Element Test Simulation Tutorial

~ PZ-Sand & PZ-Clay models ~

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1. Introduction

This document describes the parameter identification for PZ-Sand and PZ-Clay models by using the ETS (Element Test Simulation) software. The PZ-Sand model has fifteen parameters and the PZ-Clay model has ten parameters. These parameters can be identified by matching the experimental data of the consolidated-drained triaxial compression test (CD test), the consolidated-undrained triaxial compression test with pore pressure measurement ($\overline{\text{CU}}$ test), and the cyclic undrained triaxial test. For further information, please check the help in product.

2. PZ-Sand model

This is the generalized plasticity model for sand proposed by Zienkiewicz and his research group in References (1) and (2).

2.1. Constitutive law

The invariants to express the model are defined as the following equations.

$$p = \frac{1}{3}\sigma_{kk} \quad \text{(2.1.1)}$$

$$q = \sqrt{3J_2} \quad \text{(2.1.2)}$$

$$\theta = \frac{1}{3}\sin^{-1}\left(-\frac{3\sqrt{3}}{2}\cdot\frac{J_3}{J_2^{3/2}}\right) \quad \left(-\frac{\pi}{6} \le \theta \le \frac{\pi}{6}\right) \quad \text{(2.1.3)}$$

$$J_2 = \frac{1}{2}s_{ij}s_{ji} \quad \text{(2.1.4)}$$

$$J_3 = \frac{1}{3}s_{ij}s_{jk}s_{ki} \quad \text{(2.1.5)}$$

$$s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij} \quad \text{(2.1.6)}$$

where

p	: Mean principal stress
σ_{kk}	: Principal stress
q	: Deviatoric stress
θ	: Lode's angle
J_2	: Second invariant of deviatoric stress tensor
J_3	: Third invariant of deviatoric stress tensor
s_{ij}	: Deviatoric stress tensor
σ_{ij}	: Stress tensor
δ_{ij}	: Kronecker delta

The following incremental variables are defined.

$$\mathrm{d}\varepsilon_v = \mathrm{d}\varepsilon_{kk} \quad \text{(2.1.7)}$$

$$\mathrm{d}\varepsilon_s = \left(\frac{2}{3}\mathrm{d}e_{ij}\mathrm{d}e_{ji}\right)^{1/2} \quad \text{(2.1.8)}$$

$$\mathrm{d}e_{ij} = \mathrm{d}\varepsilon_{ij} - \frac{1}{3}\mathrm{d}\varepsilon_{kk}\delta_{ij} \quad \text{(2.1.9)}$$

where

$\mathrm{d}\varepsilon_v$	: Incremental volumetric strain
$\mathrm{d}\varepsilon_{kk}$	: Incremental principal strain
$\mathrm{d}\varepsilon_s$	: Incremental shear strain
$\mathrm{d}e_{ij}$	: Incremental deviatoric strain
$\mathrm{d}\varepsilon_{ij}$	: Incremental strain tensor

The dilatancy is expressed in the following equation.

$$d_g = (1+\alpha_g)(M_g - \eta) \quad \text{(2.1.10)}$$

where

$\eta = p'/q$: Stress ratio

p' : Effective mean principal stress

α_g, M_g : Model parameters

The direction of plastic flow is defined by the unit vector expressed in the following equation.

$$\mathbf{n_g} = \frac{1}{\sqrt{1+{d_g}^2}} \begin{Bmatrix} d_g \\ 1 \end{Bmatrix} \quad \text{(2.1.11)}$$

The direction of plastic flow within the hardening region is defined in the following equation. Note that this model uses the non-associative flow rules because M_f is different from M_g.

$$\mathbf{n} = \frac{1}{\sqrt{1+{d_f}^2}} \begin{Bmatrix} d_f \\ 1 \end{Bmatrix} \quad \text{(2.1.12)}$$

with its dilatancy defined as

$$d_f = (1+\alpha_f)(M_f - \eta) \quad \text{(2.1.13)}$$

where

α_f, M_f : Model parameters

The condition of loading or unloading can be identified by the vector $\mathbf{n}$ as follow.

$\mathbf{n}^T d\boldsymbol{\sigma}^e > 0$: Loading (2.1.14a)

$\mathbf{n}^T d\boldsymbol{\sigma}^e < 0$: Unloading (2.1.14b)

For M_g and M_f, the compression M_c and the extension M_e in triaxial test are expressed by using each friction angle as in the following equations.

$$M_c = \frac{6\sin\phi'_c}{3-\sin\phi'_c} \quad \text{(2.1.15a)}$$

$$M_e = \frac{6\sin\phi'_e}{3+\sin\phi'_e} \quad \text{(2.1.15b)}$$

The M is expressed in the following equations.

$$M = \frac{2M_e}{(1+C)-(1-C)\sin 3\theta} \quad \text{(2.1.16)}$$

with

$C = M_e / M_c$

The plastic modulus during loading is expressed in the following equation.

$$H_L = H_0 p' H_f (H_v + H_s) H_D \quad \text{(2.1.17)}$$

with

$$H_f = \left(1 - \frac{\eta}{\eta_f}\right)^4 \quad \text{(2.1.18)}$$

$$\eta_f = \left(1 + \frac{1}{\alpha_f}\right) M_f \quad \text{(2.1.19)}$$

$$H_v = 1 - \frac{\eta}{M_g} \quad \text{(2.1.20)}$$

$$H_s = \beta_0 \beta_1 \exp(-\beta_0 \xi) \quad \text{(2.1.21)}$$

$$\xi = \int \mathrm{d}\xi \qquad \mathrm{d}\xi = (\mathrm{d}e_{ij}^p \mathrm{d}e_{ji}^p)^{1/2} \quad \text{(2.1.22)}$$

$$H_D = \left(\frac{\varsigma_{MAX}}{\varsigma}\right)^\gamma \quad \text{(2.1.23)}$$

$$\varsigma = p' \left\{1 - \frac{\alpha_f}{1 + \alpha_f} \frac{\eta}{M_f}\right\}^{-1/\alpha} \quad \text{(2.1.24)}$$

where

$H_0, \beta_0, \beta_1, \gamma$: Model parameters

The plastic modulus during unloading is expressed in the following equation.

$$H_U = \begin{cases} H_{U0} \left(\frac{M_g}{\eta_U}\right)^{\gamma_U} & \text{for} \left|\frac{M_g}{\eta_U}\right| > 1 \\ H_{U0} & \text{for} \left|\frac{M_g}{\eta_U}\right| \le 1 \end{cases} \quad \text{(2.1.25)}$$

where

η_U : Stress ratio at the starting point of unloading
H_{U0}, γ_U : Model parameters

The bulk and shear moduli are defined as in the following equations.

$$K_{ev} = K_{ev0} P_a \left(\frac{p'}{P_a}\right)^{m_v} \quad \text{(2.1.26)}$$

$$K_{es} = K_{es0} P_a \left(\frac{p'}{P_a}\right)^{m_s} \quad \text{(2.1.27)}$$

where

P_a : Atmospheric pressure
K_{ev0}, K_{es0} : Initial constants of the bulk and shear moduli
m_v, m_s : Exponents of the bulk and shear moduli

2.2. Model parameters

The PZ-Sand model has fifteen parameters in which twelve parameters（M_g， M_f，C， α_g， α_f， m_s， m_v， K_{es0}， K_{ev0}， β_0， β_1， H_0） are identified by matching the results of the consolidated-drained triaxial compression test (CD test) or the consolidated-undrained triaxial compression test with pore pressure measurement ($\overline{\mathrm{CU}}$ test) and the remaining three parameters（H_{U0}， γ， γ_U） are identified by the Cyclic undrained triaxial test. In addition, another two experimental condition parameters are required such as the initial effective mean principal stress (p_0') and the overconsolidation ratio (OCR).

It is basically unnecessary to adjust the parameters (C, α_g， α_f， K_{es0}， K_{ev0}) while it is necessary for other parameters (M_g， M_f， m_s， m_v， β_0， β_1， H_0， H_{u0}， γ， γ_U). Adjustments of H_{u0}， γ and γ_U are necessary to replicate the liquefaction strength accurately and the values of γ and γ_U tend to increase with the liquefaction strength.

It is required for the comprehensive estimate of the parameters to match the simulation results with the experimental data. For example, it is only necessary to use the experimental data up to the strain level if stress fluctuates greatly with strain and it is necessary for the effective-stress dynamic analysis to match the critical state line (CSL) as the preferable measure because the strain level is relatively high in this case.

The results of each triaxial test are shown as follows.

(1) Consolidated-drained triaxial compression test

1) Axial strain (ε_a) and deviatoric stress (q) curve
2) Axial strain (ε_a) and volumetric strain (ε_v) curve
3) Axial strain (ε_a) and stress ratio (η) curve
4) Stress ratio (η) and dilatancy (d_g) curve

(2) Consolidated-undrained triaxial compression test with pore pressure measurement

1) Axial strain (ε_a) and deviatoric stress (q) curve
2) Axial strain (ε_a) and pore pressure (Δu) curve
3) Effective mean principal stress (p') and deviatoric stress (q) curve [Effective stress path]
4) Axial strain (ε_a) and stress ratio (η) curve

(3) Cyclic undrained triaxial test

1) Time history of cyclic deviatoric stress
2) Time history of axial strain (ε_a)
3) Time history of pore pressure (Δu) or excess pore pressure ratio (L_u)
4) Effective mean principal stress (p') and deviatoric stress (q) curve [Effective stress path]
5) Axial strain (ε_a) and deviatoric stress (q) curve
6) Number of cycles and cyclic stress ratio curve [Liquefaction strength]

The way to identify each of the parameters is shown as follows.

(1) M_g

It is a model parameter and can be identified by the following three ways.

1) By matching the $\varepsilon_a \sim \eta$ curve from CD or $\overline{\text{CU}}$ test and is approximately equal to the maximum value of stress ratio (η) that the test reaches.

2) By matching the $p' \sim q$ curve [Effective stress path] from $\overline{\text{CU}}$ test and is equal to the maximum tangent drawn from the origin to the residual stress path.

3) By matching the $\eta \sim d_g$ curve from CD test and is equal to the intercept of line.

(2) M_f

It is a model parameter and can be identified by the following two ways. The value of $D_r \times M_g$ (D_r: relative density) can serve as a good starting value.

1) By matching the stress path shape of $p' \sim q$ curve [Effective stress path] from $\overline{\text{CU}}$ test.

2) By matching the critical η where the soil behaviour changes from contractive to dilative in the case of dense sand.

(3) C

It is the ratio of the critical state line (CSL) on the side of extension and compression but is usually taken as 0.80.

It is often expressed in the following equation in the case that the friction angles of extension and compression, ϕ'_c and ϕ'_e, are same in the equations (2.1.15a) and (2.1.15b).

$$C = \frac{3}{3 + M_c} \quad \text{(2.2.1)}$$

The yield surface expressed in equation (2.1.16) on Π plane is shown in Figure 2.2.1 and the condition, $C \geq 7/9$, is required in order to maintain the outer convex shape.

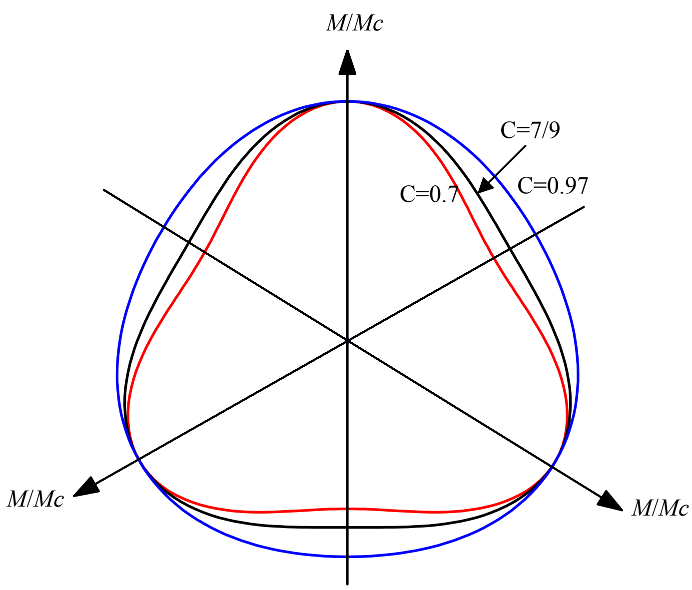


Figure 2.2.1 Yield surface shapes on Π plane depending on the parameter C

(4) α_g

It is the slope of $\eta \sim d_g$ from CD test but is usually taken as 0.45.

(5) α_f

It is usually taken to be the same as α_g .

(6) m_s

It is in the range 0.4 ~ 0.8 but is usually taken as 0.5.

(7) m_v

It is recommended to take the same value as m_s .

(8) K_{es0}

It is the initial constant of shear modulus and is estimated by the value of three times the coefficient of shear modulus at the initial effective mean principal stress following the description in Reference (2).

Therefore, using the above three times, the equation (2.1.27) and the Young's modulus E_i from the initial slope of $\varepsilon_a \sim q$ curve, this parameter is expressed in the following equation and can be identified more accurately by matching the $\varepsilon_a \sim q$ curve

$$K_{es0} = \frac{3E_i}{2(1+\nu)P_a(p'_0/P_a)^{m_s}} \quad \cdots\cdots (2.2.2)$$

with the relationship between Young's and shear moduli expressed in the following equation

$$K_{es} = \frac{E_i}{2(1+\nu)}$$

where

P_a : Atmospheric pressure (usually taken as 100 kPa)

ν : Poisson's ratio (usually taken as 0.2 ~ 0.3 in CD test and 0.5 in $\overline{\text{CU}}$ test)

(9) K_{ev0}

It is the initial constant of bulk modulus and is expressed using the equations (2.1.26) and (2.1.27) with an assumption of $m_v = m_v$ in the following equation and can be identified more accurately by matching the $\varepsilon_a \sim \varepsilon_v$ curve from CD test or the $\varepsilon_a \sim \Delta u$ curve from $\overline{\text{CU}}$ test

$$K_{ev0} = \frac{2K_{es0}(1+\nu')}{9(1-2\nu')} \quad \cdots\cdots (2.2.3)$$

with the relationship between the bulk and shear moduli expressed in the following equation

$$K_{ev} = \frac{2(1+\nu')}{3(1-2\nu')}\frac{K_{es}}{3}$$

where

ν' : Poisson's ratio (usually taken as 0.2 ~ 0.3 in both CD and $\overline{\text{CU}}$ tests)

(10) β_0

It is in the range 1 ~ 10 and its starting value is usually taken as 4.2.

(11) β_1

It is in the range 0.1 ~ 0.2 and its starting value is usually taken as 0.12.

(12) H_0

It is a material parameter and can be identified by matching the curve of $\varepsilon_a \sim q$ or also by matching the stress path shape of $p' \sim q$ [Effective stress path] from $\overline{\mathrm{CU}}$ test. It is recommended to take a value in Table 2.2.1 as the starting value because it correlates to some extent with the relative density.

Table 2.2.1 H_0 and the relative density of sand

Sand Type	Relative Density D_r	H_0
Very loose	<0.2	200 ~ 400
Loose	0.2-0.4	400 ~ 700
Compact	0.4-0.6	600 ~ 900
Dense	0.6-0.8	800 ~ 1100
Very dense	>0.8	1000 ~ 1500

(13) H_{U0}

It can be identified by matching the initial slope of the first unloading curve of $p' \sim q$ [Effective stress path] from cyclic undrained triaxial test. It is in the range 4,000 ~ 10,000 kPa [= $\mathrm{kN/m^2}$] and is usually taken as 6,000.

(14) γ

It can be identified by matching the slope of the first reloading curve of $p' \sim q$ [Effective stress path] or by matching the number of cycles in a series of loading and unloading from cyclic undrained triaxial test. It is in the range 1.0 ~ 15.0 and its starting value is usually taken as 8.0.

(15) γ_U

It can be identified by matching the slope change rate of the first unloading curve of $p' \sim q$ [Effective stress path] or by matching the number of cycles in a series of loading and unloading from cyclic undrained triaxial test. It is in the range 0.0 ~ 10.0 and its starting value is usually taken as $\gamma(\approx \gamma - 2.0)$.

In addition to the fifteen parameters, another two experimental condition parameters are required as follow.

(A1) p_0'

It is the initial effective mean principal stress and is expressed in the following equation.

$$p_0{}' = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad \cdots\cdots (2.2.4)$$

where

σ_1 : Axial stress

σ_2 , σ_3 : Confining stresses ($\sigma_2 = \sigma_3$ in triaxial test)

(A2) OCR

It is the overconsolidation ratio and is taken as 1.0 in the case of sand.

2.3. Examples of parameter identification for PZ-Sand model

The examples of parameter identification for PZ-Sand model are described using the ETS (Element Test Simulation) software. The identification is performed by matching with the experimental data of the consolidated-undrained triaxial compression test with pore pressure measurement ($\overline{\mathrm{CU}}$ test) and the cyclic undrained triaxial test.

2.3.1. Consolidated-undrained triaxial compression test with pore pressure measurement

The parameter identification of the PZ-Sand model is performed based on the result of $\overline{\mathrm{CU}}$ test.

(1) Experimental conditions and results

1) Experimental conditions

Material name	: T sand
Relative Density D_r	: 85%
Consolidated effective confining pressure σ_c'	: 98 kPa [$=\mathrm{kN/m^2}$] (Isotropic consolidation)

2) Experimental results

The results of $\overline{\mathrm{CU}}$ test are shown in Figure 2.3.1 ~ Figure 2.3.4.

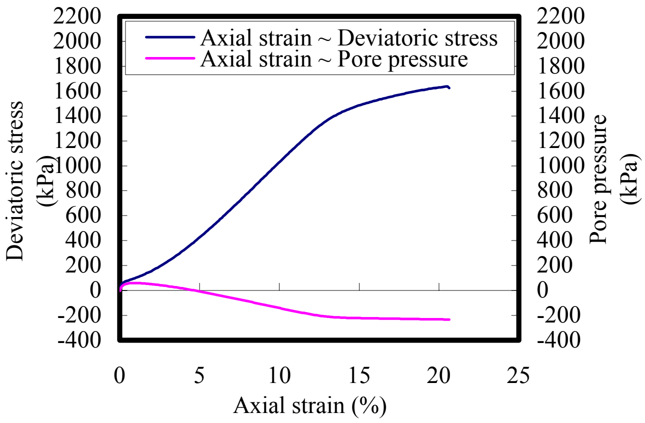


Figure 2.3.1 $\varepsilon_a \sim q$ and $\varepsilon_a \sim \Delta u$ curves

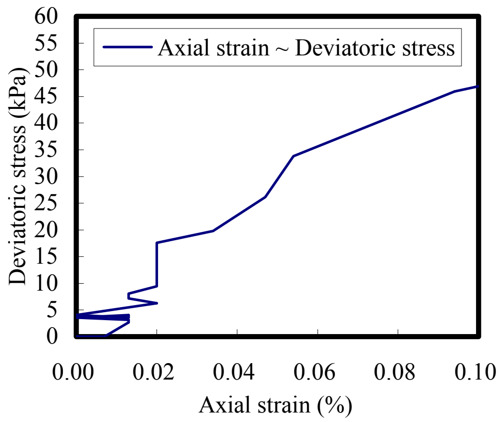


Figure 2.3.2 $\varepsilon_a \sim q$ curve

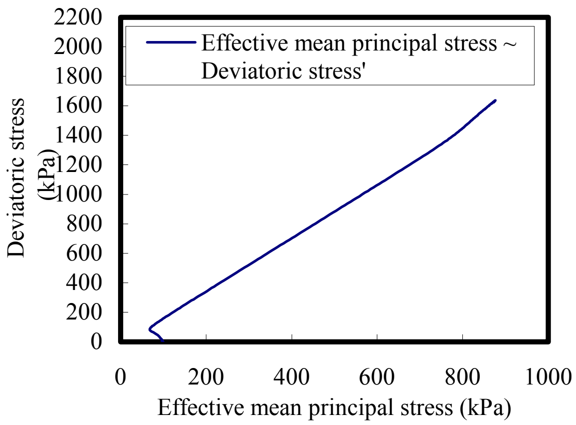


Figure 2.3.3 $p' \sim q$ curve [Effective stress path]

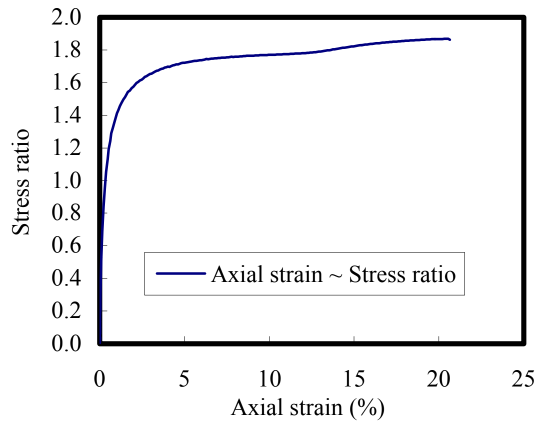
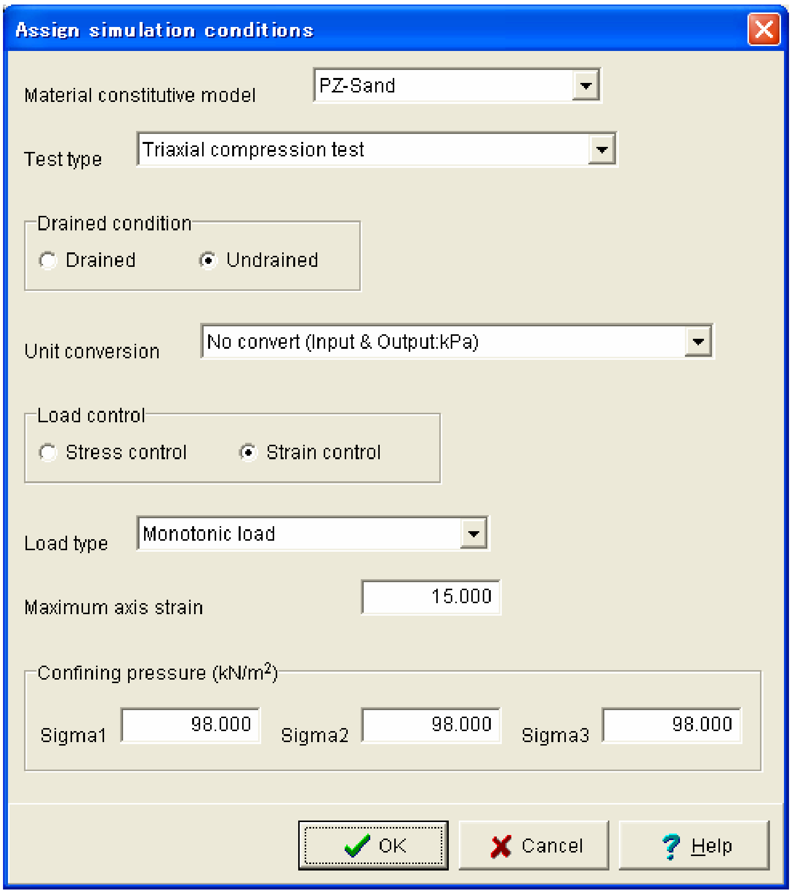


Figure 2.3.4 $\varepsilon_a \sim q/p'$ curve

(2) Input data of ETS (Element Test Simulation) software

1) Simulation conditions

Simulation conditions are assigned in the following dialog.



[Material constitutive model] combo box

'PZ-Sand' is selected from the pulldown menu.

[Test type] combo box

'Triaxial compression test' is selected from the pulldown menu for $\overline{\text{CU}}$ test.

[Drained condition] radio group

'Undrained' is selected for $\overline{\text{CU}}$ test.

[Unit conversion] combo box

'No convert (Input & Output: kPa)' is selected from the pulldown menu because both experimental and simulation data are in SI units in this case.

[Load control] radio group

'Strain control' is selected in this case.

[Load type] combo box

'Monotonic load' is selected from the pulldown menu in this static case.

[Maximum axial strain] edit

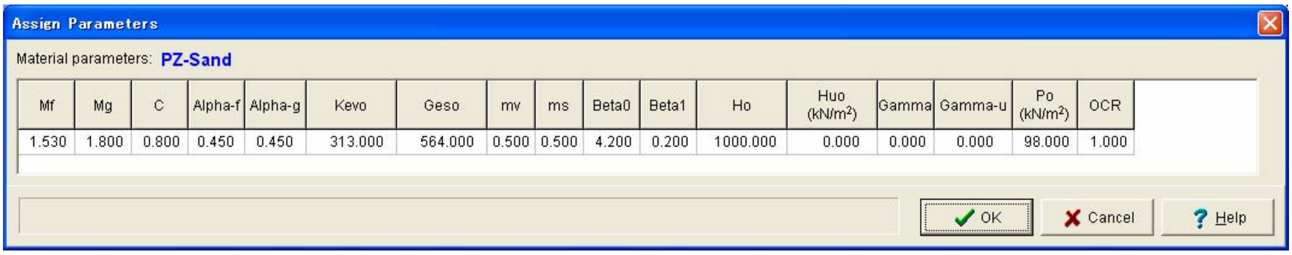
'0.15' is input to consider up to 15% of axial strain level in this case.

[Confining pressure] edit group

'98.0' is input in each edit box according to the prescribed simulation condition of isotropic consolidation.

2) Model parameters

The fifteen PZ-Sand model parameters and another two experimental condition parameters are assigned in the following dialog. The twelve parameters (M_g, M_f, C, α_g, α_f, m_s, m_v, K_{es0}, K_{ev0}, β_0, β_1, H_0), the initial effective mean principal stress (p'_0) and the overconsolidation ratio (OCR) are assigned in the case of $\overline{\mathrm{CU}}$ test. However, the remaining three parameters (H_{U0}, γ, γ_U) are assigned to be 0.0 because they are identified by the cyclic undrained triaxial test in the next example.



Mf	Mg	C	Alpha-f	Alpha-g	Kevo	Geso	mv	ms	Beta0	Beta1	Ho	Huo (kN/m2)	Gamma	Gamma-u	Po (kN/m2)	OCR
1.530	1.800	0.800	0.450	0.450	313.000	564.000	0.500	0.500	4.200	0.200	1000.000	0.000	0.000	0.000	98.000	1.000

\# M_f (=Mf)

'1.53' is input as a starting value by $D_r \times M_g = 0.85 \times 1.80 = 1.53$.

\# M_g (=Mg)

'1.80' is input by reading the maximum value of stress ratio up to 15% of axial strain level in Figure 2.3.4.

\# C (=C)

'0.80' is input as usual.

\# α_f (=Alpha-f)

'0.45' is input as usual.

\# α_g (=Alpha-g)

'0.45' is input as usual.

\# K_{ev0} (=Kevo)

'313' is input by the following equation using equation (2.2.3), $\nu' = 0.25$ and $K_{es0} = 564$ shown below.

$$K_{ev0} = \frac{2K_{es0}(1+\nu')}{9(1-2\nu')} = \frac{2 \times 564 \times (1+0.25)}{9 \times (1-2 \times 0.25)} = 313$$

\# K_{es0} (=Geso)

'564' is input by the following equation using equation (2.2.2) and $p'_0 = 98\text{kPa}$ shown below.

$$K_{es0} = \frac{3E_i}{2(1+\nu)P_a(p'_0/P_a)^{m_s}} = \frac{3 \times 55{,}830\text{kPa}}{2 \times (1+0.5) \times 100\text{kPa} \times (98\text{kPa}/100\text{kPa})^{0.5}} = 564$$

where $P_a = 100\text{kPa}$, $\nu = 0.5$, $m_s = 0.5$, and the Young's modulus $E_i = 55{,}830\text{kPa}$ shown in Figure 2.3.5.

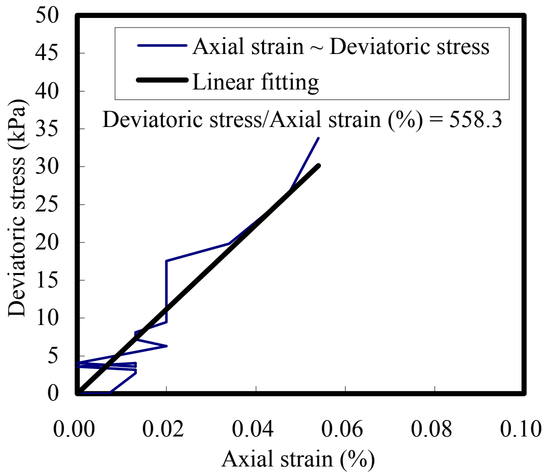


Figure 2.3.5 Young's modulus $E_i = 55{,}830\text{kPa}$ from the initial slope of $\varepsilon_a \sim q$ curve

\# m_v (=mv)

'0.5' is input as recommended to take the same value as m_s .

\# m_s (=ms)

'0.5' is input as usual.

\# β_0 (=Beta0)

'4.2' is input as usual.

\# β_1 (=Beta1)

'0.2' is input in this case.

\# H_0 (=Ho)

'1000' is input in this case by 85% of the relative density in Table 2.2.1.

\# p_0' (=Po)

'98.0' is input by the following equation using equation (2.2.4).

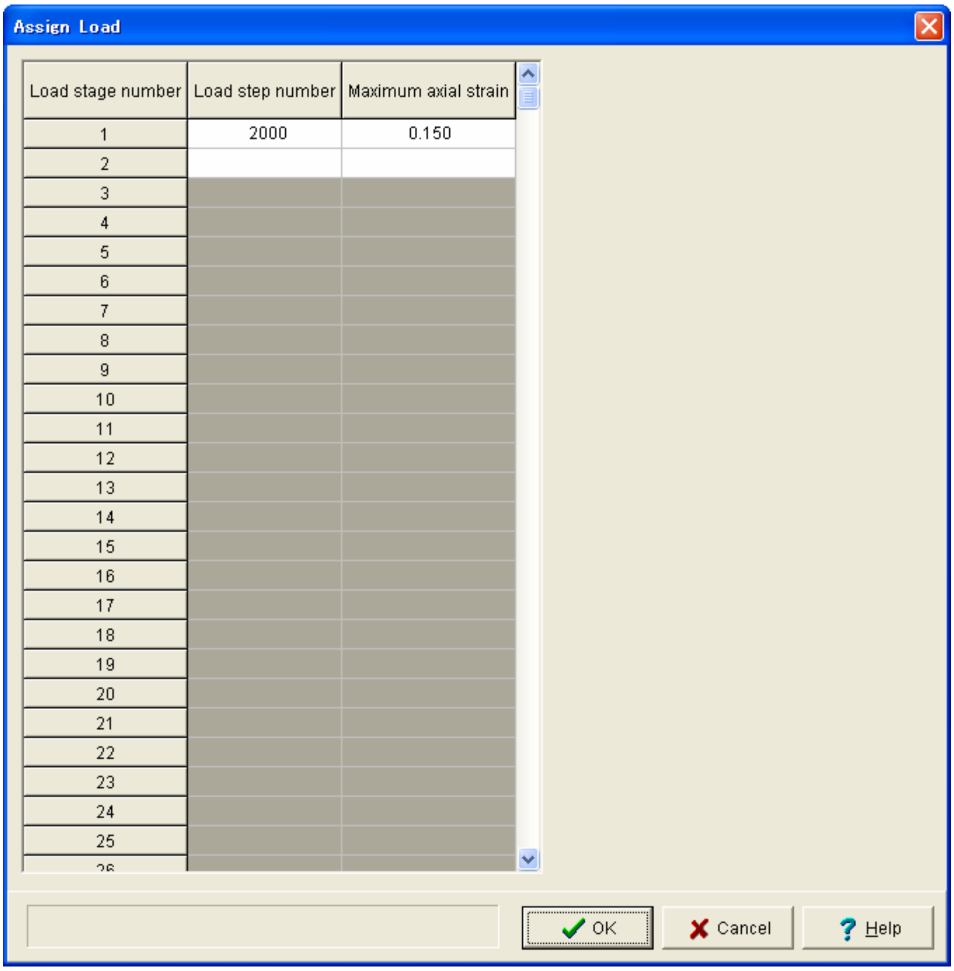
$$p_0' = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{3 \times 98\text{kPa}}{3} = 98\text{kPa}\ [= \text{kN}/\text{m}^2]$$

\# OCR

'1.0' is input in this case.

3) Load

Load is assigned in the following dialog.



\# [Load stage number]

The data of one load stage are assigned for the case of $\overline{CU}$ test.

\# [Load step number]

It is the division number of load step and is usually taken as 1,000 ~ 2,000 at each stage.

'2000' is input in this case.

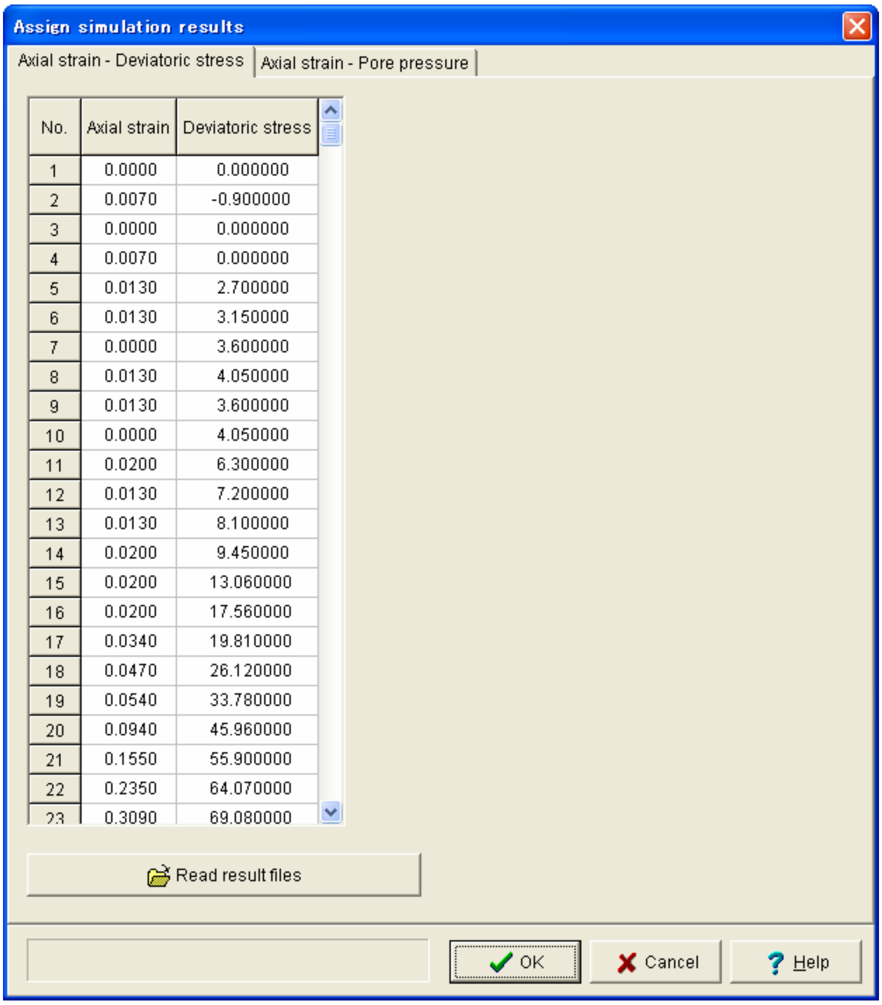
\# [Maximum axial strain]

It is the maximum axial strain which is usually the same value as set up in the [Assign simulation conditions] dialog.

'0.15' is input to consider up to 15% of axial strain level in this case.

4) Experimental results

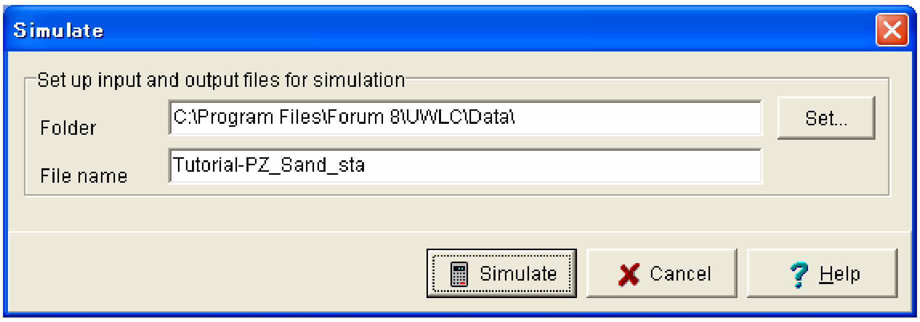
Experimental results of $\varepsilon_a \sim q$ and $\varepsilon_a \sim \Delta u$ are assigned in the following dialog by reading from file or typing.



No.	Axial strain	Deviatoric stress
1	0.0000	0.000000
2	0.0070	-0.900000
3	0.0000	0.000000
4	0.0070	0.000000
5	0.0130	2.700000
6	0.0130	3.150000
7	0.0000	3.600000
8	0.0130	4.050000
9	0.0130	3.600000
10	0.0000	4.050000
11	0.0200	6.300000
12	0.0130	7.200000
13	0.0130	8.100000
14	0.0200	9.450000
15	0.0200	13.060000
16	0.0200	17.560000
17	0.0340	19.810000
18	0.0470	26.120000
19	0.0540	33.780000
20	0.0940	45.960000
21	0.1550	55.900000
22	0.2350	64.070000
23	0.3090	69.080000

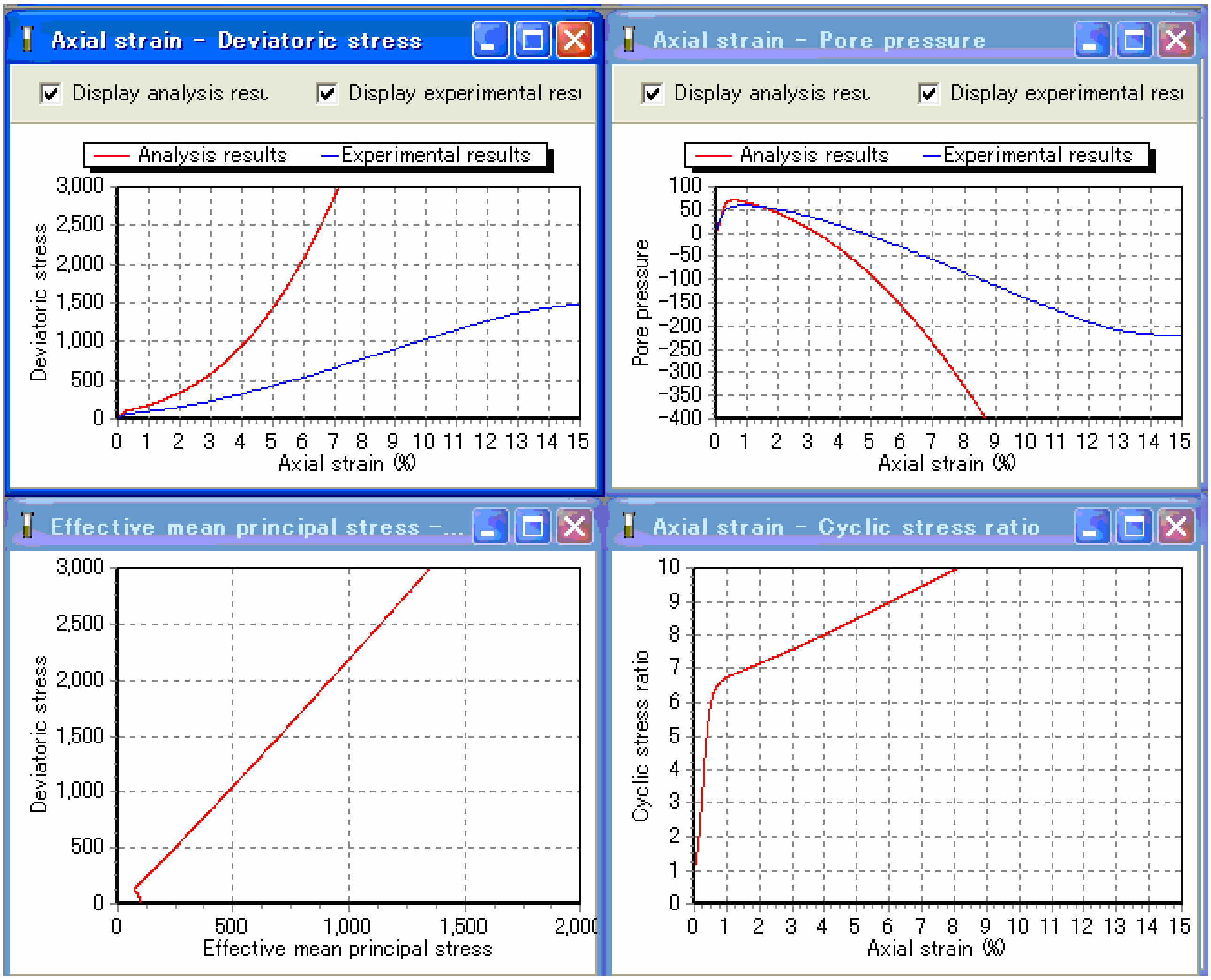
5) Simulate

The folder to save the I/O files and the file name without extension is specified and simulation can be performed by clicking the [Simulate] button in the following dialog. .



(3) Simulation results and parameter adjustments

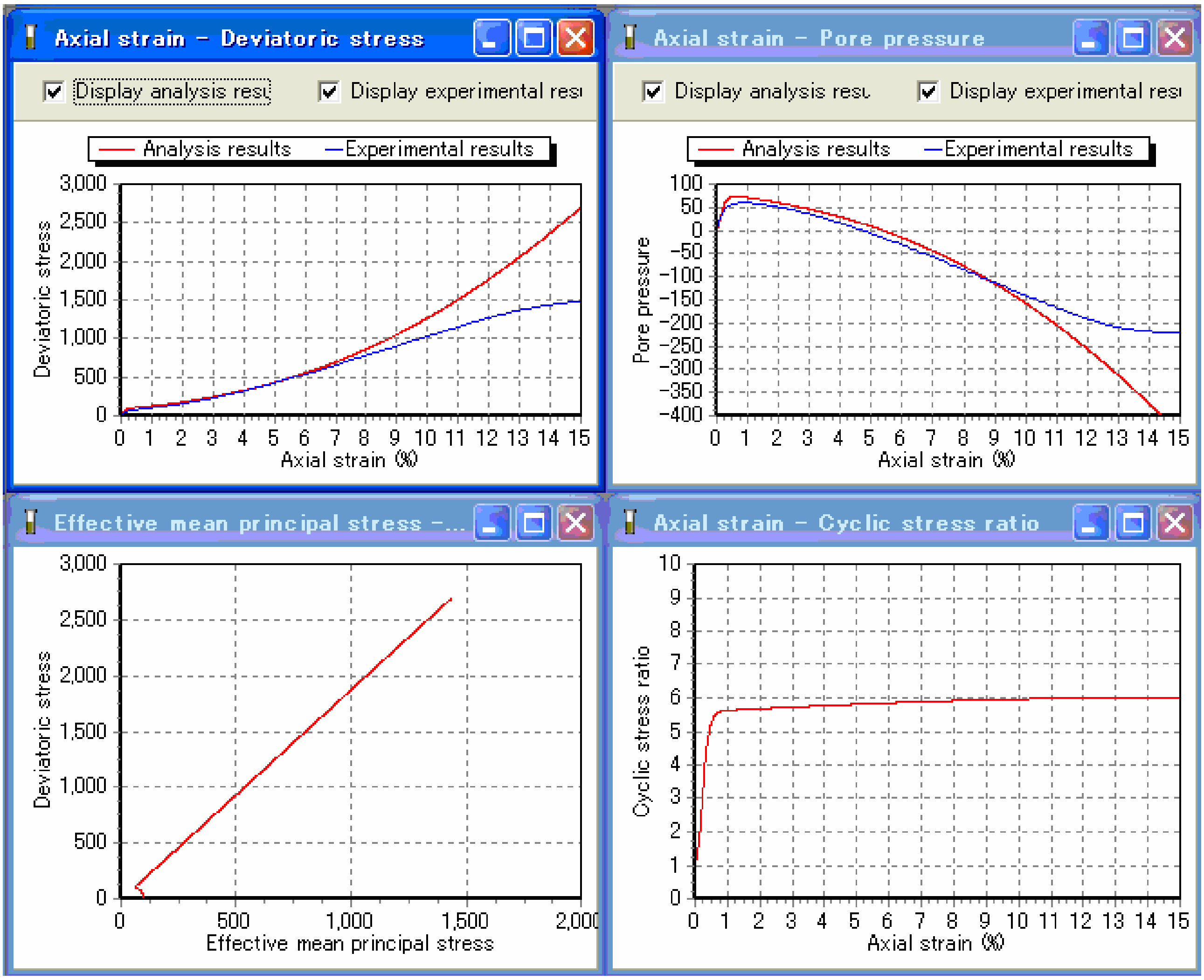
Simulation results for the assigned parameters in previous section (2) are shown below.



It is found in the above results of analysis and experiment that the deviatoric stress is overestimated and the pore pressure is underestimated with the axial strain. Then, a simulation should be repeated to improve these results by adjusting the four parameters (M_g, β_0, β_1, H_0) as in the followings.

$M_g = 1.80 \rightarrow 1.75$, $\beta_0 = 4.20 \rightarrow 6.00$, $\beta_1 = 0.20 \rightarrow 0.10$, $H_0 = 1000 \rightarrow 600$

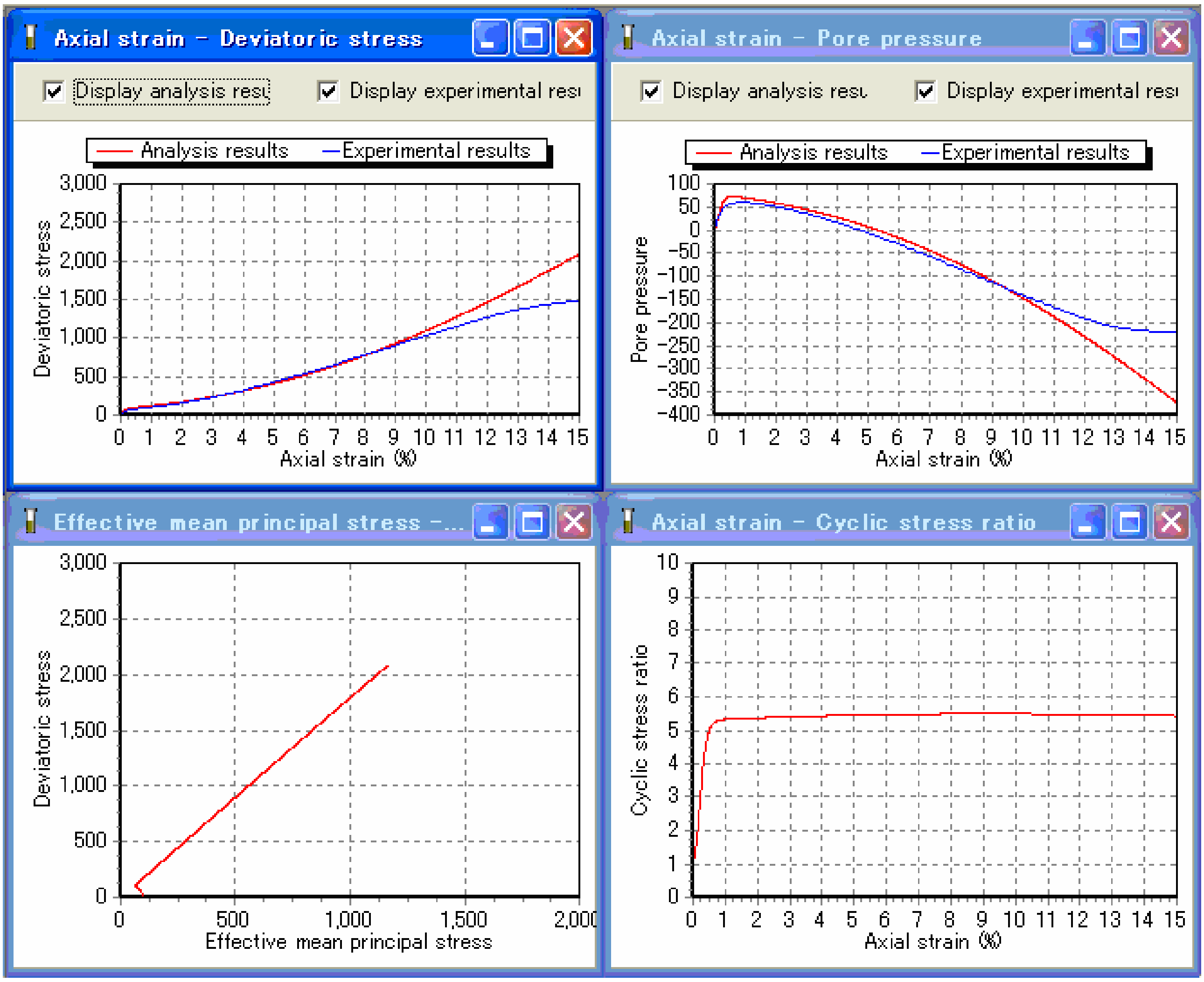
Second simulation results using the parameters above are shown below.



It is found in the above results of analysis and experiment that the deviatoric stress and the pore pressure are nearly consistent up to 8% of the axial strain. Then, a simulation might be repeated again to improve these results up to 10% of the axial strain by the same way and the parameters are identified finally in this case as in the followings.

$M_g = 1.75 \rightarrow 1.70$, $\beta_0 = 6.00 \rightarrow 9.00$, $\beta_1 = 0.10 \rightarrow 0.12$, $H_0 = 600 \rightarrow 330$

Final simulation results using the parameters above are shown below.



It is found in the above results of analysis and experiment that the deviatoric stress and the pore pressure are nearly consistent up to 10% of the axial strain.

2.3.2. Cyclic undrained triaxial test

The parameter identification of the PZ-Sand model is performed based on the result of cyclic undrained triaxial test by matching the three liquefaction strengths.

(1) Experimental conditions and results

1) Experimental conditions

Material name		: T sand
Relative Density D_r		: 85%
Consolidated effective confining pressure σ_c'		: 49 kPa [$=\mathrm{kN/m^2}$] (Isotropic consolidation)
Cyclic stress ratio $\sigma_d / 2\sigma_c'$	Case 1	: 0.154
	Case 2	: 0.204
	Case 3	: 0.129

2) Experimental results

Case 1 ($\sigma_d / 2\sigma'_c = 0.154$ **)**

The results of case 1 are shown in Figure 2.3.5 ~ Figure 2.3.7.

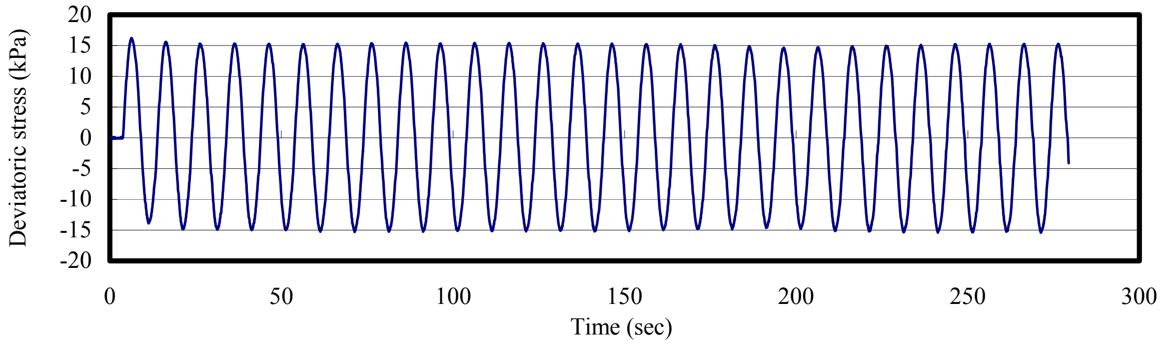


Figure 2.3.5 Time history of deviatoric stress (Case 1)

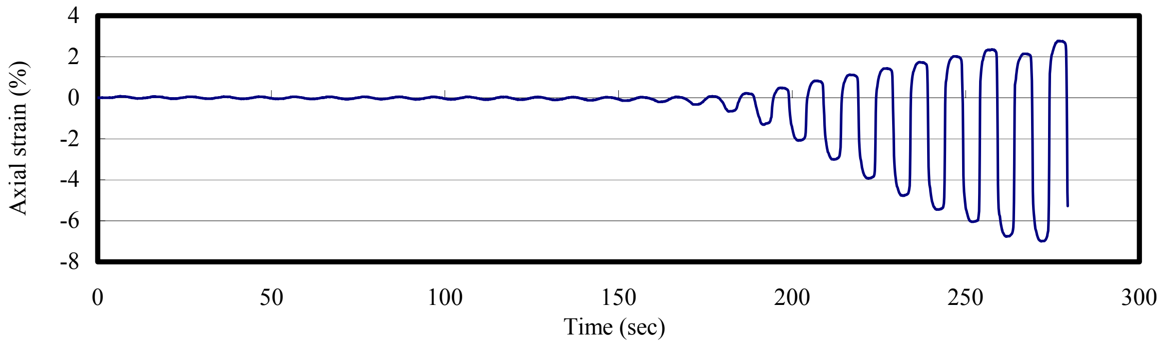


Figure 2.3.6 Time history of axial strain (Case 1)

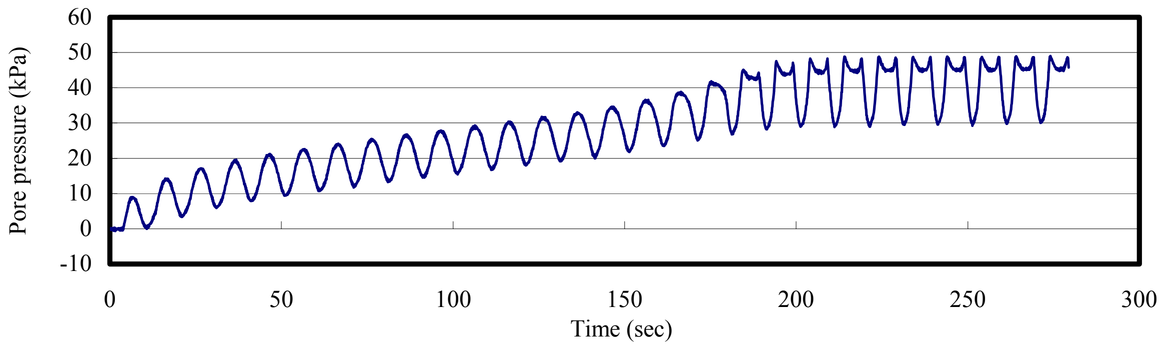


Figure 2.3.7 Time history of pore pressure (Case 1)

Case 2 ($\sigma_d / 2\sigma_c' = 0.204$)

The results of case 2 are shown in Figure 2.3.8 ~ Figure 2.3.10.

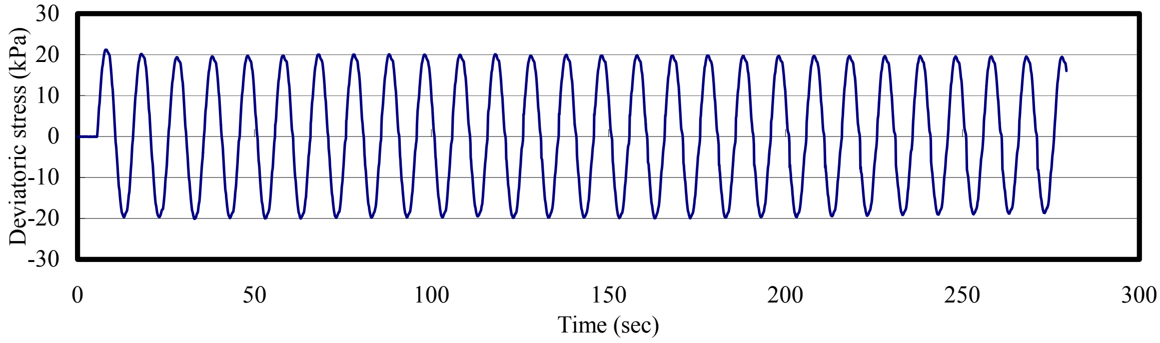


Figure 2.3.8 Time history of deviatoric stress (Case 2)

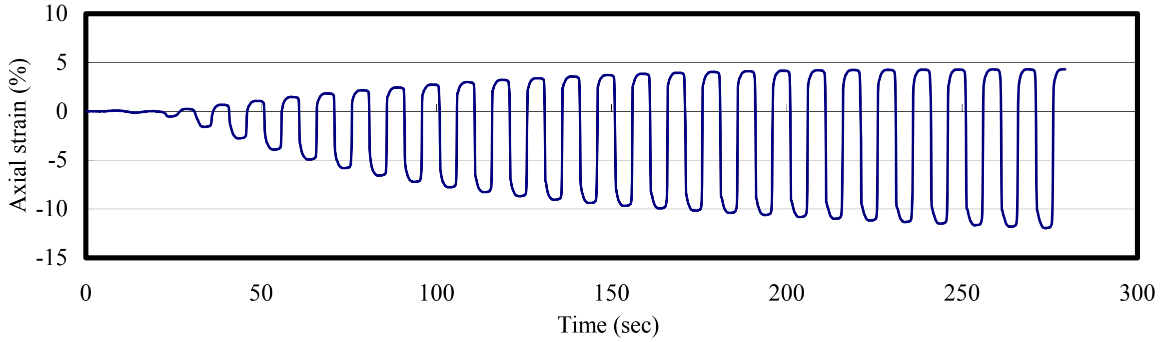


Figure 2.3.9 Time history of axial strain (Case 2)

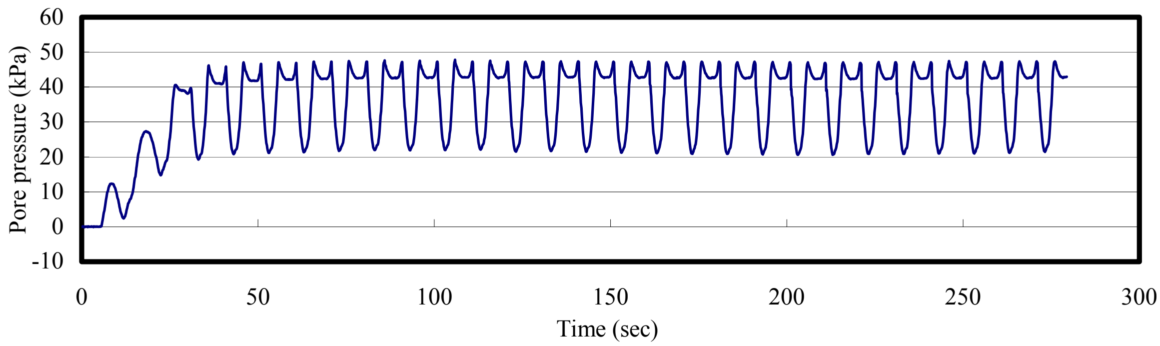


Figure 2.3.10 Time history of pore pressure (Case 2)

Case 3 ($\sigma_d / 2\sigma'_c = 0.129$)

The results of case 3 are shown in Figure 2.3.11 ~ Figure 2.3.13.

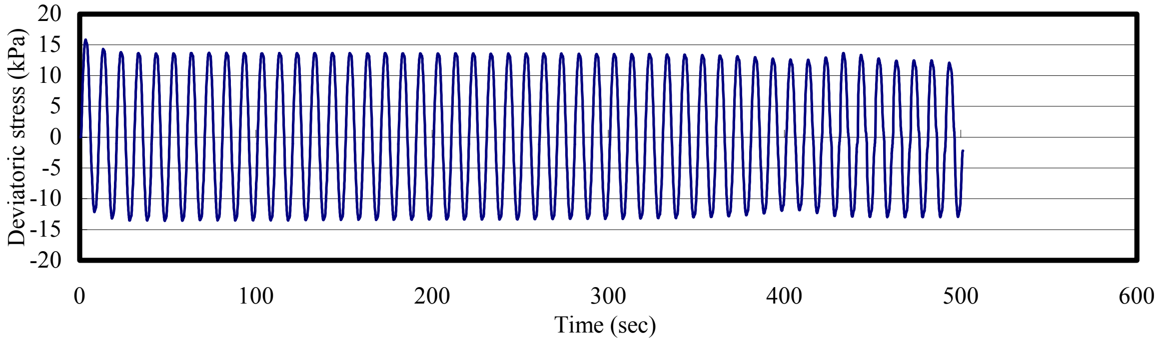


Figure 2.3.11 Time history of deviatoric stress (Case 3)

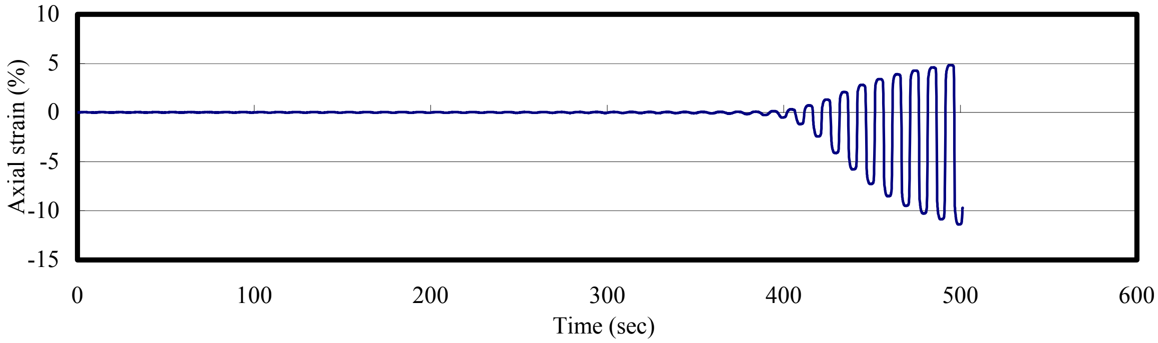


Figure 2.3.12 Time history of axial strain (Case 3)

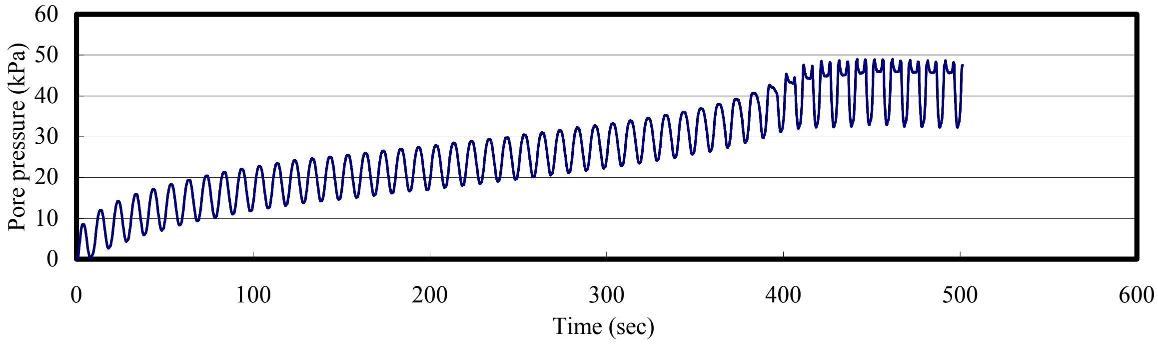


Figure 2.3.13 Time history of pore pressure (Case 3)

Liquefaction strength curve

The liquefaction strength curve is shown with the results of cases 1 ~ 3 in Figure 2.3.14.

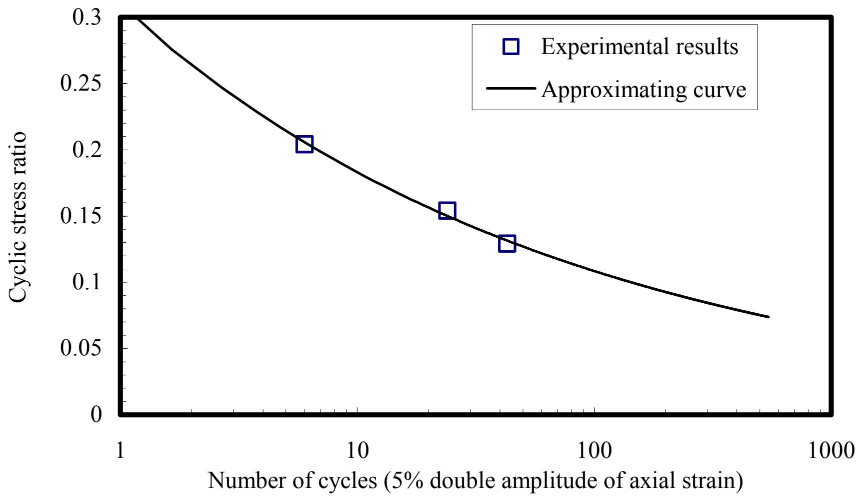


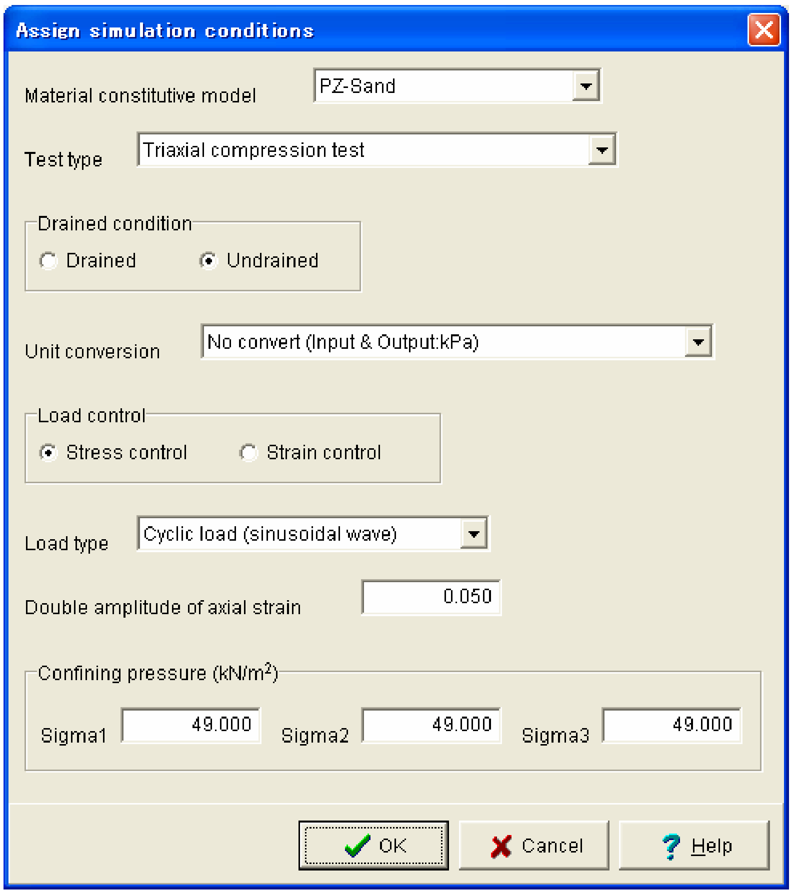
Figure 2.3.14 Liquefaction strength of experimental results from cyclic undrained triaxial test

(2) Input data of ETS (Element Test Simulation) software

The simulation is performed for case 1 that has the middle value of the cyclic stress ratio in cases 1 ~ 3. Then, the simulations for cases 1 and 2 are performed to check the identified PZ-Sand model parameters.

1) Simulation conditions

Simulation conditions are assigned in the following dialog.



[Material constitutive model] combo box

'PZ-Sand' is selected from the pulldown menu.

[Test type] combo box

'Triaxial compression test' is selected from the pulldown menu for cyclic undrained triaxial test.

[Drained condition] radio group

'Undrained' is selected for cyclic undrained triaxial test.

[Unit conversion] combo box

'No convert (Input & Output: kPa)' is selected from the pulldown menu because both experimental and simulation data are in SI units in this case.

[Load control] radio group

'Stress control' is selected in this case.

[Load type] combo box

'Cyclic load (sinusoidal wave)' is selected from the pulldown menu in this cyclic case.

[Maximum axial strain] edit

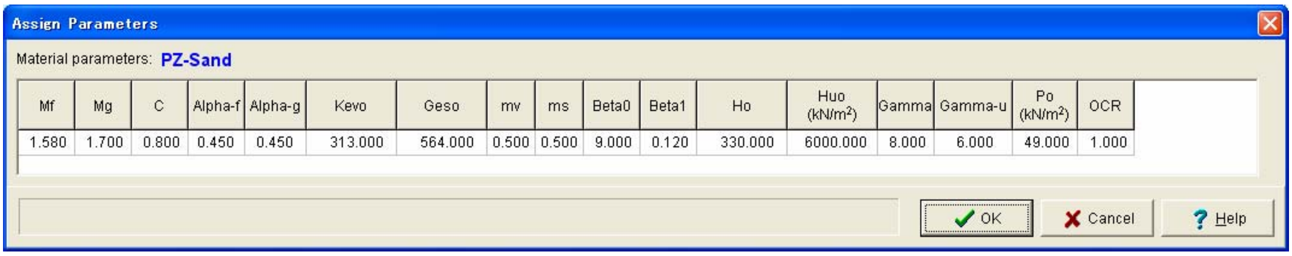
'0.05' is input to consider the number of cycles reaching 5% double amplitude of axial strain in this case.

[Confining pressure] edit group

'49.0' is input in each edit box according to the prescribed simulation condition of isotropic consolidation.

2) Model parameters

The three parameters (H_{U0}, γ, γ_U) in the fifteen PZ-Sand model parameters and the initial effective mean principal stress (p_0') are assigned in the following dialog in the case of cyclic undrained triaxial test. The remaining twelve parameters (M_g, M_f, C, α_g, α_f, m_s, m_v, K_{es0}, K_{ev0}, β_0, β_1, H_0) and the overconsolidation ratio (OCR) are same as the final values in the case of previous $\overline{\text{CU}}$ test.



Mf	Mg	C	Alpha-f	Alpha-g	Kevo	Geso	mv	ms	Beta0	Beta1	Ho	Huo (kN/m2)	Gamma	Gamma-u	Po (kN/m2)	OCR
1.580	1.700	0.800	0.450	0.450	313.000	564.000	0.500	0.500	9.000	0.120	330.000	6000.000	8.000	6.000	49.000	1.000

H_{U0} (=Huo)

'6000.0' is input as usual.

γ (=Gamma)

'8.0' is input as usual.

γ_U (=Gamma-u)

'6.0' is input as usual by $\gamma - 2.0 = 8.0 - 2.0 = 6.0$.

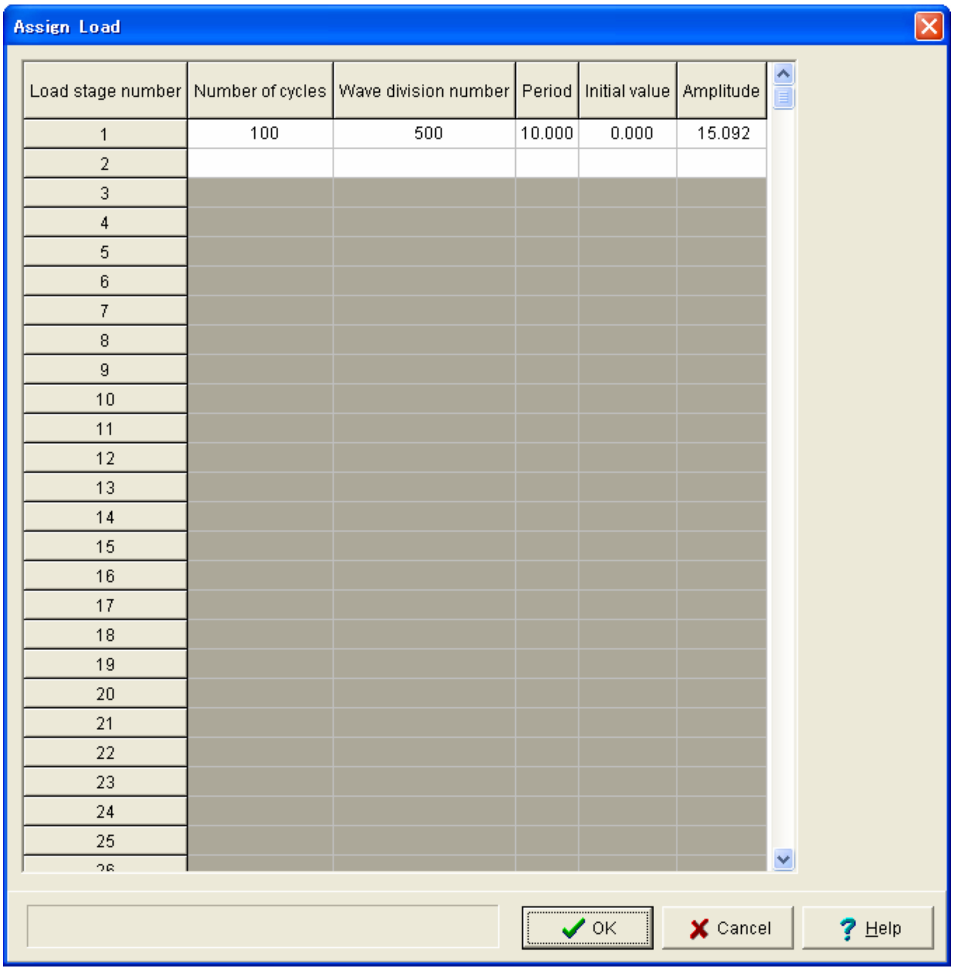
p_0' (=Po)

'49.0' is input by the following equation using equation (2.2.4).

$$p_0' = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{3 \times 49\text{kPa}}{3} = 49\text{kPa}\ [= \text{kN/m}^2]$$

3) Load

Load is assigned in the following dialog.



[Load stage number]

The data of one load stage are assigned in this case because the number of cyclic undrained triaxial test is one.

[Number of cycles]

It is the input wave number of cycles and is usually set up in reference to the experiment.

'100' is input in this case.

[Wave division number]

It is the division number of a wave in the cyclic load case and is usually taken as 200 ~ 1,000.

'500' is input in this case.

[Period]

It is the period of input cyclic wave and is usually set up in reference to the experiment.

'10.0' is input in this case.

[Initial value]

It is the initial value of cyclic load at zero time.

'0.0' is input in this case.

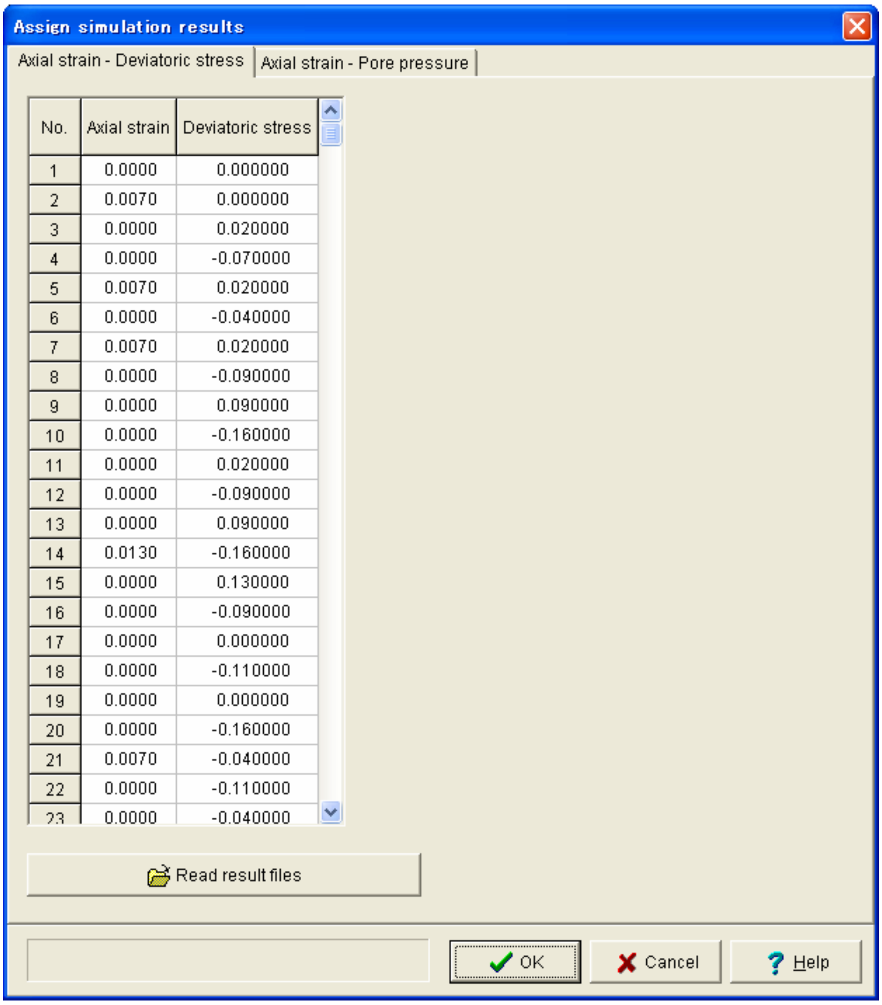
[Amplitude]

It is the amplitude of input cyclic wave and is usually set up σ_d (kPa).

'15.092' is input in Case 1 ($\sigma_d / 2\sigma'_c = 0.154$) by $2\sigma'_c \times \sigma_d / 2\sigma'_c = 2 \times 49 \times 0.154 = 15.092$.

4) Experimental results

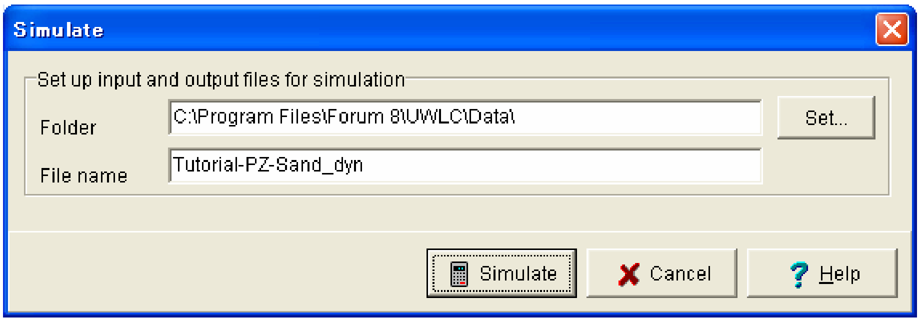
Experimental results of $\varepsilon_a \sim q$ and $\varepsilon_a \sim \Delta u$ are assigned in the following dialog by reading from file or typing.



No.	Axial strain	Deviatoric stress
1	0.0000	0.000000
2	0.0070	0.000000
3	0.0000	0.020000
4	0.0000	-0.070000
5	0.0070	0.020000
6	0.0000	-0.040000
7	0.0070	0.020000
8	0.0000	-0.090000
9	0.0000	0.090000
10	0.0000	-0.160000
11	0.0000	0.020000
12	0.0000	-0.090000
13	0.0000	0.090000
14	0.0130	-0.160000
15	0.0000	0.130000
16	0.0000	-0.090000
17	0.0000	0.000000
18	0.0000	-0.110000
19	0.0000	0.000000
20	0.0000	-0.160000
21	0.0070	-0.040000
22	0.0000	-0.110000
23	0.0000	-0.040000

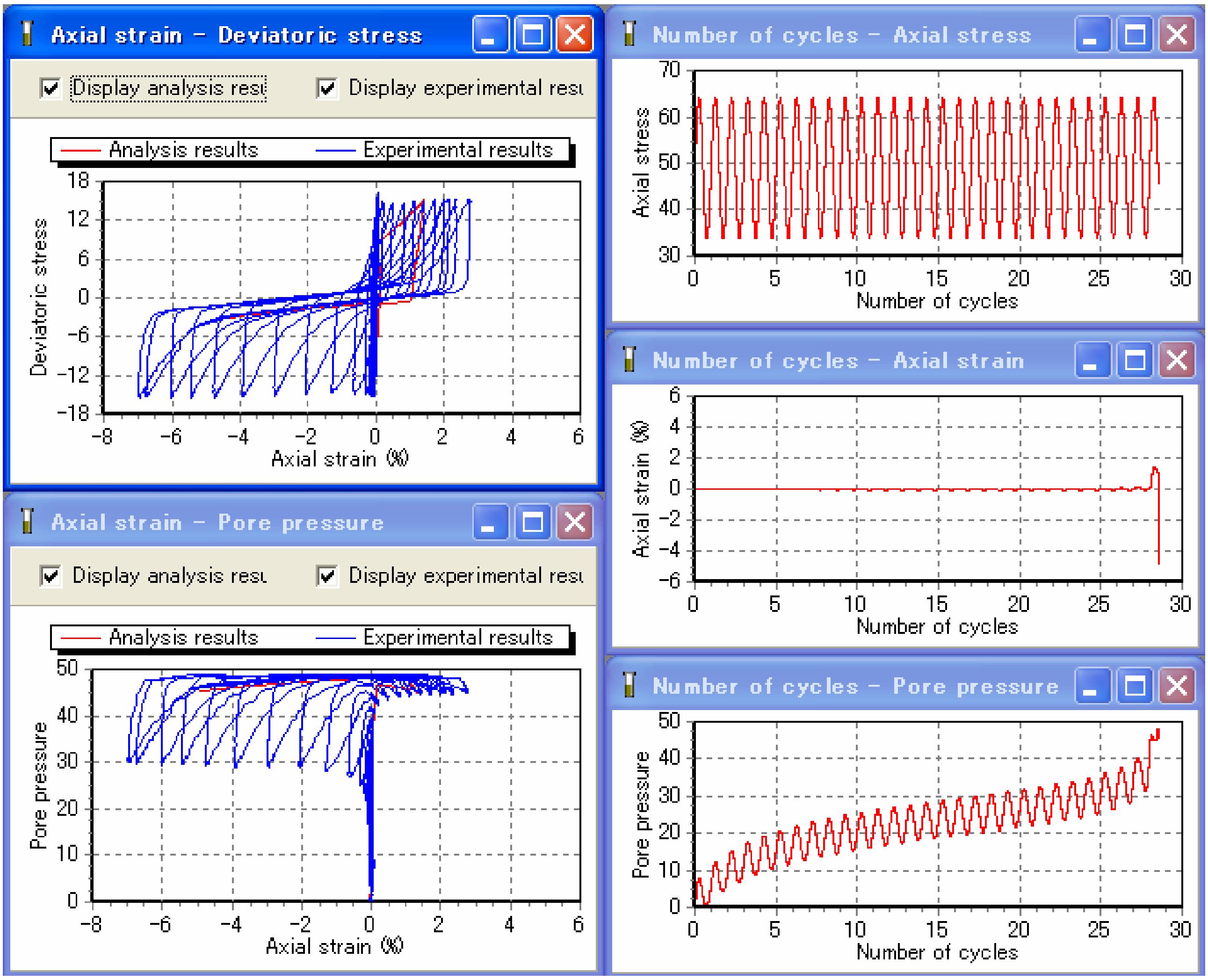
5) Simulate

The folder to save the I/O files and the file name without extension is specified and simulation can be performed by clicking the [Simulate] button in the following dialog. .



(3) Simulation results and parameter adjustments

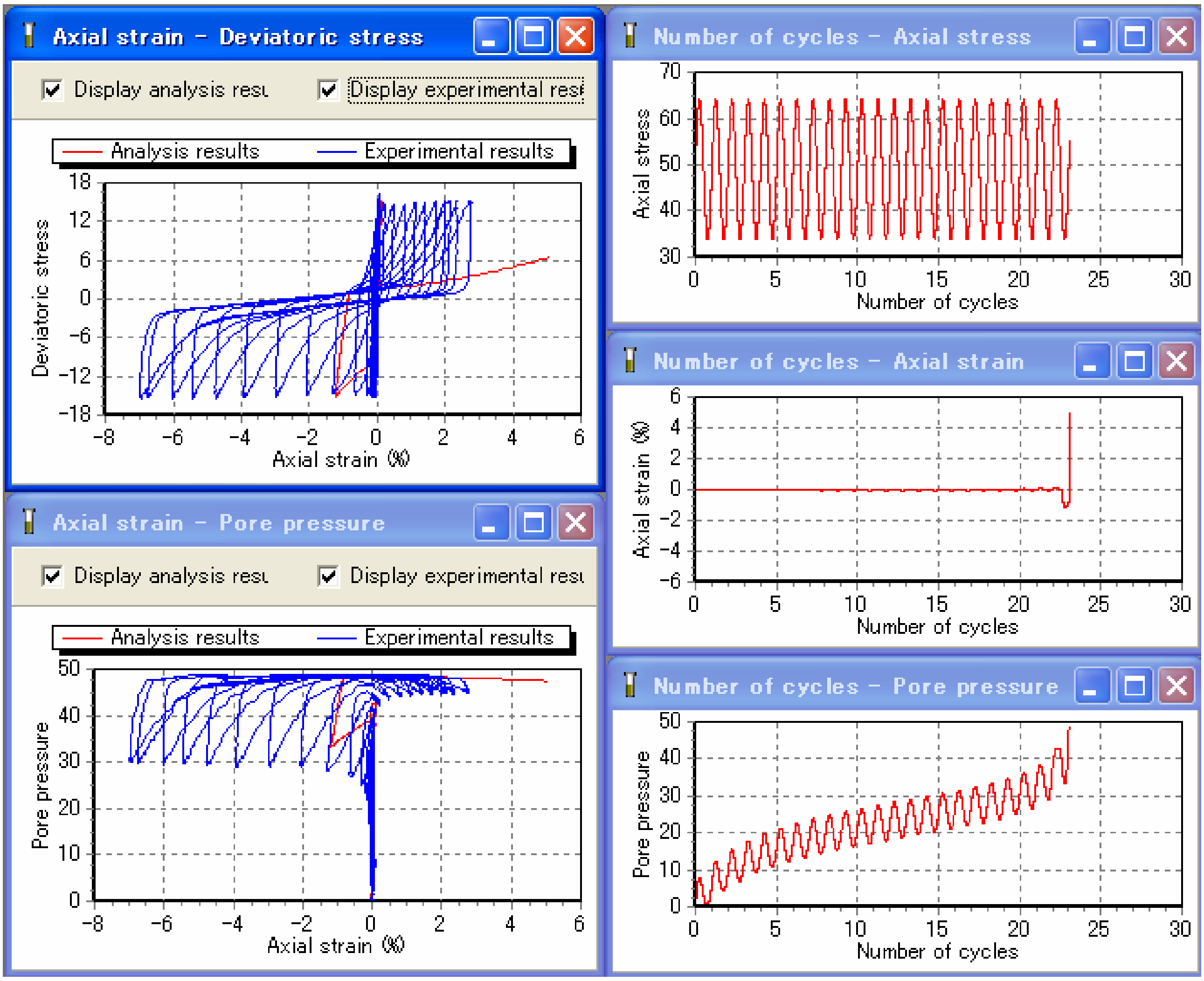
Simulation results for the assigned parameters in previous section (2) are shown below.



It is found in the above results reaching 5% double amplitude of axial strain that the number of cycles is 28 in analysis compared to 24 in experiment. Then, a simulation should be repeated to improve the analysis result by adjusting the two parameters (γ, γ_U) as in the followings.

$$\gamma = 8.0 \rightarrow 7.55, \quad \gamma_U = 6.0 \rightarrow 5.5$$

The simulation results using the parameters above are shown below.



It is found in the above results that the number of cycles is 23 in analysis compared to 24 in experiment. Then, the simulation is terminated for Case 1.

To check the identified PZ-Sand model parameters for Case 1, simulations for Cases 1 and 2 are performed similarly by changing the load condition. Their number of cycles reaching 5% double amplitude of axial strain are shown in the followings and the liquefaction strength curve is shown with those results of cases 1 ~ 3 in Figure 2.3.15.

Case 2 : 8 in analysis (6 in experiment)
Case 3 : 45 in analysis (43 in experiment)

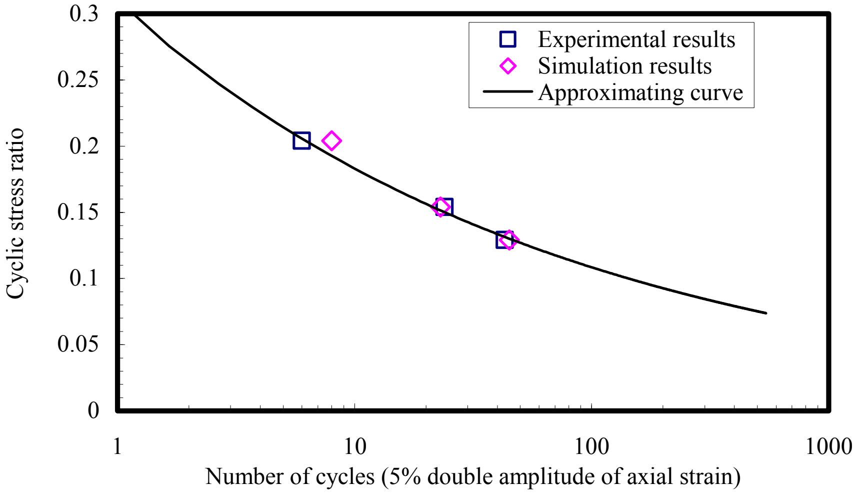


Figure 2.3.15 Liquefaction strength of simulation results from cyclic undrained triaxial test

3. PZ-Clay model

This is the generalized plasticity model for clay proposed by Zienkiewicz and his research group in References (1) and (2).

3.1. Constitutive law

The invariants to express the model are defined as the following equations.

$$p = \frac{1}{3}\sigma_{kk} \quad \cdots\cdots (3.1.1)$$

$$q = \sqrt{3J_2} \quad \cdots\cdots (3.1.2)$$

$$\theta = \frac{1}{3}\sin^{-1}\left(-\frac{3\sqrt{3}}{2}\cdot\frac{J_3}{{J_2}^{3/2}}\right) \quad \left(-\frac{\pi}{6} \le \theta \le \frac{\pi}{6}\right) \quad \cdots\cdots (3.1.3)$$

$$J_2 = \frac{1}{2}s_{ij}s_{ji} \quad \cdots\cdots (3.1.4)$$

$$J_3 = \frac{1}{3}s_{ij}s_{jk}s_{ki} \quad \cdots\cdots (3.1.5)$$

$$s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij} \quad \cdots\cdots (3.1.6)$$

where

p	: Mean principal stress
σ_{kk}	: Principal stress
q	: Deviatoric stress
θ	: Lode's angle
J_2	: Second invariant of deviatoric stress tensor
J_3	: Third invariant of deviatoric stress tensor
s_{ij}	: Deviatoric stress tensor
σ_{ij}	: Stress tensor
δ_{ij}	: Kronecker delta

The following incremental variables are defined.

$$d\varepsilon_v = d\varepsilon_{kk} \quad \cdots\cdots (3.1.7)$$

$$\mathrm{d}\varepsilon_s = \left(\frac{2}{3}\mathrm{d}e_{ij}\mathrm{d}e_{ji}\right)^{1/2} \quad \cdots\cdots (3.1.8)$$

$$de_{ij} = d\varepsilon_{ij} - \frac{1}{3}d\varepsilon_{kk}\delta_{ij} \quad \cdots\cdots (3.1.9)$$

where

$\mathrm{d}\varepsilon_v$	: Incremental volumetric strain
$\mathrm{d}\varepsilon_{kk}$	: Incremental principal strain
$\mathrm{d}\varepsilon_s$	: Incremental shear strain
$\mathrm{d}e_{ij}$	: Incremental deviatoric strain
$\mathrm{d}\varepsilon_{ij}$	: Incremental strain tensor

The dilatancy using the associative flow rules is expressed in the following equation.

$$d = (1+\alpha)(M-\eta) \quad \text{(3.1.10)}$$

where

$\eta = p'/q$: Stress ratio
p' : Effective mean principal stress
α , M : Model parameters

The direction of plastic flow is defined by the unit vector expressed in the following equation.

$$\mathbf{n} = \frac{1}{\sqrt{1+d^2}}\begin{Bmatrix} d \\ 1 \end{Bmatrix} \quad \text{(3.1.11)}$$

The condition of loading or unloading can be identified by the vector $\mathbf{n}$ as follow.

$\mathbf{n}^T d\boldsymbol{\sigma}^e > 0$: Loading (3.1.12a)

$\mathbf{n}^T d\boldsymbol{\sigma}^e < 0$: Unloading (3.1.12b)

The compression M_c and the extension M_e in triaxial test are expressed by using each friction angle as in the following equations.

$$M_c = \frac{6\sin\phi'_c}{3-\sin\phi'_c} \quad \text{(3.1.13a)}$$

$$M_e = \frac{6\sin\phi'_e}{3+\sin\phi'_e} \quad \text{(3.1.13b)}$$

The M is expressed in the following equations.

$$M = \frac{2M_e}{(1+C)-(1-C)\sin 3\theta} \quad \text{(3.1.14)}$$

with

$C = M_e / M_c$

The plastic modulus of normally consolidated clays during loading is expressed in the following equation.

$$H = H_0 p' f(\eta) \quad \text{(3.1.15)}$$

with

$$f(\eta) = \left|1-\frac{\eta}{M}\right|^{\mu}\frac{1+{d_0}^2}{1+d^2}\,sign\left[1-\frac{\eta}{M}\right] \quad \text{(3.1.16)}$$

$$d_0 = (1+\alpha)M \quad \text{(3.1.17)}$$

where

H_0 , μ : Model parameters

This model is extended to describe the behaviour of overconsolidated clays by introducing the mobilized stress function as expressed in the following equation.

$$\zeta = p'\left(1-\frac{\alpha}{1+\alpha}\frac{\eta}{M}\right)^{-1/\alpha} \quad \text{(3.1.18)}$$

The plastic modulus is expressed in this case as in the following equation.

$$H = H_0 p' \{ f(\eta) + g(\xi) \} \left(\frac{\zeta_{MAX}}{\zeta} \right)^{\gamma} \quad \text{(3.1.19)}$$

with

$$g(\xi) = \beta_1 \left(1 - \frac{\zeta}{\zeta_{MAX}} \right) \exp(-\beta_0 \xi) \quad \text{(3.1.20)}$$

$$\xi = \int \mathrm{d}\xi \qquad \mathrm{d}\xi = (\mathrm{d}e_{ij}^p \mathrm{d}e_{ji}^p)^{1/2} \quad \text{(3.1.21)}$$

Note that, for normally consolidated clays during loading, $\zeta = \zeta_{MAX}$ and $g(\xi) = 0$ are always satisfied.

The bulk and shear moduli are defined in the following equations.

$$K_{ev} = K_{ev0} p' \quad \text{(3.1.22)}$$

$$K_{es} = K_{es0} p' \quad \text{(3.1.23)}$$

where

K_{ev0}, K_{es0} : Initial constants of the bulk and shear moduli

3.2. Model parameters

The PZ-Clay model has ten parameters in which seven parameters (K_{es0}, K_{ev0}, M, C, α, H_0, μ) express the behaviour of normally consolidated clays and the remaining three parameters (β_0, β_1, γ) express the behaviour of overconsolidated clays and during cyclic loading. In addition, another two experimental condition parameters are required such as the initial effective mean principal stress (p'_0) and the overconsolidation ratio (OCR).

In parameters shown above, K_{es0}, K_{ev0} and H_0 are identified by the result of consolidation test and *M* and *C* are identified by the friction angles of the critical state. α and μ are identified by matching the effective mean principal stress and deviatoric stress curve by the consolidated-drained triaxial compression test (CD test) or the consolidated-undrained triaxial compression test with pore pressure measurement ($\overline{\mathrm{CU}}$ test). β_0, β_1 and γ are identified by the results of the cyclic undrained triaxial test.

It is required for the comprehensive estimate of the parameters to match the simulation results with the experimental data. For example, it is only necessary to use the experimental data up to the strain level if stress fluctuates greatly with strain and it is necessary for the effective-stress dynamic analysis to match the critical state line (CSL) as the preferable measure because the strain level is relatively high in this case.

The results of each triaxial test are shown as follows.

(1) Consolidated-drained triaxial compression test

1) Axial strain (ε_a) and deviatoric stress (q) curve

2) Axial strain (ε_a) and volumetric strain (ε_v) curve

3) Axial strain (ε_a) and stress ratio (η) curve

4) Stress ratio (η) and dilatancy (d_g) curve

(2) Consolidated-undrained triaxial compression test with pore pressure measurement

1) Axial strain (ε_a) and deviatoric stress (q) curve

2) Axial strain (ε_a) and pore pressure (Δu) curve

3) Effective mean principal stress (p') and deviatoric stress (q) curve [Effective stress path]

4) Axial strain (ε_a) and stress ratio (η) curve

(3) Cyclic undrained triaxial test

1) Time history of cyclic deviatoric stress

2) Time history of axial strain (ε_a)

3) Time history of pore pressure (Δu) or excess pore pressure ratio (L_u)

4) Effective mean principal stress (p') and deviatoric stress (q) curve [Effective stress path]

5) Axial strain (ε_a) and deviatoric stress (q) curve

6) Number of cycles and cyclic stress ratio curve [Liquefaction strength]

The way to identify each of the parameters is shown as follows.

(1) *M*

It is the slope of the critical state line (CSL) and is in the range 1.0 ~ 1.65 which is equivalent in friction angle to 25 ~ 40 (degree).

(2) *C*

It is the ratio of the critical state line (CSL) on the side of extension and compression but is usually taken as 0.80.

It is often expressed in the following equation in the case that the friction angles of extension and compression, ϕ'_c and ϕ'_e, are same.

$$C = \frac{3}{3 + M_c} \quad \cdots\cdots (3.2.1)$$

The yield surface expressed in equation (3.1.14) on Π plane is shown in Figure 3.2.1 and the condition, $C \geq 7/9$, is required in order to maintain the outer convex shape.

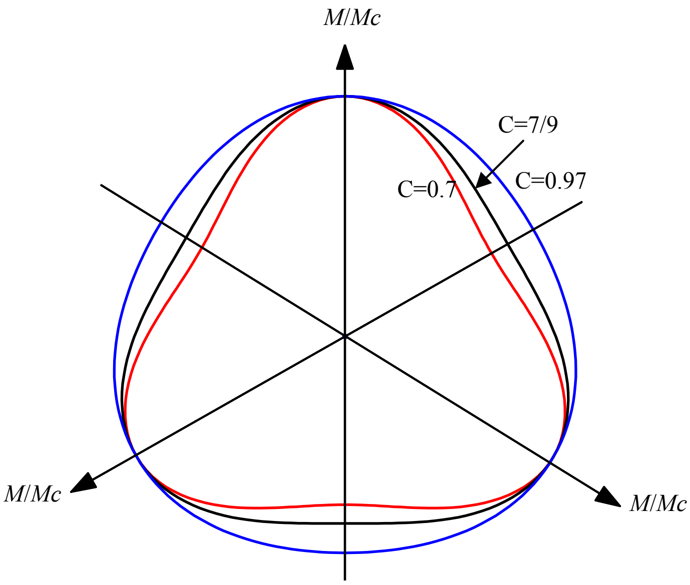


Figure 3.2.1 Yield surface shapes on Π plane depending on the parameter C

(3) α

It is the slope of the critical state line (CSL) and is available to better match the $\varepsilon_a \sim q$ curve.

In the $\alpha = 0$ case the yielding surface of PZ-Clay model is equivalent to that of the Cam-Clay model while in the $\alpha = 1$ case the maximum deviatoric stress of PZ-Clay model is equivalent to that of the modified Cam-Clay model.

α is expressed using the dilatancy d_0 at zero stress ratio and the stress ratio M at zero dilatancy from the $\eta \sim d_g$ approximating line from CD test as in the following equation.

$\alpha = d_0 / M - 1$

Meanwhile the maximum deviatoric stress q_{max} of normally consolidated clays from $\overline{\text{CU}}$ test is expressed using the initial confining pressure p_c in the following equation.

$$q_{max} = Mp_c \left(\frac{1}{1+\alpha} \right)^{1/\alpha} \quad \cdots\cdots (3.2.2)$$

Then, α can be determined by reading q_{max}/Mp_c in Figure 3.2.2, by solving the equation (3.2.2) or by solving the following approximating curve equation.

$$\alpha = 70.198 \left(\frac{q_{max}}{Mp_c} \right)^3 - 75.535 \left(\frac{q_{max}}{Mp_c} \right)^2 + 33.192 \left(\frac{q_{max}}{Mp_c} \right) - 5.491 \quad \cdots\cdots (3.2.3)$$

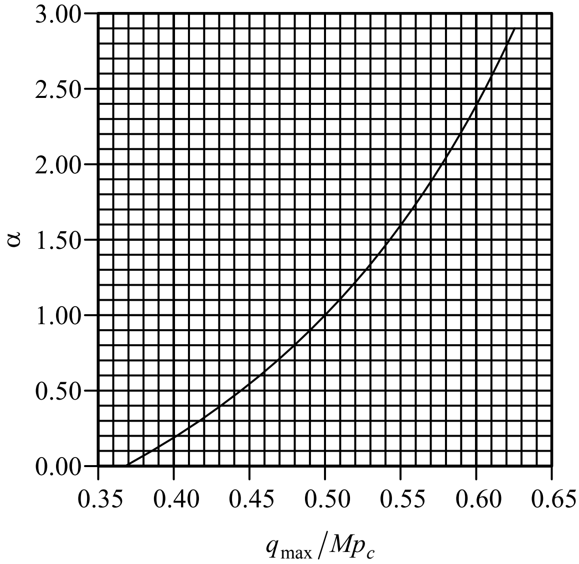


Figure 3.2.2 α and q_{max}/Mp_c of normally consolidated clays from $\overline{\text{CU}}$ test

(4) K_{ev0}

It is the initial constant of bulk modulus and is expressed in the following equation.

$$K_{ev0} = \frac{1+e_0}{\kappa} \quad \cdots\cdots (3.2.4)$$

where

κ : Slope of the elastic unloading line in the $e \sim \ln p'$ plane

e_0 : Voids ratio under pre-consolidation load

(5) K_{es0}

It is the initial constant of shear modulus and is expressed using the equations (3.1.22) and (3.1.23) in the following equation.

$$K_{es0} = \frac{9K_{ev0}(1-2\nu)}{2(1+\nu)} \quad \cdots\cdots (3.2.5)$$

with the relationship between the bulk and shear moduli expressed in the following equation

$$\frac{K_{es}}{3} = \frac{3(1-2\nu)}{2(1+\nu)} K_{ev}$$

where

ν : Poisson's ratio (usually taken as 0.2 ~ 0.3)

(6) H_0

It is a model parameter and is expressed in the following equation.

$$H_0 = \frac{1+e_0}{\lambda - \kappa} \quad \cdots\cdots (3.2.6)$$

where

λ : Slope of the normal consolidation line in the $e \sim \ln p'$ plane

κ : Slope of the elastic unloading line in the $e \sim \ln p'$ plane

e_0 : Voids ratio under pre-consolidation load

λ and κ are expressed using the plasticity index PI in the following experimental equations in Reference (3).

$\lambda = 0.02 + 0.0045PI$ and $\kappa = 0.00084(PI - 4.6)$

Meanwhile they can be expressed experimentally by $\lambda = 0.434C_c$ and $\kappa = 0.434C_S$ using the compression index C_c and the swelling index C_s.

(7) μ

It is a model parameter and is in the range 2.0 ~ 4.0 and its starting value is usually taken as 2.0.

(8) β_0

It is a model parameter controlling strain softening behaviour.

(9) β_1

It is a model parameter controlling the stress ratio of overconsolidated clays. It is in the range 0.1 ~ 0.2 and its starting value is usually taken as 0.12.

(10) γ

It is a model parameter to show strain hardening behaviour due to deviatoric stress. If it is greater than 2.0, the effect of the hardening is obvious. It is usually set up in the range 0.4 ~ 8.0.

In addition to the fifteen parameters, another two experimental condition parameters are required as follow.

(A1) p_0'

It is the initial effective mean principal stress and is expressed in the following equation.

$$p_0{}' = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad \cdots\cdots (3.2.7)$$

where

σ_1 : Axial stress

σ_2, σ_3 : Confining stresses ($\sigma_2 = \sigma_3$ in triaxial test)

(A2) OCR

It is the overconsolidation ratio.

3.3. Examples of parameter identification for PZ-Clay model

The examples of parameter identification for PZ-Clay model are described using the ETS (Element Test Simulation) software. The identification is performed for the normally consolidated Weald Clay (OCR=1 and 24) in Reference (2) by matching with the experimental data of the consolidated-undrained triaxial compression test with pore pressure measurement ($\overline{CU}$ test).

Note that the unit of kPa [= kN/m^2] is read as psi [=6.894 kPa] in this case because the unit of psi is used in the Weald Clay experimental results in Reference (2).

3.3.1. Weald Clay (OCR=1)

The parameter identification of the PZ-Clay model is performed for the normally consolidated Weald Clay (OCR=1) in Reference (2) based on the result of $\overline{CU}$ test.

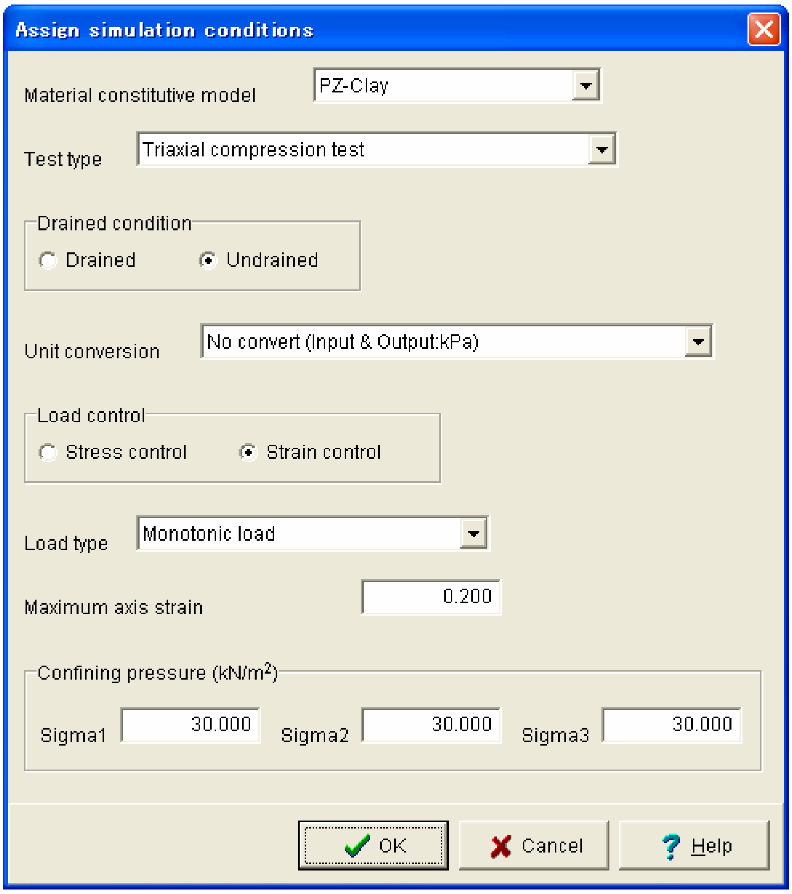
(1) Experimental conditions

Material name	: Weald Clay
Consolidated effective confining pressure σ'_c	: 30 psi (Isotropic consolidation)
Overconsolidation ratio OCR	: 1.0 (Normal consolidation)

(2) Input data of ETS (Element Test Simulation) software

1) Simulation conditions

Simulation conditions are assigned in the following dialog.



[Material constitutive model] combo box

'PZ-Clay' is selected from the pulldown menu.

[Test type] combo box

'Triaxial compression test' is selected from the pulldown menu for $\overline{\mathrm{CU}}$ test.

[Drained condition] radio group

'Undrained' is selected for $\overline{\mathrm{CU}}$ test.

[Unit conversion] combo box

'No convert (Input & Output: kPa)' is selected from the pulldown menu because both experimental and simulation data are same although the unit is written as 'kPa' in this case.

[Load control] radio group

'Strain control' is selected in this case.

[Load type] combo box

'Monotonic load' is selected from the pulldown menu in this static case.

[Maximum axial strain] edit

'0.20' is input to consider up to 20% of axial strain level in this case.

[Confining pressure] edit group

'30.0' is input in each edit box according to the prescribed simulation condition of isotropic consolidation.

Note that the unit is 'psi' although it is written as '$\mathrm{kN/m^2}$' in this case.

2) Model parameters

The ten PZ-Clay model parameters and another two experimental condition parameters of the initial effective mean principal stress (p_0') and the overconsolidation ratio (OCR) are assigned in the following dialog. The six parameters (K_{es0}, K_{ev0}, M, H_0, μ, γ) are assigned in reference to the data in Table 4.1 and Figure 4.37 of Reference (2). The remaining four parameters (C, α, β_0, β_1) are assigned based on definitions in this software.

M (=Mf)

'0.90' is input based on the data in Table 4.1 (p.140) of Reference (2).

C (=C)

'0.80' is input as usual.

α_f (=Alpha-f)

'1.0' is input in this case the maximum deviatoric stress of PZ-Clay model is equivalent to that of the modified Cam-Clay model.

K_{ev0} (=Kevo)

'26.7' is input by the following equation using equation (3.1.22) and $p_0' = 30\mathrm{psi}$.

$$K_{ev0} = \frac{800\mathrm{psi}}{30\mathrm{psi}} = 26.7$$

where K_{ev} is taken as 800 psi although the K_{ev0} in Table 4.1 (p.140) of Reference (2) is written as 800 $\mathrm{Kg/cm^2}$.

K_{es0} (=Geso)

'25.5' is input by the following equation using equation (3.1.22) and $p_0' = 30\mathrm{psi}$.

$$K_{es0} = \frac{766\mathrm{psi}}{30\mathrm{psi}} = 25.5$$

where K_{es} is taken as 766 psi although the G_0 in Table 4.1 (p.140) of Reference (2) is written as 766 $\mathrm{Kg/cm^2}$.

β_0 (=Beta0)

'0.0' is input because this parameter does not affect the result for the normally consolidated clays.

β_1 (=Beta1)

'0.0' is input because this parameter does not affect the result for the normally consolidated clays.

H_0 (=Ho)

'165.0' is input based on the data in Table 4.1 (p.140) of Reference (2).

μ (=Mu)

'3.0' is input based on the data in Table 4.1 (p.140) of Reference (2).

γ (=Gamma)

'0.40' is input based on the data in Table 4.1 (p.140) of Reference (2).

p_0' (=Po)

'30.0' is input by the followings using equation (3.2.7).

$$p_0' = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{3 \times 30\mathrm{psi}}{3} = 30\mathrm{psi}$$

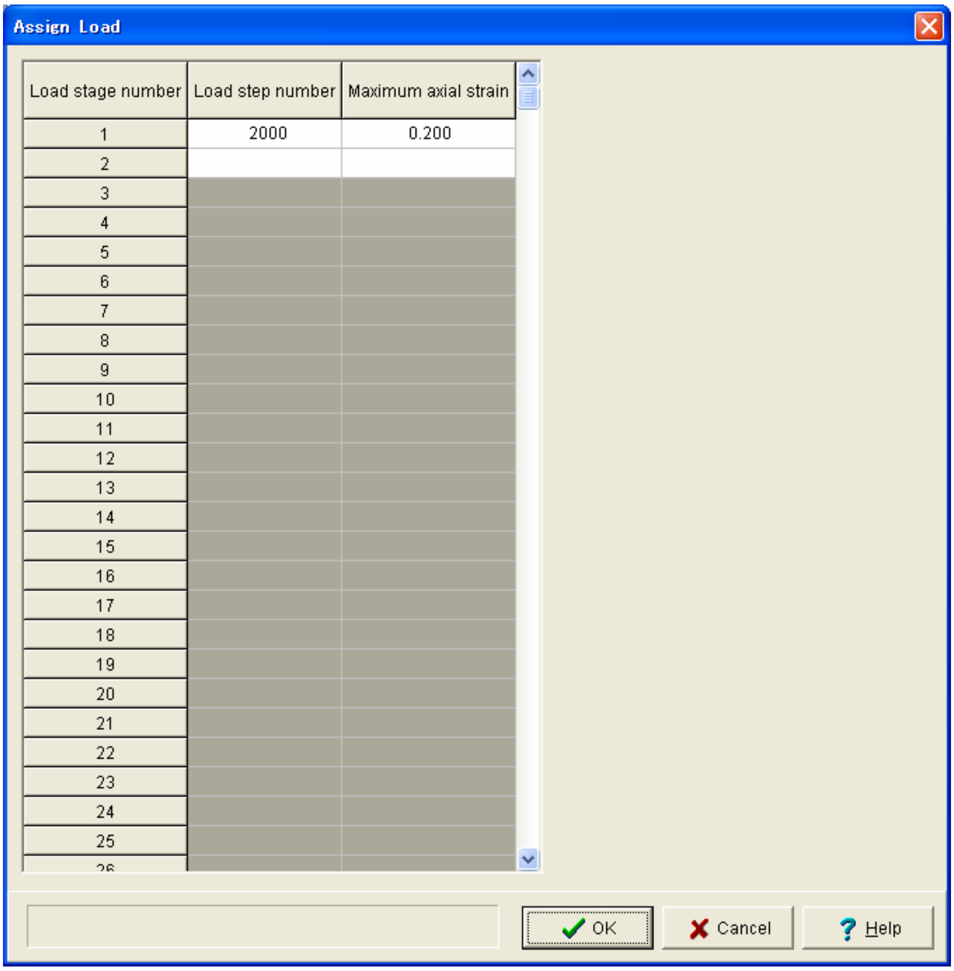
Note that the unit is 'psi' although it is written as '$\mathrm{kN/m^2}$' in this case.

OCR

'1.0' is input in this case.

3) Load

Load is assigned in the following dialog.



[Load stage number]

The data of one load stage are assigned for the case of $\overline{CU}$ test.

[Load step number]

It is the division number of the load step and is usually taken as 1,000 ~ 2,000 at each stage.

'2000' is input in this case.

[Maximum axial strain]

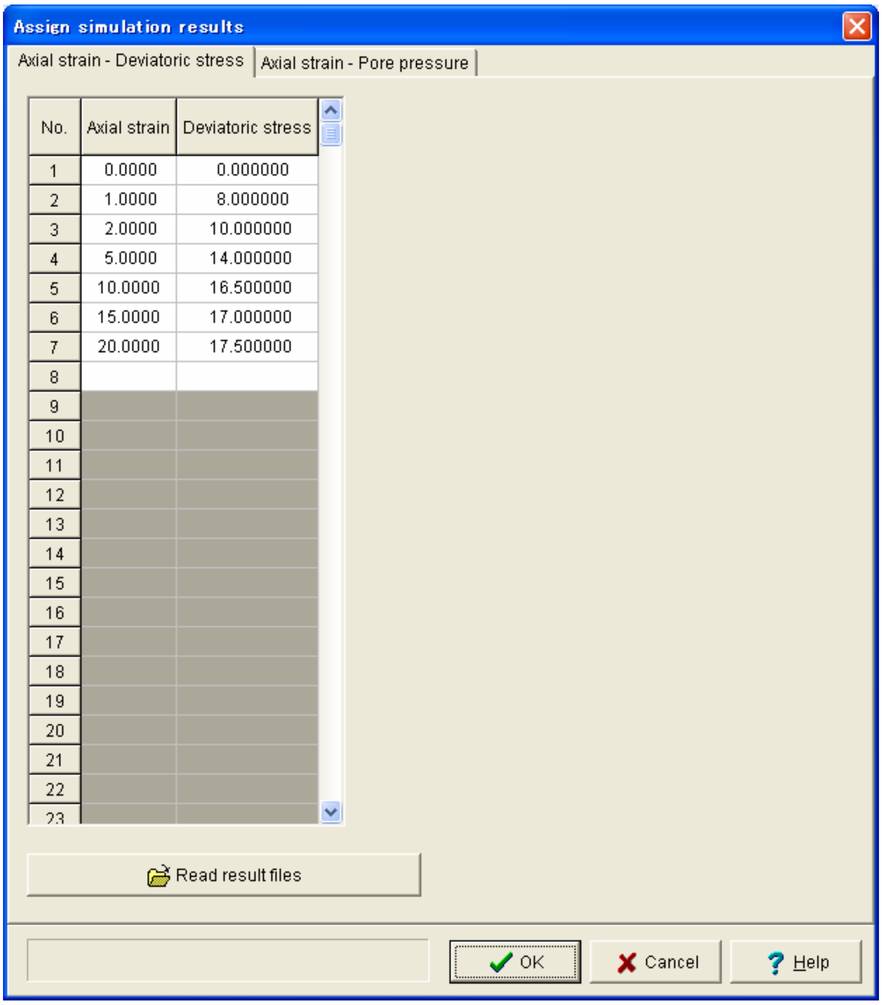
It is the maximum axial strain which is usually the same value as set up in the [Assign simulation conditions] dialog.

'0.20' is input to consider up to 20% of axial strain level in this case.

4) Experimental results

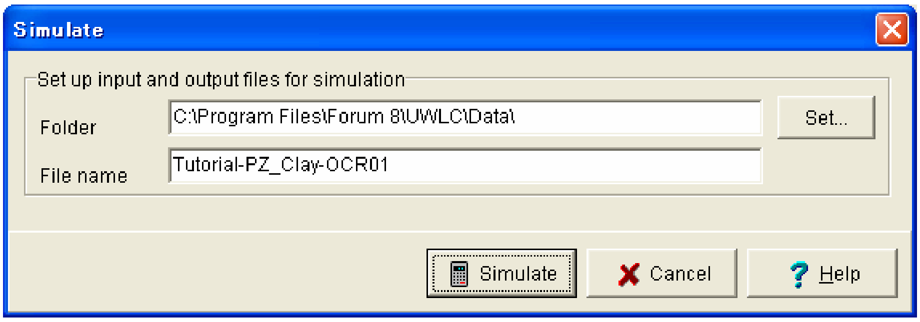
Experimental results of $\varepsilon_a \sim q$ and $\varepsilon_a \sim \Delta u$ are assigned in the following dialog by reading from file or typing.

Note that the assigned data is read from the Figure 4.37 (p.140) of Reference (2).



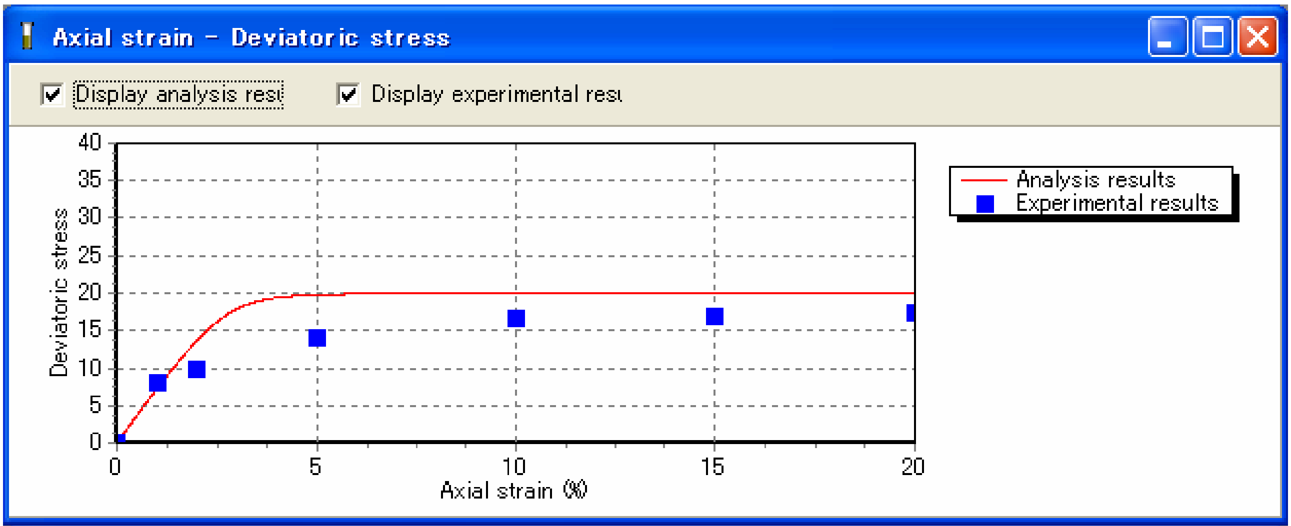
5) Simulate

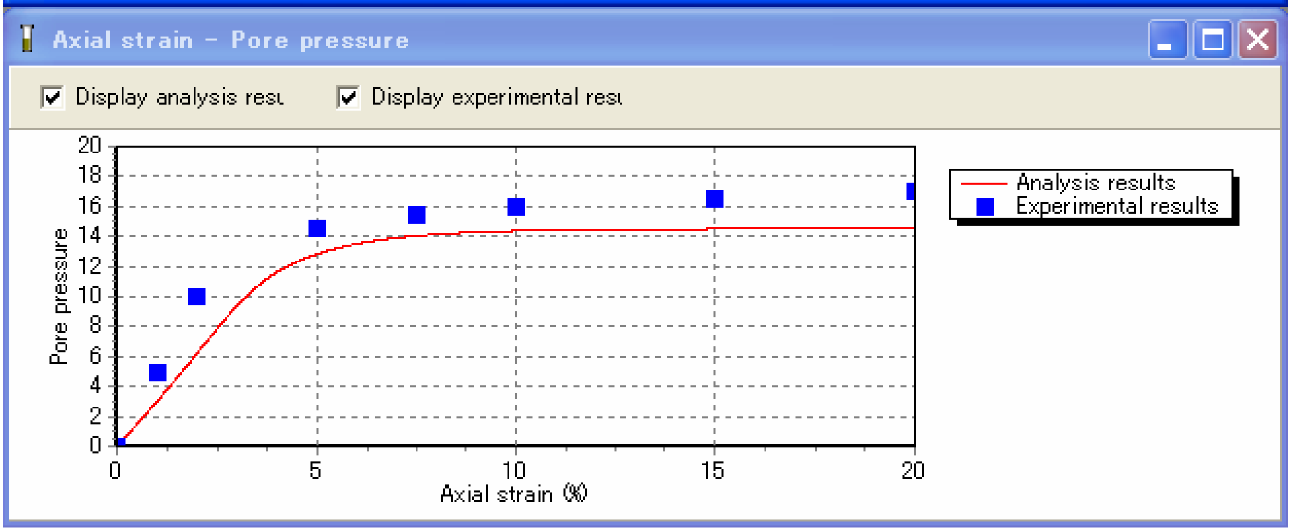
The folder to save the I/O files and the file name without extension is specified and simulation can be performed by clicking the [Simulate] button in the following dialog. .



(3) Simulation results and parameter adjustments

Simulation results for the assigned parameters in previous section (2) are shown below.





3.3.2. Weald Clay (OCR=24)

The parameter identification of the PZ-Clay model is performed for the normally consolidated Weald Clay (OCR=24) in Reference (2) based on the result of $\overline{\mathrm{CU}}$ test.

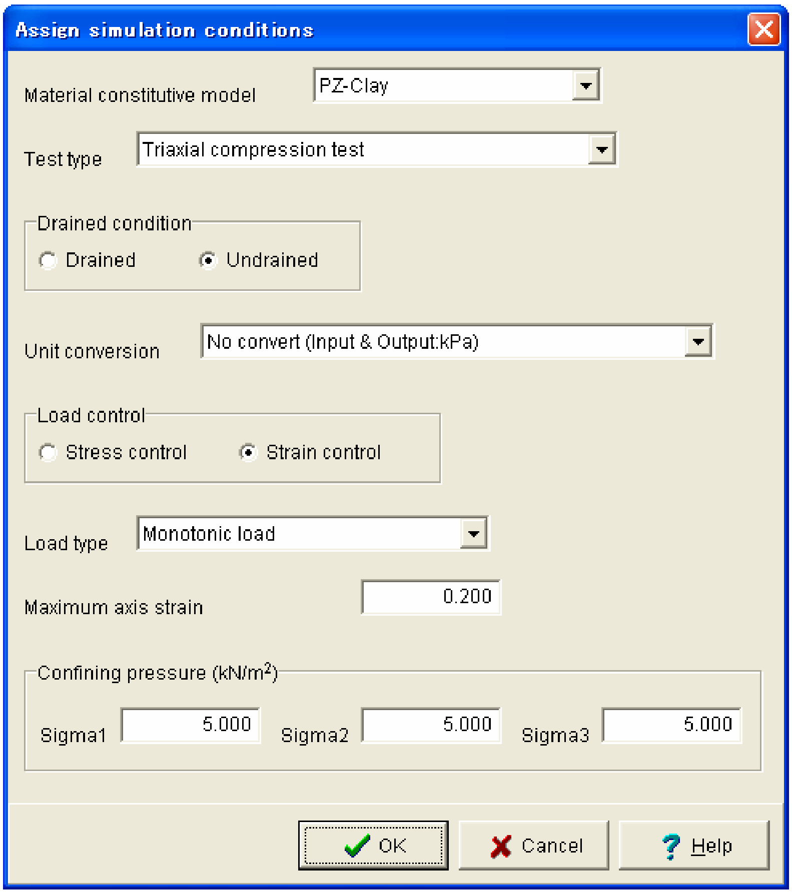
(1) Experimental conditions

Material name	: Weald Clay
Consolidated effective confining pressure σ_c'	: 5 psi (Isotropic consolidation)
Overconsolidation ratio OCR	: 24.0 (Overconsolidation)

(2) Input data of ETS (Element Test Simulation) software

1) Simulation conditions

Simulation conditions are assigned in the following dialog.



[Material constitutive model] combo box

'PZ-Clay' is selected from the pulldown menu.

[Test type] combo box

'Triaxial compression test' is selected from the pulldown menu for $\overline{CU}$ test.

[Drained condition] radio group

'Undrained' is selected for $\overline{CU}$ test.

[Unit conversion] combo box

'No convert (Input & Output: kPa)' is selected from the pulldown menu because both experimental and simulation data are same although the unit is written as 'kPa' in this case.

[Load control] radio group

'Strain control' is selected in this case.

[Load type] combo box

'Monotonic load' is selected from the pulldown menu in this static case.

[Maximum axial strain] edit

'0.20' is input to consider up to 20% of axial strain level in this case.

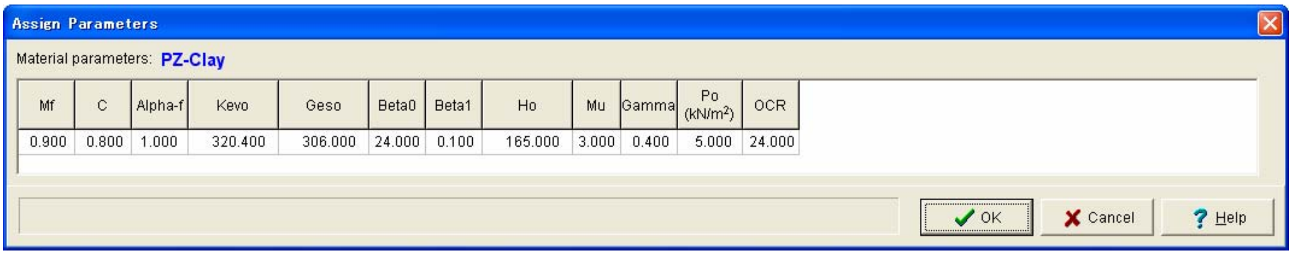
[Confining pressure] edit group

'5.0' is input in each edit box according to the prescribed simulation condition of isotropic consolidation.

Note that the unit is 'psi' although it is written as 'kN/m^2' in this case.

2) Model parameters

The ten PZ-Clay model parameters and another two experimental condition parameters of the initial effective mean principal stress (p_0') and the overconsolidation ratio (OCR) are assigned in the following dialog. The six parameters (K_{es0}, K_{ev0}, M, H_0, μ, γ) are assigned in reference to the data in Table 4.1 and Figure 4.38 of Reference (2). The remaining four parameters (C, α, β_0, β_1) are assigned based on definitions in this software.



M (=Mf)

'0.90' is input based on the data in Table 4.1 (p.140) of Reference (2).

C (=C)

'0.80' is input as usual.

α_f (=Alpha-f)

'1.0' is input in this case the maximum deviatoric stress of PZ-Clay model is equivalent to that of the modified Cam-Clay model.

K_{ev0} (=Kevo)

'320.4' is input using the twelve times the K_{ev0} value of the normally consolidated clay ($p_0' = 30\text{psi}$) and equation (3.1.22) as in the following equation.

$$K_{ev0} = 12 \times \frac{800\text{psi}}{30\text{psi}} = 320.4$$

where K_{ev} is taken as 800 psi although the K_{ev0} in Table 4.1 (p.140) of Reference (2) is written as 800 Kg/cm^2.

Note that the K_{ev0} value of overconsolidated clay is taken as the twelve times the K_{ev0} value of normally consolidated clay following the Reference (4) as usual. It is generally known that its scale factor increases with the overconsolidation ratio.

K_{es0} (=Geso)

'306.0' is input using the twelve times the K_{es0} value of the normally consolidated clay ($p_0' = 30\text{psi}$) for the same reason as the above K_{ev0} case and equation (3.1.23) as in the following equation.

$$K_{es0} = 12 \times \frac{766\text{psi}}{30\text{psi}} = 306.0$$

where K_{es} is taken as 766 psi although the G_0 in Table 4.1 (p.140) of Reference (2) is written as 766 Kg/cm^2.

β_0 (=Beta0)

'24.0' is input as a recommended starting value by $\beta_0 = \text{OCR} = 24$ for overconsolidated clays.

β_1 (=Beta1)

'0.10' is input as a recommended starting value for overconsolidated clays.

H_0 (=Ho)

'165.0' is input based on the data in Table 4.1 (p.140) of Reference (2).

μ (=Mu)

'3.0' is input based on the data in Table 4.1 (p.140) of Reference (2).

γ (=Gamma)

'0.40' is input based on the data in Table 4.1 (p.140) of Reference (2).

p'_0 (=Po)

'5.0' is input by the followings using equation (3.2.7).

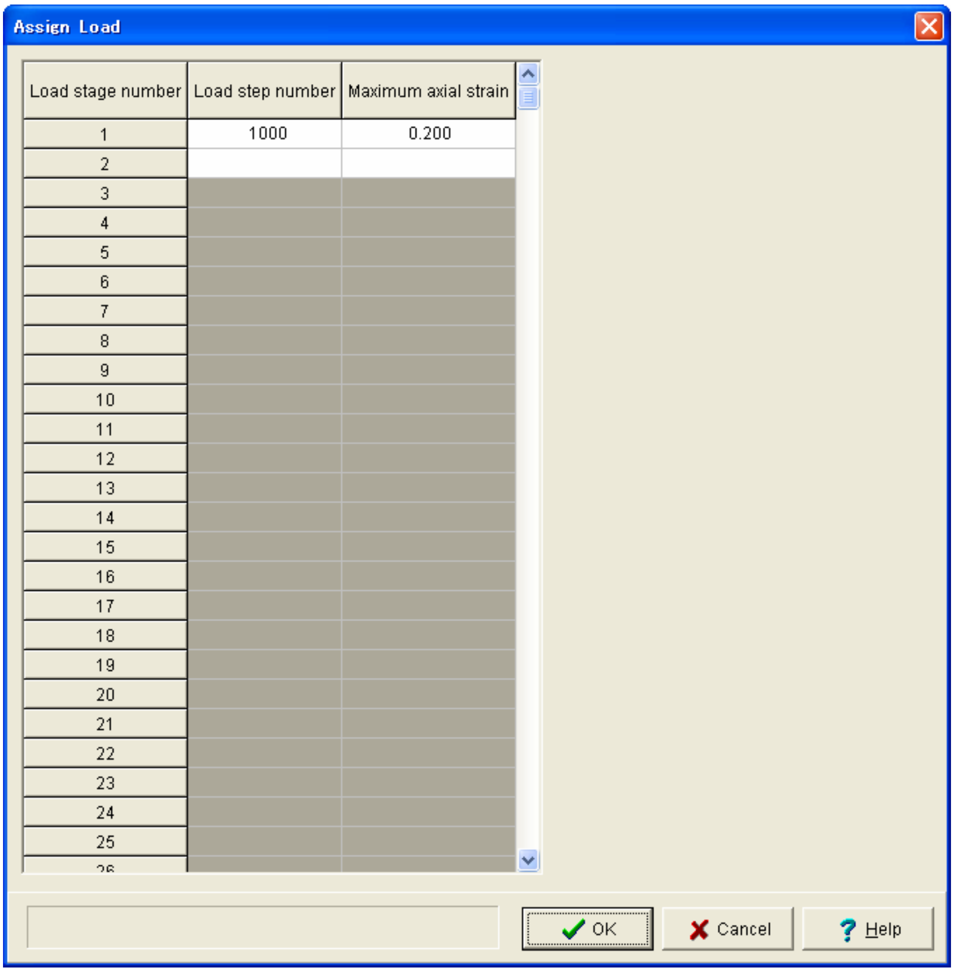
$$p'_0 = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{3 \times 5\text{psi}}{3} = 5\text{psi}$$

OCR

'24.0' is input in this case.

3) Load

Load is assigned in the following dialog.



[Load stage number]

The data of one load stage are assigned in this case because the number of $\overline{\text{CU}}$ test is one.

[Load step number]

It is the division number of the load step and is usually taken as 1,000 ~ 2,000 at each stage.

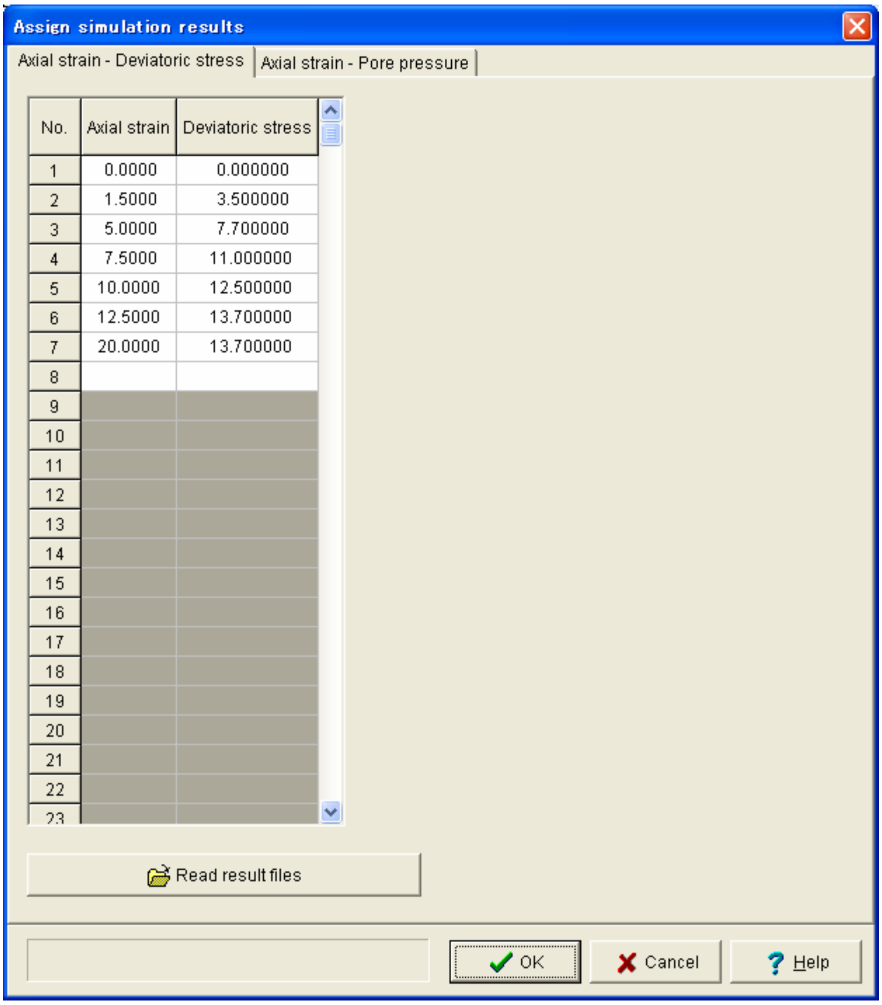
'1000' is input in this case.

[Maximum axial strain]

It is the maximum axial strain which is usually the same value as set up in the [Assign simulation conditions] dialog. '0.20' is input to consider up to 20% of axial strain level in this case.

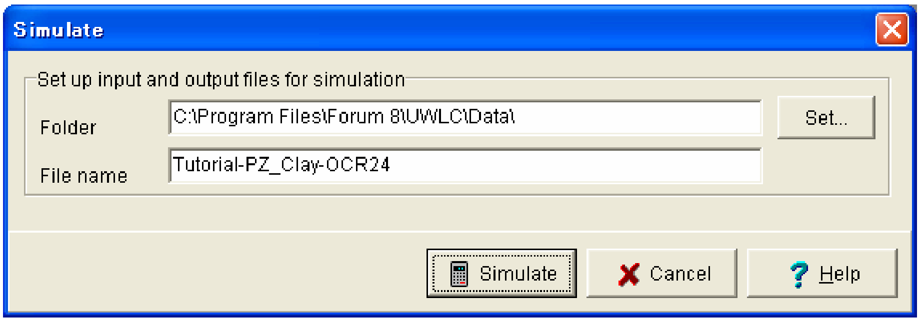
4) Experimental results

Experimental results of $\varepsilon_a \sim q$ and $\varepsilon_a \sim \Delta u$ are assigned in the following dialog by reading from file or typing. Note that the assigned data is read from the Figure 4.37 (p.140) of Reference (2).



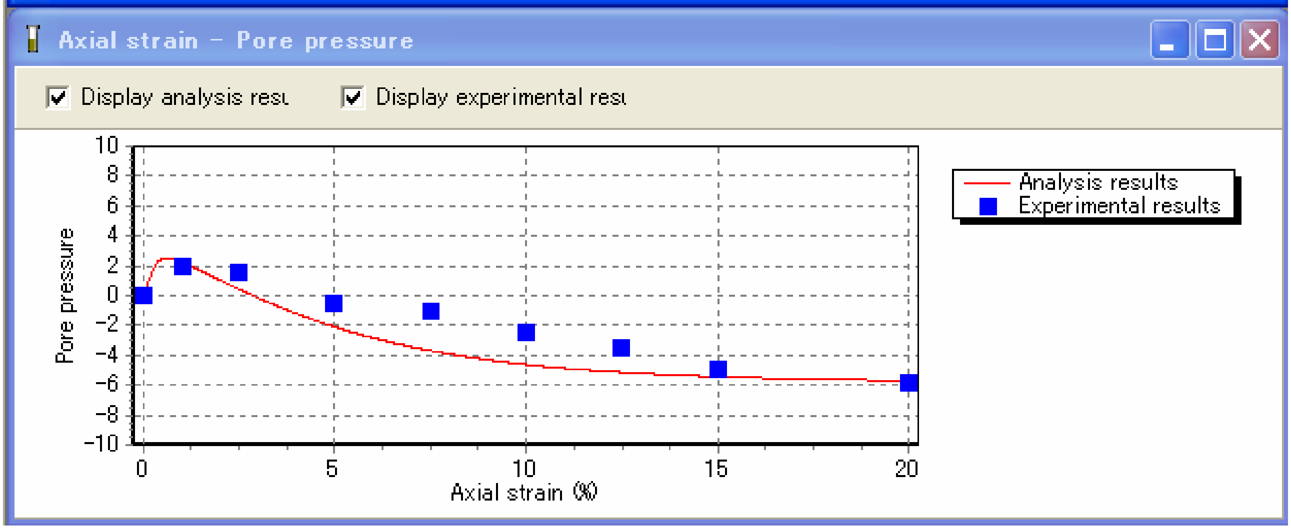
5) Simulate

The folder to save the I/O files and the file name without extension is specified and simulation can be performed by clicking the [Simulate] button in the following dialog. .



(3) Simulation results and parameter adjustments

Simulation results for the assigned parameters in previous section (2) are shown below.



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