Japanese Geotechnical Society Standard (JGS 0542-2020）
Method for cyclic triaxial test to determine deformation properties of soils

1 Scope

This standard specifies a test method to determine the deformation properties of soils in isotropic or anisotropic stress states when subjected to cyclic loading, using a triaxial testing apparatus under drained or undrained conditions. The standard applies to sandy soils, cohesive soils and gravelly soils.

Note 1: This test method applies to specimens in the saturated, air dried state, and unsaturated state.

Note 2: This test method may apply to other geomaterials.

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

For matters not prescribed in this standard in connection with carrying out this test, refer to 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
JGS 0541	Method for cyclic undrained triaxial test on soils

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 triaxial test to determine deformation properties

A test in which a constant amplitude and symmetric cyclic axial load is applied to a specimen under isotropic or anisotropic stress conditions for a constant period, under constant cell pressure and drained or undrained conditions.

3.2 Deformation properties

The equivalent Young’s modulus obtained from the cyclic deviator stress amplitude and the cyclic axial strain amplitude, and the hysteresis damping factor obtained from the hysteresis curve of the deviator stress and the axial strain.

3.3 Axial stress

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

3.4 Lateral stress

The stress acting in the radial direction of the specimen.

3.5 Deviator stress

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

3.6 Back pressure

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 Anisotropic consolidation stress ratio

The effective lateral stress at completion of consolidation divided by the effective axial stress.

3.8 Consolidation stress

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.

3.9 Axial consolidation stress

The value of consolidation stress in the axial direction of the specimen.

3.10 Lateral consolidation stress

The value of consolidation stress in the lateral direction of the specimen.

4 Equipment

The cyclic triaxial testing apparatus shall include a triaxial cell, a cell pressure and back pressure supply device, an axial loading device or an axial displacement 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 testing 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 tension axial load is acting. In order to produce a triaxial extensive stress state during cyclic loading, and ensure that there is no play between the loading piston and the cap, apparatus in which the load piston and the cap are rigidly connected before setting the specimen in the triaxial cell shall be used (see Figure 2(a) of JGS 0522 Method for consolidated undrained triaxial compression test on soils).

b) The specimen shall be covered with the cap, pedestal, and a rubber sleeve. The apparatus shall be capable of to applying the required cell pressure, back pressure, and axial load, and it shall be capable of supplying and draining 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, and 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. However, if filter paper is placed on a hard specimen, take care with the measurement of displacement. Also, if a cyclic loading test is carried out in the undrained state on a saturated specimen, the volume change of the pore water pressure measurement route due to water pressure changes shall be sufficiently small.

Note: The volume change of the pore water pressure measurement route due to water pressure changes should be in accordance with Note of Section 4b) of JGS 0541 Method for cyclic undrained triaxial test on soils.

c) During isotropic or anisotropic 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 200 kN/m^2 and higher. Also, during consolidation it shall be capable of measuring 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. The volume change of the specimen shall be measured using a burette or other device with equal or better performance.

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) The following conditions on the axial load or axial displacement shall be always satisfied.

1) In the drained or undrained state after isotropic or anisotropic consolidation, the apparatus shall be capable of continuously applying a constant amplitude cyclic axial load or cyclic axial displacement from a single amplitude axial strain $(\varepsilon_a)_{SA}$ during a loading cycle as defined in Section 5.4 of 0.001% or less to 0.1% or more.

2) The wave form shall be a sine wave or triangular wave with a frequency of 0.05 to 1.0 Hz as standard, while other wave forms may be used if it has been confirmed that the measurement accuracy indicated in this standard can be satisfied. Apart from a sine wave or a triangular wave, however, a rectangular or trapezoidal wave shall not be used.

3) In tests in which cyclic axial load is controlled and applied, the following conditions shall always be satisfied.

3.1) The fluctuation in the sum of the single amplitude compressive load P_C and the single amplitude extensive load P_E defined from the stress state when cyclic loading is started (P_C+P_E) shall be 10% or less.

3.2) $0.8 \leqq P_C / P_E \leqq 1.2$

where the single amplitude of the compressive load P_C and the single amplitude of the extensive load P_E shall be defined from the stress state prior to cyclic loading as shown in Figure 2. In both cases the positive value shall be taken. ΔP $(=P_C+P_E)$ is the double amplitude of the cyclic axial load. In Figure 2, P_0 is the axial load difference (the product of the deviator stress and the cross-sectional area of the specimen) under the stress state prior to cyclic loading.

4) In tests in which cyclic axial displacement is controlled and applied, the following conditions shall always be satisfied.

4.1) The fluctuation in the sum of the single amplitude compressive displacement ΔL_C and the single amplitude extensive displacement ΔL_E defined from the stress state when cyclic loading is started $(\Delta L_C+\Delta L_E)$ shall be 10% or less.

4.2) $0.8 \leqq \Delta L_C / \Delta L_E \leqq 1.2$

where the compressive axial displacement single amplitude ΔL_C and the extensive axial displacement single amplitude ΔL_E shall be defined from the state prior to cyclic loading, as shown in Figure 3. In both cases they shall be the positive value. ΔL $(=\Delta L_C+\Delta L_E)$ is the double amplitude axial displacement.

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 200 kN/m^2 and higher.

f) During cyclic loading, the apparatus shall be capable of continuously measuring the cell pressure (and the pore water pressure for an undrained cyclic loading test on a saturated specimen) to within an allowable tolerance of 2 kN/m^2 for pressures less than 200 kN/m^2, and 1.0% for pressures 200 kN/m^2 and higher.

g) In measuring the axial load during cyclic loading, the following conditions shall be satisfied.

1) For cyclic loading at single amplitude axial strains $(\varepsilon_a)_{SA}$ of 0.01% or more, the apparatus shall be capable of continuously measuring the cyclic axial load acting on the specimen to within an allowable tolerance of 1.0% of the double amplitude of the prescribed load, using a load cell installed within the triaxial pressure cell whose hysteresis properties can be ignored.

2) An electrical load cell that is capable of measuring the compressive load and the tension load and that is installed within the triaxial cell shall be used for measurement of the cyclic loading.

3) The output of the load cell shall not change due to a change in the cell pressure. Also, it shall not be affected by moments or horizontal forces due to eccentric axial loads. In addition, during each wave of cyclic loading, during cyclic loading in which the single amplitude axial strain $(\varepsilon_a)_{SA}$ is 0.01% there shall be no drift in excess of or equal to 1% of the measured value and no change in the calibration value of 1% or more.

4) Using a dummy specimen for calibration that has no viscous damping, the hysteresis property h_{LC} for cyclic loading shall be evaluated based on the relationship between the load cell output and the actual load for static loading and unloading obtained by the method shown in Figure 4. The value of h_{LC} shall be not more than 5% of the hysteresis damping factor h of the specimen when the single amplitude strain $(\varepsilon_a)_{SA}$ is 0.01%. The maximum value of the load applied to the load cell shall be the maximum value of the load applied in the actual test.

Load cell hysteresis property $h_{LC}=(1/2\pi)\cdot\Delta X/X$

h) In measuring the axial displacement during cyclic loading, the following conditions shall be satisfied.

1) For cyclic loading with a single amplitude axial strain $(\varepsilon_a)_{SA}$ of 0.01% or more, the apparatus shall be capable of continuously measuring the axial displacement of the specimen to within an allowable tolerance of 1.0% of the double amplitude of the prescribed axial displacement, using a displacement gauge for which the hysteresis property can be ignored. However, for single amplitude axial strains $(\varepsilon_a)_{SA}$ less than 0.1%, it shall be capable of directly measuring the axial displacement of the cap with a displacement gauge installed within the triaxial cell. For single amplitude axial strains $(\varepsilon_a)_{SA}$ equal to 0.1% or more, displacements shall be measured with a displacement gauge installed outside the triaxial cell. If the axial displacement of the specimen is obtained from the axial displacement of the cap, as a rule a displacement gauge of non-contact type shall be used.

2) If measurement of the axial displacement during cyclic loading is performed by an electric displacement gauge installed outside the triaxial cell, the deformation of the load piston, load cell, etc., located between the displacement meter and the specimen, the deformation of the fixing position of the axial displacement gauge, etc., shall be 1.0% of the axial displacement or less when the single amplitude axial strain $(\varepsilon_a)_{SA}$ is 0.1%.

3) If it is estimated that the difference between the average axial strain of the specimen and the axial strain obtained from the axial displacement of the cap or the load piston is 5% or more, and that the error in the hysteresis damping factor h defined in Section 5.4 is estimated to be 5% or more of the measured value, due to incomplete contact between the top and bottom ends of the specimen and the cap and pedestal, or slack at the top or bottom ends of the specimen due to filter paper, etc., the axial displacement of the specimen shall be measured at the side surface of the specimen by an appropriate method. In this case, the axial displacement ΔL_{local} shall be measured between two points on lines on the rubber sleeve parallel to the specimen axis at the position of the two ends of the specimen in the radial direction, referring to Figure 5. The measurement length of ΔL_{local} shall be 50

to 80% of the height of the specimen, and sliding between the rubber sleeve and the specimen shall not affect the measured value of the axial displacement. Also, the measuring instrument shall not affect the deformation of the specimen.

4) The output of the displacement gauge shall not change due to a change in the cell pressure. Also, during each wave of cyclic loading, during cyclic loading in which the single amplitude axial strain $(\varepsilon_a)_{SA}$ is 0.01% there shall be no drift in excess of or equal to 1% of the measured value and no change in the calibration value of 1% or more.

5) Using a dummy specimen for calibration that has no viscous damping, evaluate the hysteresis property h_{DT} for cyclic loading by the method shown in Figure 6, based on the static relationship between the axial displacement gauge output and the displacement applied to the axial displacement gauge that is measured with a micrometer for increasing and decreasing displacement, including cases in which the axial displacement is measured on the side surface of the specimen. Confirm that when the single amplitude axial strain $(\varepsilon_a)_{SA}$ is 0.01%, the value of h_{DT} is 5% of the hysteresis damping factor h of the specimen or less. The maximum value of displacement applied shall be the maximum value of axial displacement actually applied in the test.

Displacement gauge hysteresis property $h_{DT}=(1/2\pi)\cdot\Delta Y/Y$

i) On data recording during cyclic loading, the following conditions shall be satisfied.

1) It shall be possible to continuously and simultaneously record the cyclic axial load and the cyclic axial displacement during cyclic loading. If necessary, it shall be possible to continuously record the pore water pressure.

2) The measured values of the axial load, the axial displacement, and if necessary, the measured cell pressure and the pore water pressure during cyclic loading shall be continuously recorded using an electrical recording device such as a digital data recorder, etc. However, the number of data points in one cycle shall be 40 or more, so that it will be possible to sufficiently interpolate between two consecutive digital measurement values.

3) Using a dummy specimen for calibration that has no viscous damping, confirm that the error in the hysteresis damping factor due to the phase shift between measured results for the axial load and the axial displacement is 5% of the hysteresis damping factor of the specimen or less when the single amplitude axial strain $(\varepsilon_a)_{SA}$ is 0.01%. As shown in Figure 7, if the hysteresis damping factor linearly increases (decreases) with an increase in frequency, there is a time delay (advance) between the load P and the displacement ΔD.

5 Test method

5.1 Preparation and installation of the specimen

Preparation and installation of the specimen shall be in accordance with JGS 0520 Preparation of soil specimens for triaxial tests. The diameter of the specimen shall be 50 mm or more for a sandy soil, and 35 mm or more for a cohesive soil. The diameter of a gravelly soil specimen prepared in the laboratory shall be 10 times the maximum grain size or more as standard, but it may be up to about 5 times in the case of a soil with comparatively wide range of grain size with a uniformity coefficient of 5 or more. The specimen height shall be 1.5 to 2.5 times the diameter. However, there shall be little disturbance on the top and bottom end surfaces of the specimen, and the smoothness, flatness, and parallelism of the top and bottom surfaces of the specimen shall satisfy the following values.

a) The error in the height of any point on the top end surface relative to the bottom end surface of the specimen as standard shall be 0.5% of the height of the specimen or less.

b) The angle formed between the top end surface of the specimen when it is set on the pedestal and the bottom end surface of the cap shall be 0.5° or less.

c) The distance of the center of the top and bottom end surfaces of the specimen from the center of the loading axis shall be 1% of the height of the specimen or less.

5.2 Confirming the degree of saturation

If necessary, before consolidation or after consolidation, the pore pressure coefficient B (B value) shall be measured. If the B value is obtained, it shall be measured in accordance with the method described in Section 5.2 of JGS 0541 Method for cyclic undrained triaxial test on soils. However, for anisotropic consolidation, it shall be obtained immediately before anisotropic consolidation.

5.3 Consolidation process

Carry out either isotropic consolidation or anisotropic consolidation depending on the objective of the test. Measure the change in axial displacement ΔH_C (mm) of the specimen due to consolidation, and for a saturated specimen measure the volume change ΔV_C (mm^3) in the specimen due to consolidation. Determine completion of primary consolidation of the specimen in accordance with the method indicated in Section 5.2d) of JGS 0522 Method for consolidated-undrained triaxial compression test on soils.

a) Isotropic consolidation process

   1) Carry out consolidation with a constant back pressure by applying the prescribed isotropic stress within the triaxial cell.

   2) Consolidation shall continue at least until primary consolidation is completed.

b) Anisotropic consolidation process

   Under drained conditions, apply the axial stress that will satisfy the required anisotropic consolidation stress ratio corresponding to the effective lateral stress under the initial isotropic consolidation state. Increase the anisotropic stress state in stages with the combination of the lateral stress and the axial stress to give the required anisotropic consolidation stress ratio until the final anisotropic consolidation stress state is reached. Consolidation shall be continued until at least primary consolidation is completed.

   1) Anisotropic consolidation shall be carried out by the following method as standard.

      1.1) Apply the axial stress that will satisfy the required anisotropic consolidation stress ratio corresponding to the effective lateral stress under the initial isotropic consolidation state.

      1.2) Set $\Delta\sigma_r$ so that the difference between the effective lateral stresses at the initial consolidation stress state and the final consolidation stress state is divided equally into 5 or more. However, $\Delta\sigma_r$ shall not exceed 20 kN/m^2.

      1.3) Increment the lateral stress by just $\Delta\sigma_r$.

      1.4) Increment the axial stress to achieve the required anisotropic stress ratio.

      1.5) Check that the rate of change in axial strain is 0.1%/min or less.

      1.6) Repeat the operations in 1.3), 1.4), and 1.5) above until the final consolidation stress state is reached.

   2) If the following simplified consolidation method can be applied, it may be used.

      2.1) Carry out isotropic consolidation up to the effective lateral stress under the final consolidation stress state (= lateral consolidation stress σ'_{rc}).

2.2) Divide the difference between the effective axial stress at the final consolidation stress state (= axial consolidation stress σ'_{ac}) and the lateral effective stress σ'_{rc} into 5 equal increments to obtain $\varDelta q$.

2.3) With the specimen in the drained state, increment the axial stress by $\varDelta q$. During this time the loading rate shall be such that the excess pore water pressure in the specimen $\varDelta u$ is always 10% of σ'_{rc} or less.

2.4) Check that the rate of change of axial strain is 0.1%/min or less.

2.5) Repeat the operations in 2.3) and 2.4) above until the final consolidation stress state is reached.

5.4 Cyclic loading process

The test shall be performed in accordance with the following requirements for the cyclic loading process.

a) Confirm the required isotropic or anisotropic stress state.

b) Apply the cyclic axial load or the cyclic axial displacement in accordance with the following requirements. For saturated specimens, the conditions shall be drained or undrained, and for unsaturated or air dried specimens, the conditions shall be water drainage or air drainage conditions. In drained tests, carry out the cyclic loading with a range so that under the peak stress state in the triaxial extensive stress state the total axial stress does not become negative. The back pressure can be increased with the objective of increasing the range of cyclic loading amplitude applied to the specimen.

Note 1: The maximum cyclic axial load amplitude or axial displacement amplitude may be determined as appropriate in accordance with the condition of the specimens and the objectives of the test.

Note 2: An example of cyclic triaxial test record is shown in Figure 8.

1) First loading

1.1) For an undrained test, close the drainage valve.

1.2) Apply 11 waves of cyclic axial load or cyclic axial displacement as a sine wave or a triangular wave, at a constant amplitude and a constant frequency between 0.05 to 1.0 Hz, so that the single amplitude axial strain $(\varepsilon_a)_{SA}$ is about 0.001% or less. During loading continuously record the axial load and axial displacement, and if necessary the pore water pressure.

1.3) Measure the change in height of the test specimen due to the cyclic loading (in the case of a drained test on a saturated specimen, measure the volume change also). During cyclic loading, in the case of undrained conditions, after completion of cyclic loading the conditions shall be changed to drained, and the resulting change in height and the volume change of the specimen shall be measured.

2) Second loading

2.1) For an undrained test, close the drainage valve, while checking that the rate of change of the axial strain in 0.01%/min. or less.

2.2) Carry out loading by repeating the same loading as the first loading, so that the single amplitude axial strain $(\varepsilon_a)_{SA}$ is about double that in the first loading.

2.3) Measure the change in height of the test specimen due to the cyclic loading (in the case of a drained test on a saturated specimen, measure the volume change also). During cyclic loading, in the case of undrained conditions, after completion of cyclic loading the conditions shall be changed to drained, and the resulting change in height and the volume change of the specimen shall be measured.

3) Third and subsequent loadings

Apply the loading is the same way as the second loading. The loading shall repeat this loading stage as much as possible.

c) Observe and record the specimen deformation state, etc.

d) Measure the specimen oven-dried mass m_{s} (g).

6 Processing test results

6.1 Condition of the specimen before consolidation

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

$$V_0 = V_{\mathrm{i}} - \varDelta V_{\mathrm{i}}$$

$$H_0 = H_{\mathrm{i}} - \varDelta H_{\mathrm{i}}$$

where

V_{i} : Initial volume of the specimen (mm^3)
H_{i} : Initial height of the specimen (mm)
$\varDelta V_i$: Volume change of the specimen from the initial state to before consolidation (mm^3), where volume reduction is defined to be positive
$\varDelta H_i$: Axial displacement of the specimen from the initial state to before consolidation (mm), where compression is defined to be positive

6.2 Pore 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

$\varDelta\sigma$: Increment of isotropic stress (kN/m^2)
$\varDelta u$: Increment of pore water pressure associated with $\varDelta\sigma$ (kN/m^2)

6.3 Consolidation process

The calculation and processing method for the consolidation process shall be as follows.

a) Calculate the volume of the specimen V_{c} (mm^3) after consolidation from the following equation.

$$V_{\mathrm{c}} = V_0 - \varDelta V_{\mathrm{c}}$$

where

$\varDelta V_{\mathrm{c}}$: Volume change of the specimen due to consolidation (mm^3), where volume reduction is defined to be positive

Note 1: If the specimen is not saturated, the volume change of the specimen $\varDelta V_{\mathrm{c}}$ (mm^3) due to isotropic consolidation shall be calculated from the following equation.

$$\varDelta V_{\mathrm{c}} = \frac{3\varDelta H_{\mathrm{c}}}{H_0} V_0$$

where

ΔH_c : Axial displacement due to consolidation (mm), where compression is defined to be positive
V_0 : Volume of the specimen before consolidation (mm^3)
H_0 : Height of the specimen before consolidation (mm)

Note 2: If the specimen is not saturated, calculate the volume change of the specimen due to anisotropic consolidation by an appropriate method.

b) Calculate the height of the specimen after consolidation H_c (mm) from the following equation.

$$H_c = H_0 - \Delta H_c$$

where

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

c) Calculate the cross-sectional area A_c (mm^2) of the specimen after consolidation from the following equation.

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

d) Calculate the dry density ρ_{dc} (Mg/m^3) of the specimen after consolidation from the following equation, which shall be rounded to two digits after the decimal point.

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

where

m_s : Oven-dried mass of the specimen (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 the relative density D_{rc} (%) of the specimen after consolidation shall be calculated from the following equations.

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

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

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 loading process

The calculation and processing method for the cyclic loading process shall be as follows.

Note: If the axial strain of the specimen is 1% or less, normally it is not necessary to correct σ_d for the force acting on the rubber sleeve.

a) Calculate the volume V_n (mm^3), height H_n (mm), and cross-sectional area A_n (mm^2) of the specimen at the start of each loading stage carried out by constant amplitude cyclic axial loading or axial displacement.

Note 1: If necessary, the void ratio e_n at the start of each loading stage shall be calculated from the following equation.

$$e_n = \frac{V_n/1000 \times \rho_s}{m_s} - 1$$

where

m_s: Oven-dried mass of the specimen (g)
ρ_s: Soil particle density (Mg/m^3)

However, the void ratio e_n at the start of the initial cyclic loading stage is equal to the void ratio after consolidation e_c.

1) Calculate the volume of the specimen V_n (mm^3) at the start of each loading stage from the following equation.

$$V_n = V_c - \Delta V_n$$

where

ΔV_n: Volume change of the specimen from completion of consolidation to the start of each loading stage (mm^3), where volume reduction is defined to be positive

Note 1: If isotropic consolidation is carried out on the specimen when the specimen is not saturated, the volume change of the specimen ΔV_n due to cyclic loading may be calculated from the following equation.

$$\Delta V_n = \frac{3\Delta H_n}{H_c} V_c$$

where

ΔH_n: Axial displacement from completion of consolidation to the start of each loading stage (mm), where compression is defined to be positive
V_c: Volume of the specimen at completion of consolidation (mm^3)
H_c: Height of the specimen at completion of consolidation (mm)

Note 2: If anisotropic consolidation is carried out on the specimen when the specimen is not saturated, the volume change of the specimen ΔV_n due to cyclic loading shall be calculated by an appropriate method.

2) Calculate the height of the specimen H_n (mm) at the start of each loading stage from the following equation.

$$H_n = H_c - \Delta H_n$$

where

ΔH_n: Axial displacement from completion of consolidation to the start of each loading stage (mm), where compression is defined to be positive

3) The cross-sectional area of the specimen A_n (mm^2) at the start of each loading stage shall be calculated from the following equation.

$$A_n = \frac{V_n}{H_n}$$

b) Every 5th and 10th loading cycle in each cyclic loading stage of constant amplitude cyclic axial loading or axial displacement, the single amplitude deviator stress σ_d (kN/m^2), the single amplitude axial strain$(\varepsilon_a)_{SA}$ (%), the equivalent Young's modulus E_{eq} (MN/m^2), and the hysteresis damping factor shall be calculated.

Note 1: In tests with constant amplitude cyclic axial loading, if there is a deviation in the axial displacement $\varDelta H$ (mm) of the specimen between two consecutive cycles as shown in Figure 9, and if the amount of deviation α (mm) is equal to 2% or more of the axial displacement double amplitude $\varDelta L$ (mm), then $\varDelta L$ (mm) shall be corrected by the following method.

1) If the specimen has been compressed by consecutive cycles (Figure 9(a))

(Corrected $\varDelta L$ in the Nth cycle) = ($\varDelta L$ measured in the Nth cycle) + $\alpha/2$

2) If the specimen has been extended by consecutive cycles (Figure 9(b))

(Corrected $\varDelta L$ in the Nth cycle) = ($\varDelta L$ measured in the Nth cycle) - α /2

Note 2: In tests with constant amplitude cyclic axial displacement, if the cyclic axial load P (N) on the specimen between two consecutive cycles has deviated as shown in Figure. 10, and if the amount of deviation β (N) is 2% of the double amplitude axial load $\varDelta P$ (N) or more, $\varDelta P$ (N) shall be corrected by the following method.

1) If the specimen axial load has been reduced by consecutive cycles (Figure 10(a))

(Corrected $\varDelta P$ in the Nth cycle) = ($\varDelta P$ measured in the Nth cycle) - $\beta/2$

2) If the specimen axial load has been increased by consecutive cycles (Figure 10(b))

(Corrected $\varDelta P$ in the Nth cycle) = ($\varDelta P$ measured in the Nth cycle) + $\beta/2$

Note 3: Calculate the equivalent Young's modulus and hysteresis damping factor at loading cycles other than the 5th and the 10th, in accordance with the objectives of the test.

1) The single amplitude cyclic deviator stress σ_d (kN/m^2) shall be calculated from the following equation, which shall be rounded to three significant digits. If the precision of the measurement device is not sufficient, two significant digits shall be used.

$$\sigma_d = \frac{P_c + P_E}{2A_n} \times 1000$$

where

P_C, P_E: The single amplitude cyclic axial load on the compression side and the extension side in that cycle (N) (both positive values)
A_n: Specimen cross-sectional area at the start of that cyclic loading stage (mm^2)

2) The single amplitude axial strain $(\varepsilon_a)_{SA}$ (%) shall be calculated from the following equation, which shall be rounded to three significant digits. If the precision of the measurement device is not sufficient, two significant digits shall be used.

$$(\varepsilon_a)_{SA} = \frac{\Delta L}{2H_n} \times 100$$

where

$\varDelta L$: Double amplitude axial displacement of the specimen $\varDelta H$ in that cycle (mm)
H_n: Specimen height at the start of that cyclic loading stage (mm)

Note 1: If the axial displacement of the cap of the specimen is measured by several non-contact displacement gauges, the value of $\varDelta L$ shall be obtained from their average value.

Note 2: If the axial compression $\Delta L_{\mathrm{local}}1$ and $\Delta L_{\mathrm{local}}2$ are measured between 2 points on lines on the rubber sleeve that are parallel to the axis of the specimen at positions on the diagonal of the diameter of the specimen (Figure 5), the double amplitude ΔL (mm) of the specimen axial displacement ΔH shall be calculated from the following equation.

$$\Delta L = \{((\Delta L_{\mathrm{local}}1)/L1_{\mathrm{n}}) + ((\Delta L_{\mathrm{local}}2)/L2_{\mathrm{n}})/2\} \times H_{\mathrm{n}}$$

where

$L1_{\mathrm{n}}$, $L2_{\mathrm{n}}$: Average distance (mm) between the two points on the specimen side surface at the specimen diagonal positions respectively at the start of that loading cycle

3) The equivalent Young's modulus E_{eq} (MN/ m^2) shall be calculated from the following equation, which shall be rounded to three significant digits. If the precision of the measurement device is not sufficient, two significant digits shall be used.

$$E_{\mathrm{eq}} = \frac{\sigma_{\mathrm{d}}}{(\varepsilon_{\mathrm{a}})_{\mathrm{SA}}} \times \frac{1}{10}$$

Note: Figure 11 is an example of hysteresis curve drawn from the axial stress difference and the axial strain obtained using the specimen height and volume at the start of that cyclic loading, and it explains the equivalent Young's modulus E_{eq} (MN/m^2).

4) The hysteresis damping factor h (%) shall be calculated from the following equation, which shall be rounded to three significant digits. If the precision of the measurement device is not sufficient, two effective significant shall be used.

$$h = \frac{1}{2\pi} \cdot \frac{\Delta W}{W} \times 100$$

where

ΔW: The damping energy in that cycle, and is the area of the hysteresis curve prepared from the axial load difference P and the axial displacement ΔH (N·mm)

W: Equivalent elastic energy in that loading cycle, calculated from the following equation.

$$W = \frac{(P_{\mathrm{c}} + P_{\mathrm{E}})\Delta L}{4}$$

Note 1: Figure 12 is a diagram that explains the hysteresis damping factor $h=(1/2\pi)\cdot\Delta W/W$

Note 2: If the hysteresis curve does not close, as shown in Figure 13, the sum of the areas of the compression side hysteresis curve gbh and the extension side hysteresis curve hdf shall be taken to be ΔW (N·mm). Also, the value of W (N·mm) shall be calculated from the following equation.

1) Test with constant cyclic axial load amplitude

$$W = \frac{1}{4} \Delta P \cdot \Delta L$$

where

ΔP: Measured value (N)

ΔL: Value corrected in accordance with the method described in Section 6.4b) Note 1 (mm)

2) Test with constant cyclic axial displacement amplitude

$$W = \frac{1}{4}\Delta P \cdot \Delta L$$

where

$\varDelta L$: Measured value (mm)
$\varDelta P$: Value corrected in accordance with the method described in Section 6.4b）Note 2 (N)

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) If an undrained cyclic load test has been carried out on a saturated specimen, the magnitude of the back pressure (kN/m^2) and the *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, and dry density after consolidation (Mg/m^3)

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

f) Axial consolidation stress (kN/m^2) and lateral consolidation stress (kN/m^2)

g) Loading frequency and loading wave form, drainage conditions during cyclic loading

h) Method of measurement of axial load (N) and axial displacement (mm) during cyclic loading

Note: The position of the load cell and displacement gauge within the triaxial cell shall be reported. If the axial displacement is measured on the specimen side surface, the method shall be reported.

i) Specimen dimensions at the start of each of the second to final cyclic loading

j) Axial load (N) and axial displacement (mm) time histories and the axial load (N) and axial displacement (mm) hysteresis curve at the 5th and 10th cycles in each cyclic loading stage

Note: The axial stress and axial strain time history and the hysteresis curve may also be reported.

k) The equivalent Young's modulus E_{eq} (MN/m^2), the hysteresis damping factor h (%), and the corresponding single amplitude axial strain $(\varepsilon_a)_{SA}$ (%) at the 5th and 10th cycles in each cyclic loading stage

Note: If necessary, the equivalent Young's modulus E_{eq} (MN/m^2), the hysteresis damping factor h (%), and the corresponding single amplitude axial strain $(\varepsilon_a)_{SA}$ (%) at each cycle from the 2nd to the 10th cycle in each cyclic loading stage shall be reported.

l) The logarithmic relationship between the equivalent Young's modulus E_{eq} (MN/m^2), the hysteretic damping factor h (%), and the corresponding single amplitude axial strain $(\varepsilon_a)_{SA}$ (%) at the 5th and 10th cycles

Note: Figure 14 shows a standard example of summary of the series of test results.

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

n) Other reportable matters

An outline description of the testing apparatus, the method of saturating the specimen, the hysteresis property of the load cell and displacement gauge, synchronization of the axial load and axial displacement records, the rubber sleeve material and thickness shall be reported.

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

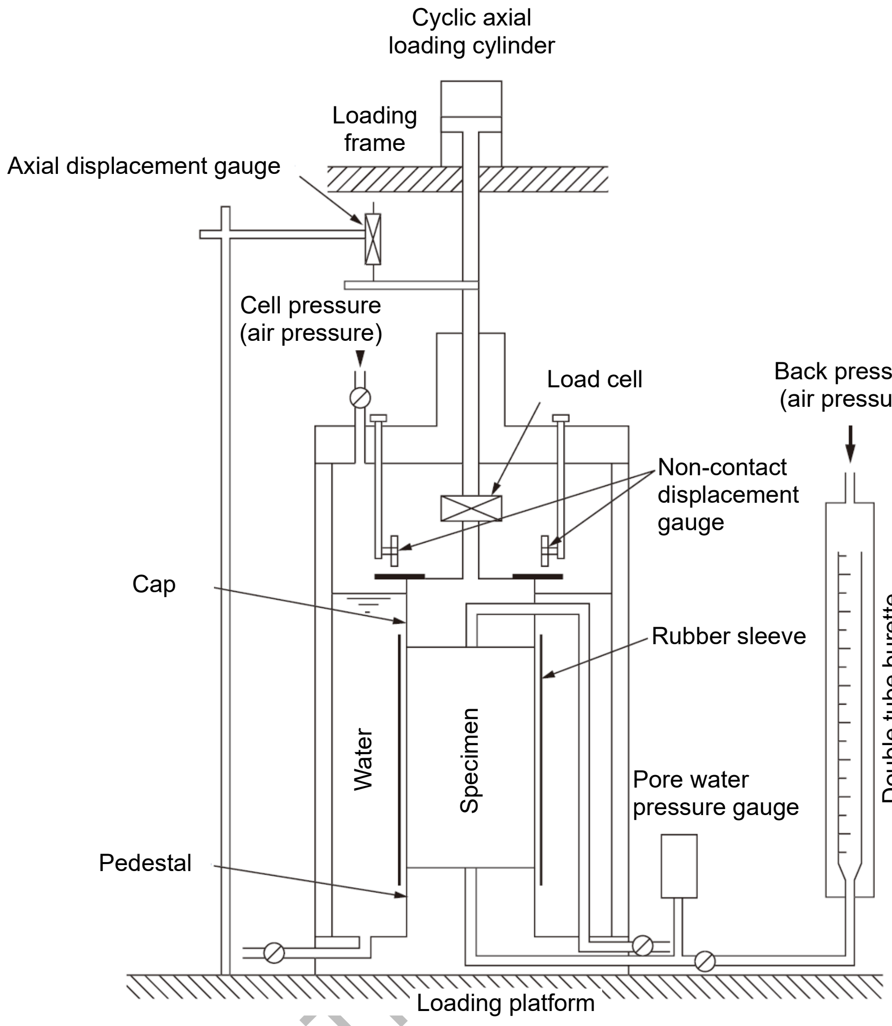

Figure 1 Example of a standard cyclic triaxial testing apparatus

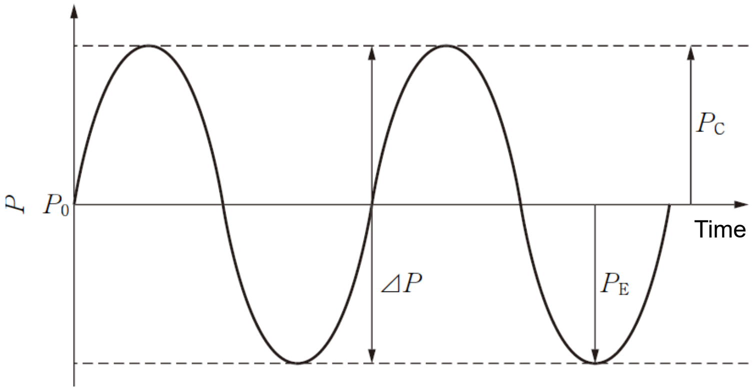

Figure 2 Definition of compressive load single amplitude P_C and extensive load single amplitude P_E for sine wave cyclic axial loading

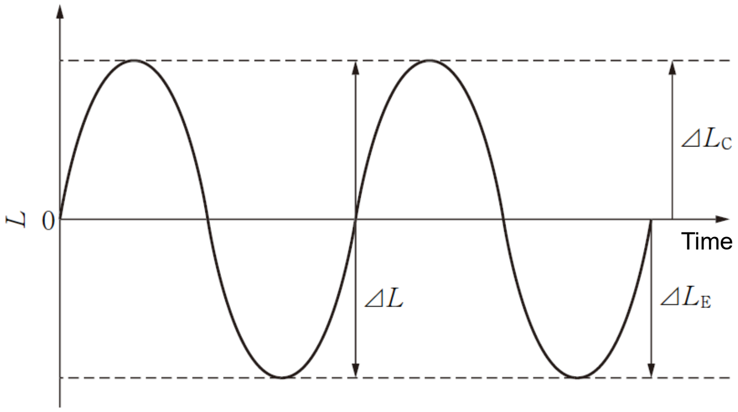

Figure 3 Definition of compressive axial displacement single amplitude $\varDelta L_C$ and extensive axial displacement single amplitude $\varDelta L_E$ for a sine wave cyclic axial displacement

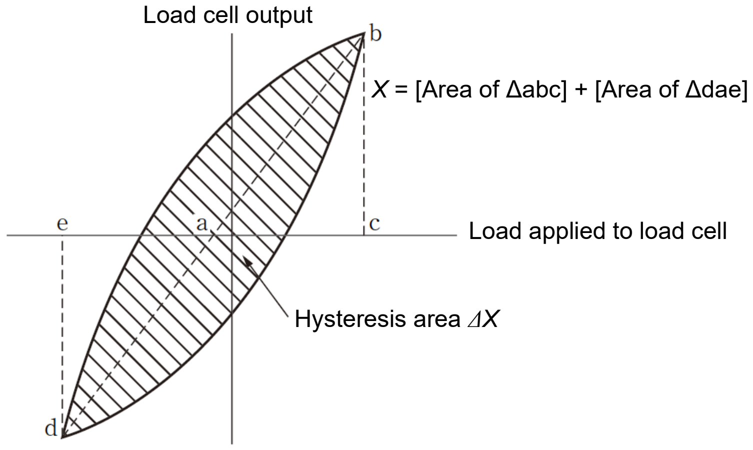

Figure 4 Definition of the hysteresis property of the load cell

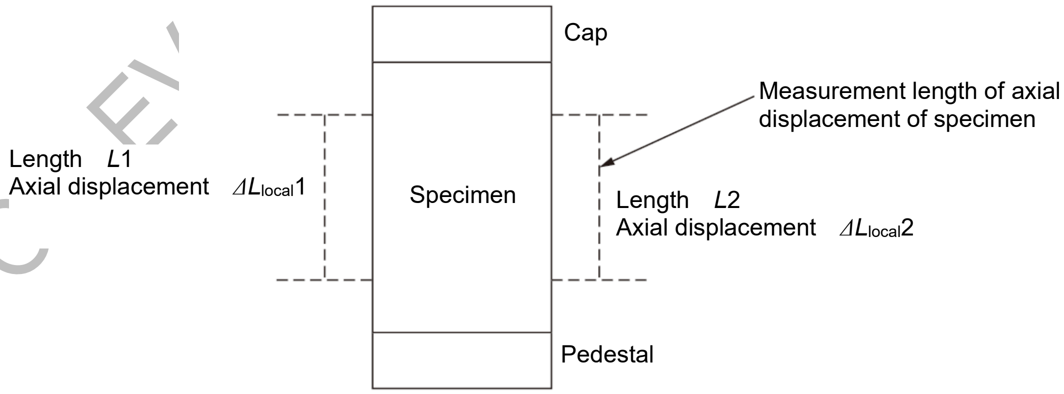

Figure 5 Example of measurement of axial displacement of the specimen at the side surface of the specimen

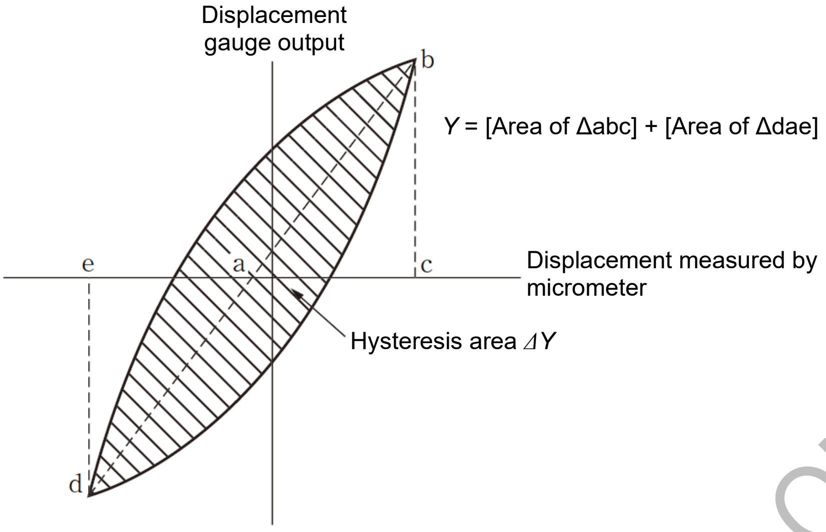

Figure 6 Definition of hysteresis property of axial displacement gauge

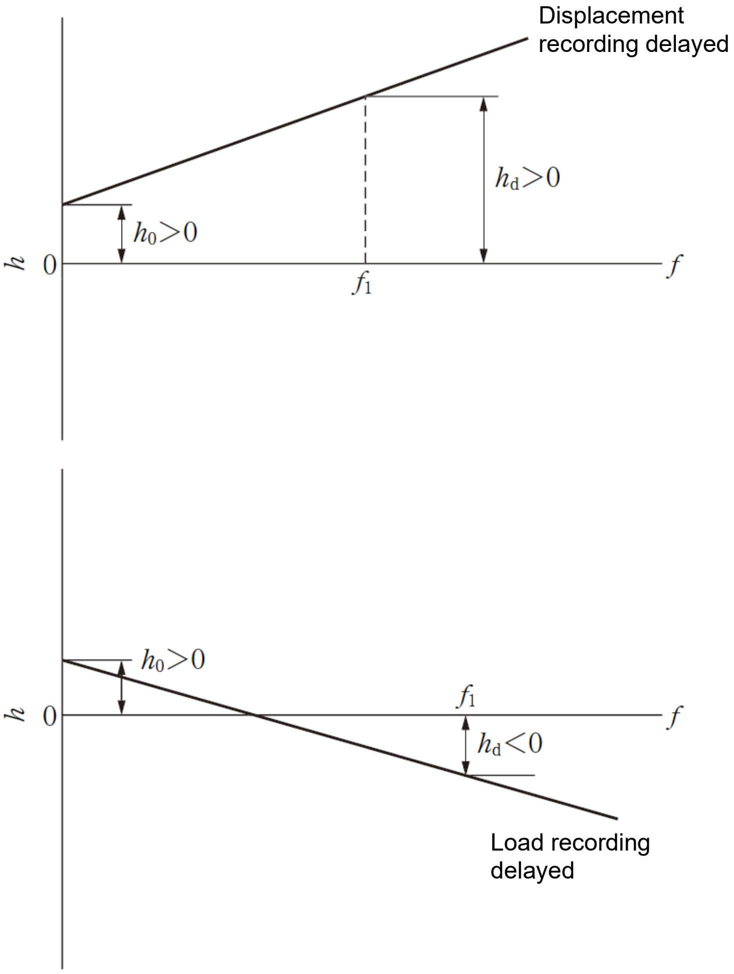

Figure 7 Apparent load frequency dependence of the measured hysteresis damping factor due to phase shift between the measured results for load and displacement when *h* does not depend on frequency *f* (h_0 is a positive value, h_d is the apparent value at f_1)

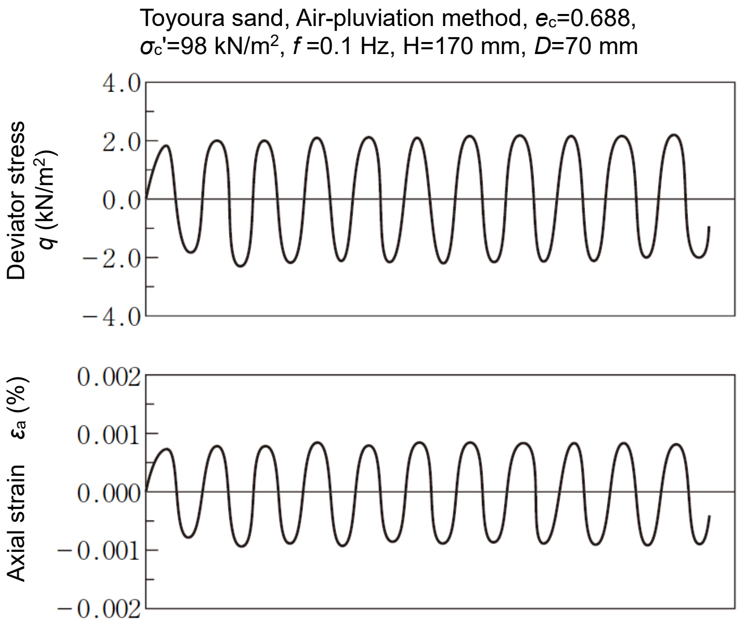

Figure 8 Example of cyclic triaxial test record with constant cyclic loading amplitude and a sinusoidal wave form

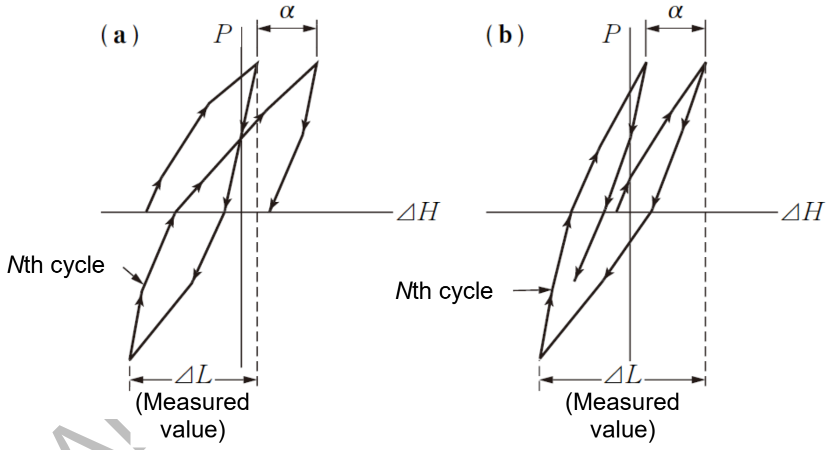

Figure 9 Explanation of the amount of deviation α of the axial displacement in 2 consecutive cycles

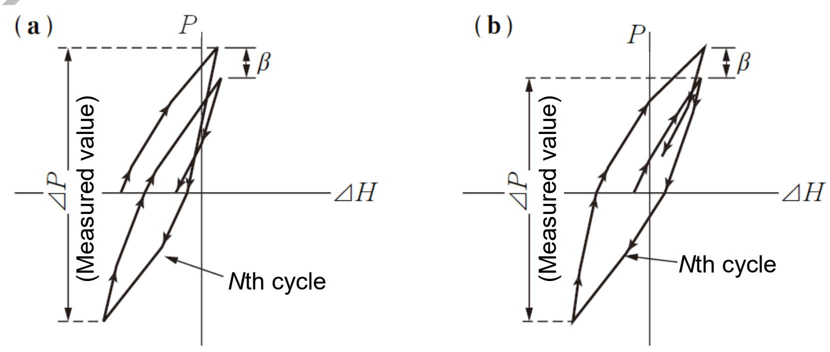

Figure 10 Explanation of the amount of deviation β of the axial load in 2 consecutive cycles

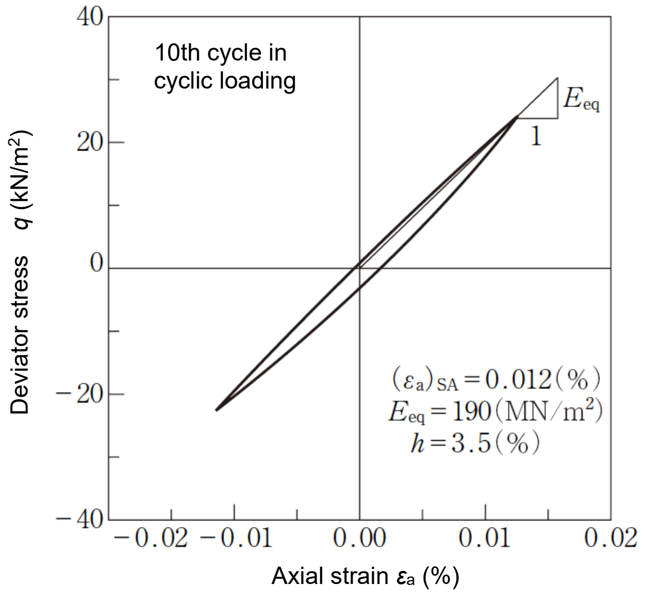

Figure 11 Example of typical hysteresis curve

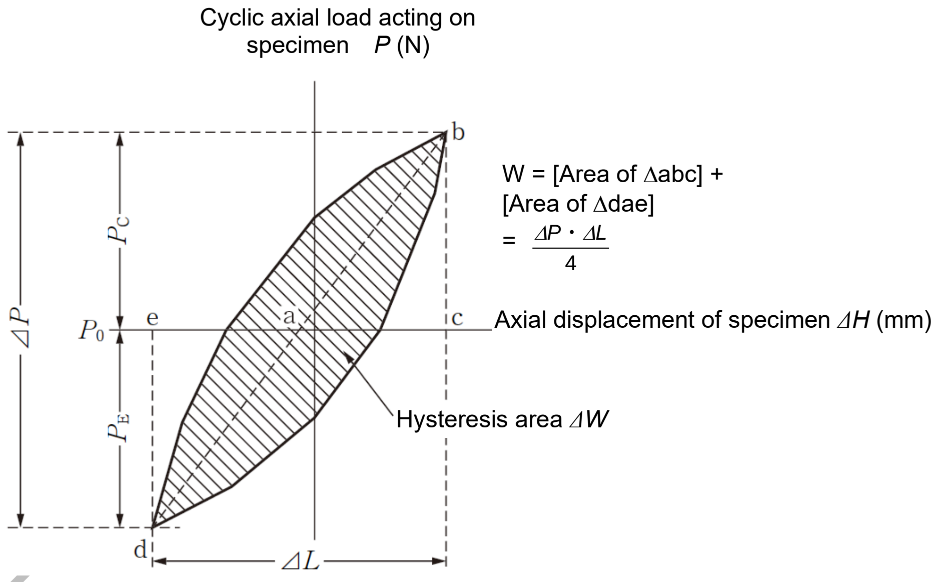

Figure 12 Explanatory diagram for hysteresis damping factor *h* (diagram for the case where P_C and P_E are equal)

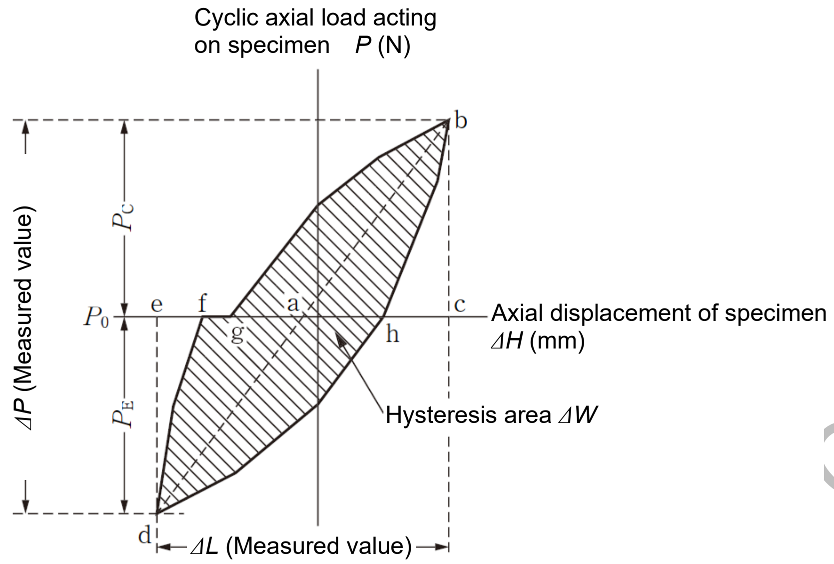

Figure 13 Explanatory diagram for hysteresis damping factor *h* when the hysteresis curve does not close (diagram for the case where P_C and P_E are equal)

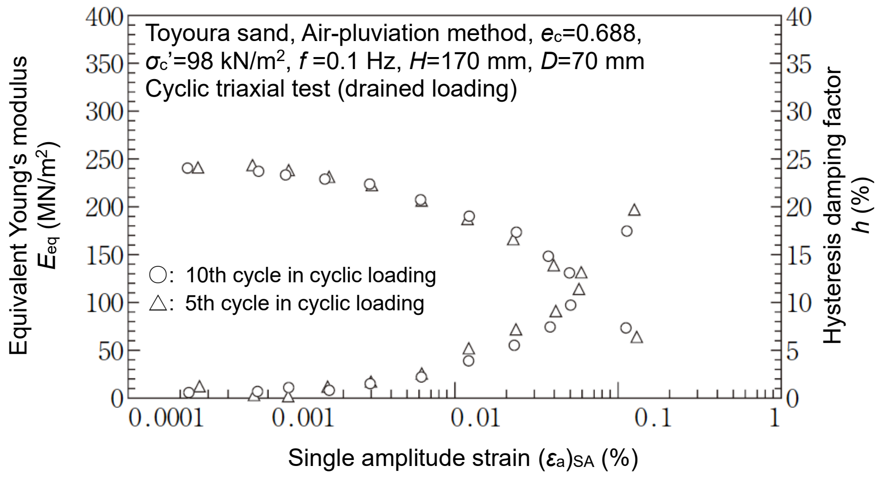

Figure 14 Example of summary of the series of test results