A Rock Test Cell with True Triaxial Capability

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Abstract

Conventional so-called triaxial test cells apply the axial stress to a cylindrical sample using steel platens, while the radial confining stress is developed by pressurising a continuous annulus around the sample. Since this annulus is continuous, it is not possible to generate a differential stress radially, seriously restricting the ability to test rock in an anisotropic, or truly triaxial stress state with major, intermediate and minor principal stresses. This inhibits the realism with which rocks can be tested - for example, what is the effect of the intermediate principal stress on the strength of the rock?

This paper describes the development and application of a new test cell - believed to be the first in the world - which does enable truly triaxial stresses to be applied to cylindrical core samples, opening up the possibility to test rocks routinely in a more realistic manner. An array of 24 trapped tubes replace the single annulus which usually generates the uniform radial stress. Selective pressurisation of the tubes enables differential radial stresses to be generated, while axial stresses are applied as before through steel platens.

Key words: true triaxial test cell, anisotropic stresses, failure criterion

Introduction

The in situ stress field is usually defined by specifying the magnitudes and directions of the three principal stresses, \(\sigma_1 > \sigma_2 > \sigma_3\). For essentially flat-lying sediments with the earth’s surface acting as a free-boundary, one principal stress will be derived from the weight of the overburden, \(\sigma_3\). The other two principal stresses must then be horizontal. Depending on the geological processes which have influenced the region, e.g. tectonic activity or uplift, significant differences can be induced between the three principal stresses, i.e. the stress state can be strongly anisotropic. Such stress anisotropy has a direct influence on the orientations of both natural and production induced fractures, and failure zones created around mine excavations. Laboratory measurements on recovered rock specimens must therefore seek to reproduce the in situ environment as closely as possible, to allow confident scaling of rock properties to the field. A new “true-triaxial cell” (Smart cell) has been designed which is capable of testing cylindrical samples taken from reservoir whole core, eliminating the need to cut rock cubes as required previously.

Previous Test Cells

Triaxial Testing of Cylindrical Specimens

Non-hydrostatic stress states are routinely imposed on core plugs during rock mechanical laboratory testing. In such conventional “triaxial” tests, a uniform radial stress is applied by fluid pressure to the curved surface of a rock cylinder, whilst simultaneously the prepared flat and parallel specimen ends are loaded axially through spherical seats and platens. The radial pressure or confinement is usually achieved using a “Hoek-Franklin-type cell”\(^1,2\) in which hydraulic fluid at pressure \(p\), acts on a synthetic rubber membrane sheathing the sample. Ideally, the axial load is applied parallel to the cylindrical specimen long axis via a stiff, servo-hydraulic controlled
compression rig. Axial loading over the specimen cross-sectional area in this manner results in an axial stress $\sigma_a$, independent of $p$.

Independent control of only $\sigma_a$ and $p$, combined with the geometrical constraints inherent in the above system, results in two admissible stress field conditions which are within the limitations of conventional "triaxial" testing capabilities. In the "triaxial" compression test the specimen is subjected to an axial stress equal to the maximum principal stress, $\sigma_a=\sigma_1$, whilst the uniform-radial confinement is set lower giving $p=\sigma_2=\sigma_3$ ($\sigma_2$ and $\sigma_3$ being the intermediate and minimum principal stresses respectively). Hydraulic cell pressure $p$ is usually held constant whilst the axial stress $\sigma_1$ is increased until the specimen ruptures. In the alternative and less common "triaxial" extension test, rupture is achieved by increasing $p$ or decreasing $\sigma_a$, in both cases the hydraulic cell pressure being higher than the axial stress in the specimen. This gives rise to the stress state $\sigma_1=\sigma_2=p>\sigma_3$ where $\sigma_3$ is the axial stress. Although $\sigma_3$ is compressive, in this case the axial strain is tensile for small $\sigma_3$, causing an increase in specimen length.$^3$

For both the "triaxial" compression and extension tests described above, it is evident that two of the three principal stresses are equal at any one time, and that for tests utilising a uniform-radial hydraulic pressure cell, the applied stress fields represent special cases of a general three dimensional or true triaxial stress state in which all three principal stresses are unequal and independent, $\sigma_1 \neq \sigma_2 \neq \sigma_3$. In the preceding discussion, triaxial is quoted in inverted commas in order to impress that either $\sigma_2=\sigma_3$ (compression) or $\sigma_1=\sigma_2$ (extension) test configurations are specified. Henceforth such stress distributions will be referred to as "axisymmetric triaxial" to avoid confusion with the general case. Thus the two conditions admissible under axisymmetric triaxial testing are $\sigma_1>\sigma_2=\sigma_3$ and $\sigma_1=\sigma_2>\sigma_3$. The importance of these two variations of the axisymmetric triaxial test is that they represent the lower and upper bounds respectively of the intermediate principal stress, and as such can be used to investigate its influence in particular upon rock failure.

Brace$^4$ performed axisymmetric triaxial compression and extension tests to failure on dolerite, dolomite, granite and quartzite specimens, which showed no significant variation between the results obtained when $\sigma_2=\sigma_3$ and when $\sigma_2=\sigma_1$. Whilst these tests included the maximum possible variation of $\sigma_2$ between $\sigma_3$ and $\sigma_1$, from which the obvious conclusion was that its magnitude had a negligible influence on rupture strength, the axisymmetric configuration precluded any extrapolation to the effects of a general triaxial stress field on the failure strength of these lithologies.

Testing of Cubic Specimens

In order to experimentally assess the effects of a truly general triaxial stress field on rock strength, some workers in this field have adopted the experimental setup whereby three independently variable principal stresses are applied to opposing faces of cubic rock specimens. This configuration is the only one capable of maintaining a uniform and homogenous stress state in the specimen, over all combinations of principal stresses sufficient to cause rupture. The polycrystal (synonymous with multiaxial or true triaxial) test as it is known, has been applied almost exclusively to study the effect of $\sigma_2$ on rock strength, to map out failure surfaces in three dimensional stress space and to formulate generalised constitutive laws for various geomaterials.
Hojem and Cook\textsuperscript{5} carried out tests using a polyaxial cell in which small flat jacks were used to subject rock cubes to a true triaxial stress state, and formulated an effective shear strain energy failure criterion\textsuperscript{6} based on the resultant data, which showed that $\sigma_2$ had a first order effect on rock strength. Mogi\textsuperscript{7}, 8, 9 tested cubic samples from a variety of lithologies and found more significant strength differences than had been reported by Brace or by Hojem and Cook. The impact of his results are summarised by Scholz\textsuperscript{10}. Mogi showed that under true triaxial stress, as $\sigma_2$ was increased above $\sigma_3$ to $\sigma_1$, microstructural deformation was such that: dilatancy occurred by the opening of microcracks in the $\sigma_3$ direction; cracking formed preferentially in the $\sigma_1$, $\sigma_2$ plane; the degree of induced anisotropy was controlled by the principal stress ratios. With regard to macroscopic strength he showed that: the increase in strength as $\sigma_2$ was increased from $\sigma_3$ to $\sigma_1$ was less than if $\sigma_2$ and $\sigma_3$ were increased in step; the macroscopic fracture formed at an acute angle to $\sigma_1$ and parallel to $\sigma_2$ in accordance with the Coulomb criterion; the minimum lateral dilatancy direction was parallel to the strike of the fracture plane. Thus the polyaxial testing conducted by Mogi showed macroscopic shear failure to be markedly dependent on both the magnitude and orientation of $\sigma_2$. Increasing $\sigma_2$ was observed to suppress dilatancy causing the rupture strength to increase. Fracture orientation was observed to be controlled by the dominant orientation of induced microcracks, which is in turn was largely controlled by the applied stress ellipsoid. However, Hoek and Brown pointed out that Mogi’s data suggested that many of his tests involved brittle/ductile transitions, which would have a resultant effect on any interpretation.

More recent polyaxial test data from cubic specimens includes that of Gau \textit{et al}\textsuperscript{11}, who tested 10-cm red sandstone cubes loaded by both rigid and flexible platens, Amadei and Robinson\textsuperscript{12}, who tested limestone under conditions of combined compression and tension with flexible fluid-filled and brush platens respectively, and Esaki and Kimura\textsuperscript{13}, who used a high pressure true triaxial box with rigid platens to apply stresses into the Gigapascal range whilst monitoring acoustic emissions. All the above demonstrated that the magnitude of $\sigma_2$ has an important effect on rock strength.

Sture and Desai\textsuperscript{14} pointed out that whether the forces are applied to the specimen through flexible membranes or via rigid platens has a great effect on the distribution of stresses and strains within the rock cube. Whilst flexible membranes ensure uniform loading distributions normal to the loading faces, and rigid platens ensure accurate measurement of strains and the application of higher stress fields, the uniformity of stresses induced by the latter system is doubtful.

Jaeger and Cook\textsuperscript{15}, list various references on the testing of ceramic materials which can be obtained in the form of thin-walled cylinders, the geometry of which ensures that the various criteria for failure can be studied under a wide range of (approximately) homogeneous stresses. Handin \textit{et al}\textsuperscript{16} utilised the method for rock testing, applying torsion to hollow cylindrical specimens of limestone, dolomite and glass under $\sigma_3$ and $p$ to obtain true triaxial stress states.

Considering that \textit{in situ} stress distributions are inherently three dimensional, the need for generalised triaxial testing to develop numerical methods and constitutive laws has never been greater. However, the polyaxial testing methods detailed above are far removed from being ideal as routine experimental procedures for providing reliable data. With particular regard to petroleum-related rock mechanical requirements, existing methods of polyaxial rock testing are especially extraneous due to:
(i) the relatively large size of specimens required from “valuable” whole core, as such sampling would be in direct competition with plugging for petrophysical evaluation. Also, the complex geometry of specimens (cubes and thin-walled cylinders) poses problems with respect to weak reservoir sandstones and shales.

(ii) Difficulties involved with the testing methods, such as “platen interference” on specimen deformation, and problems in maintaining uniformity of applied stresses across the faces of a cubic sample, which would prohibit such tests from becoming routine.

(iii) The relatively complex nature of the experimental equipment which would prove difficult to adapt to permeability measurement.

Ideally, what is required for realistic strength, deformation and fluid flow measurements under realistic three dimensional reservoir stresses, is the ability to subject small-diameter cylindrical core plugs to true triaxial stress fields, but by means of a simple experimental facility as relatively straightforward to operate as that used in axisymmetric triaxial testing. To this end, the following true triaxial cell has been designed, fabricated, proved and patented by the Rock Mechanics Group within the Department of Petroleum Engineering, Heriot-Watt University, with the specific intent of offering a new experimental facility to industry.

The New True Triaxial Cell

True Triaxial Cell Design
The true triaxial cell is as illustrated in Figure 1. Axial specimen loading is achieved through high strength 316-stainless steel platens, in an equivalent manner to the axisymmetric test, utilising a conventional stiff, servo-hydraulic compression machine. The cell is composed of aluminium with the application of radial pressure to the curved surface of a right circular cylindrical specimen 30mm in diameter developed in a stepwise manner around the core via trapped tubes. This enables an approximately elliptical radial stress distribution to be produced in the rock. The core is enveloped in a 3.5mm-thick nitrile rubber liner; the trapped tubes are arranged around the outside of the nitrile liner. Each tube is held within a recess milled into the body of the cell such that only one side of each tube is exposed to the nitrile liner. The tubes are PVC with initially circular cross-section and are heated in a mould to form a flat face (which butts onto the nitrile liner) which is permanently set into the plastic by cooling the tubes. Thus the trapped tubes develop the radial stresses on the rock core. Under pressure they expand, operating well above their rated unconfined burst capacity, while still being strong enough to withstand differences of up to 1000psi (6.9MPa) between adjacent tubes. The current design of cell utilises an array of 24 trapped tubes enabling pressures of up to 8000psi (55.2MPa) to be developed before bursting, the ultimate aim being the development of radial stresses up to 10000psi (68.9MPa) in the specimen. A finite element comparative study of the stresses developed in the major principal plane of a conventional cubic specimen loaded under $\sigma_2>\sigma_3$, and an equivalent loading generated by the true triaxial cell on a cylindrical specimen, showed that the nitrile rubber liner in the latter produced an even distribution of the radial stresses. For permeability measurements on cores, the nitrile liner also ensures a seal along the outside of the core.

Multiple Servo-Control System
A method of producing multiple servo-controlled hydraulic pressures for the array of trapped tubes has been devised with rapid response computer control and data logging. Servo-control is required on the tube pressures as volumetric strain in the rock core under testing can cause up to 30% deviation in the tube pressure when that pressure is applied with a hand pump. This is due to the high hydraulic stiffness of the trapped
tube system. The method utilises servo-control valves which operate on air or nitrogen at 0-1MPa, driving a gas:oil 100:1 intensifier.

Operation of the true triaxial cell utilises three independent servo-controlled hydraulic circuits, as shown in Figure 2, (although cells have been developed for 4 and 6 independent hydraulic circuits). Increasing the number of hydraulic circuits enables the applied radial pressure to approximate more closely to a truly elliptical stress distribution. The total of 24 trapped tubes are divided into three banks of opposing 2 against 2, 4 against 4, and 6 against 6 tubes. The configuration illustrated shows hydraulic circuit No.1 applying \( \sigma_2 \) confining pressure to a total of 4 tubes, and circuit No.3 applying \( \sigma_3 \) confining pressure to a total of 12 tubes. Hydraulic circuit No.2 is shown applying a confining pressure intermediate between \( \sigma_2 \) and \( \sigma_3 \), to a total of 8 tubes. This enables the differential pressure between hydraulic circuits No.1 and No.3 to be effectively doubled to around 2000psi (13.8MPa), without the risk of tubes bursting. The whole pneumatic-hydraulic servo-control system for the true triaxial cell is trolley-based for manoeuvrability. Stainless steel 1/8"-diameter tubing with Swagelock fittings connects the cell hydraulic circuits to their independent servo-systems. A schematic of the servo-support for a single hydraulic circuit in the true triaxial cell is shown in Figure 3. Currently, three such systems are employed for overall control of the triaxial cell circuits. The electronic control-unit presents LCD values for tube pressure, tube volume and pneumatic pressure, and enables specific individual pressures for all three circuits to be "dialled-in". The hydraulic system is charged to a certain pressure using a hand pump. Individual shut-off valves allow each circuit to be set at a different pressure. Bleed taps for the three circuits allow the oil pressure to be fine-tuned. A nitrogen communal gas receiver acts as a reservoir for the pneumatic pressure system. Electronic control enables a voltage proportional to the pneumatic pressure to be dialled up, which backs off each pneumatic-hydraulic piston to a specified pressure. The servo-unit controls this pressure. Specimen dilatancy or contractancy causes an inverse volume change in the bounding trapped tub assembly. The servo-valve can be controlled either manually, or remotely via rapid response computer control to correct for any such deviations from the initial set pressures. On specimen dilatancy and corresponding tube contraction, an additional pneumatic back-pressure system comprising a servo-valve and solenoid, provides a kick to assist in overcoming frictional forces on the piston seals, aiding it in advancing to compensate for hydraulic pressure increase. Transducers monitor piston displacements which can be converted to hydraulic volume changes knowing the piston cross-sectional area. Additional feedback is provided from a pressure transducer on the high pressure fluid side of the system. Piston displacements and hydraulic pressures are monitored on the computer, as well as axial load and displacement outputs from the compression rig.

**True-Triaxial Tests**

**Introduction**

The objective of this testing programme was to perform a series of true triaxial tests on selected samples from a UK mine. Three 30mm diameter test samples were produced from three 45mm core samples from the floor of the seam. They were medium-coarse grained siltstone, slightly sandy in places. The samples were cored using a diamond tipped, thin-walled core barrel using water flush then trimmed, using a diamond tipped saw with air flush, to produce right cylinders of a length:diameter ratio of 2:1. The ends were then dressed by a lathe to ensure the samples were of the tolerances recommended by the ISRM. Axial stresses were considered to be the maximum principal stress, the radial stresses were the intermediate and minimum principal stresses.
Test Equipment and Programme

The test equipment comprised the following:

- 100t servo-controlled stiff testing machine generating $\sigma_1$
- 30mm true triaxial cell controlled by computer linked servo valves, generating $\sigma_2$ and $\sigma_3$
- data logging equipment with XY chart recorder.

The test programme was designed to perform a series of true triaxial tests by varying the intermediate stress, $\sigma_2$ while keeping the minimum stress, $\sigma_3$ constant. Three minimum stresses were chosen: 9MPa, representative of the minimum horizontal stress found at the mine, 11MPa and 13MPa to examine the effect of increasing confinement.

The specimens were driven toward failure by increasing the axial stress $\sigma_1$. Multi-failure state tests were performed in which the minimum principal stress was kept constant (at the specified value for each particular sample throughout its test) and the intermediate principal stress was increased. The axial load and axial compression were logged and displayed on the XY recorder, the display being used to drive the tests. At the first intermediate stress, $\sigma_2$ the axial load was increased (i.e. increasing $\sigma_1$) until sample failure was imminent. Then the intermediate stress, $\sigma_2$ was increased to the next stress level. This procedure was repeated to the penultimate stress level. At the ultimate stress level, the intermediate stress, $\sigma_2$ was kept constant and the sample allowed to fail by increasing $\sigma_1$.

Before the samples from the mine were tested, three samples of Clashach sandstone were tested to prove the technique with the equipment.

Results

The results show the axial stress, $\sigma_1$ variation with the variation in intermediate stress, $\sigma_2$ and are shown in Figure 4. The three samples were tested at 9, 11 and 13MPa minimum principal stresses. As can be seen from Figure 4 the failure stress increases with increasing minimum stress, $\sigma_3$. At any particular value of minimum principal stress, the increase in intermediate principal stress produces an increase in the failure stress. Comparison of the failure stress with minimum principal stress shows as much as 10MPa increase in failure stress for an increase of 4MPa in minimum principal stress.

Conclusions

A true triaxial cell has been developed to apply independent principal stresses to a cylindrical core. The cell has been shown to work up to 55MPa.

A system has been devised to control the application of the radial stresses and to measure the radial strain developed by the cores. This dispenses with the need for strain gauges.

Testing has shown the cell capable of providing multi-failure state results. Control of the radial stress requires constant monitoring and a more effective servo-controlled system has been developed.
The effect of increasing, unequal radial stresses increases the axial stress at failure and also orientates the failure surface relative to the plane of the maximum-minimum principal stress at failure. The failure surface opens against the minimum principal stress.

References
Figure 1 True triaxial cell

Figure 2 Application of radial stresses to a core

Figure 3 Servo-control system for true triaxial cell
Figure 4 Siltstone True Triaxial Tests

Key Words: point load strength test, strength, anisotropic rocks, stress analysis, displacement functions

Introduction

Point Load Strength Test (PLST) is a convenient and inexpensive method for rock classification and rock strength estimation (e.g., Broch and Franklin, 1974; Quade et al., 1973; Biswaswari, 1974). This point load strength test can be applied equally to cylindrical or spherical, and to irregular boulders, but our main focus here is on the test for irregular boulders (see Fig. 1). Although the test is well received in engineering practice, and it has been standardized (ISRM, 1981), the theoretical basis of it has not been fully examined. The only analytic studies for PLST include the analysis of isotropic spheres subjected to a pair of diametrical point loads by Hirashima and Oka (1956), finite cylinders subjected to point loads by Wijf (1976) and Chea and Wong (1986), and finite cylinders subjected to diametrical point loads by Wijf (1981) and Chea (1997a).

All of these analytic studies are restricted to isotropic solids, there is no analytic solution for the PLST of anisotropic solids. But, in reality most of rocks are, to certain extent, anisotropic in nature. Recently, Chea and Wei (1997) derived the first analytic solution for the PLST of anisotropic solids. This presentation will summarize our main findings briefly. More specifically, Chea and Wei (1997) considered a spherically isotropic elastic sphere subjected to the point load strength test. Their solution is an extension of the classical solution for isotropic spheres obtained by Hirashima and Oka (1956) to anisotropic spheres. Five independent material constants are involved in a spherically isotropic material, which was introduced by La Verant in 1865 (see the historical account by Lavo 1844) and is the simplest type of