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Measurement of Strains in Triaxial Test Specimens: A Review

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Introduction

The design of soil structures requires an assessment of the likely deformations during the lifetime of the structures. To estimate the likely deformation, knowledge of soil modulus and its variations with stress and strain levels is very important. The stress-strain behavior of soil is nonlinear and the stiffness, normally expressed as a secant modulus (E_s) or tangent modulus (E_t), decays with axial strain (ε) by orders of magnitude, as shown in Figure 1. Jardine et al. (1984) classified the axial strain regions as very small strain ($\varepsilon = \varepsilon_o$), small strain ($\varepsilon_o > \varepsilon < 0.1\%$) and large strain ($\varepsilon_l > 0.1\%$) as shown in Figure 1. The value of ε_o is generally of the order of 0.001%. In the very small axial strain range, the modulus is constant but decays with strain once the strain exceeds the very small strain range.

For realistic estimates of ground movements, the modulus used in deformations calculations should be derived at strains corresponding to those anticipated in the field. In general, most of the soil masses (for example, in excavation under foundation and around tunnel) experience strains smaller than 0.1% as can be seen in some of the published records of measured deformations within the ground associated with buildings and excavations as described below.

- Attewell and Farmer (1974) presented some observations of ground movements resulting from the excavation of a 4.2 m diameter shield driven tunnel at a depth of 30.8 m in London clay beneath Green Park. Based on the observations made, it was concluded that within a tunnel diameter above the crown, the vertical strains exceeded 0.1% but most of the ground is strained to less than 0.05%.
- Kriegel and Weisner (1973) presented the observed settlements of foundations at various depths beneath some buildings in East Germany. Even though high bearing pressures were applied, most of the local strains did not exceed 0.1% but in some locations reached a maximum of about 0.3%. Similarly, the results of settlement measurements on a tall residential building founded on medium dense sand showed that only

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locally does the vertical strain exceed 0.1% and at all other locations the strains are less than 0.1%.

- The settlement observations for a tall residential building in northern Germany founded on boulder clay showed that the strains in the ground never exceeded 0.1% (Kriegel and Weisner 1973).
- The measurements of settlement at various depths beneath a 3.1 m x 3.1 m test footing on the crust overlying soft Champlain clay in eastern Canada (Bauer et al. 1976) showed that below a depth of 0.78 m the strains are generally less than 0.2 % at a footing pressure of 200 kPa.
- From the field investigations carried out by Burland (1989) on the Mundford test tanks founded on various grades of chalks indicated that the induced strain level in the ground in most of the cases were small (strain < 0.1%).

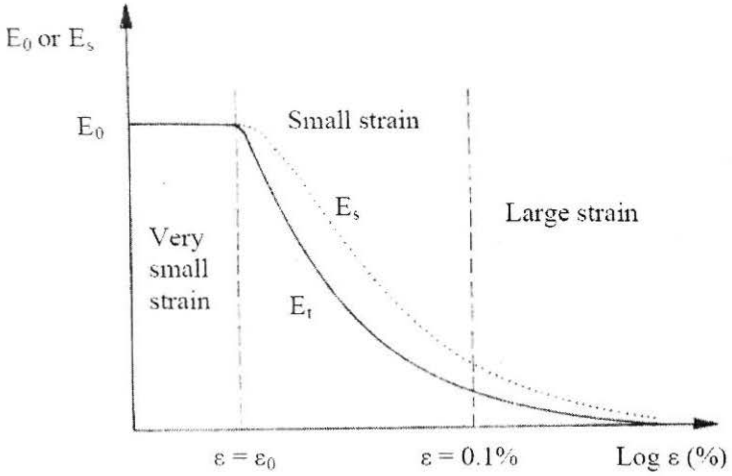


Fig. 1 Classification of Strain Regions (after Jardine et al. 1984)

From the few examples listed above, it can be anticipated that the large mass of the ground beneath and around a structure, be it an excavation or foundation, do experience direct strains of the order of 0.1 % under working loads. Only locally, close to the structure, the strains are likely to exceed this value. It follows therefore that if successful prediction of ground movements are to be made, it is necessary to ensure that reliable measurements of strain be made accurately starting from very small strains to large strains.

Figure 2 illustrates typical characteristic stiffness-strain curve for soils, which includes typical ranges of axial strain for laboratory testing along with the ranges of expected strains by various structures (after Atkinson and Sallfors 1991; Mair 1993). Soil stiffness at very small axial strain range (< 0.001%) can be measured using dynamic methods such as Bender elements. Reliable measurement of soil stiffness throughout the small strain region strains of about 0.001% to 0.1% can only be measured using on-sample instruments attached directly to the soil specimen (Jardine et al. 1984; Atkinson 2000) as the measurement of strains, of the order of 0.1 % is beyond the accuracy of most of the routine triaxial apparatus. Therefore, the results from a conventional triaxial apparatus do not always reflect the real stress-strain behaviour of soils in the very small and small strain ranges. It has been found that the stiffness values obtained from the conventional triaxial apparatus is far less than the stiffness values derived from back-calculation of the measured displacements occurred in the field. In the past, sample disturbance was believed to be the major cause for this discrepancy. However, it was realised in the recent studies that the large variation of stiffness with axial strain is the major cause for this discrepancy: that is, the stiffness measured by the conventional triaxial apparatus is at the axial strain levels larger than those normally occur in the field (Cole and Burland 1972; Wroth 1975; Burland 1979; Atkinson 2000). This is due to the fact that deformations are measured outside the triaxial cell, include not only the soil specimen deformation but also the compression/extension of several parts of the system leading to overestimation of axial strain. The contributing factors that are included in the axial strain when measured externally are illustrated in Figure 3 (Baldi et al. 1988) and explained below.

1. Seating errors due to the closing of the gaps between ram/internal load cell and top cap, and also between top cap or base pedestal and porous stones.
2. Alignment errors which may result from equipment and specimen non-conformity specifically porous stones of non-uniform thickness, non-verticality and eccentricity of loading ram, non-horizontality of platen surfaces and tilt of specimen.
3. Bedding errors caused by lack of fit or surface irregularities or voids at the ends of the specimen.
4. System compliance that may be resulted from the extension of tie bars which cause relative displacement of the top of the cell with respect to the piston, deflection of internal load cell, compression of lubricant that use lubricated ends, and the compression of porous paper.
5. Non-uniform strains along the specimen height resulting from end restraints.

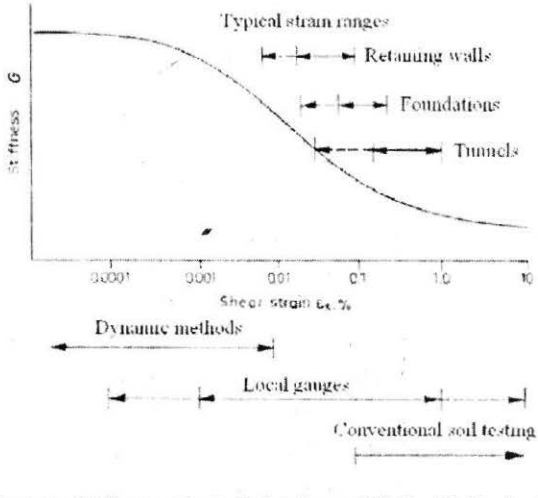


Fig. 2 Characteristic Stiffness-strain Behaviour of Soil with Typical Strain Ranges for Laboratory Tests and Structures (after Atkinson and Sallfors 1991)

The overall deflection (Δ) is the results of the above factors and the specimen compression as indicated in Figure 3. The influence of the above factors can be eliminated, if the strains are measured by fixing strain-measuring devices directly on the specimen. Many such "on-sample" strain-measuring devices were developed in the recent years and are briefly discussed in the following section.

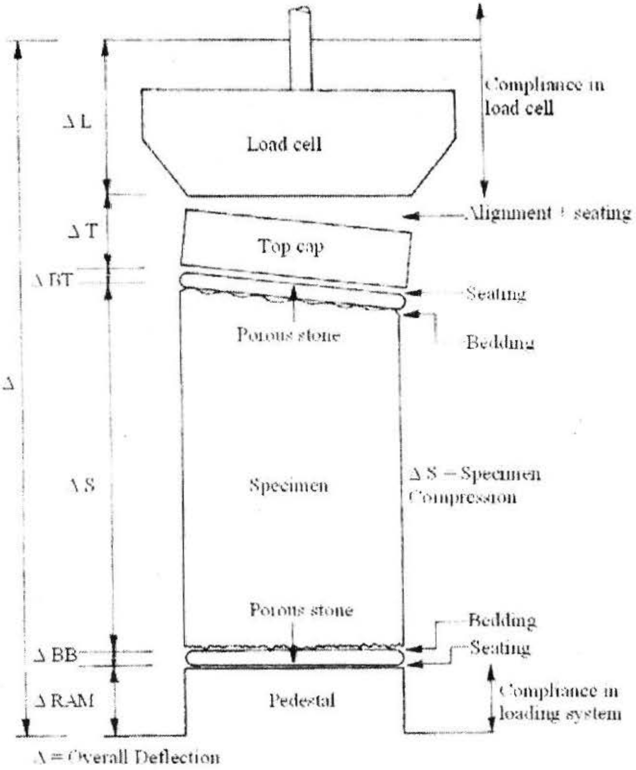


Fig. 3 Sources of Errors in Axial Deformation Measurements in Conventional Triaxial Testing (after Baldi et al. 1988)

On - Sample Strain Measuring Devices

Linear Variable Differential Transducers (LVDT) as shown in Figure 4(a) was amongst the first transducers to be used for the local measurements of axial strain (Brown and Snaith 1974; Costa-Filho 1985). Figure 4(b) shows the photograph of a LVDT mounted over a triaxial specimen. The main limitation of LVDT is that it is bulky in size and involves complicated fixing mechanisms which often lead to the disturbance of sample to be tested. Therefore, great care must be exercised in fixing it around the sample. There is also a possibility that the weight of the device could cause yielding of the soil, before the application of the confining stress. To overcome this problem, buoyant or semi-buoyant systems have been designed (Cole 1978). However, the system requires attachment to the specimen prior to immersing it in the cell fluid and also it requires the need of non-conducting cell fluid (air or silicone oil), except for a water-submersible LVDT (Costa - Filho 1985). Another notable limitation is that it is prone to jamming of the inner LVDT rod because of the tilting of the specimen, at large strains.

The application of *inclinometer type gauge* for small strain measurement in triaxial sample followed the work of Cooke and Price (1974), who monitored vertical displacements adjacent to piles using electrolytic levels. Inclinometer-type on-sample strain measurements within the triaxial cell were developed at Imperial College, London, in which the fundamental mode of operation is that the conversion of axial deformation of the triaxial specimen to tilt of the electrolyte level (Burland and Symes 1982). A schematic of the device is shown in Figure 5 and was extensively used by Jardine et al. (1984) for measurement of small strain stiffness of soils. The main drawback of the use of inclinometer levels is the errors introduced in the axial strain determination as the electrical output-axial deformation calibration is based on pad displacement along a planar surface. The errors caused by barreling of the specimen are significant at higher strain levels.

The use of *proximity transducers* for measuring strains in triaxial soil specimens has been reported by numerous workers (Cole 1978; Khan and Hoag 1979; Brown et al. 1980; Dupas et al. 1988; Hird and Yung 1987 and 1989). Schematic of the proximity transducers is shown in Figures 6(a) and (b). Proximity transducers operate on the basis of the eddy current loss principle. A coil in the transducer induces an eddy current in a conductive target. As the distance between the transducer face and target changes, the magnitude of the induced eddy current varies. Since the impedance of the coil depends on eddy current magnitude, the coil impedance is a function of the transducer target distance. The impedance can be measured by connecting the proximity transducer in a bridge circuit. The circuit is initially balanced for a specific separation so that any subsequent variation in the distance is reflected by fluctuations in the output voltage. There is a problem in mounting the target for axial strain measurements because when the specimen deforms the targets get tilted, leading to erroneous measurement of deformation.

Bender elements (Shirley and Hampton 1978; Dyvik and Madshus 1985) were originally developed to measure shear wave velocities in soft soils, from which the very small strain ($\varepsilon < 0.001\%$) shear modulus (G_0) could be derived. The equipment was modified and developed for testing stiff soils and soft rocks by Viggiani and Atkinson (1995). Bender elements are usually set into the top and bottom platens of a triaxial cell as shown in Figure 7(a). One element, usually placed at the top, is vibrated by changing the voltage across it to generate the shear wave. The shear wave propagates through the sample and vibrates the other element. The effective distance traveled by the shear wave through the sample is the tip – to - tip distance between the bender elements. The input and output voltages are continuously recorded and the travel time is determined. The quality of the measurement of the travel time is sensitive to the form, frequency and amplitude of the shear wave.

By measuring the travel time of the shear wave, the shear wave velocity v_s is determined as follows (Dyvik and Madshus 1985; Brignoli et al. 1996; Viggiani and Atkinson 1995):

$$v_s = \frac{l}{t} \tag{1}$$

where

l = the effective distance between two signal measurement points [Figure 7(b)]

t = the travel time for the shear wave from the transmitter to the receiver.

The travel time (t) of shear wave in a Bender element test can be arrived by various methods (Viggiani and Atkinson 1995; Jovicic et al. 1996) as described in Table 1 and Figure 8. From the shear wave velocity, the shear stiffness at very small strain G_o can be determined from the elastic wave propagation theory:

$$G_o = \rho v_s^{\,2} \tag{2}$$

where ρ is the bulk density of the soil specimen.

The Hall effect gauge was developed by Clayton and coworkers at the University of Surrey (Clayton and Khartrush 1986; Clayton et al. 1989). The Hall Effect is observed when a metallic or semiconductor plate, through which a current is flowing, is placed in a magnetic field where flux lines are directed perpendicular to both the plate and the current flow. This causes deflection of the charge carriers, and an output voltage is produced across the plate in a direction normal to the current flow. This phenomenon is known as the Hall Effect. The magnitude of the output voltage is a function of the flux density and varies depending upon the relative position of the semiconductor sensor within the magnetic field. A system of permanent magnets can be configured so that a linear relationship between output voltage and relative displacement of the semiconductor sensor is obtained over a specified range. Schematic of the Hall Effect transducer is shown in Figure 9.

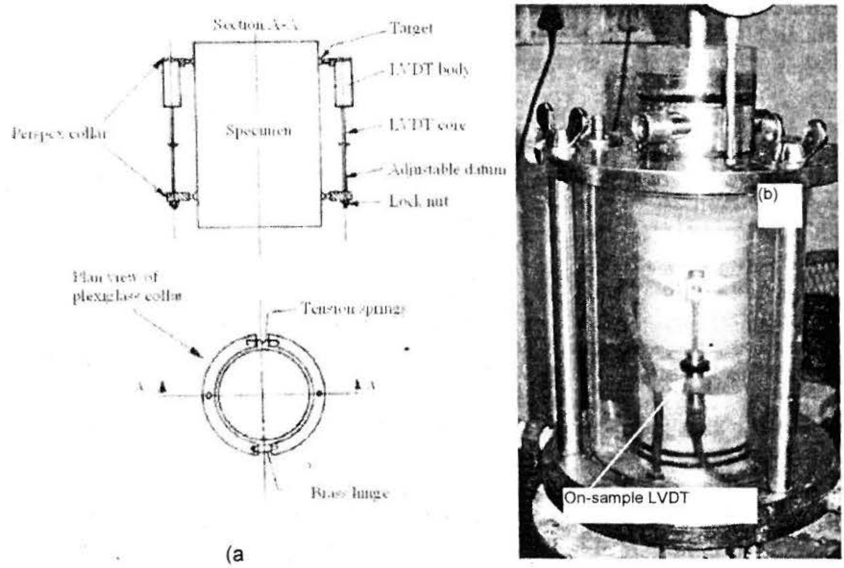


Fig. 4 (a) Linear Variable Differential Transducer (LVDT) (after Brown and Snaith 1974) and (b) Photographic View of On - sample LVDT

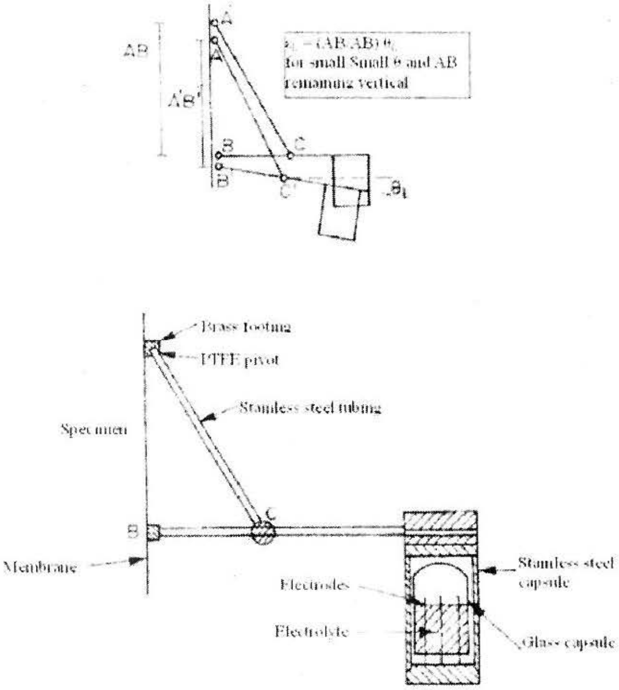


Fig. 5 On - sample Inclinometer Level (after Jardine et al. 1984)

TABLE 1: Description of Different Methods for Travel Time Determination in Bender Element Test

Method	Symbol	Description
A	$t_{st\,(1)}$	from the initial point of the input wave to the first obvious reverse point of the received wave
B	$t_{st\,(2)}$	from the initial point of the input wave to the second obvious reverse point of the received wave
C	t_{pp}	from the peak of the input wave to the peak of the received wave
D	t_{00}	from between the peak of the input wave to its trough, where the voltage is zero, to between the peak of the received wave to its trough where the voltage is zero
E	t_{tt}	from the trough of the input wave to the trough of the received wave

The major limitation of the Hall Effect gauge is the limited range of operation. In addition, the Hall Effect transducer is strongly affected by electrical noises. Difficulties may be experienced in soft clays and at low stress levels where the soil is unable to overcome the spring force. The weight of the caliper acting on the soil is another concern, which often disturbs the soil sample.

The local deformation transducer (LDT) was developed at the Institute of Industrial Science, University of Tokyo (Tatsuoka 1988; Tatsuoka et al. 1990; Goto et al. 1991). The LDT consists of thin-phosphor-bronze strain gauged strips bridging the gauge length. The strips are in contact with the specimen at each end of the gauge length, where they are balanced under their own elastic force against pseudohinged mechanisms attached to the circumference of the specimen as shown in Figure 10.

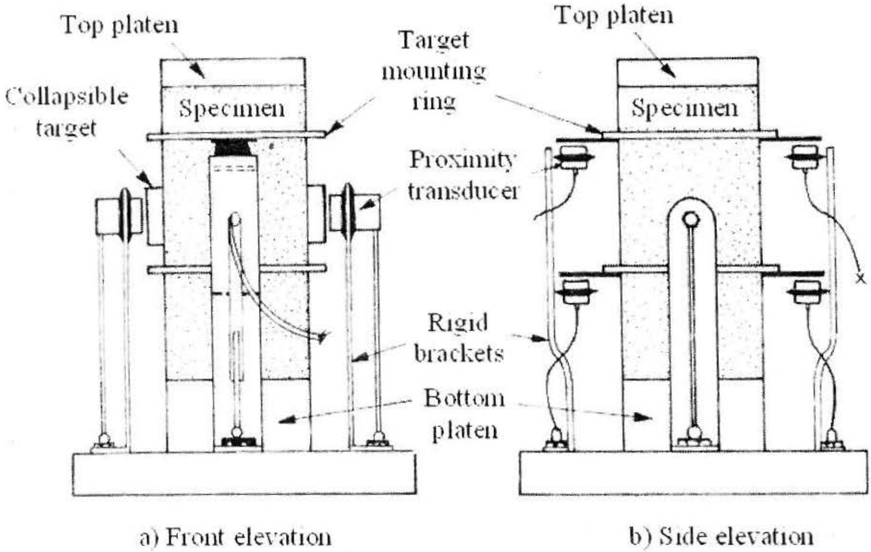
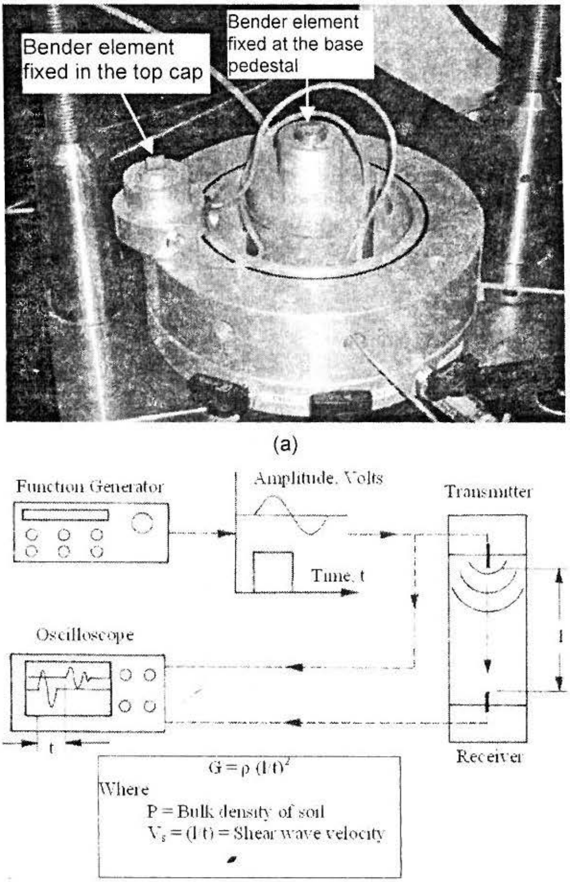


Fig. 6(a) and (b) Schematic of Proximity Transducer (after Hird and Yung 1989)

The operation principle of this transducer is that axial deformation causes relative displacement of the hinges and arching of the strips. The output is related to the bending strain developed in the strips. The device suffers from the limitations such as nonlinear output relationship, requirement of output signal conditioning and the operating range of axial deformation is limited only to 1.5 mm. For large deformations, the instrument has to be removed to prevent it from being damaged. In addition, excessive elastic stresses on the hinges will be generated at large axial strains, and transferred to the soil specimen.

Bourdeau (1993) has brought out a historic review of the use of X-ray techniques for geotechnical applications. Application of X-ray radiography techniques in soil mechanics evolved as a method of establishing stress and strain distribution within deforming soil masses. X-ray radiography studies were first applied to the evaluation of the deformation behaviour of soils beneath loaded footings. Interest increased during the early 1960s, and the technique was used for laboratory investigations of plane-strain deformation (Roscoe et al. 1963; Arthur et al. 1964; Arthur and Roscoe 1965). The basis of the X-ray technique is to monitor the displacement of elements of soil at discrete time intervals during whole body deformation. A close-spaced grid of X-ray impenetrable markers, usually made of lead-shot, is established in the soil. X-ray images obtained at intervals during loading record the grid deformation. The invasive characteristic of the X-ray technique, dictated by the need to insert some type of marker into the soil, is the primary limitation of the method. It is difficult to avoid the use of markers because X-ray techniques rely on adequate contrast to delineate displacement of soil elements. Interpretation of X-ray images is based on the assumption that the soil deforms homogeneously and continuously between the markers. Accuracy suffers mostly in the zones of large deformation, and the method is only suited to pre-failure conditions (Roscoe et al. 1963). The accuracy can not be improved by reducing the mesh indefinitely, as a lead-to-soil ratio will be reached at which the deformation behaviour is controlled entirely by the markers. Since images are obtained at discrete time intervals, the deformation record is discontinuous. Loading must be sufficiently slow so that the marker images do not appear blurred. Other practical considerations include retardation of X-ray by the cell fluid, image problems caused by the differential length of the X-ray path through the cylindrical specimen, expense, and safety requirements (Kirkpatrick and Belshaw 1968). Considering these drawbacks this method is not widely used for small strain measurements.



(a)

(b)

Fig. 7 (a) Photographic View of Bender Elements and (b) Principle of Bender Element Test (after Viggiani and Atkinson 1995)

Many of the reported devices such as inclinometer levels, LVDT, Proximity transducers, Bender elements, Hall effect gauge, LDT and X-ray technique are in use to measure the axial strains developed in the triaxial specimen. Table 2 presents the summary of the various on-sample strain measuring devises with their relative comparison. From the table, it may be noted that most of the devices are very expensive and involve complicated mechanisms to fix around the triaxial sample. Also, some of the devices are heavy resulting disturbance in the specimen. Hence, there is a need to develop simple and inexpensive technique to measure the axial strains and hence the soil stiffness at small axial strains levels.

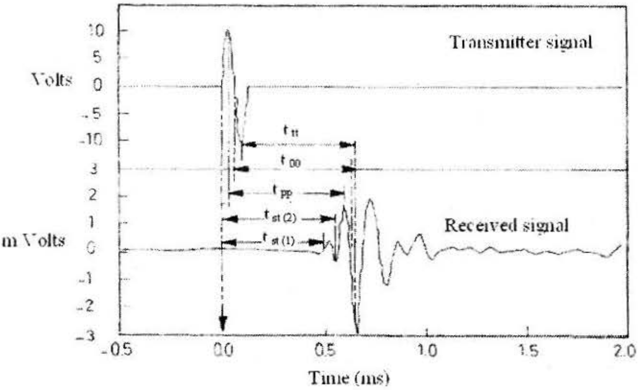


Fig. 8 Methods of Determination of Travel Time of Shear Wave in Bender Element Test (after Viggiani and Atkinson 1995)

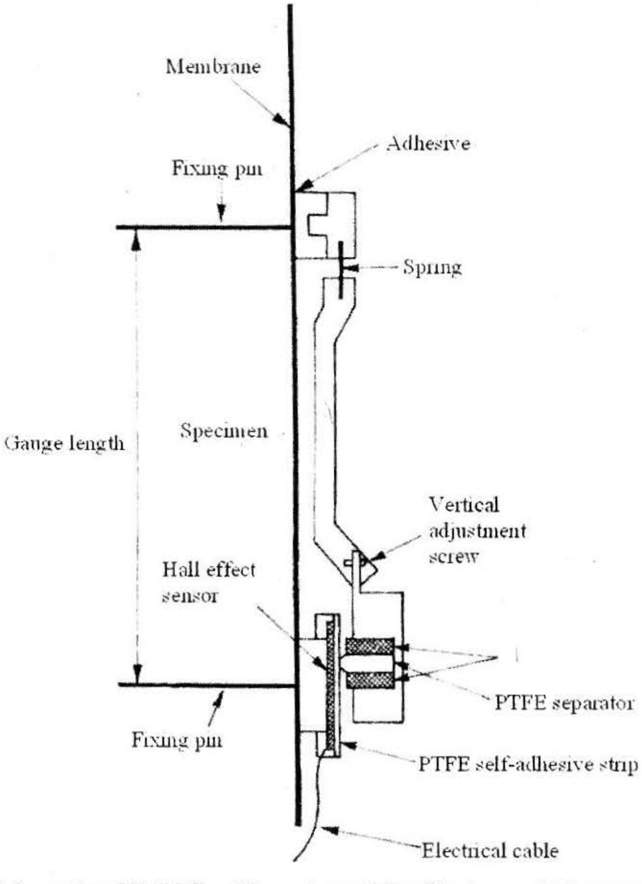


Fig. 9 Schematic of Hall Effect Transducer (after Clayton and Khartrush 1986)

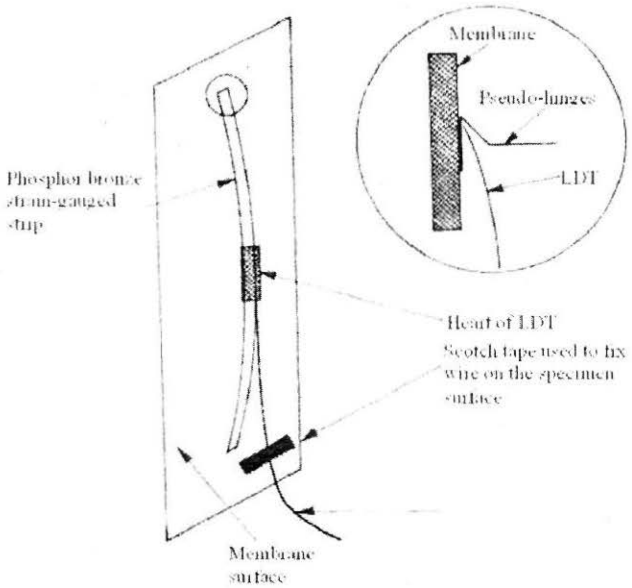


Fig. 10 Schematic of Local Deformation Transducer (LDT) (after Tatsuoka 1988)

Strain Gauges to Measure Axial Strain in Triaxial Specimen

The authors attempted to develop a method to measure strains developed in triaxial soil specimen by fixing strain gauges on its surface. In order to do so, some modifications were made in the conventional triaxial set - up, as discussed in the subsequent sections.

Generally, for triaxial testing, it is essential to create an effective confining stress (σ_3') in the soil specimen before shearing. Conventionally, the required effective confining stress is applied through water pressure and the specimen is allowed to consolidate. If strain gauges are to be used, submersible type strain gauges or water proofing had to be made. In addition, taking out the electrical cables from the triaxial cell without any leakage requires sophisticated sample-access rings. In order to eliminate these requirements and simplify the procedure, a vacuum confinement technique is adopted in the present study.

In the conventional triaxial testing procedure, if an effective confining stress of $\sigma_3' = p$ is required, a cell pressure of $\sigma_3 = p$ is applied and the specimen is allowed to consolidate so that the pore pressure, $u = 0$, after consolidation. In the vacuum confinement technique, the cell pressure σ_3 is kept zero and pore pressure of $u = (-p)$ is applied to the specimen. Now, the effective stress induced to the specimen is given by

$$\sigma_3' = p \tag{3}$$

which is same as that obtained from conventional cell pressure application.

Table 2 : Summary of Various On-Sample Strain Measuring Devices

	Name of the Devices						
Parameter	Inclinometer levels	On-sample LVDT	Proximity transducers	Bender elements	Hall effect gauge	LDT	X-ray techniques
Operating Principle	Tilt of electrolyte level	Inductance	Eddy-current loss principle	Measurement of shearwave velocity	Hall-effect	Bending strain in elastic metal strip	Discrete-X-ray images of deformation of lead-shot grid
Output characteristic	Nonlinear	Linear	Linear	Linear	Linear over limited range	Nonlinear	X-ray images
Fixing mechanism	Complicated	Requires special attention	Difficulty in mountingone target	Simple	Difficult to fix the device on stiff soils	Very complicated	Targets are to be placed in the soil
Operating range	Limited	Wide range	Limited	Suitable in the very small strain range	Limited to pre-failure state	Limited to axial deformation of 1.5 mm	Up to pre-failure state
Cellfluid restrictions	None	Non-conducting fluid if special submergible LVDT are not used	Non-conducting fluid	None	None	None	Consider X-ray retraction

The negative pressure is applied by vacuum and the magnitude of effective confinement at any point in the triaxial specimen is expected to be the same as the applied vacuum. The validity of this method was evaluated through a detailed experimental programme which was discussed in detail elsewhere (Gunasekaran and Robinson 2006).

The conventional triaxial base pedestal was used to keep the test specimen, as shown in Figure 11. The test specimen (Medium grade Ennore sand) was prepared under saturated condition as per IS 2720: Part 11: 1993. The bottom of the specimen was connected to a burette filled with deaired water. The entire water line was carefully de-aired earlier to the sample preparation phase. The open end of the burette was connected to a vacuum pump via a vacuum regulator with an indicator. The regulator has the capability of regulating and maintaining the pressure to the required value at an accuracy of 1.3 kPa. The vacuum was applied through the burette so that the volume change that occurs in the specimen at any stage of the test can be easily measured. The triaxial cell cover is not essential and therefore the sample is free to access. Now, any type of instrumentation can be made on the specimen without any difficulty in the absence of fluid cell pressure and the cell cover itself. The photographic view of the experimental set-up is shown in Figure 12 in which the specimen is under vacuum confinement, as described above. The specimen, after assembling was subjected to the required effective confining stress by vacuum pressure. Once the consolidation was over, the strain gauges were glued to the specimen at its one third height, using Quickfix, as shown in Figure 12. This one-third height was selected to reduce the effect of end restraints (Kirkpatrick and Belshaw 1968; Kirkpatrick and Younger 1970). The specimen was then sheared under drained conditions. During shearing the deviatoric stress, volume change and strains were measured. As relative displacement between rubber membrane and the soil is not permitted, the strain in the rubber membrane is equal to the strains in the soil specimen. The axial strains were measured from both the external LVDTs and the strain gauges fixed on the sample.

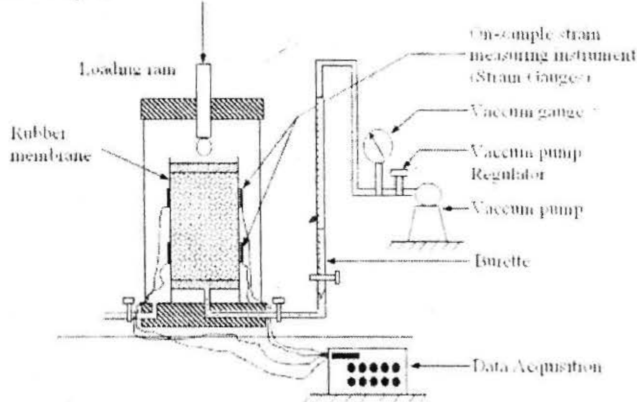


Fig. 11 Schematic of the Experimental Set-Up

Typical result is shown in Figure 13 for the Ennore sand under a confining stress of 25 kPa. It can be seen that the external LVDT recorded larger strains compared to the on-sample strain gauges for the same deviatoric stress. This is due to various reasons explained earlier. The initial tangent modulus computed based on the strains measured using the strain gauges is 31 MPa which is about 2.1 times higher than that based on the external strain measurements. Similar results are reported in the literature (Clayton and Khatrush 1986) suggesting the validity of the proposed method. However, the method is suitable for situations where the effective confining stress is less than or equal to 100 kPa, which is the maximum negative pressure that can be induced to the specimen to avoid cavitation.

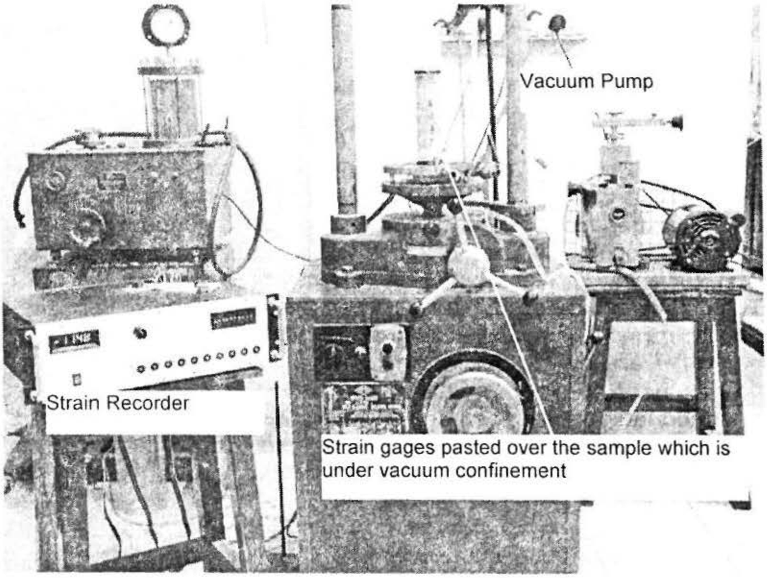


Fig. 12 Photographic View of the Experimental Set - up in which the Sample is under Vacuum Confinement and Instrumented with Strain Gauges

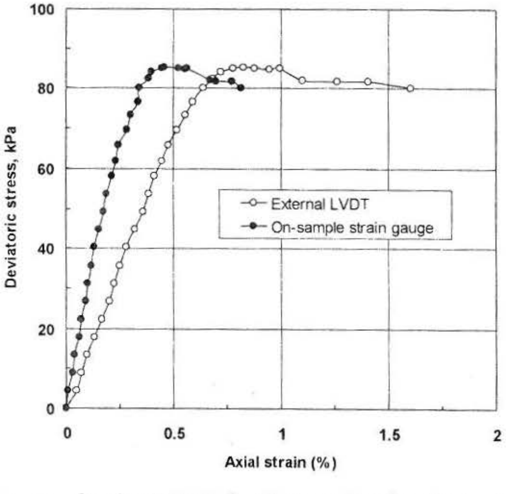


Fig. 13 Typical Stress - Strain Curves for Ennore Sand under a Confinement of 25 kPa Showing the Measurements from On-sample Strain Gauges and External LVDT

Conclusions

The stiffness measured using conventional triaxial testing procedures underestimates the stiffness values due to many errors when the strains are measured externally. In order to rectify the defect in the conventional triaxial system, many on-sample devices were developed. This paper reviewed various on-sample strain measuring devices reported in the literature. It was observed that many of the devices involve complicated fixing mechanisms leading to sample disturbance. The devices are also expensive. Therefore, the need for developing a simple method for the measurement of strains in triaxial samples was highlighted. A simple method of measuring axial strain of the specimen subjected to internal less than 100 kPa confinement by vacuum has been proposed in this paper.

Acknowledgements

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