PART TWO: ADVANCED 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.**
3. Dynamic triaxial testing.

INTRODUCTION

This paper presents a number of advanced triaxial testing options that are available to determine soil properties typically unobtainable with conventional triaxial systems, or soil response that is more closely representative of in-situ soil conditions. In particular, the topics covered in this paper are:

- Local strain measurement
- Local pore pressure measurement
- Bender element testing
- Unsaturated soil testing
- Advanced software control

LOCAL STRAIN MEASUREMENT

Conventional triaxial systems measure deformation of the test specimen globally via transducers located external to the triaxial cell. In such cases, the axial displacement transducer is typically fixed to the load ram (see Figure 2 of 'Part One: Introduction to triaxial testing'), with radial strains being estimated from back volume change and/or axial displacement readings.

While these arrangements may provide strain measurements of sufficient accuracy for routine triaxial tests, they do not allow truly accurate determination of specimen deformation at the small strain level, in which the peak stiffness and strength may occur, or in the zone of shearing most representative of in-situ soil response. This is in part due to system compliance, wherein external transducers measure extraneous system movements and component deformations unrelated to specimen straining. Bedding error, or the apparent axial strain recorded as the top-cap is pushed into full contact with the upper specimen surface, also contributes to the difficulty in obtaining accurate measurements at very small strains. Finally, friction between the specimen surfaces in contact with the end platens (top-cap and pedestal) causes lateral restraint of the soil, resulting in nonuniform deformations across the specimen height during shearing. This means only the middle third of the specimen is considered to be unrestrained, constituting the primary zone of shearing, which is most representative of in-situ soil response.

These inaccuracies can however be mitigated (or eliminated all together) by taking local strain measurements, which may be achieved through placement of axial and radial strain transducers directly on to the test specimen.

Local axial strain transducers

The local axial strain of a triaxial test specimen can be measured by fixing two displacement transducers, oriented vertically and 180° apart, across the middle third of the specimen. This is shown in Figure 1 using Hall Effect displacement transducers, although other transducer types, such as the mini Linear Variable Differential Transformer (LVDT), may be employed. Each transducer is fixed to the specimen via two mounting blocks, which displace relative to one another as the specimen deforms. It is this displacement the transducers record, requiring the local axial strain readings to be calculated using the initial distance between mounting blocks, known as the gauge length, rather than the initial specimen height.

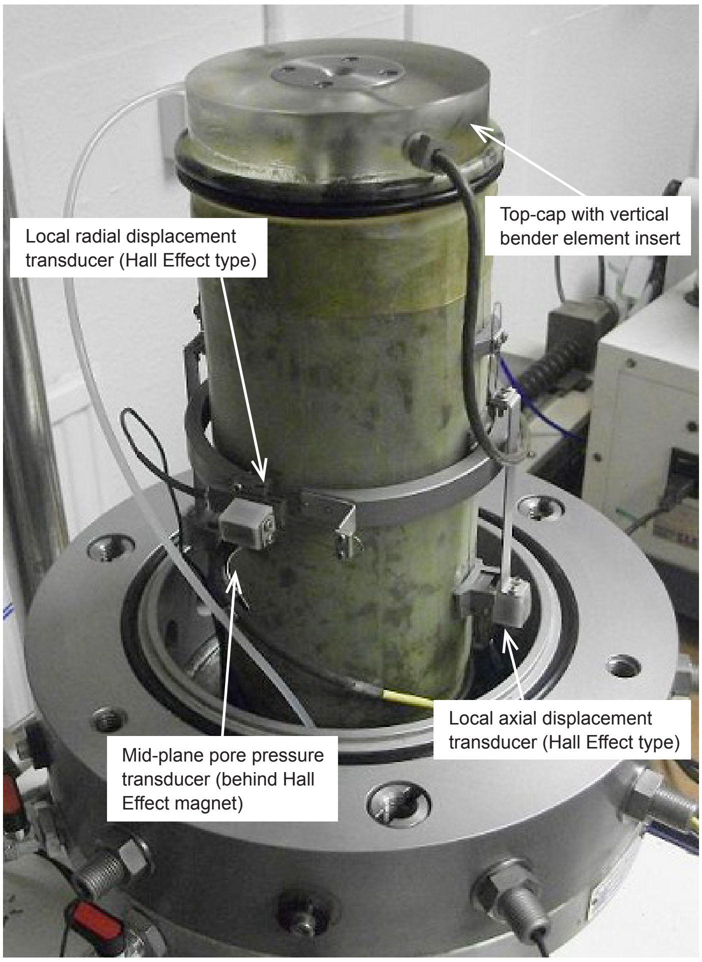

Figure 1 – Triaxial test specimen instrumented with local axial and radial Hall Effect transducers, mid-plane pore pressure transducer, and vertical bender elements.

Local radial strain transducers

The local radial strain of a triaxial test specimen may be measured by placing a displacement transducer into a horizontally-oriented caliper that is fixed about the specimen centre. The caliper is secured to the specimen via two mounting pads, again 180° apart, and is comprised of two sections connected by a hinge. This effectively makes the caliper a set of jaws that open as the specimen expands laterally, or close during lateral contraction of the specimen. The transducer is mounted across the caliper opening, resulting in a displacement measurement twice that of the change in specimen diameter when undergoing deformation. An example of a Hall Effect transducer mounted in a radial caliper is displayed in Figure 1; again an LVDT could be used if so desired.

Transducer choice, fixing methods, & practical advantages

The two types of local displacement transducer discussed in this paper (Hall Effect transducers and LVDTs) are each suitable for particular test applications. In general, Hall Effect transducers are typically smaller and more lightweight than LVDTs, making them useful when testing soft specimens that may deform significantly under a small amount of pre-loading. LVDTs are however more robust in design than Hall Effect transducers, and typically produce a higher accuracy of measurement. As such, LVDTs are often the preferred transducer choice when testing stiffer specimens, or when applying higher confining pressures.

Fixing each type of transducer to the test specimen is also dependent on the soil being tested. Typically either a contact adhesive, such as Loctite Clear Glue, or a combination of silicon sealant and stainless steel pins are used to secure the axial and radial mounting pads to the specimen. The contact adhesive option is generally preferred, as it does not puncture the specimen membrane (avoiding potential leakages during testing), but in some instances it may be necessary to pin the mounting pads in place, using the silicon sealant to prevent cell fluid leaking into the specimen. Note this is only possible when the specimen is soft enough to allow insertion of the pins into the soil.

To illustrate the advantage of using local strain transducers, Figure 2 presents the generalised response obtained during specimen shearing when both global and local axial strain measurements are made. Here the small strain response is accurately captured by the local strain transducers, eliminating the bedding error and system

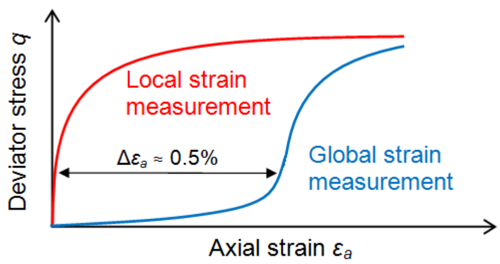

Figure 2 – Generalised specimen response during shear when taking both global and local axial strain measurements.

compliance that can produce a significant difference (i.e. $\Delta\varepsilon_a$) between local and global stress-strain curves (e.g. 0.5%), while also displaying a higher initial soil stiffness than is observable from the global strain measurement.

The higher soil stiffness recorded at small strain is typically more representative of observed field response, as shown in the Figure 3 generalised shear modulus degradation curve. By quantifying the small strain shear modulus, less conservative geotechnical designs can potentially be made, often leading to lower construction costs. Note accurate estimates of the shear modulus at small strains are also important when performing numerical soil analyses.

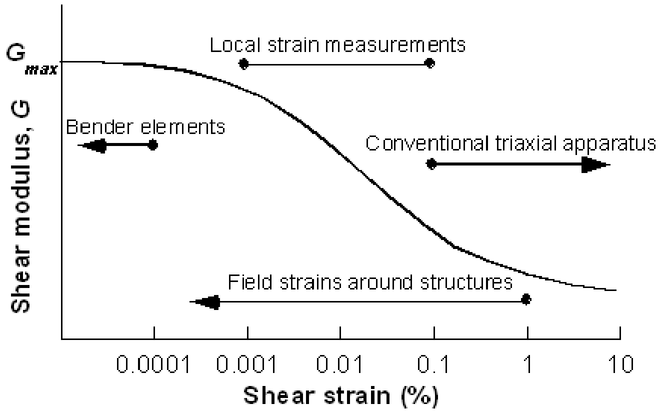

Figure 3 – Generalised shear modulus degradation curve displaying approximate obtainable strain ranges for various laboratory tests (modified from Menzies & Matthews, 1996).

LOCAL PORE PRESSURE MEASUREMENT

Just as conventional triaxial systems measure specimen deformations globally, they also tend to take pore pressure readings from transducers external to the triaxial cell. This makes the readings dependent on the pore fluid response at the ends of the specimen, rather than within the primary zone of shearing (the middle third of the specimen). Therefore, to increase the accuracy of pore pressure measurement during shear, mid-plane pore pressure transducers may be employed within a triaxial system. An schematic example of such a transducer is given in Figure 4.

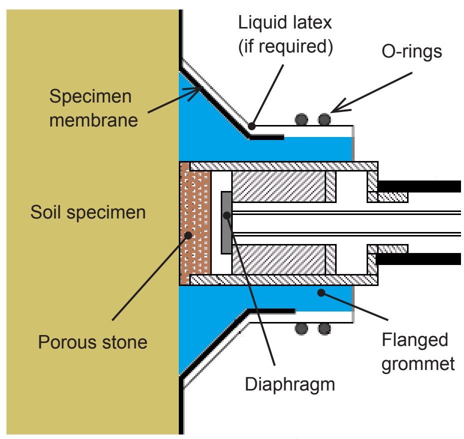

Figure 4 – Schematic illustration of a mid-plane pore pressure transducer mounted on a soil specimen (modified from Meilani et al., 2002).

As their name suggests, these transducers are fixed to the specimen at or near the mid-height. The transducer arrangement is placed in contact with the specimen surface by cutting a small hole in the specimen membrane, allowing a flanged grommet to be slipped between soil and membrane. This places the porous stone in direct contact with the soil, enabling the pore pressure to be recorded by movement of the diaphragm. It is however important to ensure the porous stone, and the void between stone and diaphragm, is fully de-aired to obtain accurate pore pressure readings.

BENDER ELEMENT TESTING

The very small strain response of a soil specimen can be determined in a triaxial system using the bender element test. As displayed in Figure 3, bender elements can enable the maximum shear modulus (G_{max}) of a specimen to be estimated, which again is an important parameter for use in geotechnical design and numerical analyses.

Bender elements themselves are made from piezoelectric ceramic bimorphs that protrude a small distance into the soil specimen. They can be placed in pairs vertically (like those noted in the Figure 1 test specimen top-cap and pedestal) and/or horizontally, allowing the stiffness anisotropy within the specimen to be assessed. When performing a test, one element is supplied with an excitation voltage to generate either a P-wave or an S-wave (both are types of body waves) in the specimen, while the other element receives the generated wave that propagates through the soil.

A typical schematic detailing a pair of vertical bender elements set in a triaxial specimen is shown in Figure 5. Note this figure includes the generated and received waveforms obtained from an S-wave test.

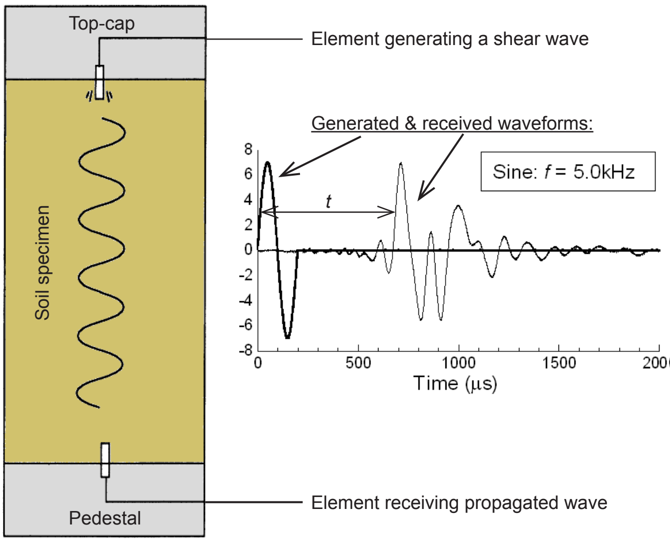

Figure 5 – Schematic illustration of an S-wave bender element test, displaying generated and received waveforms.

The difference between the two body wave types (often known as 'Primary', 'Pressure' or 'Compression', and 'Secondary' or 'Shear' respectively) is best described by the direction of soil particle motion with respect to the direction of wave propagation. P-waves are longitudinal, meaning the soil particles move in the same direction as that of the wave propagation, while S-waves are transverse, meaning the particles move in a direction perpendicular to that of the propagation. Further details about body waves moving through a soil medium can be found in the literature, but important conclusions drawn from theory that specifically relate to the bender element test are listed below:

- The velocity of a P-wave (V_p) is controlled by the bulk and shear moduli of the soil, K and G respectively.
- P-waves are transmitted through pore water, meaning specimen saturation may have a significant effect on the value of V_p.
- The velocity of an S-wave (V_s) is controlled by the shear modulus of the soil, G.
- S-waves are typically unaffected by specimen saturation alone, as water has a negligible shear modulus value.
- $V_p > V_s$.

Practically speaking, the bender element test is used to obtain estimates for V_p and V_s. This is done by recording the time, t, taken for the generated wave to travel from element to element, then dividing the distance between the elements by this travel time (typically the element tip-to-tip distance is used for this calculation). It should however be noted that determining the travel time is not necessarily straightforward, as it is often unclear at which exact time the propagated wave has arrived at the receiver element. The method for determining this arrival time should therefore be selected by the user, based on current recommendations in the geotechnical literature.

With estimations of the P-wave and S-wave velocities obtained, only the bulk density, ρ, of the specimen is required to estimate values for K and G respectively. Here the bulk density is multiplied by the square of the wave velocity, which highlights the importance of determining V_p and V_s as accurately as possible. Note V_p can sometimes be used as an indicator of specimen saturation, given the value of V_p should approach 1450 m/s (the approximate speed of a P-wave in water) as full saturation is reached.

Figure 6 displays the components of the GDS Bender Element System (BES), including the master control box used to generate and record the propagated body waves. Note an additional slave box can be added if more than one element pair is used within a triaxial system (e.g. when using both vertical and horizontal elements).

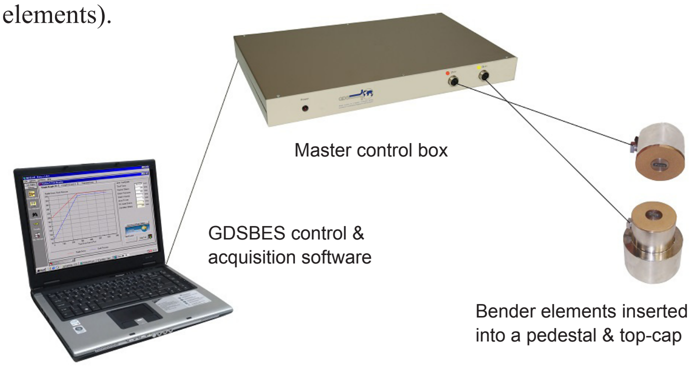

Figure 6 – GDS Bender Element System (BES) components.

UNSATURATED SOIL TESTING

The traditional triaxial test and its various advancements discussed so far in this series have required the test specimen to be fully saturated. This requirement represents field conditions in which the soil is located below the water table, as illustrated in Figure 7, however in reality many geotechnical investigations are concerned with soil response above the water table. This fact is highlighted by the estimate where 60 % of the world's population is thought to live in arid regions, in which the water table is located at significant depth, constituting zones where unsaturated soil response is the primary consideration for geotechnical projects.

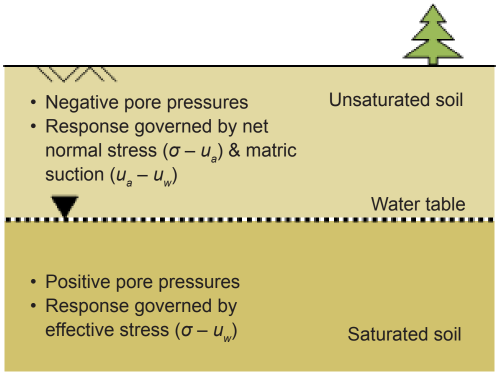

Figure 7 – Simplified illustration of saturated and unsaturated soil mechanics.

When assessing unsaturated soils, it has been suggested by Fredlund and Rahardjo (1993) that the response is not governed only by the in-situ effective stress (i.e. $\sigma - u_w$), but instead by two stress variables: the net normal stress ($\sigma - u_a$) and matric suction ($u_a - u_w$). Note σ corresponds to the total normal stress, u_w to the pore water pressure, and u_a to the pore air pressure, with $u_a > u_w$. This addition of pore air pressure, u_a, leads to additional hardware requirements when testing unsaturated soils, and results in more complex methods for measuring the specimen volume change being needed.

Application of Pore Air Pressure

Pore air pressure is typically applied to an unsaturated triaxial specimen using one of two methods: regulation of a compressed air supply, or through use of an enclosed pore air pressure/volume controller. In general, use of regulated compressed air will allow the pore air pressure to be applied more rapidly than a pressure/volume controller (this is due to the high compressibility of air), however the volume of pore air being forced into a test specimen cannot be recorded with a regulated compressed air supply.

As shown in Figure 8, the pore air pressure is conventionally applied to the specimen via the top-cap, while the back pressure (or pore water pressure) is applied through the base pedestal. This configuration is used as the base pedestal is most suited to housing a high air entry porous disc, or HAEPD. The HAEPD is required to separate the pore air and pore water, allowing matric suction (i.e. a pressure differential equal to $u_a - u_w$) to be maintained within the test specimen. This is achieved due to the nature of

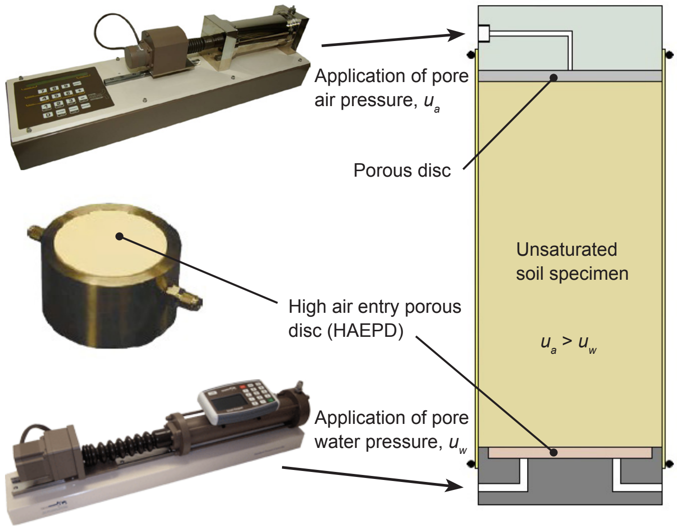

Figure 8 – Typical unsaturated soil specimen set-up.

the HAEPD ceramic material, which when fully saturated can maintain a pore air pressure on its top that is greater than the pore water pressure applied to its base. The material also prevents air passing out of the specimen, up to a pressure differential equal to a specified air-entry value. Note air-entry values for HAEPDs typically range between 300 and 1500 kPa.

Measurement of Specimen Volume Change

When conducting a triaxial test on unsaturated soil, the specimen is often initially fully saturated, then de-saturated by increasing the matric suction (information obtained when producing a soil-water characteristic curve can usually relate the degree of saturation to the value of matric suction). Shifting the soil into the unsaturated state does however complicate the measurement of specimen volume change, as the change in back volume can no longer alone be used. This is again due to the high compressibility of the pore air within the specimen, and therefore requires other methods to be implemented to measure the specimen volume change. Four hardware additions available for making this measurement are listed in the following:

1. Use of a pore air pressure/volume controller.
2. Use of an inner cell and low-range differential pressure transducer.
3. Use of a double-walled triaxial cell.
4. Use of local axial and radial strain transducers.

Each of these options uses varying techniques to measure the specimen volume change, and as such have their own advantages and limitations. However, to briefly summarise each method:

- Option One combines pore air volume and back volume measurements from two pressure/volume controllers to calculate specimen volume change.

- Option Two and Option Three measure change in the inner cell fluid head or volume respectively, as caused by contraction or dilation of the test specimen.

- Option Four takes direct measurements of the axial and radial specimen deformations via local strain transducers to estimate the volume change.

To determine which option may best suit an existing triaxial system, each measurement method should be assessed in detail, while also considering the nature of the tests to be performed.

ADVANCED SOFTWARE CONTROL

Modern PCs allow triaxial systems to automate more complicated test procedures than previously possible, reducing the time required for users to spend at the apparatus itself. This is achieved through advanced software control of the system hardware, which, via open or closed control loops, enables digital pressure/volume controller positions and load frame velocities to be regularly adjusted based on feedback from the system transducers. Examples of advanced test procedures run using specifically-coded GDS software modules are listed in the following:

- Automatic saturation - cell and back pressures are increased by regular increments, with a B-check performed between each increment. The software determines saturation is complete when a user-specified B-value is reached, based on feedback from the pore pressure transducer.

- K_0 consolidation - cell pressure is increased at a specified rate, while the frame velocity is adjusted based on feedback from a local radial strain transducer. The software targets zero change in the radial strain (i.e. one-dimensional consolidation), maintaining 'at rest' specimen stress conditions.

- Stress path control - cell pressure and frame velocity are adjusted such that a user-specified linear stress path, of which one possible option is shown in Figure 9, is applied to the specimen. Here the software must re-calculate the deviator stress, q, and mean effective stress, p', as loading progresses, which are both dependent on the internal load cell, axial displacement, and back volume readings (these are used to assess the current axial force and specimen area).

- Stress-controlled cyclic loading - frame velocity is constantly adjusted to apply a cyclic (e.g. sinusoidal) loading of deviator stress to the test specimen. Note loading frequencies of 0.015 Hz or less are typically obtainable without use of a specialised dynamic load frame.

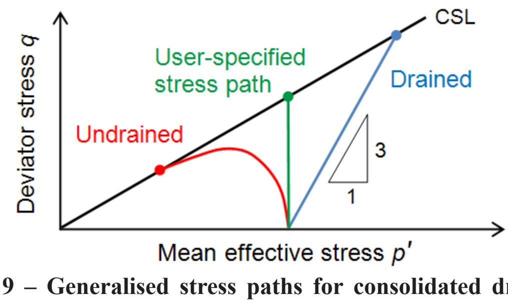

Figure 9 – Generalised stress paths for consolidated drained and undrained shearing, and a user-specified stress path in which the mean effective stress is held constant. Note all specimens are sheared to critical state, as defined by the critical state line, CSL.

REFERENCES & FURTHER READING

Clayton, C. R. I. & Khatrush, S. A. 1986. *A new device for measuring local axial strains on triaxial specimens*. Géotechnique, Vol. 36, No. 4, p 593-597.

Fredlund, D. G. & Rahardjo, H. 1993. Soil Mechanics for Unsaturated Soils, New York, John Wiley.

Jardine, R. J., Symes, M. J. & Burland, J. B. 1984. *The measurement of soil stiffness in the triaxial apparatus*. Géotechnique, Vol. 34, No. 3, p 323-340.

Meilani, I., Rahardjo, H., Leong, E-C. & Fredlund, D. G. 2002. *Mini suction probe for matric suction measurements*. Canadian Geotechnical Journal, Vol. 39, p 1427-1432.

Menzies, B. K. & Matthews, M. C. 1996. The Continuous Surface-Wave System: A modern technique for site investigation. Special Lecture: Indian Geotechnical Conference Madras, Dec 11-14.

Ng, C. W. W. & Menzies, B. 2007. Advanced Unsaturated Soil Mechanics and Engineering, Oxon, Taylor & Francis.

Yamashita, S., Kawaguchi, T., Nakata, Y., Mikami, T., Fujiwara, T. & Shibuya, S. 2009. *Interpretation of international parallel test on the measurement of G_{max} using bender elements*. Soils and Foundations, Vol. 49, No. 4, p 631-650.