Japanese Geotechnical Society Standard (JGS 0525-2020) Method for K_0 consolidated-undrained triaxial compression test on soils with pore water pressure measurements

1 Scope

This standard specifies a test method to determine the consolidation properties of soil consolidated in the K_0 condition, and the strength and deformation properties when the soil is subjected to axial compression in an undrained condition following consolidation. The test shall be performed for saturated cohesive soil.

Note: This standard may also be applied mutatis mutandis to sandy soil.

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). The soil specimens used for this test shall be prepared and installed in accordance with the following standards.

JGS 0520 Preparation of soil specimens for triaxial tests

When performing this test, the following standards shall be referenced for matters not specified in this standard.

JIS A 1217 Test method for one-dimensional consolidation properties of soils using Incremental loading
JGS 0522 Method for consolidated-undrained triaxial compression test on soils (CU)
JGS 0523 Method for consolidated-undrained triaxial compression test on soils with pore water pressure measurements ($\overline{\mathrm{CU}}$)
JGS 0524 Method for consolidated-drained triaxial compression test on soils (CD)

3 Terms and definitions

In addition to those specified in JIS A 0207, the main terms and definitions used in this standard are as follows:
Note: This test may be abbreviated to "$K_0\overline{\mathrm{CU}}\mathrm{C}$ triaxial test".

3.1 K_0 consolidated-undrained triaxial compression ($K_0\overline{\mathrm{CU}}\mathrm{C}$)

Application of axial compression force to achieve shear while simultaneously measuring pore water pressure in the undrained condition after consolidation in the triaxial K_0 condition.

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 specimen.

3.4 Principal stress difference

The difference between the axial stress and the lateral stress. The value of stress shall be defined at the mid-height of the test specimen.

3.5 Anisotropic stress state

A stress state with different axial stress and lateral stress.

3.6 K_0 condition

An anisotropic stress state in which no displacement is produced in the radial direction of the soil specimen.

3.7 Cell pressure

The pressure applied within a triaxial cell.

3.8 Back pressure

The pressure applied to the pore water within the 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 test specimen while maintaining a constant effective stress.

3.9 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.

3.10 Axial consolidation stress

Consolidation stress in the long axis direction of the specimen.

3.11 Lateral consolidation stress

Consolidation stress in the radial direction of the specimen.

3.12 Undrained compressive strength

The maximum principal stress difference that can be applied to the soil specimen when no pore water is allowed to flow in or out of the specimen.

4 Equipment

4.1 Triaxial test apparatus

The triaxial test equipment shall consist of a triaxial pressure cell, a system for applying cell pressure and back-pressure, axial loading equipment, and measurement devices for load, displacement, volume change, and pore water pressure. The apparatus shall satisfy the following conditions. Figure 1 shows an example of the configuration of K_0 consolidated triaxial test equipment that conducts tests through automatic control.

a) The apparatus shall have sufficiently high load-bearing strength and load capacity to handle the maximum cell pressure, back pressure and maximum axial load to be applied to the specimen, and shall be capable of applying axial stress and lateral stress independently during consolidation.

b) The apparatus shall be capable of continuously applying the specified cell pressure and back pressure within ±2 kN/m^2 of the target value for pressures up to 200 kN/m^2, and within ±1 % of the target value for pressures of 200 kN/m^2 or greater, for the duration of a single test.

c) The apparatus shall be capable of applying axial displacement continuously at a constant rate up to 15% of the specimen height.

d) The apparatus shall be capable of measuring the cell pressure, the back pressure and the pore water pressure inside the soil specimen, with an allowable tolerance of 2 kN/m^2 for pressures up to 200 kN/m^2 and 1 % for pressures of 200 kN/m^2 or greater.

Note: Normally, a diaphragm type pressure transducer is used as the pore water pressure measurement device. If the volume of the test specimen is V, and the volume change of the measuring system including the pressure transducer is ΔV

for a change in pore water pressure Δu, then a proper transducer shall be selected so that its performance satisfies $(\Delta V/V)/\Delta u < 5\times10^{-6}$ m^2/kN. Also, the measured values of the pore water pressure are affected by temperature changes, so it is desirable that the change in temperature within the measurement room be controlled to within ±2 °C.

e) The apparatus shall be capable of measuring the axial force up to the specimen's maximum axial compressive force within an allowable tolerance of 1 %. As a standard, a load cell shall be provided inside the triaxial cell, and in this case, any effect of cell pressure shall be calibrated, and the axial compression force measurement shall be corrected. In the case of test equipment in which the load cell is provided outside the triaxial cell, the friction force of the piston and the sliding section of the pressure chamber shall be measured and the axial compression force measurement shall be corrected.

f) The apparatus shall be capable of measuring the axial displacement up to 15 % of the specimen height within an allowable tolerance of 0.02 %.

g) The apparatus shall be capable of measuring the volume change of the specimen up to its maximum value within an allowable tolerance of 0.05 % of the specimen's initial volume. When measuring lateral displacement and controlling K_0 consolidation, the apparatus shall be capable of conducting measurements with an allowable tolerance of 0.025 % of the initial diameter of the soil specimen.

5 Test method

5.1 Preparation and set-up of test specimen

The preparation and placement of the soil specimen shall conform to the method specified in JGS 0520 Preparation of soil specimens for triaxial tests. However, the height of the soil specimen shall be at least twice the diameter. The drain filter attached to the soil specimen shall be made of a material that exhibits little compression or expansion when the cell pressure is changed.

Note 1: Correction should be performed when there is a great change in volume of the drain filter.

Note 2: When performing a test for K_0 consolidation only, the height of the soil specimen may be reduced.

5.2 Confirmation of degree of saturation

The pore pressure coefficient B (B value) shall be measured through the final stage of back pressure application. Figure 2 shows procedures for back pressure loading and the process of measuring the B value at the final stage, taking a loading sage of the last 1/4 of back pressure as example.

a) Close the drainage valve.

b) In an isotropic stress state, increase the lateral stress σ_r by $\Delta\sigma$ in a period of approximately 1-2 minutes. The standard value of $\Delta\sigma$ shall be 10 to 50 kN/m^2. Note that the value of σ_r after applying $\Delta\sigma$ shall not exceed the lateral stress at the end of the consolidation.

c) Measure the increase in pore water pressure Δu when the pore water pressure has stabilized to a constant value.

d) Open the drainage valve after applying the back pressure that is equivalent to $\Delta\sigma$.

Note: Refer to Section 4.6 of JGS 0520 Preparation of soil specimens for triaxial tests.

5.3 Consolidation process

The consolidation procedures of the test shall be in accordance with the following requirements.

a) Make zero adjustments to the displacement transducer and pore water pressure transducer, and confirm that the pore water pressure measurement system is indicating the desired value of back pressure

u_b (kN/m^2) by opening the valve in the pore water pressure measurement system. At the same time, take the initial reading of the burette.

If the piston and cap have not been rigidly connected, connect the load cell, piston and cap before performing this operation.

b) Perform K_0 consolidation up to the specified consolidation stress, while maintaining the back pressure u_b at a constant level, using one of the following methods. The control time interval for K_0 consolidation shall be selected appropriately in accordance with the rate (when gradually increasing the consolidation stress load) or the magnitude of the isotropic stress that is applied (when applying the consolidation stress in stages), as well as the consolidation properties of the soil specimen, in order to prevent lateral strain of ±0.05 % or greater from being produced.

1) A method by which loading is conducted with the axial compression force gradually increased and the cell pressure is controlled

Open the drainage valve and increase the axial compression force or axial displacement at a uniform rate until the axial stress reaches the specified consolidation stress. During this process, control the cell pressure so the lateral strain ε_r of the soil specimen is always 0.05 % or less.

2) A method by which loading is conducted with the cell pressure gradually increased and the axial compression force is controlled

Open the drainage valve and increase the cell pressure at a uniform rate until the lateral stress reaches the specified consolidation stress. During this process, control the axial compression force so the lateral strain ε_r of the soil specimen is always 0.05 % or less.

3) A method by which staged loading is conducted and the cell pressure is controlled

With the drainage valve closed, apply an isotropic stress load of approximately 1/5–1/3 the final consolidation stress in the axial direction. Then quickly open the drainage valve and, with the axial stress maintained at a constant level, control the cell pressure so the lateral strain ε_r of the soil specimen is always ±0.05 % or less. Repeat this process in several (3–5) stages until the axial stress reaches the specified consolidation stress.

4) A method by which staged loading is conducted and the axial compression force is controlled

With the drainage valve closed, apply an isotropic stress load of approximately 1/5–1/3 the final consolidation stress in the lateral direction. Then quickly open the drainage valve and, with the cell pressure maintained at a constant level, control the axial compression force so the lateral strain ε_r of the soil specimen is always ±0.05 % or less. Repeat this process in several (3–5) stages until the lateral stress reaches the specified consolidation stress.

The lateral strain ε_r of the specimen during K_0 condition shall be determined using one of the following methods, in accordance with the type of triaxial cell that is used.

1) A method where ordinary triaxial test equipment is used

Measure the change in volume of the soil specimen using a differential pressure transducer or similar device, and then determine the lateral strain ε_r (%) using the following equation.

$$\varepsilon_r = \frac{1}{2V_0}(\Delta V_t - A_0 \times \Delta H_t) \times 100$$

where

ΔH_t: Axial displacement of soil specimen (mm)

ΔV_t: Change in volume of soil specimen after correction of filter absorption and drain water quantity (mm^3)

A_0: Cross-sectional area of soil specimen before consolidation (mm^2)
V_0: Volume of soil specimen before consolidation (mm^3)

2) A method where open type dual cell triaxial test equipment with a free water surface is used
Measure the change in water level inside the cell using a non-contacting displacement gauge or similar device, and then determine the lateral strain ε_r (%) using the following equation.

$$\varepsilon_r = \frac{1}{2V_0}\left\{\left(A_p \times \Delta H_t - A_w \times \Delta H_w\right) - A_0 \times \Delta H_t\right\} \times 100$$

where

ΔH_w: Change in water level inside cell (rise is positive) (mm)
A_w: Area of free water surface inside cell (mm^2)
A_p: Cross-sectional area of loading piston at free water surface position inside cell (mm^2)

3) A method where the lateral displacement Δd_t of the soil specimen is measured directly
Determine the lateral strain ε_r (%) using the following equation.

$$\varepsilon_r = \frac{\Delta d_t}{D_0} \times 100$$

where

Δd_t: Amount of reduction of soil specimen diameter (mm)
D_0: Soil specimen diameter before consolidation (mm)

Note: Loading of axial compression force and cell pressure should be done in a way that ensures that no sudden changes in stress or changes in strain are produced in the soil specimen, and that the stress distribution and strain distribution in the soil specimen do not become excessively unbalanced. During this process, even if the axial compression force applied to the loading piston is the same, if the cell pressure should change, the axial stress acting on the soil specimen will change, so the relationship between the axial stress acting on the soil specimen and the diameter and dead weight of the loading piston shall be determined in advance.

c) Measure the axial displacement ΔH_t (mm), the change in volume (equivalent to the drain quantity from the soil specimen) ΔV_t (mm^3), the lateral displacement Δd_t (mm), and the axial stress σ_{at} (kN/m^2) and lateral stress σ_{rt} (kN/m^2) during consolidation, atand plot these values at appropriate elapsed time t values. Measure the axial displacement ΔH_c (mm), the change in volume ΔV_c (mm^3), the axial stress σ_{ac} (kN/m^2) and the lateral stress σ_{rc} (kN/m^2) at the completion of consolidation.

Note: Refer to 5.2d) in JGS 0522 Method for consolidated-undrained triaxial compression test on soils, for the time at which consolidation shall be completed.

5.4 Undrained compression process

The undrained compression process shall be carried out in accordance with the following procedure.

a) Check and adjust the zero reading of the load cell and displacement transducer.

b) Close the drainage valve.

c) Start compressing the specimen continuously at a constant strain rate keeping the cell pressure constant. To ensure that the pore water pressure is uniformly distributed in the specimen, the standard axial compression rate shall be about 0.1 %/min for silty soils and about 0.05 %/min for clayey soils.

d) Record the axial compression force P (N), the axial displacement ΔH (mm) and the pore water pressure u (kN/m^2).

Note: If the axial compression force, the axial displacement, and the pore water pressure are not recorded continuously, the measurement time intervals should be sufficiently small to enable smooth curves for the principal stress difference –

axial strain curve and the pore water pressure – axial strain to be drawn.

e) Terminate the compression either when an axial strain of more than 3 % has been reached since the maximum axial load reading, when the load has fallen to about 2/3 of its peak value, or when an axial strain of 15 % has been reached.

f) Remove the specimen from the triaxial pressure cell, and observe and record its deformed shape, failure mode, and other features. The observation shall be made in the direction that captures the features of failure most clearly. If a slip surface is found, observe it from the direction in which the steepest gradient is determined and record it so that the gradient angle can be approximately read. Any heterogeneity of the specimen and the presence of any foreign materials shall be observed and recorded.

g) Measure the oven-dried mass of the specimen m_s (g).

Note: This step in the process may be omitted if the water content of the specimen is determined from the trimmed waste of the sample.

6 Processing test results

6.1 State of soil specimen before consolidation

Calculate the volume of the soil specimen before consolidation V_0 (mm^3), the height of the soil specimen H_0 (mm), and the diameter of the soil specimen D_0 (mm), using the following equations.

$$V_0 = V_i - \Delta V_i$$

$$H_0 = H_i - \Delta H_i$$

$$D_0 = 2\sqrt{\left(V_0 / \left(\pi H_0\right)\right)}$$

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 between the initial state and prior to the start of consolidation (mm^3), where compression is defined to be positive
ΔH_i : Axial displacement of the specimen between the initial state and prior to the start of consolidation (mm), where compression is defined to be positive

6.2 Pore pressure coefficient *B*

Calculate the *B* value for the specimen just before the start of K_0 consolidation, using 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

The method used to calculate the data from the consolidation process shall be as follows.

a) Calculate the volume of the specimen during consolidation V_t (mm^3) and the volume of the specimen after consolidation V_c (mm^3), using the following equations.

$$V_t = V_0 - \Delta V_t$$

$$V_c = V_0 - \Delta V_c$$

where

ΔV_t: Volume change of the specimen during consolidation (mm^3), where compression is defined to be positive

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

Note: If necessary, the void ratio of the soil specimen after consolidation e_c (before undrained compression) shall be calculated using the following equation.

$$e_c = \frac{V_c/1000 \times \rho_s}{m_s} - 1$$

where

ρ_s: Density of soil particles (Mg/m^3)

b) Calculate the height of the specimen during consolidation H_t (mm) and the height of the specimen after consolidation H_c (mm), using the following equations.

$$H_t = H_0 - \Delta H_t$$

$$H_c = H_0 - \Delta H_c$$

where

ΔH_t: Axial displacement during consolidation (mm), where compression is defined to be positive

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

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

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

d) Calculate the axial strain of the specimen during consolidation ε_{at} (%), using the following equation, where compression is defined to be positive.

$$\varepsilon_{at} = \frac{\Delta H_t}{H_0} \times 100$$

e) Calculate the volumetric strain of the specimen during consolidation ε_{vt} (%), using the following equation, where compression is defined to be positive.

$$\varepsilon_{vt} = \frac{\Delta V_t}{V_0} \times 100$$

f) Calculate the lateral strain of the specimen during consolidation ε_{rt} (%), using the following equation, where compression is defined to be positive.

$$\varepsilon_{rt} = \frac{\Delta d_t}{D_0} \times 100 \quad \text{or} \quad \varepsilon_{rt} = \frac{1}{2}(\varepsilon_{vt} - \varepsilon_{at})$$

where

Δd_t: Lateral displacement of the specimen during consolidation (mm)

g) Calculate the effective axial consolidation stress σ'_{ac} (kN/m^2) and the effective lateral consolidation stress σ'_{rc} (kN/m^2) of the soil specimen when consolidation is completed, using the following equations, which shall be rounded to three significant digits.

$$\sigma'_{rc} = \sigma_r - u_c$$

$$\sigma'_{ac} = (\sigma_a - \sigma_r) + \sigma'_{rc}$$

$$\sigma_a - \sigma_r = \frac{P_c - P_0}{A_c} \times 1000$$

where

P_c: Axial compression force applied to the specimen when consolidation is completed (N)
P_0: Axial compression force applied to the specimen through piston to maintain initial isotropic stress state at the stage prior to the start of consolidation (N)
u_c: Pore water pressure applied to the specimen when consolidation is completed (kN/m^2)

h) Calculate the stress ratio K_0 when consolidation is completed, using the following equation, which shall be rounded to three significant digits.

$$K_0 = \frac{\sigma'_{rc}}{\sigma'_{ac}}$$

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

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

where

m_s: Oven-dried mass of the specimen (g)

Note: 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.

6.4 Undrained compression process

The method of calculation for the undrained compression process shall be as follows.

a) Calculate the axial strain of the specimen ε_a (%) using the following equation (compression is positive).

$$\varepsilon_a = \frac{\Delta H}{H_c} \times 100$$

where

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

b) Calculate the principal stress difference ($\sigma_a - \sigma_r$) (kN/m^2) under axial strain ε_a (%) and the increase in pore water pressure resulting from axial compression u_e (kN/m^2), using the following equations.

$$\sigma_a - \sigma_r = \frac{P - P_0}{A_c}\left(1 - \frac{\varepsilon_a}{100}\right) \times 1000$$

$$u_e = u - u_b$$

where

P: Axial compression force (N) acting on the specimen at the axial strain ε_a (%)
u: Pore water pressure (kN/m^2) measured at the axial strain ε_a (%)
u_b: Back pressure (kN/m^2)

c) Draw graphs with the principal stress difference and the pore water pressure on the vertical axis versus axial strain on the horizontal axis, to obtain the principal stress difference – axial strain curve and the pore water pressure increment due to axial compression – axial strain curve.

d) Obtain the maximum principal stress difference $(\sigma_a - \sigma_r)_{max}$ in the axial strain range of $0 < \varepsilon_a \leq 15$ %, and this value shall be taken as the compressive strength (kN/m^2), which shall be rounded to three significant digits. Also, determine the corresponding axial strain ε_f from these figures, which shall be rounded to one digit after the decimal point.

e) Determine the ratio s_u/σ'_{ac} of undrained shear strength $s_u = (\sigma_a - \sigma_r)_{max}/2$ to effective axial consolidation stress σ'_{ac}, which shall be rounded to three significant digits.

f) Calculate the effective principal stress σ'_a (kN/m^2) and σ'_r (kN/m^2) in the undrained compression process from the following equations, and draw an effective stress path diagram with $\sigma_a - \sigma_r$ on the vertical axis and $(\sigma'_a+2\cdot\sigma'_r)/3$ on the horizontal axis.

$$\sigma'_r = \sigma_r - u$$

$$\sigma'_a = (\sigma_a - \sigma_r) + \sigma'_r$$

Note: If necessary, draw an effective stress path diagram with $(\sigma_a - \sigma_r)/2$ on the vertical axis and $(\sigma'_a+\sigma'_r)/2$ on the horizontal axis.

g) Calculate the effective principal stresses at the maximum principal stress difference σ'_{af} (kN/m^2) and σ'_{rf} (kN/m^2), using the following equations, which shall be rounded to three significant digits.

$$\sigma'_{rf} = \sigma_{rf} - u_f$$

$$\sigma'_{af} = (\sigma_a - \sigma_r)_{max} + \sigma'_{rf}$$

where

σ_{rf}: Lateral stress at maximum principal stress difference (kN/m^2)
u_f: Pore water pressure at maximum principal stress difference (kN/m^2)

Note: Obtain σ'_a and σ'_r at $(\sigma'_a/\sigma'_r)_{max}$, if necessary.

7 Reporting

The following test results and other items shall be reported.

a) Method of specimen preparation

b) Dimensions of the specimen before the consolidation

c) Magnitude of the back pressure (kN/m^2)

d) Time needed for B value and pore water pressure to stabilize (min)

e) Stress loading method at stages in which consolidation is in progress (note the stress in the case of staged loading)

f) Change in volume during consolidation process (mm^3), axial displacement (mm), and relationship of $\sigma_{af} - u_b$ (kN/m^2), $\sigma_{rf} - u_b$ (kN/m^2) and time (min)

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

Note: Report the void ratio of the specimen after consolidation, if necessary.

h) Relationship of $(\sigma_{rf} - u_b) / (\sigma_{af} - u_b)$, ε_r (%) and elapsed time (min)

i) Relationship between $(\sigma_{rf} - u_b) / (\sigma_{af} - u_b)$ and $\sigma_{af} - u_b$ (kN/m^2)

j) Axial consolidation stress σ'_{ac}, (kN/m^2), lateral consolidation stress σ'_{rc} (kN/m^2) and stress ratio $\sigma'_{rc}/\sigma'_{ac}$ (= K_0)

k) Strain rate of undrained compression process (%/min)

l) Principal stress difference versus axial strain curve, pore water pressure increase versus axial strain curve, and maximum principal stress difference (kN/m^2) and axial strain at that time (%)

m) Effective stress path diagram

n) Failure mode of soil specimen

o) Effective principal stress (kN/m^2) and s_u/σ'_{ac} at maximum principal stress difference

Note: Report the values of σ'_a and σ'_r at $(\sigma'_a/\sigma'_r)_{max}$, if necessary.

p) When testing multiple soil specimens with the same sample, the relationship between undrained shear strength and consolidation stress

q) If the method used deviates in any way from this standard, give details of the method used.

r) Other reportable matters

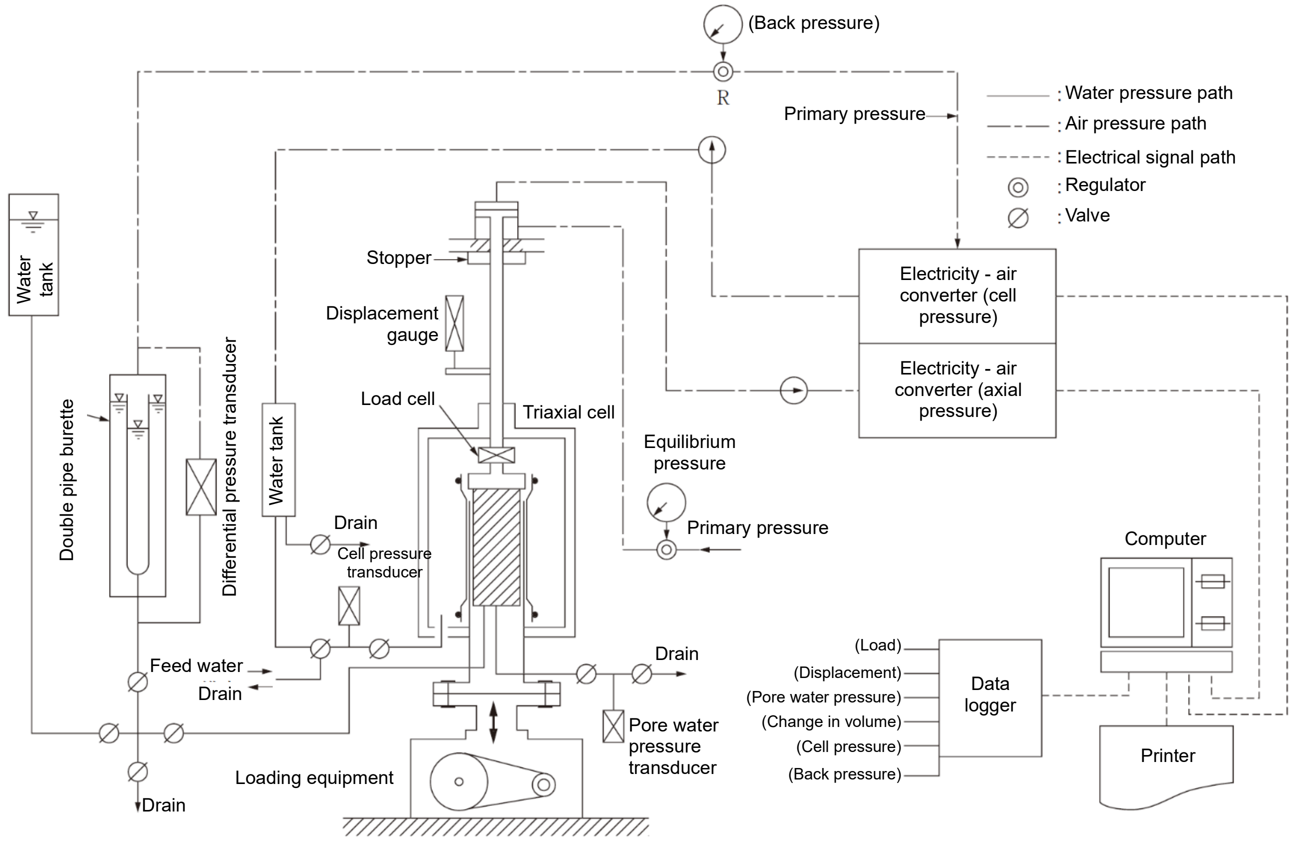

Figure 1 Example of configuration of K_0 consolidated triaxial test equipment that conducts tests through automatic control

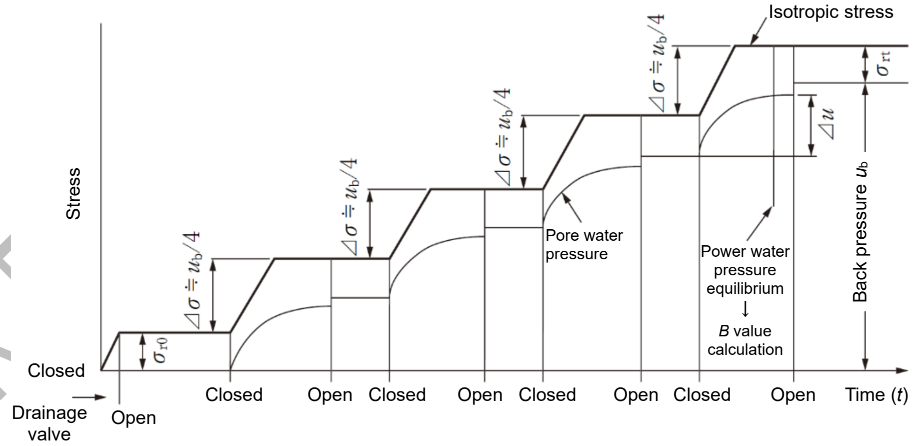

Figure 2 Procedure for back pressure loading and method for measuring B value