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Advances in triaxial testing

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Triaxial testing techniques have advanced significantly over the last two decades. Improvements have been made both with regard to measurement instrumentation and to measurement techniques. These improvements have led to a better conceptual understanding of soil behaviour. This paper reviews the advances in measurement instrumentation and measurement techniques and illustrates the impact of these developments on geotechnical practice.

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INTRODUCTION

The process of laboratory testing can be divided into a number of hierarchical levels. At the highest level of this hierarchy is a conceptual model of soil behaviour. Such a model may range from a very simple strength or stiffness model to a complex constitutive model that relates the shear and volumetric stresses to the shear and volumetric strains of the soil and may even include time effects. At the second level of the testing hierarchy is the testing technique, which addresses the stress and strain conditions imposed on the soil specimen. The testing technique should be designed in view of the parameters required to quantify the conceptual model. At the lowest level of the hierarchy is the measurement instrumentation that detects the response of the soil under investigation. Each of the levels that form part of the testing hierarchy introduces certain limitations to the process and it is therefore important that the practitioner has a thorough understanding of soil behaviour, the measurement techniques as well as the instrumentation. Equipped with this knowledge the practitioner can develop a testing programme that is suited to the design requirements.

The triaxial test is widely used as a tool to investigate soil behaviour. It was initially developed to measure soil strength and therefore only relatively simple testing techniques such as drained and undrained loading were required (Bishop & Henkel 1962). More complex loading paths became possible with the development of the stress path cell (Bishop & Wesley 1975). Also once the effects of loading rate were fully appreciated, rapid development occurred in cyclic and dynamic testing techniques. In recent years the focus in the development of triaxial testing has been on improvements of the instrumentation used to measure soil response during testing. These improvements have led to a number of new measurement techniques, most notable of which has been the accurate measurement of soil stiffness. In addition the testing of unsaturated soil has received considerable attention.

This paper focuses on the triaxial test and first examines the recent advances made in triaxial instrumentation. This is followed by a discussion on how these advances resulted in new testing techniques and finally the practical advantages of these new testing techniques are illustrated.

ADVANCES IN MEASUREMENT INSTRUMENTATION

In theory the triaxial test is a relatively simple test. Under idealised conditions it may be considered to be a single element test where uniform stresses and strains occur throughout the specimen. In the most basic tests the experimentalist needs to have control over the drainage condition and to be able to measure the cell pressure and the axial load applied to the specimen. More sophisticated tests require the measurement of pore fluid pressure, axial strain, radial strain, volume change and body wave velocities. The following sections describe the difficulties in measuring these quantities and the recent improvements made to the instrumentation used to measure these quantities.

Fluid pressure measurement

Fluid pressure measurement forms an integral part of triaxial testing. In particular accurate measurement of the cell fluid pressure and pore fluid pressures is essential. The pressurised cell fluid imposes an isotropic total stress on the specimen. A mechanical or electronic pressure transducer, connected to the cell fluid via the cell port, conducts measurement of cell fluid pressure. When conducting tests on saturated soils de-aired water should be used in the cell chamber. This stems from the fact that latex membranes, commonly used to protect the specimen, are permeable to air (Bishop & Henkel 1962). Consequently a good de-airing system is essential and the appropriate measures are required to ensure that no air enters the system during testing. In particular, air-water interfaces impermeable to air are necessary if compressed air is used to supply the cell and back pressures. Menzies and Sutton (1980) developed a self-contained water pressure source based on a screw pump mechanism whereby pressure is applied directly to the water by a motorised piston in a cylinder and the pressure is controlled by a micro-processor based feedback system. This system allows the application of relatively high pressure (up to 5 000 kPa) and avoids problems associated with air entering the system.

Measurement of the specimen pore fluid pressure is required for effective stress testing and a number of factors need to be addressed when measuring pore fluid pressure. These include pressure gradients in the specimen, the fact that the pore fluid pressure may be either positive or negative, and that the pore spaces may be either fully or partially saturated.

When a specimen is partially saturated, knowledge of total stress (σ), the pore water pressure (u_w), the pore air pressure (u_a) and the fraction of the cross sectional area that is occupied by water (χ) are required to determine the effective stress (σ'):

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \qquad (1)$$

The term ($u_a - u_w$) is known as the matric suction and is a function of the water surface tension and the radius of curvature of the meniscus. For a fully saturated specimen ($\chi = 1$) and only knowledge of the total stress (σ) and the pore water pressure (uw) is necessary to determine the effective stress:

$$\sigma' = \sigma - u \qquad (2)$$

For saturated triaxial testing it is essential to ensure that the specimen and backpressure system is fully saturated. If not, the measured pore pressures will be in error and the true effective stress in the specimen will be higher than those calculated from the measured values. This will lead to erroneously high strength and stiffness measurements and produce design parameters in error on the unsafe side.

Traditionally under saturated conditions the pore fluid pressure has been measured at the base pedestal. However, non-uniform pore pressures are likely to occur during undrained triaxial tests as a result of end constraints (Bishop *et al* 1960). This generates pressure gradients in the specimen that require time to reach equilibrium and subsequently the test has to be conducted at a sufficiently slow rate in order that the pore pressures measured at the specimen end are representative of the pore pressure at the failure surface. This problem may be overcome by measuring the pore fluid pressure close to the centre of the specimen by means of a pore pressure probe (also termed mid-plane probe).

Pore pressure probes

Pore pressure probes measure the pore fluid pressure 'locally' close to the failure plane and therefore the rate of testing may be increased, as pore pressure equalisation is no longer a requirement. Two types of pore pressure probes have found favour amongst practitioners. These are the flushable push in probe (Sodha 1974) and the surface probe introduced by Hight (1982). The push in probe consists of a cylindrical high air entry ceramic fitted into a stainless steel casing (see figure 1). The probe is inserted in a hole drilled into the side of the specimen. O-rings in conjunction with a rubber grommet are used to seal the specimen from the cell water. Two small bore stainless steel tubes are braised to the back of the probe casing and guided from the cell through a plug in the cell base. Two tubes are required in order to flush the probe at any time during the test. This is often necessary if desaturation occurs at installation of the probe when high pore fluid suctions are present in the specimen. Flushing ensures a stiff measurement system with fast response to changes in pore fluid pressure.

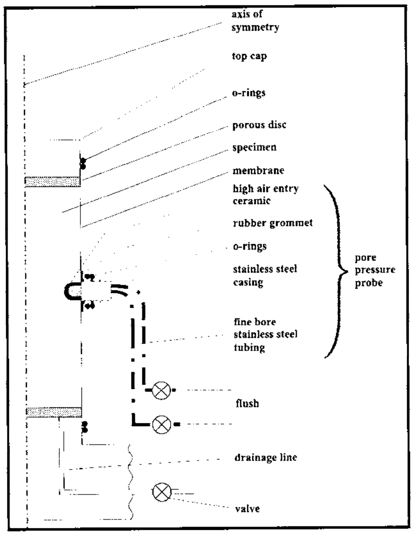

Figure 1 Push-in pore pressure probe

Hight (1982) described a pore pressure probe based on a miniature silicon diaphragm pressure transducer mounted with its porous ceramic face flush with the cylindrical sample. The advantage of this probe is that it does not penetrate the sample, making it particularly useful for small-diameter specimens. Hight noted two operational difficulties with the probe. First, as the probe cannot be flushed, care is required to ensure that it stays saturated. This may prove impossible when installing it against a sample with high suction because cavitation of the water between the porous ceramic and the silicon diaphragm may occur. Second, as a consequence of the small gap between the porous ceramic and the diaphragm (50 µm), these two components could come into contact at high effective stresses, impeding the correct operation of the sensor.

Pore pressure probes are of considerable practical benefits, since more accurate effective stress measurements as well as significant time and cost savings are achieved. Bishop and Henkel (1962) pointed out that serious errors will be introduced if base measurements are used in undrained tests conducted at a rate which does not allow sufficient equalisation of pore pressures throughout the specimen. When the failure envelope is calculated using pore pressure measurements taken at the specimen base for a specimen sheared too fast, an erroneously high cohesion intercept will be calculated. This may lead to an unsafe design.

Many commercial laboratories aim at completing an undrained shear test within one working day. Results presented by Bishop and Henkel (1962) showed that under one-dimensional flow conditions this is not possible for most clays without introducing significant errors. The difficulty may be addressed to some extent by using side drains. However, such side drains will result in non-uniform stresses, strengths and water contents inside the specimen (Atkinson *et al* 1985), therefore the soil near the periphery of the specimen will undergo primarily volumetric strains, whilst the soil near the centre will undergo primarily shear strains. In essence such a test can therefore no longer be considered a single element test. In contrast a mid-plane probe will not introduce such problems whilst significantly reducing the testing time. Hight (1982) showed that the time to failure during undrained shear of a till (cv = 1 to 2 m^2/year) could be reduced from 23 hours to 0,5 hours and retain consistency of the results over the entire stress path.

Suction probes

Pore water pressures in triaxial samples are often found to be negative. This is true for both saturated and unsaturated samples and may be as a result of total stress relief or because the material was unsaturated in situ. Conventional pore pressure instruments can theoretically measure negative water pressures down to –1 atm before breakdown occurs on account of cavitation. However, in practice breakdown will occur significantly before –1 atm. If the soil is saturated, the pore water pressure can be made positive by increasing the total stress on the sample whilst preventing drainage. This will induce positive pore water pressures without changing the effective stress. If the soil is unsaturated, the pore water pressure can be made positive by applying a sufficiently high air pressure, again without changing the effective stress. These methods are known as axis translation.

Ridley and Burland (1993) described a pore pressure probe capable of directly measuring negative pore water suctions without axis translation. The probe consists of a pressure transducer fitted into a metal casing and a high air entry ceramic allowing hydraulic contact between the fluid pressurising the transducer (cavity water) and the pore water. The key factor to the successful operation of the probe is de-airing the ceramic and the cavity water. This is done by pre-pressuring. This principle was illustrated by Richards and Trevena (1976). They were able to apply a tensile stress of 3 500 kPa to water without cavitation after de-airing the water using pre-pressurising. Another important characteristic of the probe is the dimension of the cavity between the transducer and the ceramic which has to be kept as small as possible to minimise the water that may potentially cavitate. Ridley and Burland used a ceramic with an air entry value of 1 500 kPa and showed suction measurements down to –1 200 kPa.

A number of further advantages of pore pressure probes are listed in table 2 on page 28.

Force measurement

Measurement of the axial force applied to the specimen is required to determine the total vertical stress. Traditionally the axial force has been measured external to the cell by means of a proving ring (Bishop & Henkel 1962). Ram friction causes inaccuracies in external axial force measurement. Bishop and Henkel showed that errors due to ram friction are increased when a lateral load is applied to the ram. This often occurs at large strains when the specimen deforms non-uniformly. They reported errors of up to 5% of the applied load. In addition, o-rings are commonly used to seal the ram at the cell top. The magnitude of the inaccuracy from the o-ring friction depends on various factors, such as the number of rings, cell pressure and the precision of ram fit. Friction always acts in the direction opposing movement and the problem of ram friction is therefore exacerbated during cyclic loading and stress path testing.

External force measurements suffer from a further complication. The tendency of the cell pressure to expel the load ram makes the externally measured force sensitive to changes in cell pressure. This leads to practical difficulties during stress path testing where the cell pressure may change continuously.

A significant advance was made with the introduction of internal load measurement instrumentation. Internal load cells directly measure the load applied to the specimen and therefore eliminate load ram friction from the load measurement. In addition, well designed internal load cells are insensitive to changes in cell pressure. Bishop *et al* (1975) developed an electronic load cell that can be submersed in the cell fluid. The load cell was based on a design that transformed axial load into bending of a strain gauged plate. The oil-filled load cell was not significantly affected by cell pressure and only marginally affected by lateral and eccentric loads. However, it has a number of disadvantages including high compliance (because of the bending plate), a discontinuous load-compliance response when changing from compressive to tensile loads (Jardine *et al* 1985), as well as hysteresis on account of friction between the bending plate and load cell body.

A shear web type load cell was developed by Maywood Instruments Ltd in the early 1990s. The sensing element of the cell consists of a circular disc of 75 mm diameter that transforms axial load into shear of four web elements. Shear strain gauges are bonded to these elements and the sensitivity of the load cell can be modified at the design stage by specifying the appropriate shear web thickness. Eight gauges are arranged in a full Wheatstone bridge configuration so as to minimise the effect of eccentric loading. This design has all the advantages of the bending plate load cell, but in addition it ensures high transducer stiffness and low hysteresis. The low hysteresis is of particular importance during cyclic tests. Typical full-scale ranges of the shear web type load cell are between 1 kN and 25 kN.

The performance of the two types of internal load cells is compared in figure 2. The 5 kN shear web load cell was calibrated in both compression and tension, whilst the 4,5 kN bending plate load cell was calibrated only in compression. Figure 2 shows the smooth transition between tensile and compressive loads exhibited by the shear web load cell. This is to be expected given the load cell design. Both load cells display some non-linearity and hysteresis, but as shown in figure 2 on both accounts the performance of the shear web load cell is superior to that of the bending plate load cell.

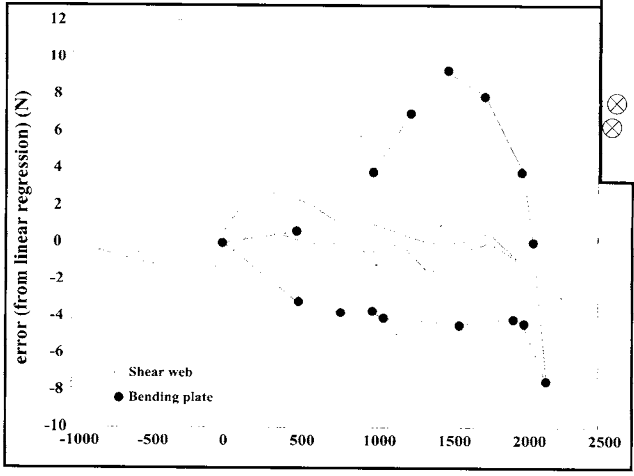

Figure 2 Comparison of shear web load cell with bending plate load cell (bending plate load cell data from Matthews 1997, shear web load cell data from Heymann 1998).

It is clear that internal load cells produce more accurate load measurements than external transducers. In addition, for cyclic and stress path testing internal load cells have further advantages because knowledge of the direction of the ram movement is not required and no correction for cell pressure is necessary.

Axial strain measurement

In early versions of the triaxial test apparatus external deformation measurements were made by measuring the relative movement between the loading ram and a remote position such as the top of the triaxial cell. This introduces a number of errors in the strain measurements (Jardine *et al* 1984, Baldi *et al* 1988 and Goto *et al* 1991). These errors are shown schematically in figure 3 and include

- seating errors due to gaps at the interface between the apparatus components (loading ram, internal load cell, top cap, porous stones and pedestal)
- bedding errors as a result of surface irregularities at the interface between the specimen and porous stone or lubricated membranes
- errors from the compliance of the apparatus components such as the loading ram, load cell, top cap, pedestal, porous stones and cell tie bars
- non-uniform sample strains as a result of end restraints

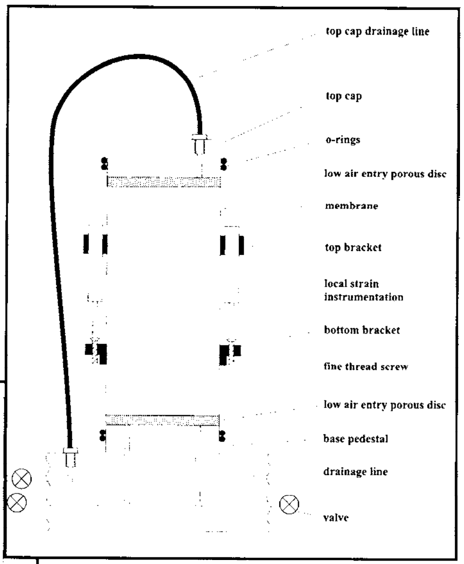

Figure 3 Sources of error for external measurement of axial deformation

The errors noted above illustrate the difficulty in accurately measuring axial deformations of triaxial specimens using external measurement techniques. The problem may be overcome by measuring strains directly on the specimen and remote from the sample ends. This type of strain measurement is termed local strain measurement.

Local strain instrumentation

In recent years experimentalists have used a wide variety of displacement transducers for local measurement of axial deformation of triaxial soil samples. Figure 4 shows a typical layout of a triaxial specimen fitted with local strain instrumentation. Some of the instruments used to measure local strains are purpose-built instruments specifically designed to address the particular problems of displacement measurement in the triaxial test. These include electrolytic levels (Burland & Symes 1982), Hall effect transducers (Clayton & Khatrush 1986) and linear displacement transducers (Tatsuoka 1988). General instruments that are widely used in industry to measure linear displacement have also been used. Examples are LVDTs (Brown & Snaith 1974 and Cuccuvillo & Coop 1997) and proximity transducers (Hird & Yung 1989). Typical measurement characteristics of local displacement instruments as reported in the literature are shown in table 1.

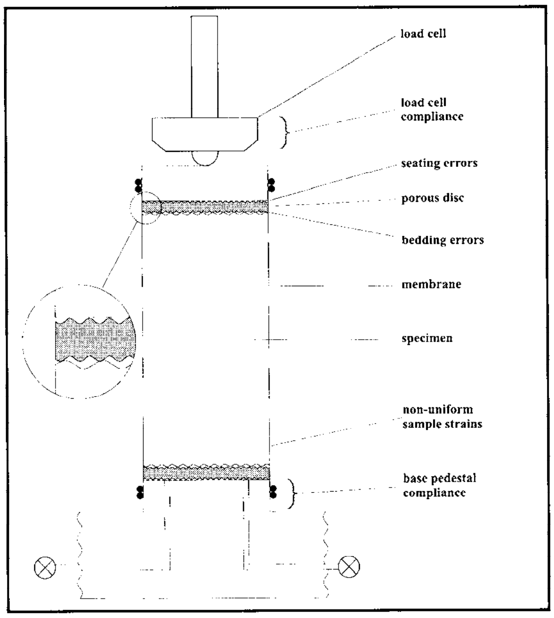

Figure 4 Typical layout of a triaxial specimen fitted with local strain instrumentation

Table 1 Characteristics of local displacement instrumentation

Instrument	Range (mm)	Accuracy (μm)	Resolution (μm)	Ref
LVDT	10 0,1	±16 ±0,13	2,7 0,012	5
Proximity transducer	5	±2	1	6
Electro level gauge	15	±2	< 1	1, 7
Hall effect gauge	2,5 7	±6 ±30	< 1 –	2, 3
Linear displacement transducer (LDT)	0,2	0,09*	0,12	4

* Calibrated against a proximity transducer with 0,1 μm resolution (see Goto *et al* 1991).

1 Burland and Symes (1982)
2 Clayton and Khatrush (1986)
3 Clayton *et al* (1989)
4 Goto *et al* (1991)
5 Heymann *et al* (1997)
6 Hird and Yung (1989)
7 Jardine *et al* (1984)

The ideal local strain instrument should be relatively compact and lightweight and able to withstand large strains without being damaged. In addition the instrumentation should be accurate and suitable for operation submerged in cell fluid under pressure. The above instruments all adhere to these requirements to a greater or lesser extent and in many cases a compromise is required to find the most suitable instrument.

Volumetric strain measurement

Volume change measurements are required during consolidation as well as for drained triaxial tests in order to fully describe the state of the soil during the test. Volume change of a specimen may be determined by measuring the volume of water that flows into or out of the specimen. For this technique it is essential that the specimen be fully saturated and it is therefore not suitable for tests on partially saturated soils. In addition, this technique suffers from the effect of membrane penetration as the pressure difference inside and outside the specimen tends to force the membrane into the recesses created by particles on the specimen surface. The magnitude of the errors is dependent on the size of the soil particles and the characteristics of the membrane. Numerous methods have been proposed to compensate for this effect (Ali *et al* 1995).

Recent advances in volume strain measurements have been twofold. First, a number of electronic volume change gauges have been developed to allow automated logging of volume changes. For a discussion on these developments, see Araruna et al (1995). However, regardless of the accuracy of the specific measurement device, all these techniques suffer from membrane penetration. The second development has been to measure volume changes locally. This is done by measuring radial strains at mid height on the specimen in conjunction with local axial strain measurement. Radial strains are typically measured either by a radial calliper (eg Bishop & Henkel 1962) or by two diametrically opposed proximity transducers each sensing a target placed against the specimen (eg Hird & Yung 1989).

The choice of local or external volume change measurements has to be balanced between the required measurement accuracy and the cost of equipment and labour. For routine drained triaxial testing external measured volume changes are often sufficient. But in specialised testing where high accuracy is required or where zero lateral strain (K_0) stress paths have to be followed, local measurement of volume changes may be essential.

ADVANCES IN MEASUREMENT TECHNIQUES

The advances in triaxial instrumentation discussed above have allowed the development of a number of new triaxial measurement techniques. These include new methods of measuring soil stiffness, collapse potential and shear wave velocity.

Soil stiffness measurement

The development of internal load cells and local strain instrumentation has significantly improved the accuracy with which soil stiffness may be measured. This is particularly true at small strain levels. An example is shown in figure 5. Clayton and Khatrush (1986) compared the stiffness of a fine sand during drained shear using external strain measurements with the stiffness from locally measured strains of the same sample. It may be seen that at small strains the stiffness determined from the local strain measurements is almost four times greater than the stiffness measured by conventional external strain measurements. This illustrates that the difference is sufficient to have a significant impact on geotechnical design for this material. The same effect has been observed for a wide variety of materials including stiff clays (Jardine *et al* 1984), weak rocks (Tatsuoka *et al* 1993) and gravels (Tatsuoka *et al* 1990).

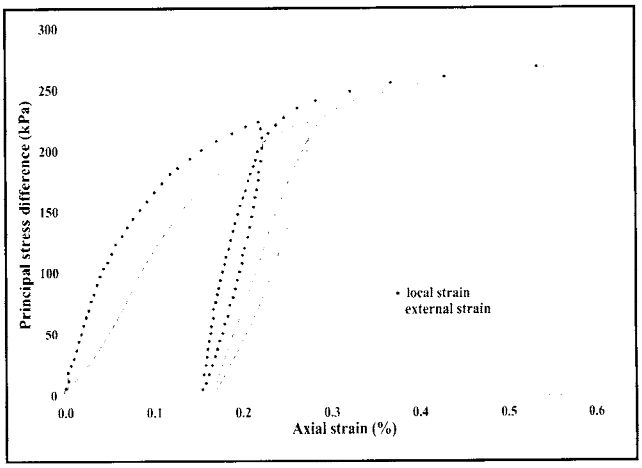

Figure 5 Comparison of local and external strain measurement for a fine sand during drained shear (from Clayton & Khatrush 1986)

Indeed, the development of highly accurate local strain instrumentation calibrated against an interferometer (Heymann 1998) has proven the long-held hypothesis that soils exhibit linear stress-strain response at very small strains (Clayton & Heymann 2000). It was shown that geomaterials with widely differing stiffnesses ranging from a soft clay to a weak rock all have a linear stress-strain response up to a strain level of approximately 0,002%. This finding opens up the prospect of correlating triaxial and field geophysical stiffnesses directly. The field stiffness may therefore be used as a benchmark against which the laboratory stiffness (at very small strains) may be compared. A good correlation will provide significant confidence in the resulting stiffness. In addition this technique may be used to investigate factors such as sampling disturbance.

The triaxial collapse potential test

A test developed as a result of the recent advances in triaxial instrumentation is the triaxial collapse potential test (Heymann & Rust 2000). Collapsible geomaterials exhibit an open fabric in a metastable state. The particles are often held in this open fabric state by weak bonding or suction pressures at inter-particle contacts. A triggering mechanism may cause the material to collapse inducing large volumetric strains with the particles rearranging into a denser state. This collapse phenomenon has been observed for a large number of geomaterials, but in southern Africa collapse is most often associated with partially saturated transported or residual soils (Knight 1961 and Schwartz 1985).

Traditionally the collapse behaviour of unsaturated soils has been assessed by conducting tests in the oedometer. Two tests have become popular. The first is the double oedometer where compression tests are conducted on two identical specimens, one at natural moisture content and the other under saturated conditions (Jennings & Knight 1956 and 1957). Comparing the difference in behaviour the collapse may be quantified. The second test is an index test known as the collapse potential test (Jennings & Knight 1975). A single specimen is placed in the oedometer, loaded to a total vertical stress of 200 kPa before inundation with water. The vertical strain on inundation is defined as the collapse potential and typically varies from less than 1% at low collapse potential to more than 10% at high collapse potential (Jennings & Knight 1975).

The triaxial collapse potential test is conducted in the triaxial apparatus using local strain instrumentation on a specimen initially at natural moisture content. The required cell pressure is applied before flushing the specimen with deaired water and observing the collapse which is defined as the measured vertical strain. Compared with the oedometer test, this new test has the advantage that bedding and seating errors are avoided, producing a significantly more repeatable determination of the collapse potential.

Figure 6 shows a typical result of a collapse test conducted in the triaxial apparatus on partially saturated fine residual sand. It is clear from the figure that the introduction of water to the soil at 200 kPa cell pressure had a dramatic effect on its behaviour inducing an axial strain of 2,6%. The result also indicates the difference in volumetric stiffness of the material before and after inundation with a higher stiffness at natural moisture content. This may be the consequence of the reduced pore water suctions and possible destructuring of the bonding during inundation.

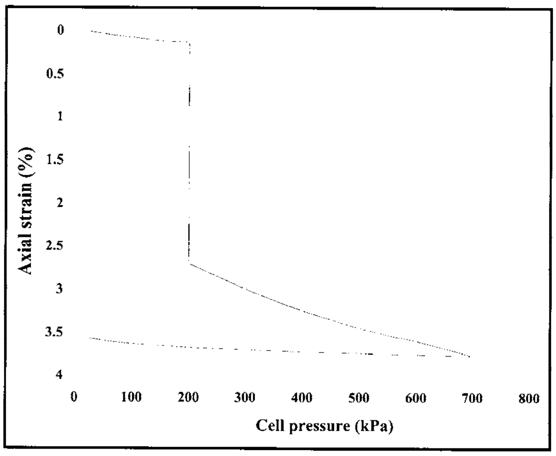

Figure 6 Typical triaxial collapse potential test result (from Heymann & Rust 2000)

Heymann and Rust pointed out that the triaxial collapse potential test has some shortcomings relating to the stress condition applied and the strains measured. In general the stresses exerted by a foundation consist of a combination of isotropic and octahedral stresses. The test imposes only isotropic stresses on the specimen and measures the axial strains locally. This does not allow a comparison of stress and strain increments on the bases of established constitutive relationships unless isotropy of strains is assumed. However the authors argue that the improved precision from the local instrumentation outweighs this limitation and it was suggested that the new test would be useful to quantify the collapse potential of partially saturated geomaterials.

Triaxial shear wave velocity

A recent trend in geotechnical measurements has been the use of surface and body waves to measure the stiffness of soil. It may be shown from elasticity theory that the shear stiffness (G_{max}) of a continuum may be described in terms of its mass density (ρ) and the velocity with which shear waves are propagated through the medium (V_s):

$$G_{max} = \rho V_s^2 \qquad (3)$$

Shear wave velocity has been used to measure the stiffness of soil both in the field and in the laboratory. In particular, the shear wave velocity in a triaxial specimen may be measured by means of bender elements (Shirley & Hampton 1977, Viggiani & Atkinson 1995, and Jovicic & Coop 1997). Bender elements are made from piezo electric ceramics that contract or elongate when subjected to a potential difference. When two flat ceramics are fixed together and one is made to contract and the other to elongate, the combined plate will bend. Bender elements may be fitted to the top cap and base pedestal in a triaxial apparatus or diametrically opposed into the sides of the specimen. One bender element is used as the sender, which generates shear waves in the soil by oscillating from side to side. The other bender element acts as the receiver, as any shear waves that arrive at the ceramic will bend the ceramic and produce an output signal. The wave travel time and distance between bender elements are used to determine the shear wave velocity from which the very small strain stiffness of the soil is determined.

In addition to stiffness measurements, bender elements make another valuable contribution to triaxial testing as they allow the level of sampling disturbance to be evaluated. The shear wave velocity of soil measured in situ may be compared directly to the shear wave velocity measured in the triaxial apparatus using bender elements (Pennington *et al* 1997). Once effects such as stress condition, anisotropy and wave propagation direction are accounted for, the shear wave velocities from the two techniques should be the same, and any difference will indicate sampling disturbance.

Summary of advantages of recent improvements in triaxial instrumentation

The previous sections described a number of recent developments with regards to triaxial measurement instrumentation and illustrated how these new instruments have lead to new testing techniques. Table 2 summarises the uses and advantages gained by this improved triaxial instrumentation.

Table 2 Advantages of recent improvements in triaxial instrumentation

Pore pressure probe	• Substantial time savings can be made when using a pore pressure probe during drained and undrained shear test on low permeability soil. • The full stress path of clays can be determined during conventional quick undrained triaxial test as the requirement for pore pressure equalisation can be lifted. • Significant improvement in the accuracy with which the initial mean effective stress can be measured. • Soil permeability may be meas ured in the triaxial apparatus by controlling the flow rate and measuring the hydraulic gradient between two points on the specimen using pore pressure probes. • Allows double check on pore pressure measurement (check for saturation levels and leaks).
Suction probe	• Allows routine effective stress testing to be conducted on unsaturated soil.

Internal load cell	• Improvement in load measurement accuracy during monotonic tests. Improved accuracy may only be moderate for stiff soil, but could be substantial for soft clay. • Essential for cyclic or dynamic testing as it eliminates the effect of hysteresis caused by friction between the loading ram and o-ring seals. • Simplifies stress path testing as the force measured by an internal load cell is largely independent of changes in cell pressure.
Local strain instruments	• Allow accurate stiffness measurement over a large strain range. • Produce precise measurements of collapse potensial • Essential to obtain stiffness parameters for numerical modelling. • Local strain instrumentation of the highest accuracy can measure small strain stiffness which can be compared with in situ or laboratory measured geophysically determined stiffness.
Bender elements	• Measure shear wave velocity from which the very small strain stiffness may be determined. • Allow the evaluation of sampling disturbance by directly comparing field and laboratory shear wave velocities.

The new triaxial testing techniques described above give numerous options to the design engineer when specifying triaxial testing as part of the design process. However, the additional cost of the equipment and time required to set up and monitor the equipment requires a balance to be found between the complexity and cost of the test and the impact that these parameters will have on the design.

IMPACT OF ADVANCES IN TRIAXIAL TESTING ON GEOTECHNICAL PRACTICE

Recent advances in triaxial testing have had a significant impact on geotechnical practice. Particular fields in which such impact has been made include soil structure interaction analysis, collapse potential measurements and quantifying sampling disturbance. In addition the recent developments of the suction probe have created the potential to conduct effective stress tests on unsaturated soils thereby improving our understanding of the mechanics of these soils.

Soil-structure interaction

Until recently the accurate prediction of movements close to geotechnical structures by means of analytical methods was virtually impossible (Simpson *et al* 1979). However, more accurate stiffness measurements of geomaterials when using local strain measurements in conjunction with sophisticated numerical models have led to improved prediction of soil-structure interaction behaviour. Jardine *et al* (1991) compared the movements predicted by numerical analysis to the observed movements for a range of geotechnical soil-structure interaction cases. These included a deep basement excavation, a cut and cover tunnel, a bored tunnel, a pipe-jacked tunnel, a gravity oil boring platform, and a tension pile structure. In all these cases the input parameters for the numerical analysis were obtained from triaxial tests using local strain instrumentation. Figure 7 shows that remarkably good agreement was found between the predicted and measured movements. Such accurate analytical prediction were impossible before the advent of stiffness measurement in the triaxial apparatus using internal load cells and local strain instrumentation and clearly demonstrates the practical advantages of these developments.

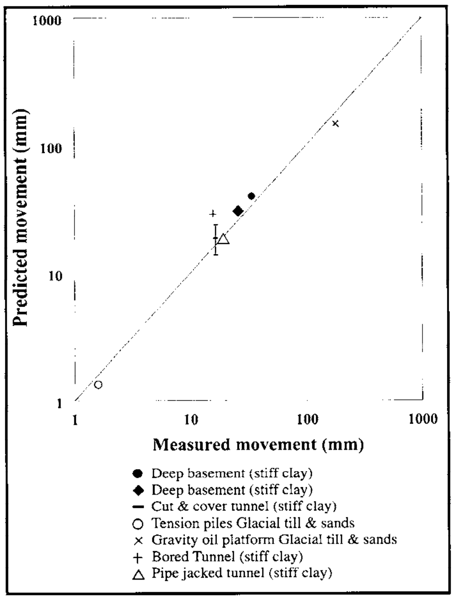

***Figure 7** Comparison between predicted and observed measurements for a number of geotechnical structures (from Jardine et al 1991)*

Collapse potential

Figure 6 shows a result from the recently developed triaxial collapse potential test using local strain instrumentation to measure the axial strain during soil collapse. In 'The triaxial collapse potential test' on page 28 it was argued that because local strain instrumentation does not suffer from bedding and seating errors, the collapse potential will be determined more precisely by this test compared with the more conventional oedometer collapse potential test. Such a comparison was made for sand of predominantly fine particle size (D_{50} = 0,2 mm). The material was aeolian dune sand that was reworked during a marine transgression and deposited offshore to form tubular fine sandstone. Subsequent exposure and weathering resulted in a 15 to 20 m thick residual soil profile (McKnight 1999). The dry density (1 690 kg/m^3) and void ratio (0,55) were fairly uniform with depth with 5% average moisture content of the in situ soil (McKnight 1999).

Figure 8 compares the results of collapse potential tests conducted on the residual soil in an oedometer (McKnight 1999) with those from triaxial collapse potential tests (Heymann & Rust 2000). All specimens were prepared from block samples. The oedometer specimens were subjected to a one-dimensional vertical load at natural moisture content and inundated at a total vertical stress of 1 000 kPa. Large scatter of the data points was evident, as shown in figure 8, and a clear pattern of the variation of collapse potential with depth was not obvious. The collapse potential as measured in the triaxial apparatus was taken as the vertical strain measured by the local gauges upon wetting at a cell pressure of 400 kPa. The scatter in the triaxial collapse potential observed at a depth of 7 m was less that 1% for each of the two sampling positions and less than 2% between sampling positions. This is significantly better than the 12% scatter observed for the oedometer collapse potential tests conducted on samples from the same depth. The data clearly indicate that the repeatability of the triaxial collapse potential tests was significantly better compared with those conducted using the oedometer.

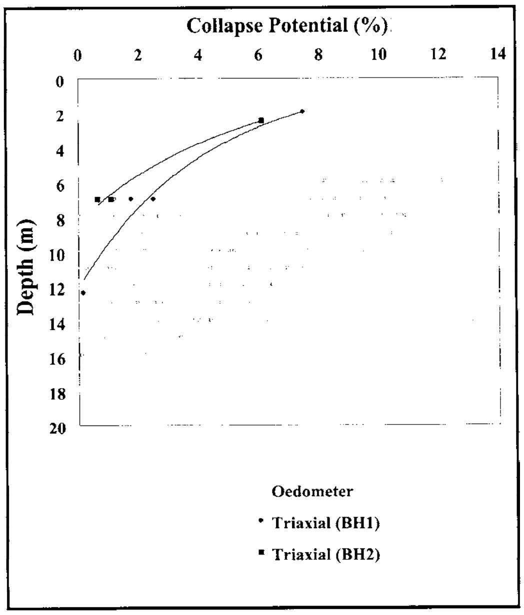

***Figure 8** Comparison between oedometer and triaxial collapse potential test results (oedometer data from McKnight 1999, triaxial data from Heymann & Rust 2000)*

Two further conclusions may be drawn from the result shown in figure 8. First, from the geological setting it is to be expected that the collapse potential will decrease with depth as the level of weathering decreases. The triaxial collapse potential results confirm this trend. Second, figure 8 suggests that sampling disturbance cannot account for the large scatter in the oedometer data, as the material for both types of test was prepared from block samples.

Sampling disturbance

Recent developments that allow the measurement of shear wave velocity in the triaxial apparatus by means of bender elements have provided a much better understanding of the disturbance that occurs during sampling of soils. Sampling disturbance may be evaluated by comparing the triaxial shear wave velocity directly with the shear wave velocity measured in situ. Alternatively, if sufficiently accurate local strain instrumentation is available, the small strain stiffness from triaxial shear tests may be compared with the field geophysical stiffness. Shibuya *et al* (1996) compared laboratory stiffness with stiffness based on in-situ shear wave velocity propagation for a wide range of geomaterials including soft clay, stiff clay, sands, gravels and soft rocks. The results are shown in figure 9. Good agreement was found for the materials that were less susceptible to sampling disturbance or where good sampling techniques were used. Such cases were the clays using thin wall sampling as well as the sands and gravels using in-situ freezing and soft rock using block sampling. In contrast, relatively poor agreement was found for sands sampled by thin-walled and triple tube sampler. The author concluded that the lack of agreement for these sands was indicative of the disturbance that occurred during sampling of the material.

Unsaturated soils

To date, the operation of the suction probe to measure negative pore fluid pressures during shear of clays in the triaxial apparatus has only been demonstrated under fully saturated conditions. Nevertheless, this development holds significant potential for unsaturated soil design. In theory the suction probe will allow the shear characteristics of soils to be investigated in terms of effective stresses under unsaturated conditions. It follows that design parameters of such soils will be quantified using effective stress parameters, thereby allowing design of geotechnical structures in unsaturated soils in terms of effective stress theory. This will have a significant impact on geotechnical design of man-made structures constructed from unsaturated soils such as earth dams and embankments, as well as for geotechnical engineering in arid regions where soils are often permanently in an unsaturated state.

CONCLUSIONS

Significant advances have been made in triaxial testing techniques in recent years. This paper focused on the developments of triaxial instrumentation and measurement techniques and demonstrated the impact thereof on geotechnical practice. From the discussion a number of conclusions may be drawn.

The advances in measurement instrumentation and measurement techniques have significantly improved the accuracy with which soil stiffness can be measured. This has made analysis possible which closely simulates the behaviour of complex geotechnical structures. Such accurate analysis was impossible prior to the development of local strain instrumentation.

The recently developed triaxial collapse potential test gives rise to a substantial improvement in the precision with which the collapse potential can be measured compared with the conventional oedometer test. This enables the design engineer to assess the impact of collapse on geotechnical structures with much greater confidence.

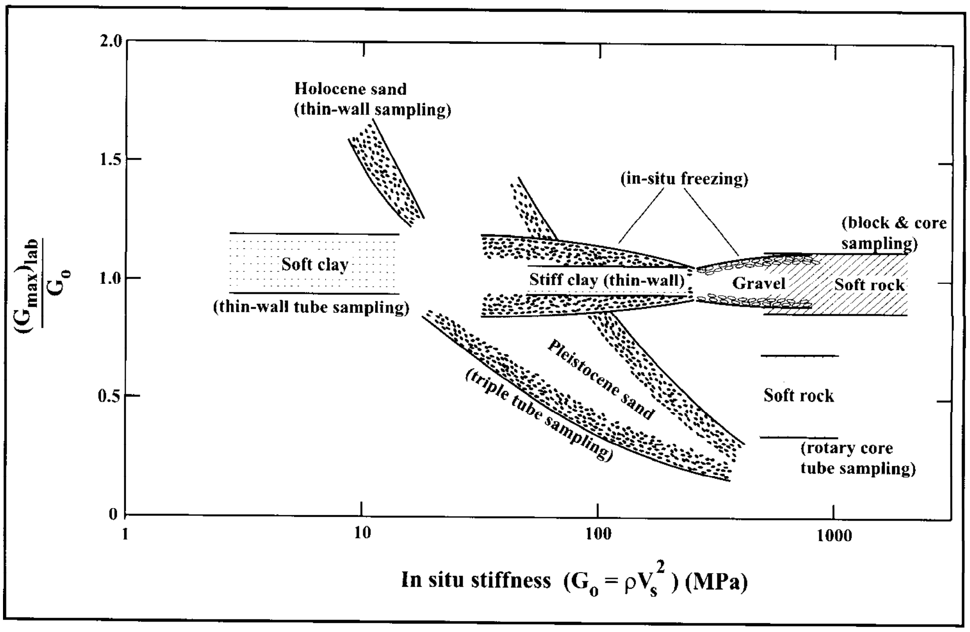

Figure 9 Comparison of laboratory and geophysical stiffness (from Shibuya et al 1996)

Shear wave velocity measurement in the triaxial apparatus opens some exciting possibilities in geotechnical engineering. Firstly it may be used to determine the soil stiffness at very small strain levels that may be used as the basis to predict the stiffness of soils for design purposes. In addition, it allows the effect of sampling disturbance to be quantified when comparing results with in situ measured shear wave velocities.

The development of measurement techniques to directly measure soil suctions is particularly promising for regions where unsaturated soils are common. These developments can potentially allow the routine measurement of unsaturated soil behaviour and design of geotechnical structures in terms of effective stress principles.

It is clear from the above than recent advances in triaxial testing have numerous important practical implications. It is therefore essential that practitioners should be aware of these developments in order to develop laboratory testing programmes that add value to the design process.

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