = 900 kPa.

Figure 2 reproduces characteristic curves showing 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 normal compression line the void ratio is $e = e_{ref}$.

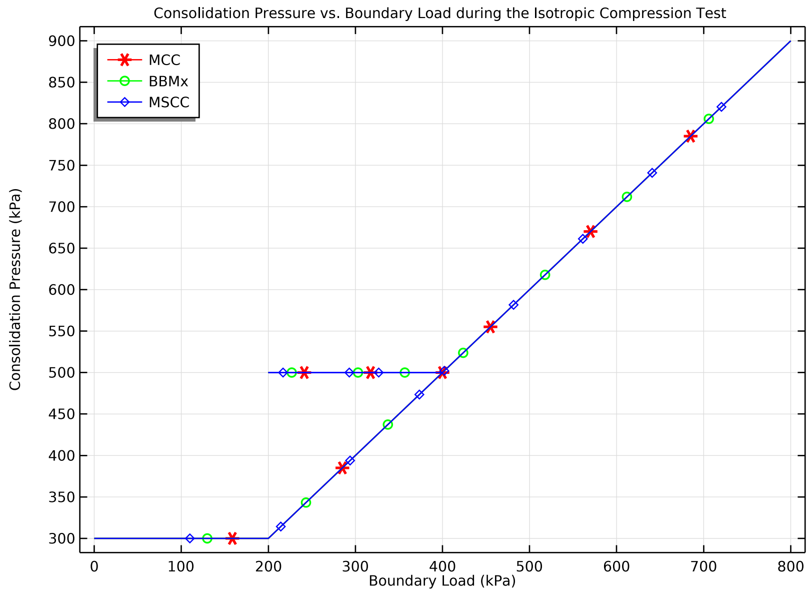

Figure 3: Void ratio versus pressure in the isotropic compression test.

Figure 3 shows the variation of the void ratio versus pressure for Modified Cam-Clay model, the Extended Barcelona Basic model, and Modified Structured Cam-Clay model. The predicted behavior is the same for all soil models. This verifies the correctness of the BBMx model for saturated soils and MSCC model for destructured soil, where it portraits similar curves in the void ratio versus pressure space as shown by the MCC model.

As expected, once the stress level reaches the modified Cam-Clay ellipse in the stress space, ($p = p_{c0}$, parameter 0.2), the soil sample starts deforming plastically. Isotropic hardening expands the major semi-axis of the ellipse, with the expansion given 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 material models.

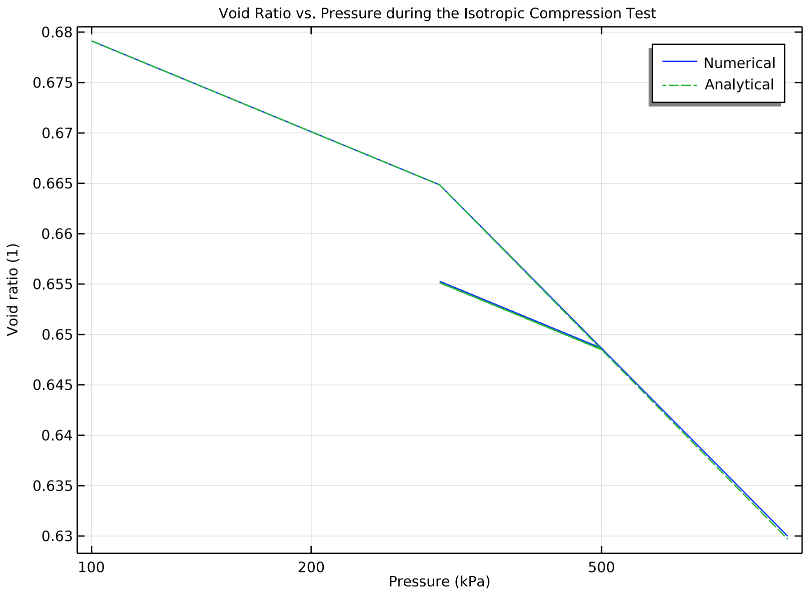

Figure 4: Increase in consolidation pressure due to isotropic hardening.

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 **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
p0	200[kPa]	2E5 Pa	Pressure

DEFINITIONS

Boundary Load

1 In the **Home** toolbar, click f(X) **Functions** and choose **Local>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
0.2	1*p0
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**.

The interpolation function is used to define the boundary load. The boundary load first compresses the soil sample, then it relaxes, and finally it compresses the sample again.

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]`.

5 Click **Build All Objects**.

DEFINITIONS

Integration 1 (intop1)

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

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

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

4 Select Point 4 only.

5 Locate the **Advanced** section. From the **Method** list, choose **Summation over nodes**.

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]`.

Roller 1

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

2 Select Boundary 2 only.

Boundary Load 1

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

2 Select Boundaries 3 and 4 only.

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

4 From the **Load type** list, choose **Pressure**.

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

The load function goes from 0 to $4*p_0$ with an unloading/reloading loop.

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.

3 Locate the **Material Contents** section. 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
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/m³	Basic

MESH 1

Mapped 1

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

Size

1. In the **Model Builder** window, click **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. From the **Predefined** list, choose **Extremely coarse**.
4. Click **Build All**.

STUDY: MCC

1. In the **Model Builder** window, click **Study 1**.
2. In the **Settings** window for **Study**, type `Study: MCC` in the **Label** text field.
3. Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Stationary

Set up an auxiliary continuation sweep for the `para` parameter.

1. In the **Model Builder** window, under **Study: MCC** click **Step 1: Stationary**.
2. In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.
3. 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(0,0.01,1)`	

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

RESULTS

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 **Manual**.
4. In the **Title** text area, type `Void Ratio vs. Pressure during the Isotropic Compression Test`.

5 Locate the **Plot Settings** section. Select the **x-axis label** check box.

6 In the associated text field, type `Pressure (kPa)`.

7 Select the **y-axis label** check box.

8 In the associated text field, type `Void ratio (1)`.

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

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

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

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

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

14 In order to plot the e vs. `ln` (p) characteristic plot, use a log scale for the x-axis.

15 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 1 (comp1)>Solid Mechanics>Soil material properties>Modified Cam-Clay>solid.epsm1.evoid - Void ratio**.

4 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**.

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: MCC/Solution 1 (sol1)**.

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

5 Locate the **Annotation** section. In the **Text** text field, type `p=eval(intop1(solid.pm), kPa) kPa`.

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

7 Locate the **Position** section. In the **R** text field, type `intop1(solid.pm)/1000`.

8 In the **Z** text field, type `intop1(solid.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**.

Annotation 2

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

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

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

Annotation 3

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

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

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

Annotation 4

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

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**.

Annotation 5

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

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 2

1 In the **Model Builder** window, under **Results>Void Ratio (MCC)** right-click **Point Graph 1** and choose **Duplicate**.

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

3 In the **Expression** text field, type `solid.epsm1.evoidref-solid.epsm1.lambdaComp*log(solid.epsm1.p/solid.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 **Manual**.

4 In the **Title** text area, type `Void Ratio vs. Pressure during the Isotropic Compression Test`.

5 Locate the **Plot Settings** section. Select the **x-axis label** check box.

6 In the associated text field, type `Pressure (kPa)`.

7 Select the **y-axis label** check box.

8 In the associated text field, type `Void ratio (1)`.

9 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 1 (comp1)>Solid Mechanics>Soil material properties>Modified Cam-Clay>solid.epsm1.evoid - Void ratio**.

4 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/m^2**.

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`

Point Graph 2

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

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

3 In the **Expression** text field, type `solid.epsm1.evoidref-(solid.epsm1.lambdaComp-solid.epsm1.kappaSwelling)*log(solid.epsm1.pc/solid.epsm1.pref)-solid.epsm1.kappaSwelling*log(solid.epsm1.p/solid.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**.

Add an Extended Barcelona Basic Material Model with zero suction in order to replicate the behavior shown by the Modified Cam-Clay Model.

SOLID MECHANICS (SOLID)

Extended Barcelona Basic Model (BBMx)

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

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 In the *s* text field, type 0.

The common material parameters should be kept the same. The additional material parameters in the BBMx model related to the suction are chosen randomly since the suction will be kept zero throughout the analysis.

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**
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

STUDY: MCC

Step 1: Stationary

Disable the BBMx model in the first study.

1 In the **Model Builder** window, under **Study: MCC** 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)>Solid Mechanics (Solid)> Extended Barcelona Basic Model (BBMx)**.

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

Add a second study for the BBMx model and disable the MCC model in this study.

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: BBMX

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

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

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

Step 1: Stationary

1 In the **Model Builder** window, under **Study: BBMx** 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)>Solid Mechanics (Solid)>Modified Cam-Clay Model (MCC)**.

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

6 Locate 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(0,0.01,1)`	

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

In order to replicate the results of the Modified Cam-Clay model with the Modified Structured Cam-Clay Material Model, set the initial structural strength and the additional void ratio to zero. Also set the plastic potential shape parameter to 2.

SOLID MECHANICS (SOLID)

Modified Structured Cam-Clay Model (MSCC)

1. In the **Model Builder** window, right-click **Modified Cam-Clay Model (MCC)** and choose **Duplicate**.
2. In the **Settings** window for **Elastoplastic Soil Material**, type `Modified Structured Cam-Clay Model (MSCC)` in the **Label** text field.
3. Locate the **Elastoplastic Soil Material** section. From the **Material model** list, choose **Modified Structured Cam-Clay**.
4. From the M list, choose **Match to Mohr-Coulomb criterion**.
5. From the p_{bi} list, choose **User defined**. From the ζ list, choose **User defined**. In the associated text field, type `2`.
6. From the Δe_{i} list, choose **User defined**.

The common material parameters should be kept the same as the MCC model. The additional material parameters in the MSCC model are chosen randomly as they will not affect the analysis.

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

STUDY: MCC

Step 1: Stationary

Disable the MSCC model in the first and second studies.

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

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

3 In the tree, select **Component 1 (Comp1)>Solid Mechanics (Solid)> Modified Structured Cam-Clay Model (MSCC)**.

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

STUDY: BBMX

Step 1: Stationary

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

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

3 In the tree, select **Component 1 (Comp1)>Solid Mechanics (Solid)> Modified Structured Cam-Clay Model (MSCC)**.

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

Add a third study for the MSCC model and disable the MCC and BBMx models in this study.

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: MSCC

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

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

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

Step 1: Stationary

1 In the **Model Builder** window, under **Study: MSCC** 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)>Solid Mechanics (Solid)>Modified Cam-Clay Model (MCC)** and **Component 1 (Comp1)>Solid Mechanics (Solid)>Extended Barcelona Basic Model (BBMx)**.

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

6 Locate 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(0,0.01,1)`	

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

RESULTS

Void Ratio, MCC vs. BBMx vs. MSCC

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 vs. BBMx vs. MSCC` in the **Label** text field.

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

4 In the **Title** text area, type `Void Ratio vs. Pressure during the Isotropic Compression Test`.

5 Locate the **Plot Settings** section. Select the **x-axis label** check box.

6 In the associated text field, type `Pressure (kPa)`.

7 Select the **y-axis label** check box.

8 In the associated text field, type `Void ratio (1)`.

9 In order to plot the e vs. ln (p) characteristic plot, use a log scale for the x-axis.

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

Point Graph 1

1 Right-click **Void Ratio, MCC vs. BBMx vs. MSCC** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study: MCC/Solution 1 (sol1)**.

4 Select Point 4 only.

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> Modified Cam-Clay>solid.epsm1.evoid - Void ratio**.

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

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

12 In the table, enter the following settings:

Legends
MCC

Point Graph 2

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

2. In the **Settings** window for **Point Graph**, locate the **Data** section.
3. From the **Dataset** list, choose **Study: BBMx/Solution 2 (sol2)**.
4. Select Point 4 only.
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.epsm2.evoid - Void ratio**.
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/m^2**.
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. In the **Number** text field, type 10.
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
BBMx

Point Graph 3

1. Right-click **Void Ratio, MCC vs. BBMx vs. MSCC** and choose **Point Graph**.
2. In the **Settings** window for **Point Graph**, locate the **Data** section.
3. From the **Dataset** list, choose **Study: MSCC/Solution 3 (sol3)**.
4. Select Point 4 only.
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> Modified Structured Cam-Clay>solid.epsm3.evoid - Void ratio**.
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/m^2**.
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 In the **Number** text field, type `12`.

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
MSCC

14 In the **Void Ratio, MCC vs. BBMx vs. MSCC** 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 **Manual**.

4 In the **Title** text area, type `Consolidation Pressure vs. Boundary Load during the Isotropic Compression Test`.

5 Locate the **Plot Settings** section. Select the **x-axis label** check box.

6 In the associated text field, type `Boundary Load (kPa)`.

7 Select the **y-axis label** check box.

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

3 From the **Dataset** list, choose **Study: MCC/Solution 1 (sol1)**.

4 Select Point 4 only.

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>Modified Cam-Clay>solid.epsm1.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 **Red**.

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

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
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: BBMx/Solution 2 (sol2)**.

4 Select Point 4 only.

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.epsm2.pcs - Consolidation pressure at current suction - 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 In the **Number** text field, type `10`.

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

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

15 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: MSCC/Solution 3 (sol3)**.

4 Select Point 4 only.

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> Modified Structured Cam-Clay>solid.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 In the **Number** text field, type `12`.

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

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

15 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 8.85 e-12 **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 1 (comp1)>Solid Mechanics>Soil material properties>Modified Cam-Clay>solid.epsm1.evoid - Void ratio**.

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

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

Point Evaluation 2

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

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

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

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

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

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

Point Evaluation 3

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

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

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

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

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

5 In the **Final Void Ratio** toolbar, click = **Evaluate**.