

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 $\rho = 2000 \text{ kg/m}^3$, reference pressure $p_{\text{ref}} = 1 \text{ kPa}$, and critical effective deviatoric plastic strain $\varepsilon_{\text{dc}}^{\text{P}} = 0.1$.
- 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.

Material property	Osaka clay	Marl clay
G	3000 kPa	45000 kPa
Μ	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
$d_{ m v}$	0.6	0.7
d_{s}	1	1
p_{c0}	100 kPa	4150 kPa
$p_{\rm bi}$	30 kPa	300 kPa

TABLE I: MATERIAL PROPERTIES OF OSAKA AND MARL CLAYS.

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

Material property	$A_{\rm W} = 6\%$	$A_{ m W} = 9\%$	$A_{ m w} = 18\%$
G	6000 kPa	8000 kPa	40000 kPa
Μ	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

Material property	$A_{ m W} = 6\%$	$A_{ m W} = 9\%$	$A_{\rm W} = 18\%$
Δe_{i}	1.50	2.25	2.65
ζ	1.8	0.5	0.1
$d_{ m v}$	0.15	0.01	0.001
d_{s}	10	10	30
p_{c0}	50 kPa	200 kPa	1800 kPa
$p_{\rm bi}$	50 kPa	100 kPa	650 kPa

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

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

Material property	$A_{ m W} = 5\%$	$A_{ m W}$ = 10%	$A_{ m W} = 15\%$
G	14000 kPa	16000 kPa	30000 kPa
Μ	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
$d_{ m v}$	0.02	0.01	0.01
d_{s}	10	30	30
p_{c0}	150 kPa	430 kPa	600 kPa
$p_{\rm bi}$	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

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

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 $p = p_{c0}$ 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

- I 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

- I In the Model Builder window, under Global Definitions click Parameters I.
- 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 **P**i Parameter Case.
- 6 In the Settings window for Case, type Natural Osaka Clay in the Label text field.
- **7** In the **Home** toolbar, click P_i **Parameter Case**.
- 8 In the Settings window for Case, locate the Parameters section.
- 9 Click 📂 Load from File.
- IO Browse to the model's Application Libraries folder and double-click the file isotropic_compression_mscc_marl_parameters.txt.

- II In the Label text field, type Natural Marl Clay.
- **12** In the **Home** toolbar, click P_i **Parameter Case**.
- 13 In the Settings window for Case, locate the Parameters section.
- 14 Click 📂 Load from File.
- IS 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 **P**_i **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 P_i **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 P_i **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 P_i **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 **P**; **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.
- 4 In the Label text field, type Cemented Bangkok Clay, Aw = 15%.

Parameters 2

- I In the Home toolbar, click P_i 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

- I In the Home toolbar, click f(x) 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 I

Rectangle 1 (r1)

- I 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 틤 Build Selected.

MATERIALS

Clay Material

- I In the Model Builder window, under Component I (compl) 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 I

- I In the Model Builder window, under Component I (compl) 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 $\epsilon_{dc}{}^p$ 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

- I 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 I

- I In the Physics toolbar, click Boundaries and choose Roller.
- 2 Select Boundary 2 only.

MATERIALS

Clay Material (mat1)

- I In the Model Builder window, under Component I (compl)>Materials click Clay Material (matl).
- 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/m²	Bulk modulus and shear modulus
Swelling index for structured clay	kappaSwellingS	kappas	I	Structured Cam-Clay
Compression index for destructured clay	lambdaCompS	lambdas	I	Structured Cam-Clay
Void ratio at reference pressure for destructured clay	evoidrefS	ee	I	Structured Cam-Clay
Destructuring index for volumetric deformation	dvS	dvs	I	Structured Cam-Clay
Destructuring index for shear deformation	dsS	dss	I	Structured Cam-Clay
Slope of critical state line	М	ММ	I	Structured Cam-Clay
Additional void ratio at initial yielding	Deltaei	deltae	I	Structured Cam-Clay
Initial structure strength	pbi	Pbi	Pa	Structured Cam-Clay
Plastic potential shape parameter	zetaS	zeta	I	Structured Cam-Clay
Density	rho	Rho	kg/m³	Basic

MESH I

Mapped I

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

Size

I 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 I

- I In the Model Builder window, click Study I.
- 2 In the Settings window for Study, locate the Study Settings section.
- **3** Clear the **Generate default plots** check box.

Parametric Sweep

- I 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.

- I In the Model Builder window, click Step I: 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

I In the Home toolbar, click 🚛 Add Plot Group and choose ID Plot Group.

- 2 In the Settings window for ID Plot Group, type Natural Osaka Clay in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Study I/ Parametric Solutions I (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 Manual.
- 8 In the Title text area, type Void Ratio vs. Pressure during the Isotropic Compression Test.
- 9 Locate the Plot Settings section.
- **IO** Select the **x-axis label** check box. In the associated text field, type **Pressure** (kPa).

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

Point Graph 1

- I 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 I (compl)> Solid Mechanics>Soil material properties>Modified Structured Cam-Clay> solid.epsml.evoid - Void ratio.
- 4 Click Replace Expression in the upper-right corner of the x-Axis Data section. From the menu, choose Component I (comp1)>Solid Mechanics>Stress>solid.pm - 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

Point Graph 2

- I Right-click Point Graph I 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.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 3

- I In the Model Builder window, under Results>Natural Osaka Clay right-click Point Graph I 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.evoidrefdsolid.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 Marl Clay

- I In the Model Builder window, right-click Natural Osaka Clay and choose Duplicate.
- 2 In the Settings window for ID 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

- I In the Model Builder window, expand the Natural Marl Clay node, then click Point Graph I.
- 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 **I** Plot.

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

Cemented Ariake Clay

- I In the Model Builder window, right-click Natural Marl Clay and choose Duplicate.
- 2 In the Settings window for ID 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

- I In the Model Builder window, expand the Cemented Ariake Clay node, then click Point Graph I.
- 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

- I 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 I/Parametric Solutions I (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

- I In the Model Builder window, click Cemented Ariake Clay.
- 2 In the Settings window for ID 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.

Cemented Bangkok Clay

- I Right-click Cemented Ariake Clay and choose Duplicate.
- 2 In the Settings window for ID 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

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

- I 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 **O** Plot.