

PART ONE: INTRODUCTION TO TRIAXIAL TESTING

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Overview: This three part series has been written to introduce one of the most versatile tests in the geotechnical laboratory – the triaxial test. The papers provide a detailed introduction to the subject of triaxial testing, including the many variations available for assessing soil response across a range of engineering applications. The series is split into the following topics:

1. Introduction to triaxial testing.
2. Advanced triaxial testing (Part 2 is due to be released May 2013 - visit www.gdsinstruments.com for more info).
3. Dynamic triaxial testing.

INTRODUCTION

This paper provides an introduction to the triaxial test, explaining why the test is performed, the stress state of a tested soil, required test system components, and the general procedure for running a triaxial test. It assumes a basic knowledge of soil mechanics – for those readers unfamiliar with some terms in this paper, it is recommended they revisit Part One of the GDS Introduction to Soil & Rock Testing series, which briefly covers the key terminology and engineering parameters discussed herein.

Why conduct a triaxial test?

The triaxial test is one of the most versatile and widely performed geotechnical laboratory tests, allowing the shear strength and stiffness of soil and rock to be determined for use in geotechnical design. Advantages over simpler procedures, such as the direct shear test, include the ability to control specimen drainage and take measurements of pore water pressures. Primary parameters obtained from the test may include the angle of shearing resistance ϕ' , cohesion c' , and undrained shear strength c_u , although other parameters such as the shear stiffness G , compression index C_c , and permeability k may also be determined. Figure 1 gives an example of the engineering application of the test – here triaxial compression provides strength information at the top of a cut slope, whilst triaxial extension allows parameters for soil elements at the slope base to be determined.

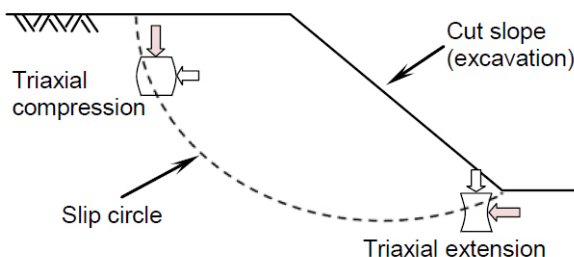


Figure 1 – Example of an engineering application of the triaxial test.

What does a triaxial test involve?

The triaxial test typically involves placing a cylindrical specimen of soil, ranging from 38mm to 100mm diameter, into a cell that can be pressurised. Most specimens have an approximate 2:1 height-to-diameter ratio, and are sealed within a rubber

membrane. Following this initial preparation the specimen is saturated, consolidated, and sheared, allowing the soil response to be observed under conditions that may approximate those in-situ. During the shear stage the soil is loaded axially, either in compression, or less-commonly in extension. The general set-up of a triaxial specimen inside a triaxial cell is shown in Figure 2.

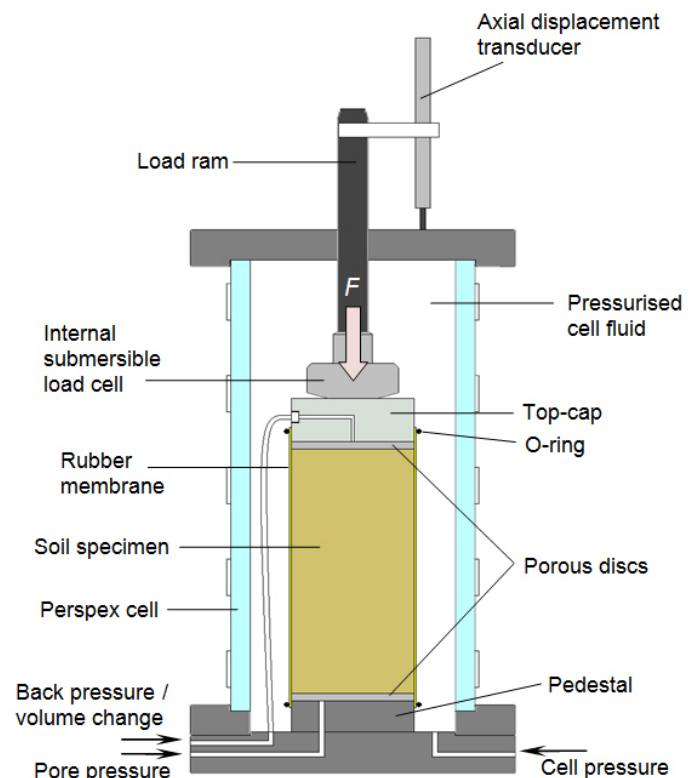


Figure 2 – General set-up of a soil specimen inside a triaxial cell.

What are the types of triaxial test?

There are three primary triaxial tests conducted in the laboratory, each allowing the soil response for differing engineering applications to be observed. These are:

- Unconsolidated Undrained test (UU)
- Consolidated Undrained test (CU)
- Consolidated Drained test (CD)

The unconsolidated undrained (UU) test is the simplest and fastest procedure, with soil specimens loaded whilst only total stresses are controlled and recorded. This allows the undrained shear strength c_u to be determined, which is suitable for assessing soil stability in the short-term (e.g. during or directly following a construction project). Note this test is generally performed on cohesive soil specimens.

The consolidated drained (CD) test on the other hand is applicable to describing long-term loading response, providing strength parameters determined under effective stress control (i.e. ϕ' and c'). The test can however take a significant time to complete when using cohesive soil, given the shear rate must be slow enough to allow negligible pore water pressure changes.

Finally the consolidated undrained (CU) test is the most common triaxial procedure, as it allows strength parameters to be determined based on the effective stresses (i.e. ϕ' and c') whilst permitting a faster rate of shearing compared with the CD test. This is achieved by recording the excess pore pressure change within the specimen as shearing takes place.

STRESS STATE DURING A TRIAXIAL TEST

The stresses applied to a soil or rock specimen when running a triaxial compression test are displayed in Figure 3. The confining stress σ_c is applied by pressurising the cell fluid surrounding the specimen – it is equal to the radial stress σ_r , or minor principal stress σ_3 . The deviator stress q is generated by applying an axial strain ϵ_a to the soil – the deviator stress acts in addition to the confining stress in the axial direction, with these combined stresses equal to the axial stress σ_a , or major principal stress σ_1 . The stress state is said to be isotropic when $\sigma_1 = \sigma_3$, and anisotropic when $\sigma_1 \neq \sigma_3$.

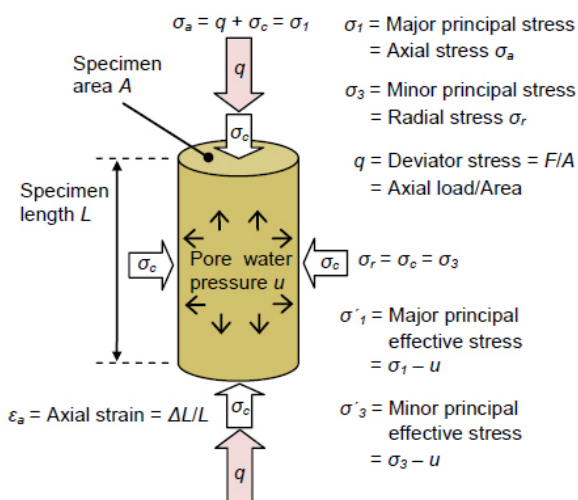


Figure 3 – Specimen stress state during triaxial compression.

Note the principal stress directions rotate by 90° when a triaxial extension test is performed – in such a case the radial stress corresponds to the major principal stress direction, with the axial stress providing the minor principal stress.

TRIAXIAL SYSTEM COMPONENTS

To perform a triaxial test the system must contain a number of components to enable the desired specimen stress state to be reached, and shear the specimen whilst recording the soil response. Table 1 lists each primary component of a GDS triaxial system, along with its main function. A complete system diagram is presented in Figure 4.

Table 1 – Primary components of a GDS triaxial automated system.

Component	Main function
Triaxial cell	House the specimen and cell fluid
Pedestal & top-cap	Provide specimen seating and drainage ports
Rubber membrane, O-rings & porous discs	Seal the specimen from the cell fluid, allowing control over the effective stress and drainage
Cell pressure / volume controller	Apply confining stress to the specimen ($\sigma_c = \sigma_3$) by pressurising the cell fluid
Back pressure / volume controller	Apply back / pore pressure u to the specimen and measure volume change ΔV
Velocity-controlled load frame	Shear the specimen through axial movement of a loading platen at a constant rate
Internal submersible load cell	Measure the change in axial load F applied to the specimen during shear
Pore water pressure (PWP) transducer	Measure the change in pore water pressure u within the specimen
Axial displacement transducer	Measure the change in height (and hence axial strain ϵ_a) of the specimen
Data acquisition unit	Convert analogue readings from the load cell, PWP and axial displacement transducers to digital data
GDSLab control & acquisition software	Control test hardware and record digital readings taken from the data acquisition unit

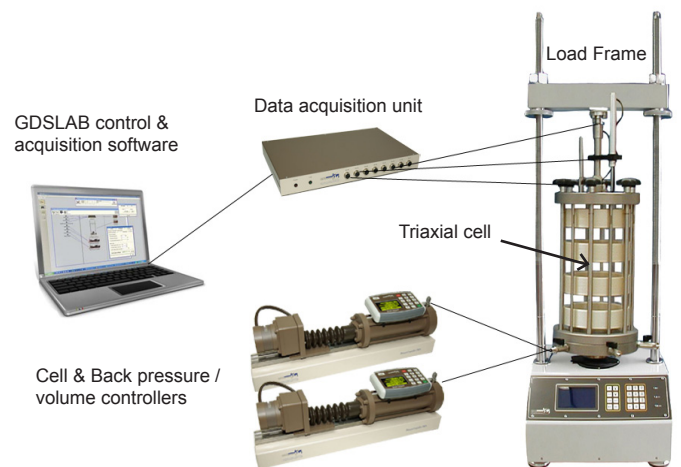


Figure 4 - GDS Triaxial Automated System (TAS) components.

GENERAL TRIAXIAL TEST PROCEDURE

As briefly mentioned in the Introduction section of this paper, the triaxial test as described by geotechnical test standards (for example BS 1377: Part 8: 1990) typically consists of four main stages: specimen and system preparation, saturation, consolidation, and shearing (note saturation and consolidation stages are not required for the UU test – see BS 1377: Part 7: 1990). General outlines of each stage are discussed in the following based on use of a GDS triaxial automated system.

Specimen & System Preparation

The test specimen itself must firstly be prepared from a sample of soil before placing into the triaxial cell. For cohesive soils this may involve trimming undisturbed specimens extruded from Shelby tubes or cut from block samples, whilst for granular soils the specimen may require preparation directly on the pedestal using a split-part mould. In the case of cohesive specimens such as that shown in Figure 5, a membrane suction stretcher can be used to place the rubber membrane around the soil once in position on the pedestal. Note that disturbance to the specimen should be kept to a minimum during preparation.



Figure 5 – Trimmed cohesive specimen (left); membrane suction stretcher (middle); split-part mould for granular specimen preparation (right).

Following placement of the specimen, the triaxial cell and other system components are assembled. During this stage the cell is filled with fluid, pressure / volume controllers connected, and transducer readings set as required.

Saturation

The saturation process is designed to ensure all voids within the test specimen are filled with water, and that the pore pressure transducer and drainage lines are properly de-aired. This may be achieved by firstly applying a partial vacuum to the specimen to remove air and draw water into the transducer and drainage lines, followed by a linear increase of the cell and back pressures. The latter process is shown in Figure 6, during which a constant effective stress should be maintained – at no point should the effective stress increase above the value required for shearing, as this leads to specimen over-consolidation. To assist the specimen in reaching full saturation, the following steps may be taken:

- Use of de-aired water to fill specimen voids.
- Increase of back pressure to force air into solution.

Note that a significant period of time, and/or back pressures in the range of 700kPa or above, may be required to fully saturate a specimen, particularly if de-aired water is not used.

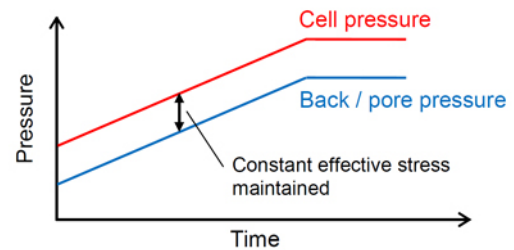


Figure 6 – Specimen saturation by increasing back pressure.

To check the degree of specimen saturation is sufficiently high before moving to the consolidation stage, a short test is performed to determine Skempton's B -value. This is called a B -check, and requires specimen drainage to be closed whilst the cell pressure is raised by approximately 50kPa. Figure 7 details this test, with $B \geq 0.95$ typically used to confirm full specimen saturation. Note however that B is soil-dependent, so whilst a normally-consolidated soft clay will produce $B \approx 1.00$ at full saturation, a very dense sand or stiff clay may only show $B \approx 0.91$, even if full saturation has been reached.

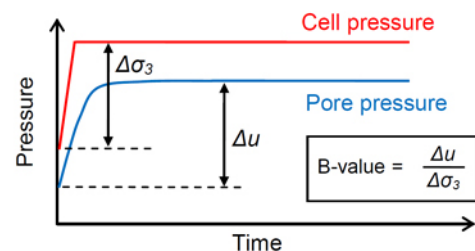


Figure 7 – B -check to confirm specimen saturation.

Consolidation

The consolidation stage is used to bring the specimen to the effective stress state required for shearing. It is typically conducted by increasing the cell pressure whilst maintaining a constant back pressure (often equal to the pore pressure reached during the final saturation B -check), as shown in Figure 8. This process is continued until the volume change ΔV of the specimen is no longer significant, and at least 95% of the excess pore pressure has dissipated. The consolidation response can also be used to estimate a suitable rate of strain when shearing cohesive specimens.

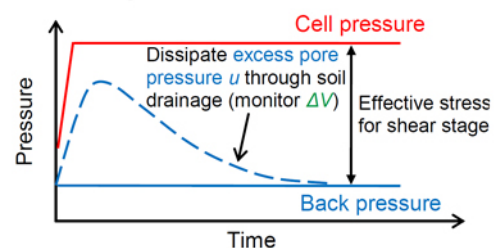


Figure 8 – Consolidation of test specimen.

Shearing

The soil is sheared by applying an axial strain ϵ_a to the test specimen at a constant rate through upward (compression) or downward (extension) movement of the load frame platen. This rate, along with the specimen drainage condition, is dependent on the type of triaxial test being performed. Table 2 summarises the conditions for each test type (note a constant confining pressure is maintained for each).

Table 2 – Summary of test conditions during shear stage.

Test type	Rate of axial strain	Drainage
UU	Typically fastest, reaching failure criterion in 5 – 15 minutes	Closed, no excess pore pressure measurement
CU	Slow enough to allow adequate equalisation of excess pore pressures	Closed, record excess pore pressure
CD	Slow enough to result in negligible pore pressure variation	Open, record ΔV & maintain constant back pressure

Specimen response during the shear stage is typically monitored by plotting the deviator stress q or effective principal stress ratio σ'_1/σ'_3 against the axial strain ϵ_a . The stage is continued until a specified failure criterion has been reached, which may include identification of the peak deviator stress or peak effective principal stress ratio, observation of constant stress and excess pore pressure / volume change values, or simply a specific value of axial strain being reached (for example $\epsilon_a = 20\%$). Generalised response for a normally-consolidated clay is presented in Figure 9, including the excess pore pressure generated during a CU test, and observed specimen volume change during a CD test. The figure also displays a cohesive specimen after completion of the shear stage, with the plane of failure highlighted (i.e. the plane in which the majority of shear strain occurs).

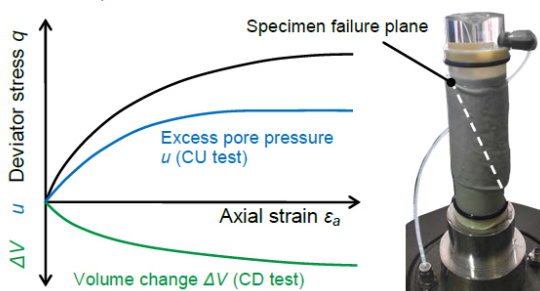


Figure 9 – Generalised specimen response during shear for a normally-consolidated clay (left); cohesive specimen post-shear showing failure plane (right).

Following specimen shearing the system can be dismantled, with post-test specimen measurements then taken (e.g. final moisture content).

STRESS PATH TRIAXIAL TESTING SYSTEMS

The triaxial system and test procedures discussed thus far have focused on standard constant rate of strain-controlled tests, wherein the specimen shear stress is induced through axial movement of a velocity-controlled load frame platen. To apply and control the axial stress of a test specimen, stress-path triaxial cells have traditionally been employed. These use a pressurised lower chamber to transmit axial stresses to the soil, with axial strains induced by this stress application. Such systems were developed to allow specimens to be tested under more complex stress conditions when compared with velocity-controlled load frames, and have therefore been more associated with research projects. An example of a stress-path triaxial system is shown in Figure 10, although it should be noted that modern PC control via transducer feedback enables both load frame and stress-path systems to perform the same complex tests, with only minor differences in performance (load frames are slightly more suited to strain-control; stress-path systems to stress-control).

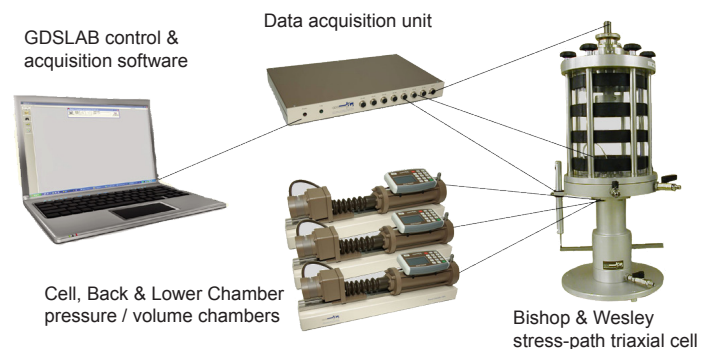


Figure 10 – GDS Triaxial Testing System (TTS) components.

FURTHER READING

The following texts contain much of the information presented in this paper, and are recommended references when investigating the triaxial test procedure in further detail (not including specific laboratory test standards):

- Day, R. W. 2001. Soil Testing Manual: Procedures, Classification Data, and Sampling Practices, New York, McGraw-Hill.
- Head, K. H. 1998. Manual of Soil Laboratory Testing Volume 3: Effective Stress Tests, Chichester, John Wiley & Sons Ltd.
- Knappett, J. A. & Craig, R. F. 2012. Craig's Soil Mechanics, Oxon, Spon Press.
- Simons, N., Menzies, B. & Matthews, M. 2002. A Short Course in Geotechnical Site Investigation, London, Thomas Telford Ltd.