Created in COMSOL Multiphysics 6.2

Isotropic Compression Test for Structured Clays

Introduction

Isotropic compression tests are common in soil testing to characterize the properties of the soil. It is also a common test for verification of new material models as a wide range of experimental data is available. In this example, the Modified Structured Cam-Clay (MSCC) soil model is examined, in particular the relation between the void ratio and the logarithm of the hydrostatic pressure or mean stress for four structured clays is studied.

This is a benchmark example given in the Ref. 1, where authors present experimental data as well as their simulation data. The four clays analyzed are: naturally structured Osaka clay, naturally structured Marl clay, artificially structured Ariake clay, and artificially structured Bangkok clay. Also, different cement contents by weight are considered for the two artificially structured clays.

Model Definition

In this example, a clay 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.

Boundary loads are applied on the exterior boundaries to produce isotropic compression conditions.

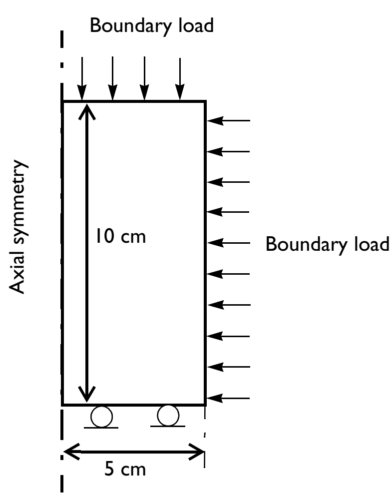

Figure 1: Dimensions, boundary conditions, and boundary load for the isotropic compression test.

MODIFIED STRUCTURED CAM-CLAY MATERIAL PROPERTIES

- The four clays analyzed here are naturally structured Osaka clay, naturally structured Marl clay, artificially structured Ariake clay, and artificially structured Bangkok clay. Also, different cement contents by weight (A_w) are considered for the two artificially structured clays.
- The common material parameters are density $\rho = 2000\ \mathrm{kg/m^3}$, reference pressure $p_{ref} = 1$ kPa, and critical effective deviatoric plastic strain $\varepsilon_{dc}{}^{p} = 0.1$.
- Material properties like the shear modulus G, slope of critical state line M, compression index for destructured clay λ_d, swelling index for structured clay κ_s, void ratio at reference pressure for destructured clay e_{refd}, additional void ratio at initial yielding Δe_i, plastic potential shape parameter ζ, destructuring index for volumetric deformation d_v, destructuring index for shear deformation d_s, initial consolidation pressure p_{c0}, and initial structure strength p_{bi} for the four different clays are shown in Table 1, Table 2, and Table 3.

TABLE 1: MATERIAL PROPERTIES OF OSAKA AND MARL CLAYS.

Material property	**Osaka clay**	**Marl clay**
G	3000 kPa	45000 kPa
M	1.15	1.30
λ_d	0.147	0.025
κ_s	0.027	0.009
e_{refd}	1.92	0.67
Δe_i	0.62	0.085
ζ	2	1.5
d_v	0.6	0.7
d_s	1	1
p_{c0}	100 kPa	4150 kPa
p_{bi}	30 kPa	300 kPa

TABLE 2: MATERIAL PROPERTIES OF ARIAKE CLAY WITH DIFFERENT CEMENT CONTENT.

Material property	$A_w = 6\%$	$A_w = 9\%$	$A_w = 18\%$
G	6000 kPa	8000 kPa	40000 kPa
M	1.60	1.45	1.35
λ_d	0.44	0.44	0.44
κ_s	0.06	0.024	0.001
e_{refd}	4.37	4.37	4.37

TABLE 2: MATERIAL PROPERTIES OF ARIAKE CLAY WITH DIFFERENT CEMENT CONTENT.

Material property	$A_w = 6\%$	$A_w = 9\%$	$A_w = 18\%$
Δe_i	1.50	2.25	2.65
ζ	1.8	0.5	0.1
d_v	0.15	0.01	0.001
d_s	10	10	30
p_{c0}	50 kPa	200 kPa	1800 kPa
p_{bi}	50 kPa	100 kPa	650 kPa

TABLE 3: MATERIAL PROPERTIES OF BANGKOK CLAY WITH DIFFERENT CEMENT CONTENT.

Material property	$A_w = 5\%$	$A_w = 10\%$	$A_w = 15\%$
G	14000 kPa	16000 kPa	30000 kPa
M	1.13	1.13	1.13
λ_d	0.26	0.26	0.26
κ_s	0.02	0.01	0.005
e_{refd}	2.86	2.86	2.86
Δe_i	0.55	0.60	0.75
ζ	1.5	0.2	0.1
d_v	0.02	0.01	0.01
d_s	10	30	30
p_{c0}	150 kPa	430 kPa	600 kPa
p_{bi}	60 kPa	400 kPa	500 kPa

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 magnitude of the boundary load is different for different clays in order to cover an appropriate range of loading.

In order to reproduce the numerical and experimental results of Ref. 1, the load is controlled in a parameter continuation sweep.

Results and Discussion

Figure 2 reproduces the characteristic curves showing the Normal Compression Line (NCL) and the Swelling Line (or Initial Loading Line) of Osaka clay. The results match very closely with the numerical results given in Ref. 1. Unlike the case for the Modified

Cam-Clay model, the NCL obtained with the MSCC model is not a straight line. The clay behavior is elastic on the initial loading line; on the NCL, the clay deforms elastoplastically. The dashed line is an Intrinsic Compression Line (ICL) for destructured clay, which has a slope defined by the compression index, λ_d. At $p = p_{ref}$ on the normal compression line, the void ratio is $e = e_{refd}$.

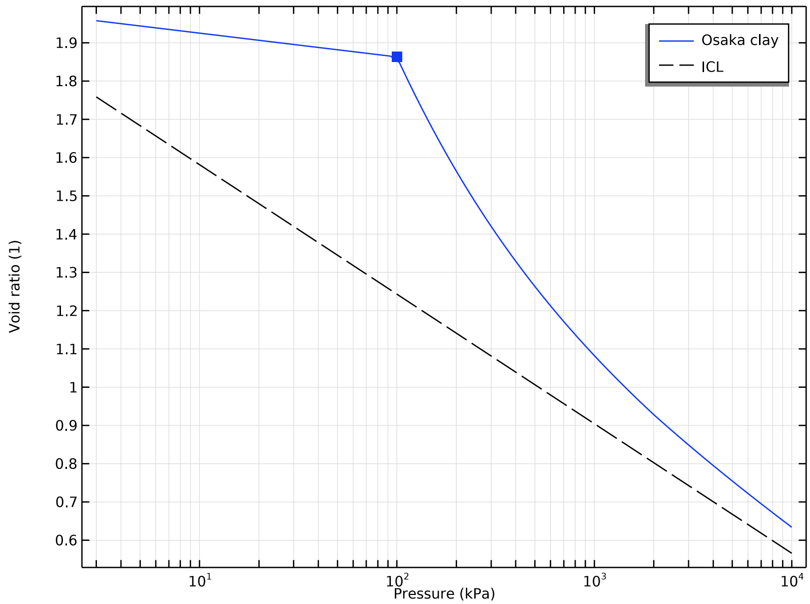

Figure 2: Void ratio as a function of the logarithm of the pressure in an isotropic compression test for Osaka clay.

The void ratio versus the logarithm of the pressure characteristics for Marl clay is shown in Figure 3. The results match very closely with numerical results given in Ref. 1. The initial loading line of Marl clay crosses the ICL approximately at $p = 20$ kPa and $e = 0.587$ in the reference, and at $p = 20.5$ kPa and $e = 0.594$ in the COMSOL Multiphysics solution.

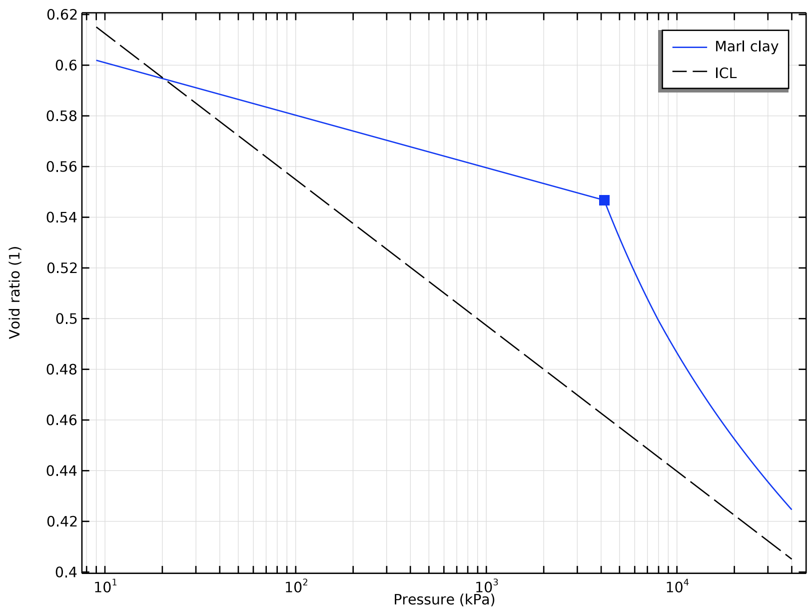

Figure 3: Void ratio as a function of the logarithm of the pressure in an isotropic compression test for Marl clay.

The void ratio versus the logarithm of the pressure characteristics for Ariake clay with different cement contents are shown in Figure 4, replicating a similar behavior as observed in Ref. 1. As the cement content increases, the difference between the ICL of destructured clay and the NCL of structured clay increases drastically, indicating the need for a sophisticated material model like MSCC for structured clays. A similar observation can be noted for Bangkok clay, see Figure 5.

However, for Bangkok clay there is one notable difference between the results presented in Ref. 1 and those obtained in COMSOL Multiphysics. The void ratio in the elastic region (including at initial consolidation pressure) increases in COMSOL Multiphysics when the cement content (A_w) is changed from 10% to 15%, as opposed to the results presented in Ref. 1. In Ref. 1, the void ratio at initial consolidation pressure (e_{refc0}) decreases with an increase in the cement content. However, the results obtained in COMSOL Multiphysics can be verified analytically.

The void ratio at initial consolidation pressure (e_{refc0}) is given by

$$e_{\mathrm{refc0}} = e_{\mathrm{refd}} - \ln\left(\frac{p_{\mathrm{c0}}}{p_{\mathrm{ref}}}\right) + \Delta e_{\mathrm{i}} \tag{1}$$

Based on material properties given in Table 3, the void ratio at the initial consolidation pressure (e_{refc0}) is 2.1072, 1.8834, and 1.9467 for Bangkok clay with a cement content (A_w) of 5%, 10%, and 15%, respectively. The COMSOL Multiphysics results matches these values at $p = p_{\mathrm{c0}}$ exactly, indicating their correctness.

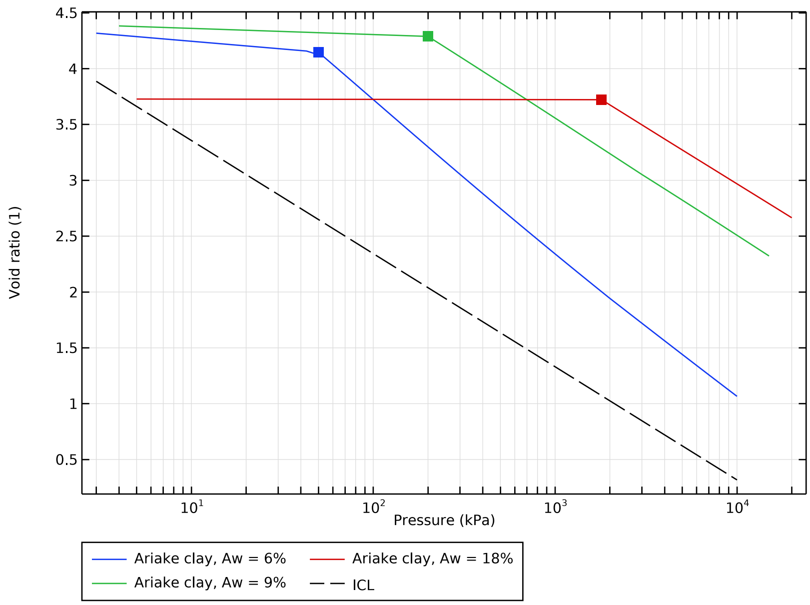

Figure 4: Void ratio as a function of the logarithm of the pressure in an isotropic compression test for Ariake clay with different cement content.

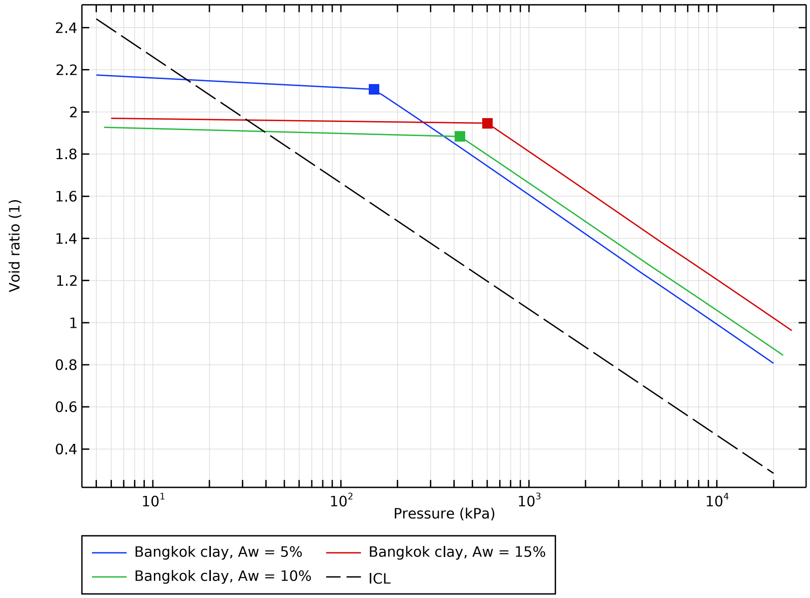

Figure 5: Void ratio as a function of the logarithm of the pressure in an isotropic compression test for Bangkok clay with different cement content.

Notes About the COMSOL Implementation

Note that the `log` operator used in the definition of the void ratio is implemented in base "*e*" and not in base "10".

Reference

1. J. Suebsuk, S. Horpibulsuk, and M.D. Liu, "Modified Structured Cam Clay: A Generalized Critical State Model for Destructured, Naturally Structured and Artificially Structured Clays," *Computer and Geotechnics*, vol. 37, pp. 956–968, 2010.

Application Library path: `Geomechanics_Module/Verification_Examples/isotropic_compression_mscc`

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**.

The four different structured clays are analyzed in this model using a parametric switch option. Eight different **Parameter Case** nodes are created to model the eight different clay materials shown in Table 1, Table 2, and Table 3.

Load the material properties from different text files for each parameter case.

GLOBAL DEFINITIONS

Clay Material Properties

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

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

3 Locate the **Parameters** section. Click **Load from File**.

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

5 In the **Home** toolbar, click **Parameter Case**.

6 In the **Settings** window for **Case**, type `Natural Osaka Clay` in the **Label** text field.

7 In the **Home** toolbar, click **Parameter Case**.

8 In the **Settings** window for **Case**, locate the **Parameters** section.

9 Click **Load from File**.

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

11 In the **Label** text field, type `Natural Marl Clay`.

12 In the **Home** toolbar, click **Parameter Case**.

13 In the **Settings** window for **Case**, locate the **Parameters** section.

14 Click **Load from File**.

15 Browse to the model's Application Libraries folder and double-click the file `isotropic_compression_mscc_ariake_Aw6_parameters.txt`.

16 In the **Label** text field, type `Cemented Ariake Clay, Aw = 6%`.

17 In the **Home** toolbar, click **Parameter Case**.

18 In the **Settings** window for **Case**, locate the **Parameters** section.

19 Click **Load from File**.

20 Browse to the model's Application Libraries folder and double-click the file `isotropic_compression_mscc_ariake_Aw9_parameters.txt`.

21 In the **Label** text field, type `Cemented Ariake Clay, Aw = 9%`.

22 In the **Home** toolbar, click **Parameter Case**.

23 In the **Settings** window for **Case**, locate the **Parameters** section.

24 Click **Load from File**.

25 Browse to the model's Application Libraries folder and double-click the file `isotropic_compression_mscc_ariake_Aw18_parameters.txt`.

26 In the **Label** text field, type `Cemented Ariake Clay, Aw = 18%`.

27 In the **Home** toolbar, click **Parameter Case**.

28 In the **Settings** window for **Case**, locate the **Parameters** section.

29 Click **Load from File**.

30 Browse to the model's Application Libraries folder and double-click the file `isotropic_compression_mscc_bangkok_Aw5_parameters.txt`.

31 In the **Label** text field, type `Cemented Bangkok Clay, Aw = 5%`.

32 In the **Home** toolbar, click **Parameter Case**.

33 In the **Settings** window for **Case**, locate the **Parameters** section.

34 Click **Load from File**.

35 Browse to the model's Application Libraries folder and double-click the file `isotropic_compression_mscc_bangkok_Aw10_parameters.txt`.

36 In the **Label** text field, type `Cemented Bangkok Clay, Aw = 10%`.

37 In the **Home** toolbar, click **Parameter Case**.

38 In the **Settings** window for **Case**, locate the **Parameters** section.

39 Click **Load from File**.

40 Browse to the model's Application Libraries folder and double-click the file `isotropic_compression_mscc_bangkok_Aw15_parameters.txt`.

41 In the **Label** text field, type `Cemented Bangkok Clay, Aw = 15%`.

Parameters 2

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

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 an interpolation function to define the boundary load.

Boundary Load

1 In the **Home** toolbar, click **Functions** and choose **Global>Interpolation**.

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

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

4 In the table, enter the following settings:

t	f(t)
0	0.01*p0
1	10*p0
2	50*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]`.

5 Click **Build Selected**.

MATERIALS

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 `Clay 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 In the **Settings** window for **Elastoplastic Soil Material**, locate the **Domain Selection** section.

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

4 Locate the **Elastoplastic Soil Material** section. From the **Material model** list, choose **Modified Structured Cam-Clay**.

5 From the **Specify** list, choose **Shear modulus**.

6 From the $\varepsilon_{dc}{}^{p}$ list, choose **User defined**. In the associated text field, type `0.1`.

7 In the p_{ref} text field, type `1[kPa]`.

8 In the p_{c0} text field, type `Pc0`.

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)`.

Roller 1

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

2 Select Boundary 2 only.

MATERIALS

Clay Material (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Clay 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	`GG`	N/m^2	Bulk modulus and shear modulus
Swelling index for structured clay	kappaSwellingS	`kappas`	1	Structured Cam-Clay
Compression index for destructured clay	lambdaCompS	`lambdas`	1	Structured Cam-Clay
Void ratio at reference pressure for destructured clay	evoidrefS	`ee`	1	Structured Cam-Clay
Destructuring index for volumetric deformation	dvS	`dvs`	1	Structured Cam-Clay
Destructuring index for shear deformation	dsS	`dss`	1	Structured Cam-Clay
Slope of critical state line	M	`MM`	1	Structured Cam-Clay
Additional void ratio at initial yielding	Deltaei	`deltae`	1	Structured Cam-Clay
Initial structure strength	pbi	`Pbi`	Pa	Structured Cam-Clay
Plastic potential shape parameter	zetaS	`zeta`	1	Structured Cam-Clay
Density	rho	`Rho`	kg/m^3	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 **Coarser**.

4 Click **Build All**.

Add a **Parametric Sweep** node and choose the **Parametric switch** option in the study settings.

STUDY 1

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

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

3 Clear the **Generate default plots** check box.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 From the **Sweep type** list, choose **Parameter switch**.

4 Click **Add**.

Step 1: Stationary

Set up an auxiliary continuation sweep for the `para` parameter to incrementally increase the boundary load.

1 In the **Model Builder** window, 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(0,0.001,0.01)` `range(0.015,0.005,1)` `range(1.02,0.02,2)`	

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

RESULTS

Use the following instructions to plot the void ratio versus logarithm of pressure curve for Osaka clay.

Natural Osaka Clay

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

2 In the **Settings** window for **1D Plot Group**, type `Natural Osaka Clay` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

4 From the **Clay Material Properties** list, choose **From list**.

5 In the **Clay Material Properties** list, select **Natural Osaka Clay**.

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

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

8 Locate the **Plot Settings** section.

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

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

Point Graph 1

1 Right-click **Natural Osaka Clay** and choose **Point Graph**.

2 Select Point 4 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 Structured Cam-Clay> solid.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 1 (comp1)>Solid Mechanics>Stress>solid.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
`Osaka clay`

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 `solid.epsm1.evoidc0`.

4 Locate the **x-Axis Data** section. In the **Expression** text field, type `solid.epsm1.pc0`.

5 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Cycle (reset)**.

6 From the **Width** list, choose **3**.

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

8 Locate the **Legends** section. Clear the **Show legends** check box.

Use the following instructions to plot the Intrinsic Compression Line (ICL) for destructured clay.

Point Graph 1

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

Point Graph 3

1 In the **Model Builder** window, click **Point Graph 3**.

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

3 In the **Expression** text field, type `solid.epsm1.evoidrefd-solid.epsm1.lambdaCompS*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 From the **Color** list, choose **From theme**.

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

Legends
ICL

7 In the **Natural Osaka Clay** toolbar, click **Plot**.

Duplicate to plot the void ratio versus logarithm of pressure curve for Marl clay.

Natural Osaka Clay

In the **Model Builder** window, right-click **Natural Osaka Clay** and choose **Duplicate**.

Natural Marl Clay

1 In the **Model Builder** window, under **Results** click **Natural Osaka Clay 1**.

2 In the **Settings** window for **1D Plot Group**, type `Natural Marl Clay` in the **Label** text field.

3 Locate the **Data** section. In the **Clay Material Properties** list, select **Natural Marl Clay**.

Point Graph 1

1 In the **Model Builder** window, expand the **Natural Marl Clay** node, then click **Point Graph 1**.
2 In the **Settings** window for **Point Graph**, locate the **Legends** section.
3 In the table, enter the following settings:

Legends
`Marl clay`

4 In the **Natural Marl Clay** toolbar, click **Plot**.

Duplicate to plot the void ratio versus logarithm of pressure curve for Ariake clay.

Natural Marl Clay

In the **Model Builder** window, right-click **Natural Marl Clay** and choose **Duplicate**.

Cemented Ariake Clay

1 In the **Model Builder** window, under **Results** click **Natural Marl Clay 1**.
2 In the **Settings** window for **1D Plot Group**, type `Cemented Ariake Clay` in the **Label** text field.
3 Locate the **Data** section. In the **Clay Material Properties** list, choose **Cemented Ariake Clay, Aw = 6%**, **Cemented Ariake Clay, Aw = 9%**, and **Cemented Ariake Clay, Aw = 18%**.

Point Graph 1

1 In the **Model Builder** window, expand the **Cemented Ariake Clay** node, then click **Point Graph 1**.
2 In the **Settings** window for **Point Graph**, locate the **Legends** section.
3 In the table, enter the following settings:

Legends
`Ariake clay, Aw = 6%`
`Ariake clay, Aw = 9%`
`Ariake clay, Aw = 18%`

Point Graph 3

1 In the **Model Builder** window, click **Point Graph 3**.
2 In the **Settings** window for **Point Graph**, locate the **Data** section.
3 From the **Dataset** list, choose **Study 1/Parametric Solutions 1 (sol2)**.
4 From the **Clay Material Properties** list, choose **From list**.

5 In the **Clay Material Properties** list, select **Cemented Ariake Clay, Aw = 6%**.

Cemented Ariake Clay

1 In the **Model Builder** window, click **Cemented Ariake Clay**.

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

3 From the **Layout** list, choose **Outside graph axis area**.

4 From the **Position** list, choose **Bottom**.

5 In the **Number of rows** text field, type `2`.

6 In the **Cemented Ariake Clay** toolbar, click **Plot**.

Duplicate to plot the void ratio versus logarithm of pressure curve for Bangkok clay.

7 Right-click **Cemented Ariake Clay** and choose **Duplicate**.

Cemented Bangkok Clay

1 In the **Model Builder** window, under **Results** click **Cemented Ariake Clay 1**.

2 In the **Settings** window for **1D Plot Group**, type `Cemented Bangkok Clay` in the **Label** text field.

3 Locate the **Data** section. In the **Clay Material Properties** list, choose **Cemented Bangkok Clay, Aw = 5%**, **Cemented Bangkok Clay, Aw = 10%**, and **Cemented Bangkok Clay, Aw = 15%**.

Point Graph 1

1 In the **Model Builder** window, expand the **Cemented Bangkok Clay** node, then click **Point Graph 1**.

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

3 In the table, enter the following settings:

Legends
`Bangkok clay, Aw = 5%`
`Bangkok clay, Aw = 10%`
`Bangkok clay, Aw = 15%`

Point Graph 3

1 In the **Model Builder** window, click **Point Graph 3**.

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

3 In the **Clay Material Properties** list, select **Cemented Bangkok Clay, Aw = 5%**.

4 In the **Cemented Bangkok Clay** toolbar, click **Plot**.