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The detailed study on the Development of the Triaxial Equipment in the soil mechanics: A Review

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Abstract
Triaxial shear testing is conceived as one of the most significant investigations in geotechnical laboratories. It is recommended in geotechnical engineering for designing specific projects and for studying and understanding soil behavior. Since Casagrande designed this modern shear apparatus at Harvard University, it has been developed to obtain an accurate characterization of shear strength behavior. This research paper aims to provide a brief description of the development of triaxial equipment. This is a part of the selection of the triaxial apparatus that is easy to set up, prepare for testing, and operate reliably simple and inexpensive laboratory testing. The main objective of this study is to contribute to the accurate determination of suitable techniques and devices that respond to specific testing objectives. The theoretical background of the triaxial apparatus along with the direct shear box is reviewed. The basic working principles of different volume change measurement techniques using the triaxial device are illustrated. Different operational principles that have been used in designing volume change devices for soil testing are presented. The paper identifies that some of these devices require quite complex operational techniques and equipment that are difficult to perform on a repetitive testing basis. Hence, the desirable requirements for a volume change device should be sturdiness and ease of operation in soil mechanics testing.

Keywords: Triaxial equipment, direct shear box, shears testing, soil mechanics, volume change measurement

1. Introduction

The laboratory investigation is a key feature of almost all geotechnical projects [1]. In Soil mechanics, triaxial equipment is a requirement for studying and understanding soil behavior [2]. Recent stability and deformation analysis methods require a range of test data that can be obtained appropriately only with the triaxial apparatus [3]. An apparent consensus dates the soil testing back to the early theoretical work of Coulomb. However, controversy about its practical implementation still persists. In fact, the direct shear test (DST) seems to be as old as soil mechanics history. A review of the literature reveals a considerable agreement that DST is the earliest soil testing method. However, it considerably indicates less agreement about when exactly the shear box was introduced. In Szabó [4] words, “It is not known exactly when the direct shear box was introduced, and whether Coulomb did apply at all?”. Despite such doubt, an apparent consensus credits Coulomb with the provision of the theoretical framework of the shear test. Holtz, Kovacs [5] argues that Coulomb was the first to use a type of shear box test more than 200 years ago. TW and Whitman [6] also advocate that Coulomb used a conceptually simple shear test for soil testing as early as 1776. A major factor in the late development of Soil Mechanics as a systematic branch of Civil Engineering is the failure to appreciate the significance of excess pore pressure in strength measurement. The use of the direct shear test is considered a major cause of such lag. Terzaghi is credited as the first to appreciate the significance in the engineering practice of pore pressure in fine-grain soils. Using the Casagrande apparatus, Terzaghi originated the application of the triaxial test under controlled conditions of drainage [3]. Thus, the triaxial apparatus was developed in the early 1930s by Casagrande at Harvard. It appeared to overcome some of the serious shortcomings of the direct shear box [7]. These limitations entail uncontrolled rotation of principal planes and stresses; the failure plane is forced to be horizontal and uncontrolled drainage [8]. In this regard, providing a brief historical account of the development of the triaxial shear apparatus plays a significant role in studying the mechanical behaviour of soil. Further, it contributes to the accurate determination to suitable techniques and devices that respond to specific testing objectives. Literature on the development of techniques of triaxial testing are scarce. But some researchers have worked on the developments of triaxial equipment and triaxial testing procedures such as [3, 2].

The study begins with a short Theoretical background in which the genesis of the triaxial apparatus design is underlined. Then a general description of the triaxial apparatus, structure, and function is presented. Advances are covering triaxial specimen setup, triaxial cell, confining pressure supply. The research emphasizes the development of the volume change measurement for its unique relation to soil behavior.

2. Theoretical background

2.1 Direct shear box

According to Skempton [9], the development of a direct shear apparatus is credited to the French engineer Alexandre Collin in 1846. Collin used a split box, 350 mm long, in which a sample of clay 40 x 40 mm section was subjected to double shear under a load applied by hanging weights [10]. Later in 1915, the British engineer Bell made the earliest measurements that constructed a device that was to be the prototype for subsequent developments of the shear box. Bell was the pioneer to perform and publish result practical shear tests on various types of soil [9].

Despite controversy about the origins of the direct shear box, it is highly agreed that Arthur Casagrande designed the modern direct shear apparatus at Harvard University in 1932 [9, 11]. Subsequently in 1934, a simple shear box with a single plane of shear using the 'stress control' principle where the load was applied in increments by progressively adding weights to a pan was designed [12]. However, it had some shortcomings as it required considerable care and judgment on the part of the operator in order to ascertain the load at which failure.

In 1946, a constant rate of displacement machine was developed by Gilboy at MIT [8]. The machine applies the 'strain control' principle using a fixed-speed motor [13]. Bishop then presented the improvements of design using this principle in detail. Another shear box apparatus that can perform both the drained and undrained test was developed by Vickers in 1984 (Fig.1) [8]. Today, the displacement control principle is still the basis for most commercial shear box machines. Since its founding, the conventional direct shear apparatus has been modified, and now it can control the pore air pressure U_a and pore water pressure U_w.

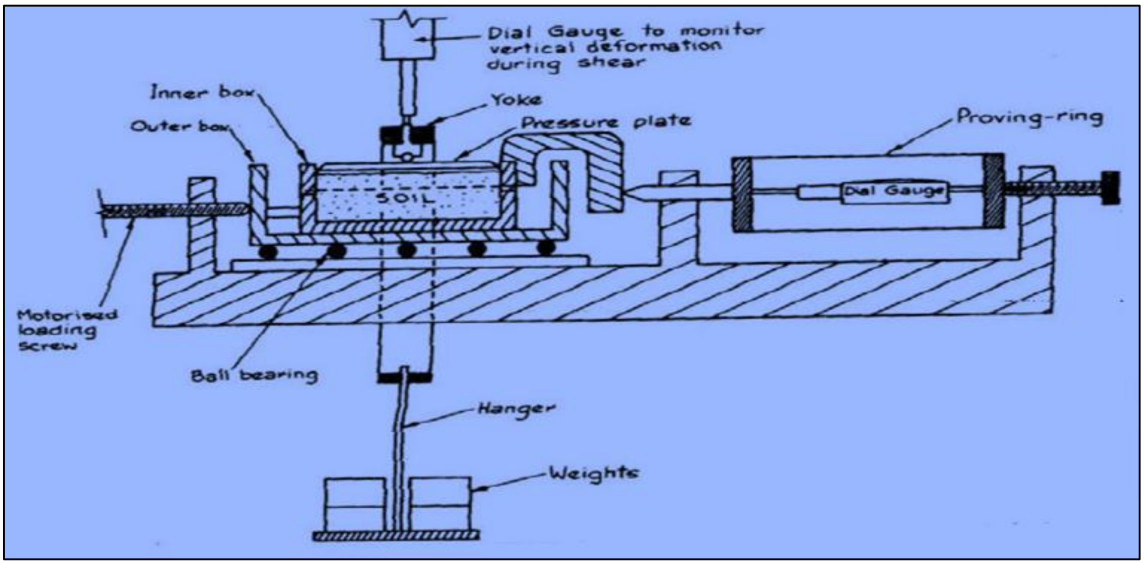

Fig 1: Shear box apparatus Vickers (1984) [8].

2.2 Triaxial apparatus Casagrande Design:

The design of the triaxial apparatus has been long but no mean story. It dates back to 1910, 1911 as Lade [2] noted, when Von Karman designed the first triaxial compression test device for rock testing (Figure 2). The scale may be deduced from the fact that the specimen is 4 cm in diameter [14]. However, Karman attempt was overshadowed by Casagrande design. It is worth noting that other early devices with many of the characteristics of conventional triaxial were originated by Buismen in 1924 and Hveem1934 [15].

By 1930, Casagrande famous letter to Terzaghi at the Technical University in Vienna carried the idea of the apparatus. Casagrande was impressed with his visit to the hydraulics laboratory in Berlin. There he noticed an apparatus for measuring the permeability of the soil. He thought that applying a vertical (axial) loading on the cylindrical specimen in this device could indicate its strength. Hence, he suggested building a prototype and Terzaghi proposed to build the same [2].

Casagrande design was immediately utilised by Rendulic [16] for tests with and without membranes (Figure 3). The results obtained by Terzaghi and Rendulic were revolutionary in soil testing at a time when the effective stress principle was still being questioned. Their testing facilitated the understanding of the effective stress principle as well as the role of pore water pressure and consolidation on shear strength [17, 18].

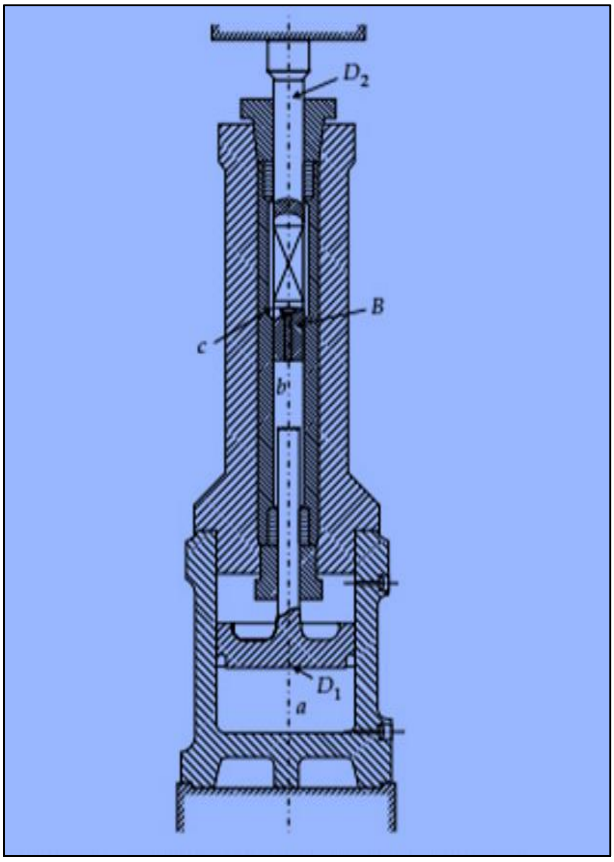

Fig 2: Triaxial apparatus designed and constructed for testing of rock cores by von karaman (1910, 1911) by [2].

Fig 3: Historical devices in the laboratory founded by Karl v. Terzaghi at Vienna University of Technology in 1929: Worldwide, the first triaxial apparatus for pore water pressure measurement. Pictures taken at the Institute for Geotechnics and published with permission of Em. O. Univ.-Prof. Dipl.-Ing. Dr. techn. Dr. h.c. mult. Heinz Brandl, TU Vienna, Austria [19].

3. Triaxial Apparatus Development:

The triaxial equipment developments are arranged according to the area of modification.

3.1 Typical Triaxial Cell

A typical triaxial cell comprises the general setup of the triaxial specimen. The dimensions of the cell have changed over time. The samples which are most commonly used today normally range from 38 mm to 100 mm, although samples considerably larger can be tested with the correct equipment. According to Al-Hussaini [20], The 1.5 in diameter specimen was the generally accepted standard in Great Britain for testing soil force from stones. For compacted samples, the cell for 4 in diameter was also developed to test the soil with maximum grain size.

Owing to the variability of parameters such as unit weights, modulus values, shear strength parameters, and permeabilities most often the triaxial specimen has a cylindrical shape with diameters varying from 35 mm ‘1.4 in’ to 150 mm ‘6.0 in’[2].

3.2 Cell Pressure Controlling.

Early methods used for controlling pressure include the use of an air reservoir, the use of a reducing valve as the pressure control, and the loaded ram. Bishop and Henkel had experimented with several of such principal methods and none of them had proved to be satisfactory for accurate work [3].

At Imperial College, London (1953) they developed the so-called 'self-compensating mercury control apparatus' for applying cell pressure as shown in (Figure 4) below [2, 3, 8]. Pressure, as explained by the authors, comes from a column of mercury, and the unit weight of mercury is about 13.546 grams/ml at 20° Celsius. So, the mercury pressure increases at a rate of about 5.87 psi per foot of elevation change. It requires considerable headroom. Moreover, it is worth noting that the apparatus has been used successfully for pressures as high as1000 psi [3].

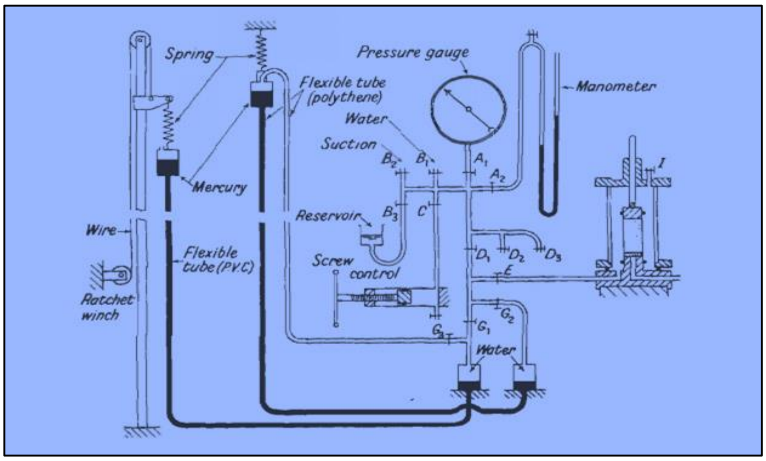

Fig 4: The layout of the self-compensating mercury control with extended pressure range [3].

3.3 Pore Pressure Controlling

The null method for pore pressure measurement (such as that used by Rendulic 1937) was developed, as Bishop and Henkel [3] pointed out, to overcome some undesirable results of the flow of pore water. It was originally utilized at Imperial College in the form illustrated diagrammatically in (Figure 5) below.

The pore-pressure connexion at the base of the triaxial cell is connected through valve (*a)* to one limb (*b)* of a small-bore glass -tube by a water-filled tube. To the other limb (*c)* is connected a pressure gauge (*d)* and a small water-filled cylinder (*e*), from which water can be displaced by a screw-controlled piston. The lower part of the -tube is filled with mercury. This can be levelled before a test by opening valve (*f*) which remains closed during the measurement of pore pressure. Such a method had in fact been used successfully by the Delft, Soil Mechanics Laboratory (1948), and Penman (1953) [3].

However, while such a system may be automated by modern methods, as indicated by [21], it is not often used today, because it may be substituted with a closed (dead end) electrical pressure transducer which automatically maintains undrained conditions while the pore pressure is measured [2].

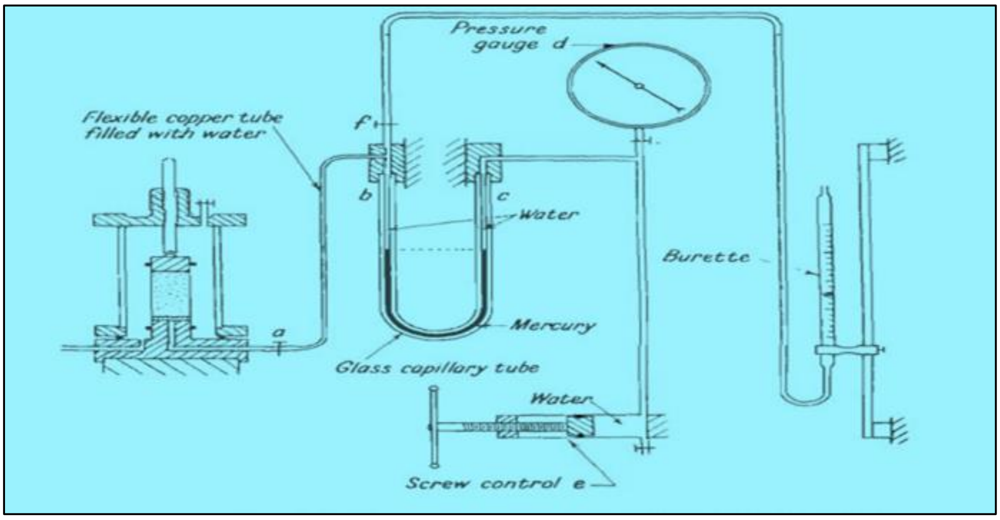

Fig 5: Null method of pore pressure measurement; original arrangement [3].

3.4 Measuring Volume Change

Volume change measurement is entirely the core emphasis of soil mechanics. Its accurate determination is fundamental in the characterization of soil behavior. Hence, the volume change measurement devices have relatively developed thanks to the soil mechanicians' creativity [2].

The three basic methods of measuring volume change include (a) measurement of the cell fluid, (b) measurement of the air and water volumes separately, and (c) direct measurement of the soil specimen [2, 3, 22]. The comparison of these three measurement techniques is displayed in table 1 below. In this regard, examples of the most common volume change devices are briefly presented.

Bishop and Henkel [23] developed a buret-type volume change device suitable for a fully saturated sample [2]. The device is based on the principle that a volume change can only occur under the action of the cell pressure or of an axial load if water is permitted to drain from the sample. A direct measure of the volume change is the volume of water expelled which may be measured in a burette [3].

The design for automatic datalogging consists of a simple buret that can be read manually as shown in (Figure 6). A simpler modification to the device, as proposed by Bishop [24] and by Tatsuoka [25], is by enclosing the buret in an outer chamber, The device is attached to another pressure transducer for measuring pore water pressure as well as cell pressure.

A modified version of the design is shown in (Figure 7). The device, as described by Lade [2], consists of four graduated burets connected through a 5-way valve to a differential pressure transducer. As proposed by Bishop [24], the four glass or polycarbonate tubes are enclosed in a chamber, consisting of a 6.4 mm (0.25 in.) thick, transparent acrylic plastic tube and two end-plates made of stainless steel detained together with three tie-rods.

For unsaturated tests, Bishop and Henkel [23] Lade [2] designed a relatively simple constant pressure air system as displayed in (Figure 8). The change in mercury level is adjusted to maintain constant reading on the oil manometer in order to measure the volume of air coming from the triaxial specimen. This maintains atmospheric pressure inside the closed system of the specimen and air volume change device [2].

Progressively, the use of mercury was substituted by water due to safety reasons [2, 26]. Mitchell (1981) devised a hydraulic system for testing rock or large diameter soil specimens [27]. In the hydraulic system which is presented in (Figure 9), large loads can be generated with relatively compact apparatus. The usual procedure is to use a single hydraulic cylinder, a high-pressure pump, and a set of metering valves. The valves can be computer-controlled so loads can be applied at any reasonable rate, and cyclic loadings are easily achieved [8].

Bishop and Wesley [28] devised a hydraulic triaxial apparatus which integrated cell pressure and axial loading capability [2, 22]. This apparatus requires hydraulic pressures supplied to the cell and to the axial loading cylinder that forms the pedestal. It also comes with a self-contained loading system; an external loading frame is not required. Its schematic diagram is displayed in (Figure 10).

Menzies [29] innovated the digital pressure controllers providing for automatic control as well as datalogging through a computer [2]. A typical triaxial setup with the Bishop–Wesley device, as indicated by Lade [2] requires three digital controllers; one for the axial load or displacement, one for the cell pressure, and one for the back pressure/volume change measurements. (Figure 11) shows such a setup.

A modified version of Bishop and Wesley system has been developed by Hong Kong laboratory [22]. The design of a total volume change measurement is shown in (Figure 20). The basic principle of this measuring system, as described by Ng and Menzies [22], is that the overall volume change in an unsaturated-saturated specimen is determined by monitoring the differential pressures between the water inside the open-ended, bottle-shaped inner cell and the water inside a reference tube using a high-accuracy DPT.

Bishop and Donald (1961) developed a modified triaxial cell known as the first suction controlled triaxial apparatus [2, 22, 26]. Figure 12 illustrates the principal design of the device using an internal or inner cylindrical cell wall sitting around the specimen [2, 22]. This device has been used to apply stresses to unsaturated soils [26], by minimizing the effects of expansion –compression of the cell and volume change in the cell fluid [22].

Wheeler (1988) modified Bishop and Donald's system by using a double cell triaxial cell as displayed in (Figure 13), [2, 22, 26]. The inner cell is completely saturated and enclosed in the outer cell [2]. The inner cell is sealed at both ends and the same pressure is acting in the inner and outer cells [2, 22].

Romero *et al*. (1997) in Barcelona developed an advanced suction controlled triaxial cell using a laser technique [2, 26]. The exact shape of the sample is monitored during shearing by means of a mobile electro-optical laser system mounted outside the chamber [26]. This advanced apparatus is illustrated in (Figure 14).

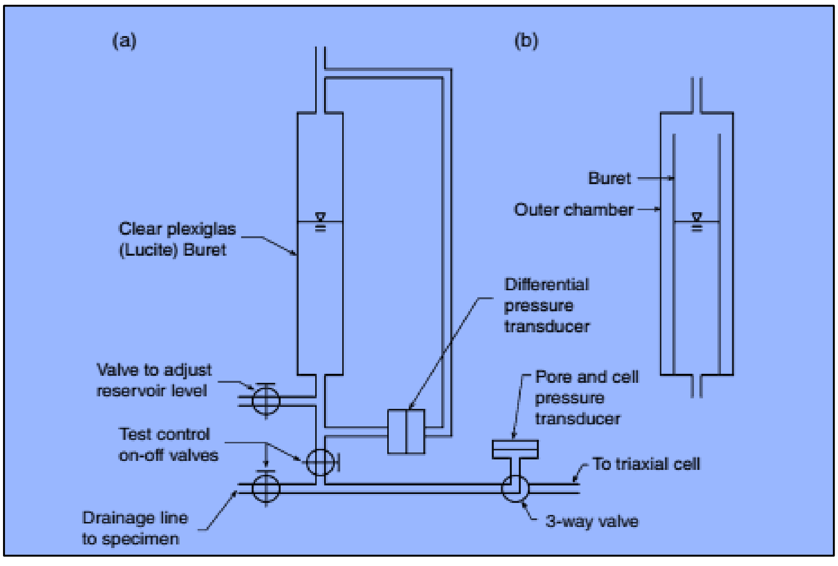

Fig 6 (a): Simple buret-type device designed for automatic logging volume change device and pressure data (b) alternate buret with outer chamber [24].

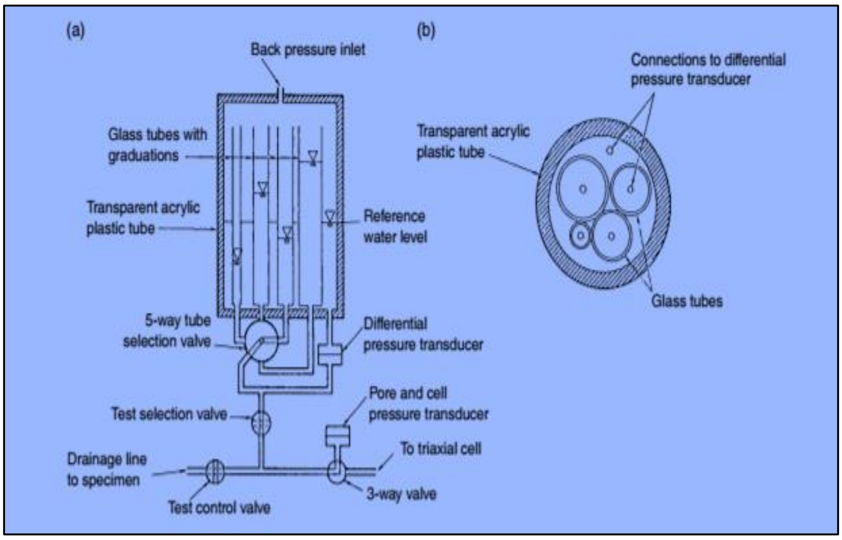

Fig 7 (a): Schematic diagram of buret type volume change device for automatic data logging and (b) actual lay-out of tube assembly [16].

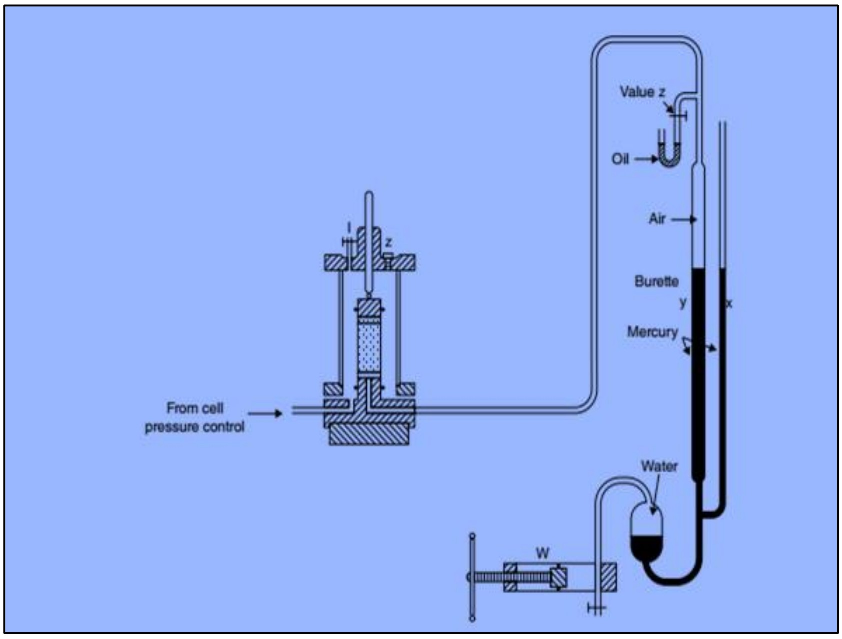

Fig 8: Measurement of the volumes of both air and water expelled from a partly saturated specimen [3].

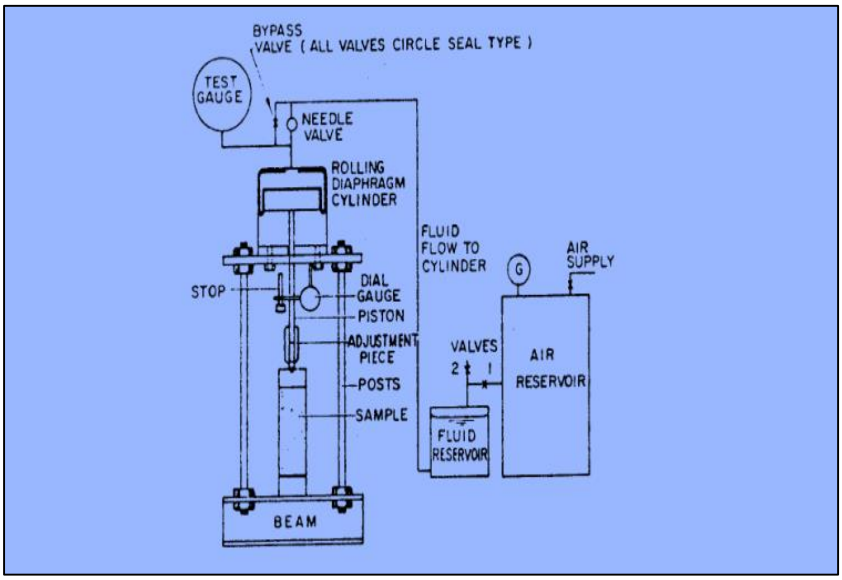

Fig 9: Triaxial Cell with Associated Hydraulic Loading System [8].

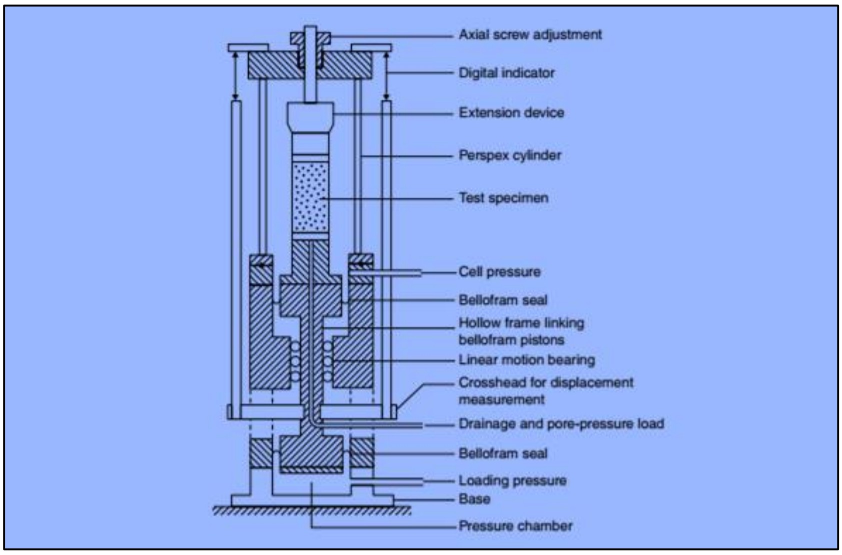

Fig 10: Schematic drawing of hydraulic triaxial apparatus (after [2, 28]).

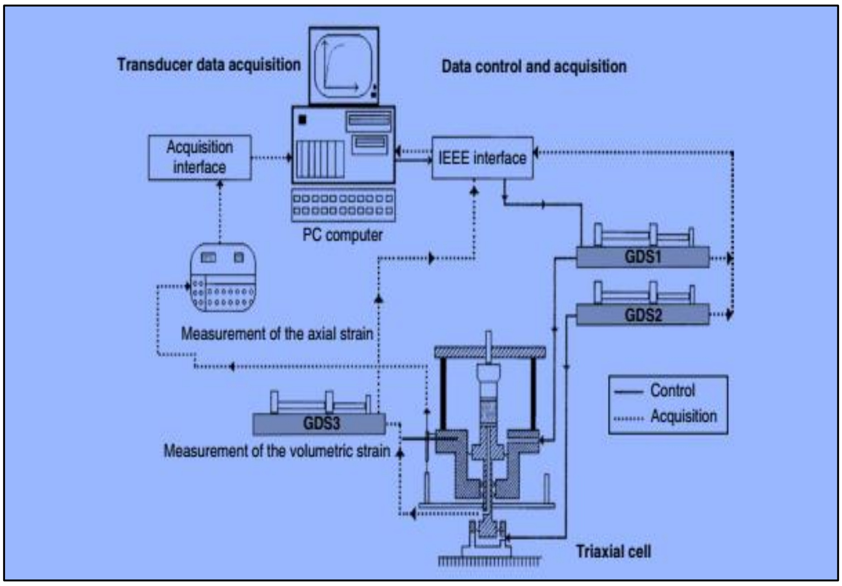

Fig 11: Triaxial testing setup with Bishop–Wesley hydraulic loading apparatus and stepper motors used for test control and for data acquisition. Reproduced from Hattab and Hicher 2004 by permission of Elsevier [2].

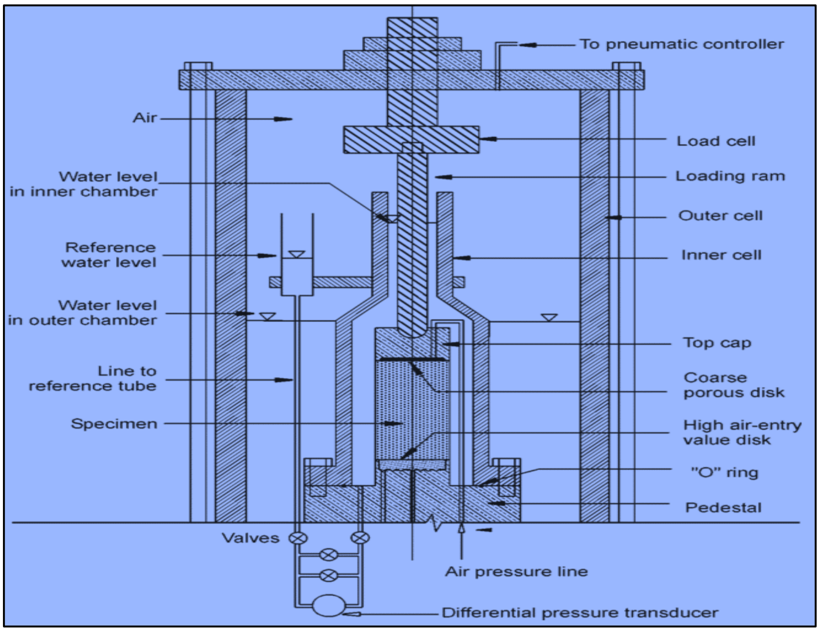

Fig 12: A new total volume measuring system for triaxial testing of unsaturated soils after Ng *et al* 2002a [22].

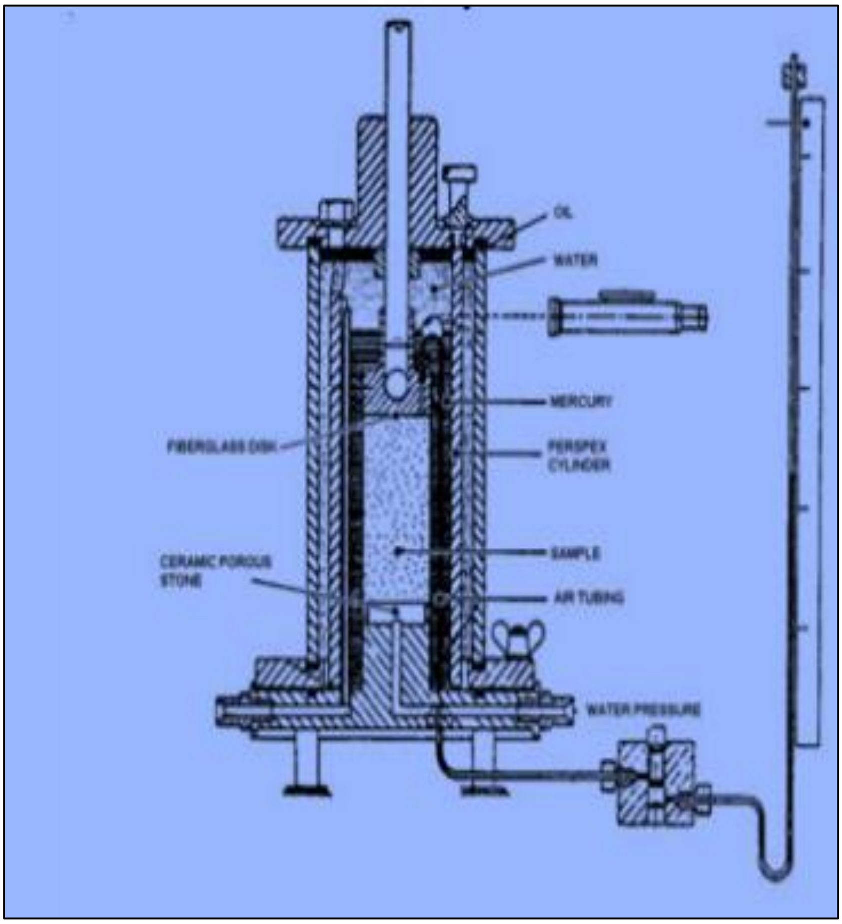

Fig 13: Suction controlled triaxial apparatus after Bishop and Donald 1961 [26].

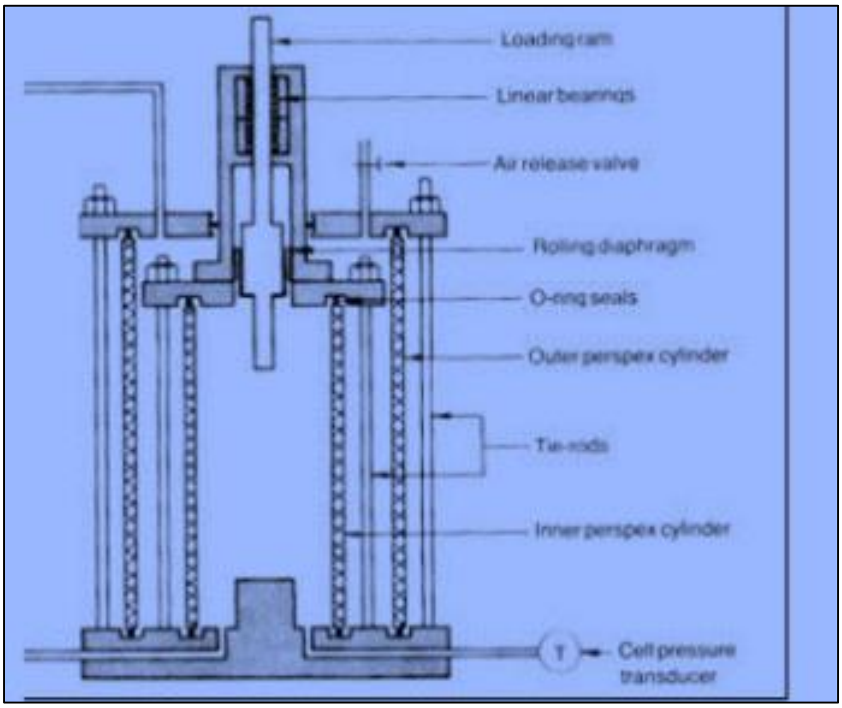

Fig 14: Double wall triaxial cell after wheeler 1988 [26].

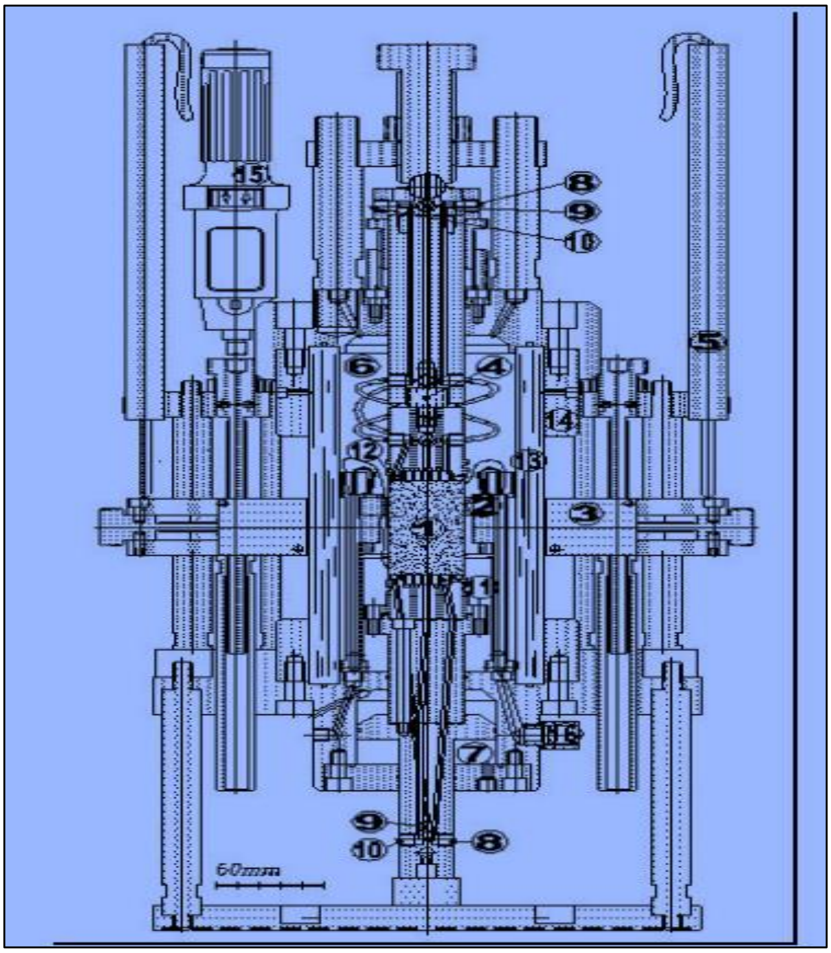

Fig 15: Barcelona advanced triaxial cell after Romero *et al*.1997 [26].

Table 1: Comparison of three methods of volume change measurements for partly saturated soils (modified after Laloui *et al*. 2006 by permission of Elsevier) [2].

Type of device	Advantages	Limitations	Absolute errors on ΔV (α) and εv (β)
		Method (a): Cell liquid measurements	
Standard triaxial cell (a1)	Use of standard cell, without modifications	Indirect method, involving long calibration process	$\alpha = \pm0.45$ cm3 $\beta = \pm0.22\%$
Inner cylinder (a2)	Minimizes or strongly decreases the undesired volumetric changes observed with (a1) as the confining pressure is imposed on both sides of the inner wall	Indirect method, involving calibration process	$\alpha = \pm0.21$ cm3 $\beta = \pm0.08\%$ Bishop and Donald (1961): *Vspec* = 100 cm3: $\alpha = \pm0.1$ cm3 $\beta = \pm0.1\%$
Double walled cell (a3)	Same as (a2) Enables continuous measurements	Indirect method, involving calibration process	For specimens of 100 cm3: $\alpha = \pm0.6$ to 1.02 cm3 $\beta = \pm0.6$ to 1.0 % depending on the cell. The average global accuracy is believed to be better
		Method (b): Air–water volume measurements	
Air filled controller (b1)	Direct measurement or imposition of the volume of air	Air volume is strongly influenced by temperature and atmospheric pressure. Undetectable air leakage	$\alpha = \pm2.2$ cm3 $\beta = \pm1.1\%$ +Continuous air leakage of 2–3 cm3/day
Mixed air–water filled controller (b2)	Same as (b1) Minimizes the air volume and the possible errors	Same as (b1), but less important	$\alpha = \pm2.2$ cm3 $\beta = \pm0.11\%$ +Continuous air leakage of 0.2 cm3/day
		Method (c): Direct measurements on the specimens	
Hall effect captor with radial strain measurements (c1)	Direct measurement on specimen Enables continuous measurements	Conceived for small strain measurements Problems of accuracy for barrel-shaped specimens equipped with only one radial strain gage. Mounting or sealing transducer on the specimen is quite delicate and requires an initially fairly rigid specimen	
Laser technique (c2)	Direct, continuous, non-contacting measurements Measurement of entire specimen profile Possible measurement all around specimen	High costs and long calibration process	Estimate based on Romero *et al*. (1997): $\beta = \pm0.007\%$
Image processing (c3)	Direct, non-contacting measurements Measurement of entire specimen profile Computer controlled calibration process	Not valid for asymmetric specimen when using only one camera	$\alpha = \pm0.25$ cm3 $\beta = \pm0.1\%$

4. Conclusion

The triaxial shear device developed over a period of years. Earlier attempts to develop the conventional triaxial apparatus were held by geotechnical engineers from the late 1950s. Each time the device falls short in performing a test, it has been modified to adapt with experiment limitations. Therefore, the triaxial equipment developments are arranged according to the area of modification in this study. The research pinpoints that the genesis of the triaxial apparatus is revolutionary in geotechnical engineering. Triaxial testing has contributed to the development of soil mechanics as it provides accurate characterization of soil behaviour. The paper illustrates some basic working principles of different volume change measurement techniques using the triaxial device. These include different operational principles that have been used in designing volume change devices for soil testing. The paper identifies that some of these devices require quite complex operational techniques and equipment that are difficult to perform on a repetitive testing basis. Hence, the desirable requirements for a volume change device should be sturdiness and ease of operation in soil mechanics testing. The paper concludes that advances from the 1990s onwards have employed laser and image processing techniques to triaxial equipment. These may be attributed to novel methods of shear testing that call for accurate determination of volume change, pore pressure, and axial load measurement. As long as some shear tests can only be manipulated with the triaxial apparatus, it is still being modified and upgraded.

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