Japanese Geotechnical Society Standard (JGS 0541-2020)
Method for cyclic undrained triaxial test on soils

1 Scope

This standard specifies a test method to obtain the relationship between the number of load cycles to reach a specific double amplitude strain and a specific excess pore water pressure and the single amplitude of the cyclic deviator stress under undrained conditions or the cyclic stress amplitude ratio, for saturated specimens that were consolidated under isotropic stress conditions. The standard applies mainly to saturated sandy soils.

Note 1: Sandy soil referred to here is soil that consists mainly of sand fraction.

Note 2: Soils that have been saturated after the test specimen is prepared are included. Also, this standard is also applicable to saturated cohesive soils and gravelly soils.

2 Normative references

The following standards shall constitute a part of this standard by virtue of being referenced in this standard. The latest versions of these standards shall apply (including supplements).

JGS 0520 Preparation of soil specimens for triaxial tests

Matters not prescribed in this standard shall be in accordance with the following related codes and standards.

JGS 0522 Method for consolidated-undrained triaxial compression test on soils
JGS 0523 Method for consolidated-undrained triaxial compression test on soils with pore water pressure measurements
JGS 0524 Method for consolidated-drained triaxial compression test on soils

For coarse-grained soil with maximum particle size exceeding about 20 mm, the test specimens to be used in the test shall be prepared and installed in accordance with the following standard.

JGS 0530 Preparation of specimens of coarse granular materials for triaxial tests

3 Terms and definitions

In addition to those specified in JIS A 0207, the main terminology and definitions used in this standard shall be as follows.

3.1 Cyclic undrained triaxial test

A test in which a constant amplitude and symmetric cyclic axial load is applied to an isotropically consolidated specimen for a constant period, under constant cell pressure and undrained conditions.

3.2 Axial stress

The stress acting on the specimen in the cylinder axis direction.

3.3 Lateral stress

The stress acting in the radial direction of the test specimen.

3.4 Cyclic deviator stress

The difference between the axial and lateral stresses in the cyclic undrained loading process. The stress value shall be defined at the mid-height of the specimen.

3.5 Cell pressure

The pressure applied to the triaxial pressure cell. The lateral stress is equal to the cell pressure.

3.6 Back pressure

Refers to the pressure applied to the pore water within the test specimen (JIS A 1227).

Note: In this standard, the back pressure means the pore water pressure applied to the specimen to achieve a higher degree of saturation of the specimen while maintaining a constant effective stress.

3.7 Consolidation stress

Refers to the stress of soil element that induces consolidation.

Note: In this Standard, the consolidation stress means the difference between the externally applied stress on the test specimen and the back pressure during the consolidation process.

3.8 Effective confining pressure

The external stress acting on a test specimen immediately before the cyclic undrained loading process minus the back pressure. In the case of normal consolidation the effective confining pressure is equal to the consolidation stress at completion of consolidation.

3.9 Cyclic stress amplitude ratio

Half the single amplitude of the cyclic deviator stress divided by the effective confining pressure.

4 Equipment

The cyclic triaxial apparatus shall include a triaxial pressure cell, a cell pressure and back pressure supply device, an axial loading device, and load, displacement, volume change, pore water pressure measuring and recording devices, and shall satisfy the following conditions. An example of a cyclic triaxial apparatus is shown in Figure 1.

a) The test equipment shall have sufficient capacity and load resistance with respect to the maximum cell pressure, back pressure, the maximum axial compressive load and the maximum axial tensile load on the specimen. The triaxial cell shall be fixed to a loading platform or similar, so that the triaxial cell is not raised up when the maximum axial tensile load is acting. In order to produce a triaxial extensile stress state during cyclic loading, as a standard, a triaxial cell in which the load piston and the cap are rigidly connected shall be used (refer to Figure 2(a) of JGS 0522 Method for consolidated undrained triaxial compression test on soils), and the load piston and cap shall be rigidly connected before setting the specimen in the triaxial cell.

Note: If the specimen is set in the triaxial cell without rigidly connecting the load piston and cap, the load piston and the cap should be connected after a sufficiently large effective stress is applied to the specimen.

b) The specimen shall be covered with the cap, pedestal, and a rubber sleeve, it shall be possible to apply the required cell pressure, back pressure, and axial load, and it shall be possible to supply and drain water at the top and bottom ends of the specimen. The diameter of the cap and pedestal shall be the same as the diameter of the specimen as standard, and the two surfaces of the cap and pedestal shall be flat and parallel to each other, which shall be normal to the load piston. A porous plate with sufficient water permeability shall be used on the water drainage surfaces, and if necessary an appropriate filter paper shall be used. Also, the volume change of the pore water pressure measurement line (see Figure 2), which includes the pore water meter pressure receiving unit, and the water drainage line between the specimen and the water drainage valve, due to water pressure changes shall be sufficiently small.

Note: If the volume of the specimen is V, and the volume change of the pore water pressure measurement line for a change in pore water pressure Δu is ΔV, then $\{(\Delta V/V)/\Delta u\}$ should be $<5\times10^{-6}$ m^2/kN.

c) During isotropic consolidation, the apparatus shall be capable of continuously applying the required cell pressure, back pressure, and axial stress within a range of fluctuation of ±2 kN/m^2 for pressures less than 200 kN/m^2, and ±1.0% for pressures more than 200 kN/m^2. Also, during consolidation it shall be possible to measure the axial displacement and volume change of the specimen with an allowable tolerance in the height of the specimen and the volume of 0.02% and 0.05%, respectively.

Note: The burette shall have a structure to enable the back pressure to be applied, and should have a structure so that the water level in the burette does not change due to changes in the back pressure.

d) In the undrained state after isotropic consolidation, the apparatus shall be capable of continuously applying the cyclic load until the double amplitude axial strain *DA* as defined in Section 6.3 is more than 5%. During cyclic axial loading, the cell pressure shall not fluctuate due to the load piston entering and exiting the triaxial pressure cell. The wave form shall be a sine wave with a frequency of 0.1 to 1.0 Hz as standard, and cyclic axial load other than a sine wave may be used if it has been confirmed that the cyclic axial load amplitude can be accurately controlled and measured. However, a rectangular or trapezoidal wave shall not be used. The following conditions shall be always satisfied until the cyclic axial load reaches *DA* = 2%.

1) The fluctuation in the sum of the single amplitude P_C of the compressive load and the single amplitude P_E of the extensile load defined from the isotropic stress state, ($P_C + P_E$) shall be less than 10%.

2) $0.9 \leqq P_C/P_E \leqq 1.1$

where the single amplitude P_C of the compressive load and the single amplitude P_E of the extensile load shall be defined from the isotropic stress state as shown in Figure 3. In the figure, *P* is the cyclic axial load which is taken to be zero under an isotropic stress state. The axial load acting on the load piston is the sum of the cyclic axial load *P* and the force acting on the load piston due to the cell pressure.

Note: The load frequency need not to be limited to the range 0.1 to 1.0 Hz if it has been confirmed that the effect on the test results is negligible.

e) During cyclic loading, the apparatus shall be capable of continuously applying the required cell pressure to within a range of fluctuation of pressure of ±2 kN/m^2 for pressures less than 200 kN/m^2, and ±1.0% for pressures more than 200 kN/m^2.

f) During cyclic loading, it shall be possible to continuously measure the pore water pressure and if necessary the cell pressure to within an allowable tolerance of 2 kN/m^2 for pressures less than 200 kN/m^2, and 1.0%for pressures more than 200 kN/m^2. An electric pressure transducer shall be used to measure the pore water pressure during cyclic loading.

g) During cyclic loading, the axial load shall be measured by satisfying the following conditions.

1) During cyclic loading it shall be possible to continuously measure the cyclic axial load acting on the specimen to within an allowable tolerance of 0.5% of the required load double amplitude.

2) An electrical load cell shall be used for measuring the cyclic axial load. If the load cell is inside or outside the triaxial cell, when the diameter of the load piston is sufficiently smaller than the diameter of the specimen, a load cell capable of measuring both the compressive force and the tensile force shall be used. If the load cell is outside the triaxial cell, when the diameter of the load piston is comparatively large, a load cell that is capable of measuring the compressive force only may be used.

3) When the load cell is outside the triaxial pressure cell, the single amplitude friction force *F* at the bearing of the triaxial pressure chamber based on the cell pressure shall satisfy the following condition. When the measured value of the friction force *F* of the load piston does not satisfy the condition, either the piston friction shall be deducted from the measured P_C and P_E, or the load cell shall be installed inside the triaxial pressure cell.

$F < 0.02 \times$ (effective confining pressure σ'_0)×(specimen cross-sectional area)

4) If the load cell is installed inside the triaxial cell, the effect of the cell pressure shall be determined, and the measured value of the axial compression force shall be corrected.

5) If the axial displacement gauge is located between the load cell and the specimen, an axial displacement gauge for which the reaction force can be ignored shall be used.

h) The axial displacement during cyclic loading shall be measured continuously to within an allowable tolerance of 0.05% of the height of the specimen. The amount of axial displacement during cyclic loading may be measured with an electric displacement gauge installed outside the triaxial cell, where the displacement of the load piston located between the axial displacement gauge and the specimen, the displacement of the load cell, etc., and the displacement of the fixing location of the displacement cell, etc., shall be sufficiently small so that they can be ignored.

i) During cyclic loading it shall be possible to continuously record the pore water pressure, cyclic axial load, axial displacement, and if necessary the cell pressure. As a standard, they shall be continuously recorded using an electric recording device such as a data recorder or similar. However, when a digital data recorder is used, the number of data points in one cycle shall be more than 40, so that it will be possible to sufficiently interpolate between two consecutive digital measurement values.

5 Test method

5.1 Preparation and installation of the specimen

Preparation of the specimen shall be in accordance with JGS 0520 Preparation of soil specimens for triaxial tests. The diameter of the specimen shall be more than 50 mm for a sandy soil, and more than 35 mm for a cohesive soil, and the height of the specimen shall be 1.5 to 2.5 times the diameter.

5.2 Checking the degree of saturation of the specimen

Before consolidation and if necessary after consolidation, the pore water pressure coefficient *B* (*B* value) shall be measured. The *B* value shall be obtained under an isotropic stress state.

a) The *B* value before consolidation shall be obtained by the following method.

1) Close the drainage valve.

2) Increase the isotropic stress $\Delta\sigma$ for 1 to 2 minutes. The value of $\Delta\sigma$ shall be about 10 to 50 kN/m^2 as standard. However, after $\Delta\sigma$ is applied, the cell pressure shall not exceed the cell pressure at completion of isotropic consolidation.

3) When the pore water pressure has settled to a constant value, the increment in the pore water pressure Δu shall be measured.

4) Calculate the pore pressure coefficient B ($=\Delta u/\Delta\sigma$). When the *B* value is higher than 0.95, either open the water drainage value and start isotropic consolidation, or open the drainage valve after incrementing the isotropic stress to a prescribed value when consolidation is completed. If the *B* value is smaller than 0.95, reduce the isotropic stress by $\Delta\sigma$ and return to the beginning, and increase the degree of saturation by the method described in Section 4.6a) of JGS 0520 Preparation of soil specimens for triaxial tests, so that the *B* value is 0.95 or higher.

b) Instead of obtaining the *B* value before starting consolidation, it may be obtained by the method described in Section 5.2a) above, at a stress stage lower than the prescribed consolidation stress. However, the primary consolidation at that stress stage shall be completed.

c) For specimens with *B* value 0.95 or higher and consolidation time 8 hours or less, the *B* value after consolidation need not be obtained. However, if air remains within the triaxial pressure cell and if there is a possibility that air has entered the specimen through the cell water due to the cell pressure being applied for 8 hours or longer, the *B* value after consolidation shall be obtained by the following method.

1) After primary consolidation of the specimen is completed, close the water drainage valve.

2) Reduce the isotropic stress by $\Delta\sigma$ for 1 to 2 minutes. $\Delta\sigma$ shall be about 10 to 50 kN/m^2 as standard.

3) Measure the reduction in pore water pressure Δu_u.

4) At the same time as 2) increment the isotropic stress by $\Delta\sigma$.

5) Measure the increment in pore pressure Δu_1.

6) Calculate the pore water pressure coefficient B (=(Δu_u+Δu_1)/(2$\Delta\sigma$)).

7) Open the drainage valve.

8) When the *B* value is 0.95 or higher, go to Section 5.4. When the *B* value is smaller than 0.95, increase the degree of saturation by the method described in Section 4.6a) of JGS 0520 Preparation of soil specimens for triaxial tests, so that the *B* value is 0.95 or higher.

5.3 Consolidation process

The test shall be carried out in accordance with the following requirements for the consolidation process.

a) Carry out consolidation with a constant back pressure by applying isotropic stress to the specimen up to the prescribed consolidation stress σ'_c. The value of back pressure shall be sufficiently large so that during cyclic loading the pore water pressure u (= back pressure u_b + excess pore water pressure Δu) does not become negative under triaxial extensile stress conditions, and shall be more than 100 kN/m^2 as standard.

b) Consolidation shall be continued until at least the primary consolidation is complete. For sandy soils with a fine fraction content of less than 10%, if the primary consolidation of the specimen is completed within 5 minutes, discontinue it at a suitable time in excess of 30 minutes. If it is necessary to quantitatively determine completion of primary consolidation, measure the volume change and if possible the change in axial displacement during consolidation with time, in accordance with the method prescribed in Section 5.2d) of JGS 0522 Method for consolidated-undrained triaxial compression test on soils.

c) Measure the volume change of the specimen (assumed to be equal to the quantity of water drained from the specimen) ΔV_c (mm^3) and the axial displacement of the specimen ΔH_c (mm) due to consolidation.

5.4 Cyclic undrained loading process

The test shall be carried out in accordance with the following requirements for the cyclic undrained loading process.

a) Confirm the isotropic stress state with the prescribed effective confining pressure σ'_0. It is necessary that the ratio of axial consolidation stress (= effective axial stress at completion of consolidation) σ'_{ac} and the lateral consolidation stress (= effective lateral stress at completion of consolidation)σ'_{rc} shall satisfy $0.98 < \sigma'_{ac}/\sigma'_{rc} < 1.02$. In particular, if the consolidation stress is about 50 kN/m^2 or less, the cell pressure shall be carefully controlled. Also, the axial load shall be accurately controlled taking into consideration the load acting on the load piston due to the cell pressure and the self weight of the load piston, etc., and the isotropic stress state shall be carefully checked.

b) Close the drainage valve.

c) Apply the cyclic axial load, and continuously record the axial load, axial displacement, pore water pressure, and if necessary the cell pressure. The first wave shall be the compressive load. If it has been confirmed that the cell pressure does not fluctuate during cyclic loading, the cell pressure needs not be continuously recorded. An example of cyclic undrained triaxial test record is shown in Figure 4.

d) Terminate the cyclic loading if the number of cycles exceeds about 200, or if the double amplitude axial strain DA (=$\Delta L/H_c$) ×100 is 5% or higher. Where, ΔL is the double amplitude of the axial displacement (ΔH) of the specimen during cyclic loading, and H_c is the height of the specimen after consolidation.

Note: The maximum number of cycles may be determined as appropriate in accordance with the condition of the specimen and the objectives of the test.

e) The deformation and failure state of the specimen shall be observed and recorded.

f) Measure the dry mass m_s of the specimen (g).

5.5 Tests with cyclic loading amplitude varied

This shall refer to a series of tests carried out under the same effective confining pressure, using the necessary number of similar specimens, but with the cyclic loading amplitude varied as appropriate. The number of specimens shall be a minimum of 4.

Note: The magnitude of the cyclic axial load amplitude shall be adjusted so that at least 2 specimens have the number of load cycles to reach double amplitude axial strain DA of 5% in the range of about 5 to 50.

6 Processing test results

6.1 Specimen state before consolidation

The specimen volume V_0 (mm^3) and specimen height H_0 (mm) before consolidation shall be calculated from the following equation.

$$V_0 = V_i - \Delta V_i$$

$$H_0 = H_i - \Delta H_i$$

where

- V_i: Initial volume of the specimen (mm^3)
- H_i: Initial height of the specimen (mm)
- ΔV_i: Volume change of the specimen from the initial state to before consolidation (mm^3), where volume reduction is defined to be positive
- ΔH_i: Axial displacement of the specimen from the initial state to before consolidation (mm), where compression is defined to be positive

6.2 Pore water pressure coefficient *B*

The B value of the specimen before consolidation shall be calculated from the following equation, which shall be rounded to two significant digits.

$$B = \frac{\Delta u}{\Delta \sigma}$$

where

- $\Delta\sigma$: Increase in isotropic stress (kN/m^2)
- Δu: Increase in pore water pressure as a result of $\Delta\sigma$ (kN/m^2)

6.3 Consolidation process

Calculation of the consolidation process and method of adjustment shall be as follows.

a) The volume of the specimen after consolidation V_c (mm^3) shall be calculated from the following equation.

$$V_c = V_0 - \Delta V_c$$

where

ΔV_c: Volume change of the specimen due to consolidation (mm^3), where volume reduction is defined to be positive

b) The specimen height after consolidation H_c (mm) shall be calculated from the following equation.

$$H_c = H_0 - \Delta H_c$$

where

ΔH_c: Axial displacement of the specimen due to consolidation (mm), where compression is defined to be positive

c) The specimen cross-sectional area after consolidation A_c (mm^2) shall be calculated from the following equation.

$$A_c = \frac{V_c}{H_c}$$

d) The dry density of the specimen after consolidation ρ_{dc} (Mg/m^3) shall be calculated from the following equation.

$$\rho_{dc} = \frac{m_s}{V_c} \times 1000$$

where

m_s: Specimen oven-dried mass (g)

Note 1: The values of densities that have been expressed conventionally with a unit of g/cm^3 are the same as those expressed with a unit of Mg/m^3.

Note 2: If necessary the void ratio e_c and relative density D_{rc} (%) after consolidation shall be calculated from the following equation.

$$e_c = \frac{\rho_s}{\rho_{dc}} - 1$$

$$D_{rc} = \frac{e_{max} - e_c}{e_{max} - e_{min}} \times 100$$

where

ρ_s: Soil particle density (Mg/m^3)
e_{max}: Void ratio of the specimen from a minimum density test
e_{min}: Void ratio of the specimen from a maximum density test

6.4 Cyclic undrained loading process

Calculation of the cyclic undrained loading process and method of adjustment shall be as follows.

a) Obtain the number of load cycles N_c for the double amplitude axial strain DA equal to 1, 2, and 5%, and if necessary 10%, or another appropriate value of DA.

1) The double amplitude axial strain DA (%) shall be calculated from the following equation, which shall be rounded to two significant digits.

$$DA = \frac{\varDelta L}{H_c} \times 100$$

where

$\varDelta L$: Double amplitude of the axial displacement of the specimen $\varDelta H$ during cyclic loading (mm)

2) The number of loading cycles N_c when a specific double amplitude axial strain DA is produced shall be calculated from the following equation, which shall be rounded to integer.

$$N_c = \frac{DA - DA(N_i)}{DA(N_i + 0.5) - DA(N_i)} \times 0.5 + N_i$$

where, the specific double amplitude strain DA (N_i), DA (N_i+0.5) when DA is 1, 2, 5, or 10%, etc., is the value of DA at N_i, (N_i+0.5) cycles respectively, and N_c is the number of cycles corresponding to DA (see Figure 5). However, calculation of N_c within the range 1 or higher and fewer than 10 shall be rounded in units of 0.5. Also, if at N_c=1 cycle a DA (1) is already produced larger than a specific magnitude of double amplitude axial strain DA, and it is necessary to define N_c for that specific DA that is 1 or less, it shall be calculated from the following equation, which shall be rounded to one digit after the decimal point.

$$N_c = \frac{DA}{DA\,(1)}$$

b) If necessary the number of load cycles N_{u95} at which the maximum value of the excess pore water pressure $\varDelta u$ in each cycle becomes 95% of the effective confining pressure σ'_0 shall be obtained, which shall be rounded to integer.

c) The single amplitude of the cyclic deviator stress σ_d (kN/m^2) under the occasions described below shall be calculated from the following equation, which shall be rounded to three significant digits.

$$\sigma_d = \frac{P_C + P_E}{2A_C} \times 1000$$

where

P_C, P_E: Compression and extension cyclic axial loading single amplitude, respectively (N)

1) The average value for the double amplitude axial strain DA to reach 1%

2) If necessary, when DA=1, 2, and 5%

Note: The average value of σ_d for the double amplitude axial strain DA to reach 1% may be obtained from the envelope of peak values of the continuously recorded axial load.

d) Obtain the average value of the ratio P_C/P_E of the single amplitude compressive load P_C and the single amplitude extensile load P_E up to DA=1%, which shall be rounded to three significant digits.

6.5 Plotting the results

For the series of specimens, plot the average value up to DA=1% for single amplitude of the cyclic deviator stress σ_d or the cyclic stress amplitude ratio $\sigma_d/2\sigma'_0$ on the vertical axis, and the log of the number of loading cycles N_c at a specific double amplitude strain DA and if necessary that of N_{u95} on the horizontal axis. The series of specimens shall refer to the multiple specimens of the same material on which cyclic undrained triaxial tests were carried out at the same effective confining pressure σ'_0.

7 Reporting

The following items of the test results shall be reported.

a) Method of preparing the specimens

b) Dimensions of the specimens before consolidation

c) *B* value and its measurement method

d) Volume change (mm^3) and axial displacement (mm) due to consolidation

e) Oven-dried mass of the specimen (g) and dry density after consolidation (Mg/m^3)

Note: If necessary, the void ratio and the relative density after consolidation shall be reported.

f) Consolidation stress (kN/m^2), effective confining pressure (kN/m^2), back pressure (kN/m^2), load frequency (Hz), and load wave form

g) Continuous record of axial load (N), axial displacement (mm), and pore water pressure (kN/m^2) during cyclic loading, and if necessary a continuous record of the cell pressure (kN/m^2)

h) The average value of P_C/P_E up to DA=1%

i) The average value of single amplitude of cyclic deviator stress σ_d (kN/m^2) up to DA=1%

Note: If necessary the values of single amplitude cyclic deviator stress σ_d when DA=1, 2, and 5% shall be reported.

j) The relationship between the average value up to DA=1% for the single amplitude of the cyclic deviator stress σ_d or the cyclic stress amplitude ratio $\sigma_d/2\sigma'_0$, and the number of load cycles N_c to induce specific DA values

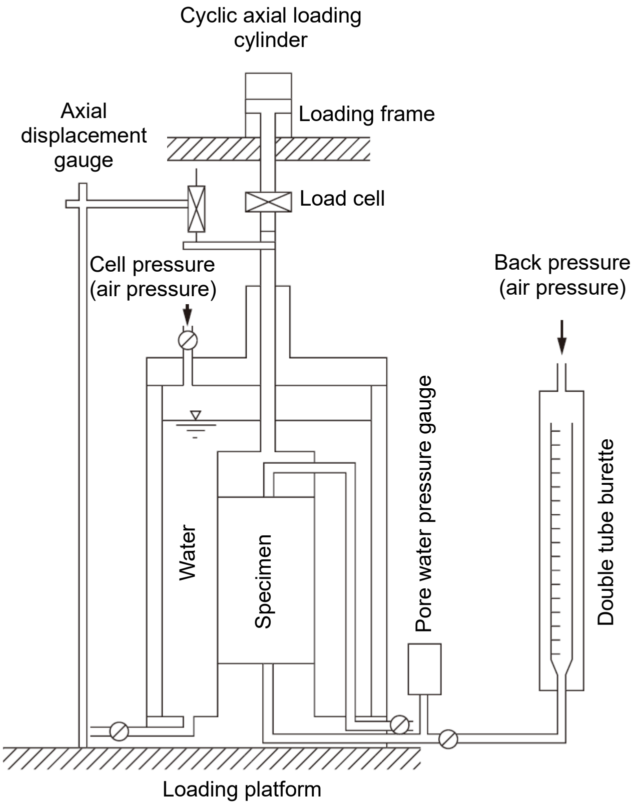
Note: If necessary, the relationship between the average value up to DA=1% for the single amplitude of the cyclic deviator stress σ_d or the cyclic stress amplitude ratio $\sigma_d/2\sigma'_0$, and the N_{u95} value shall be reported. Figure 6 shows a standard example of summary of series of test results.

k) If a method that partially differs from this standard was used, give details of the points of difference.

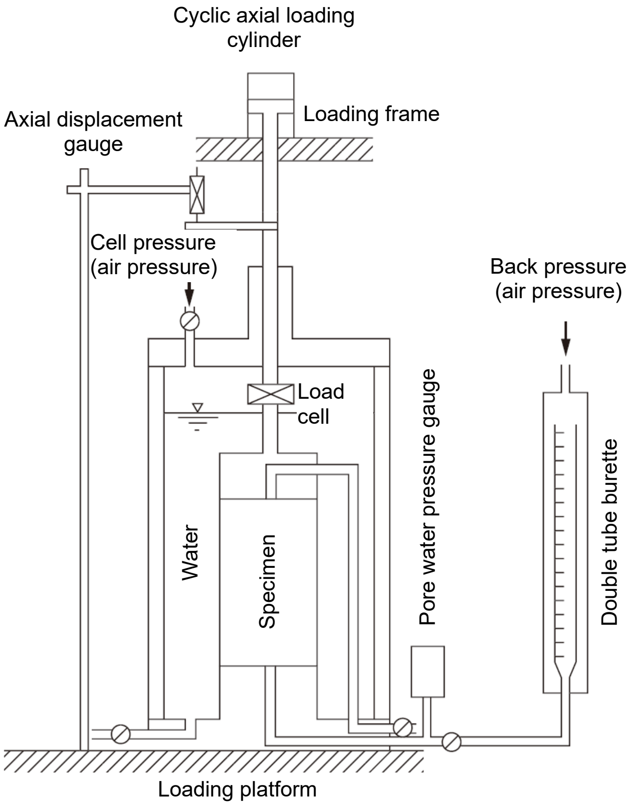
l) Other reportable matters

   1) A general description of the test equipment, the method of saturating the specimen, the position of the load cell, the load piston friction correction, the volume change on the pore water pressure measurement line, the material and thickness of the rubber sleeve, and whether or not there was a correction for the amount of rubber sleeve penetration shall be reported.

   2) The alternation of strata state of the specimen, and the failure state such as necking, etc., shall be reported.

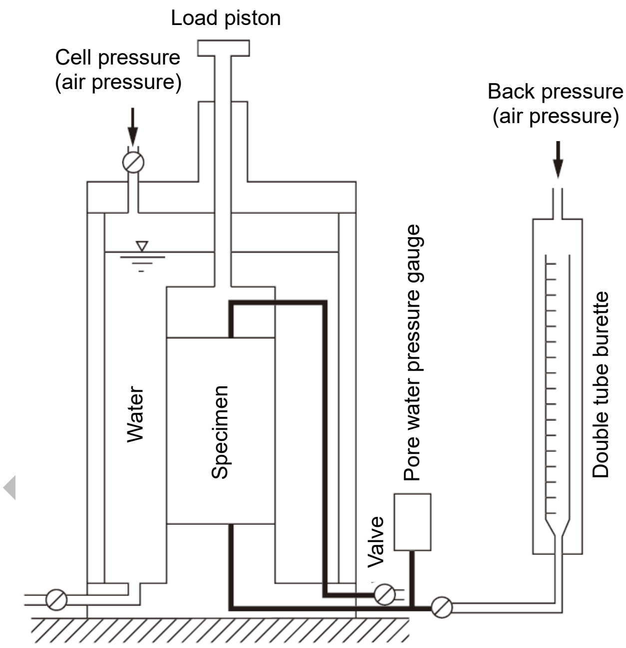


(a) Triaxial cell with load cell outside

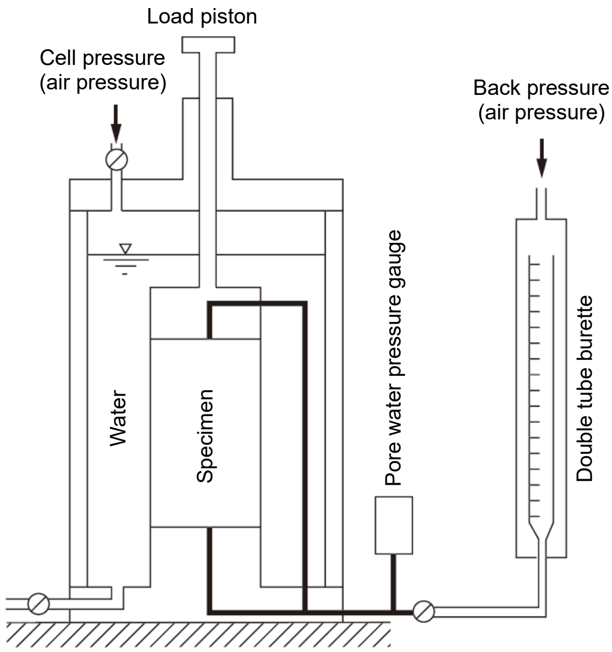


(b) Triaxial cell with load cell inside

Figure 1 Example of a cyclic triaxial apparatus



(a) Example 1



(b) Example 2

Figure 2 Definition of pore water pressure measurement route (tube and joints, valve shown on the figure)

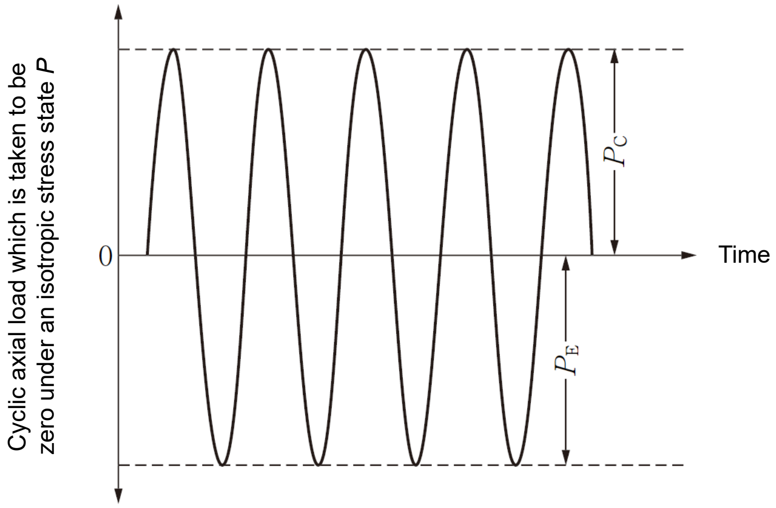


Figure 3 Definition of single amplitude P_C of the compressive load and the single amplitude P_E of the extensile load for sine wave cyclic loading

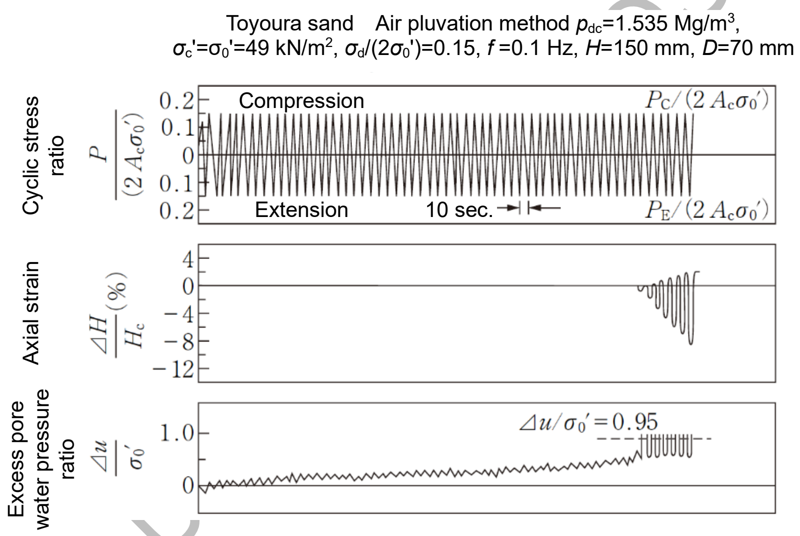


Figure 4 Example of cyclic undrained triaxial test record

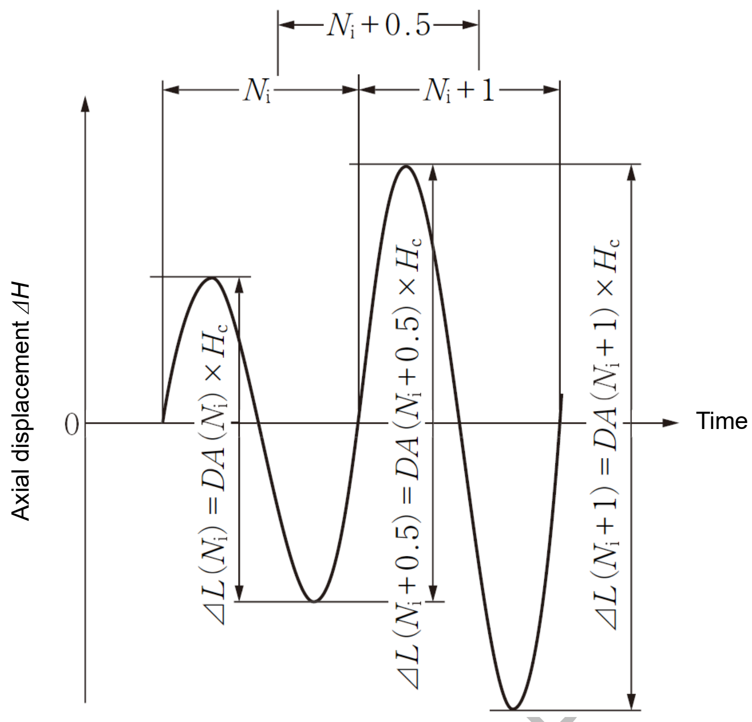


Figure 5 Explanation of the definition of the number of loading cycles N_C for a specific *DA*

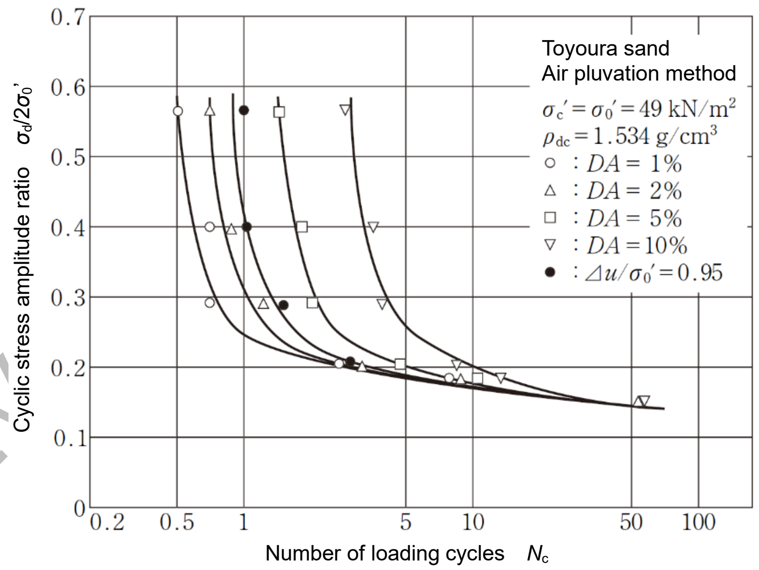


Figure 6 Example of summary of series of test results (note g/cm^3=Mg/m^3)