Indian Geotechnical Journal, 38(1), 2008, 33-48

On-Sample Measurement of Strains In Triaxial Samples using Strain Gauges

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Introduction

Back analysis of many geotechnical structures showed that the strains developed in the field are small and often of the order of 0.1% (Burland 1989; Atkinson 2000). For the realistic estimates of deformations, the stiffness of the soil to be used in the design should therefore correspond to the small strain range. The stress-strain curves observed in the conventional triaxial system are subjected to many errors, especially at small strain range, when the deformations are measured externally. The most common errors observed are seating errors, alignment errors, bedding errors, system compliance and end restraints (Baldi *et al*. 1988). These errors are added to the deformation measurements, if measurements are made externally and the stiffness values are under estimated. To properly characterize the stress-strain behaviour of soil at small strains, new techniques and devices are being developed. It was found that the errors listed above could be eliminated if strain measurements are made internally, by fixing transducers called on-sample transducers directly on the triaxial specimen. Many researchers have developed various on-sample strain measuring devices to measure the strains accurately, so as to compute stiffness at small strain levels. A detailed review and the advantages and disadvantages of on-sample transducers developed over the years are critically reviewed by Gunasekaran and Robinson (2007). A brief description is given in the following section.

Inclinometer-type on-sample strain measurements within the triaxial cell were developed by Burland and Symes (1982), in which the fundamental mode of operation is the conversion of axial deformation of the triaxial specimen to the tilt of the electrolyte level. *Linear Variable Differential Transducers (LVDTs)* were also often used for the local measurements of axial strain (Brown and Snaith 1974; Costa-Filho 1985). The main problem with LVDT is that it is bulky in size and involves complicated fixing mechanisms, which may lead to the disturbance of sample to be tested (Scholey *et al*. 1995 and Atkinson 2000). Therefore, great care must be exercised in fixing them around the sample, especially when the sample is soft. 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. It also requires the need of non-conducting cell fluid (air or silicone oil), except for a

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water-submersible LVDT (Costa-Filho 1985). Numerous workers (Cole 1978; Khan and Hoag 1979; Brown *et al*. 1980; Dupas *et al.* 1988; Hird and Yung 1987 and 1989) have reported the use of *proximity transducers* for measuring strains in triaxial soil specimens. *The Hall Effect gauge* was developed by Clayton and Khartrush (1986), in which the Hall Effect principle is used to measure the deformations. *The local deformation transducer (LDT)*, developed by Tatsuoka *et al*. (1990), 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 pseudo-hinged mechanisms attached to the circumference of the specimen. The operation principle of this transducer is that the 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.

Most of the sophisticated devices reported above are expensive and involve complicated mechanisms to fix around the triaxial sample. In addition, some of the devices are heavy that lead to disturbance of soil samples. Hence, there is a need to develop simple and inexpensive technique to measure the strains and hence the soil stiffness at small strain levels. This paper presents a new technique to measure strains in triaxial specimens by fixing strain gauges on the triaxial sample. The effective confining stress was applied to the sample by vacuum confinement. The results obtained from the on-sample strain gauges were compared with those measured from a state-of-the-art submersible LVDT.

Experimental Procedure

Vacuum Confinement Technique

In the present investigation, an attempt is made to measure the axial strains developed during the shearing stage of a triaxial sample by fixing strain gauges on the sample. 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 sample is allowed to consolidate. The effective confining stress induced to the sample is given by

$$\sigma_3' = \sigma_3 - u = p \tag{1}$$

If strain gauges are to be fixed on the sample, when the cell water is present, they have to work under water. In addition, taking out the electrical cables from the triaxial cell without any water leakage requires sophisticated sample-access rings. In order to eliminate these requirements and simplify the procedure, the effective confining stress is achieved by vacuum confinement. In this technique the cell pressure σ_3 is kept zero and pore pressure of $u = (-p)$ is applied to the sample. The effective stress induced to the sample will now become,

$$\sigma_3' = \sigma_3 - u = p \tag{2}$$

which is the same as Eqn. (1). The negative pressure is applied by vacuum and the magnitude of effective confinement at any point in the triaxial sample is expected to be the same as the vacuum applied to the sample. The validity of this method is evaluated through the experimental program described below.

Experimental Set-up

The experimental set-up used to apply the effective confining stress through vacuum confinement is shown in Figure 1. The conventional triaxial base pedestal was used to keep the test specimen. The test specimen was prepared under saturated condition as per IS: 2720-Part 11 (1993). The bottom of the sample was connected to a burette that was filled with deaired water. The entire water line was carefully de-aired during the sample preparation phase itself so that cavitation is eliminated during the application of suction. The open end of the burette was connected to a vacuum pump via a vacuum regulator with an indicator so that the volume change that occurs in the sample at any stage of the test can be easily measured from the burette reading. The regulator has the capability of regulating and maintaining vacuum to the required value at an accuracy of 1.3 kPa.

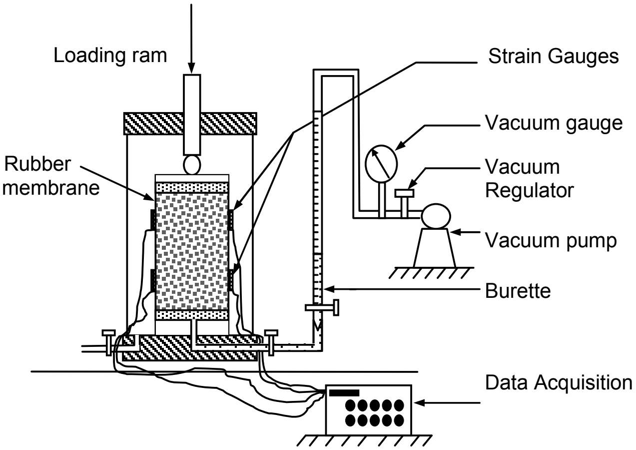


Fig. 1 Schematic of the Experimental Set-up

As the sample is free from cell pressure, it is free to access and any type of on-sample transducers could be fixed on the sample without difficulty**.** The triaxial cell cover is not essential but may be adopted for aligning the load axially**.** The photographic view of the experimental set-up is shown in Figure 2 in which the sample is under vacuum confinement, as described above. Once the consolidation was over, the strain gauges were glued on the triaxial sample using an adhesive. Four strain gauges were fixed and the average value was used for computation of strain. In the present study, foil type strain gauges were used which has resistance of 119.5 to 119.9 ohms with gauge factor varying from 1.9 to 2.3. The gauge length of the strain gauge is 10 mm. It was connected with the strain recorder with a gauge resistance of 100 to 10000 ohms.

Soils used and sample preparation

In order to evaluate the validity of the proposed procedure, two types of soils such as Ennore sand and Kaolinite clay were used. The index properties of the soils are listed in Table 1. The sand is classified as SW and the kaolinite is classified as CL, as per unified soil classification system.

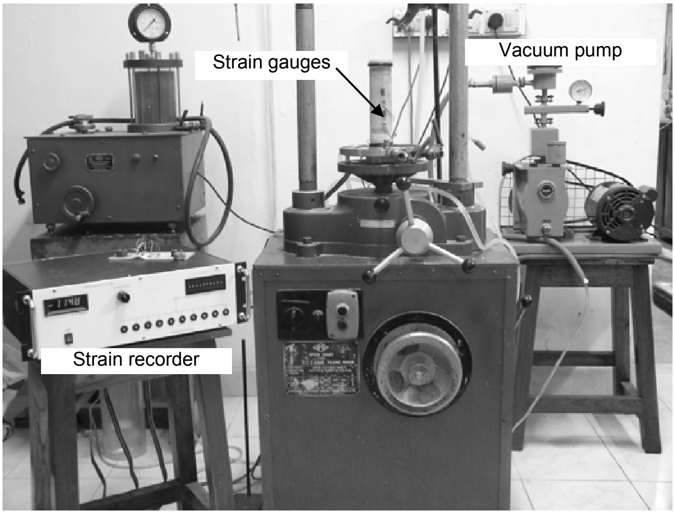


Fig. 2 Photograph of the Experimental Set-up in which the Sample is under Vacuum Confinement and Instrumented with Strain Gauges

Table 1 Properties of Soils Used

Material	*Property*	*Value*
Ennore Sand	Specific gravity	2.63
	D_{60} (mm)	1.35
	D_{30} (mm)	0.55
	D_{10} (mm)	0.21
	Uniformity coefficient, C_u	6.43
	Coefficient of curvature, C_c	1.07
	Maximum void ratio, e_{max}	0.78
	Minimum void ratio, e_{min}	0.53
Kaolinite Clay	Specific gravity	2.65
	Liquid limit, w_l (%)	50
	Plastic limit, w_p (%)	30
	Plasticity Index (%)	20
	Sand (%)	0
	Silt size (%)	33
	Clay size (%)	67

Tests on sand were conducted on saturated samples at a relative density of 60% under drained conditions. The required density values were achieved by careful tamping. The clay samples were prepared by consolidating the soil from slurry state. Kaolinite clay was mixed with water and made into slurry of water content of about 1.5 times the liquid limit water content. The slurry was then consolidated in a mould of 50 mm diameter and 150 mm height to a consolidation pressure of 50 kPa. Once the consolidation was over, triaxial samples were trimmed to 50 mm diameter using a soil lathe. These samples were set-up in the triaxial cell and experiments were conducted under drained and undrained conditions. All triaxial tests carried out in the present investigation were on samples of 50 mm diameter and 125 mm height.

Experimental Program to Validate Vacuum Confinement Technique

Before proceeding to the actual on-sample strain measurements using strain gauges, a series of experiments were carried out with the aim of proving, through experiments, that the application of vacuum confinement to the triaxial sample has the same effect as that by conventional cell pressure application. Experiments were carried out on Ennore sand under drained condition at effective confining pressures of 25 kPa, 50 kPa and 75 kPa by the proposed vacuum confining technique. These test results were compared with the results of experiments in which the same magnitude of effective confining pressures were applied by the conventional cell pressure application system using water pressure. In this series of experiments, the strain measurements were made externally by placing a dial gauge over the triaxial cell.

For the Kaolinite clay, consolidated drained and consolidated undrained tests were conducted at confining pressures of 25 kPa, 50 kPa and 75 kPa. For the consolidated drained test, a deformation rate of 0.02% per minute was adopted that was calculated as per standard procedures (Head 1998). During the shearing stage, volume change was measured using the burette that was connected to the sample. For the undrained test, pore pressure was not measured, as they are negative. If pore pressure data are needed, devices capable of measuring negative pressures need to be adopted. A deformation rate of 0.1% per minute was adopted for undrained tests.

Experimental Program for On-sample Strain Measurements

In this series of experiments, on-sample strain measurements were made using strain gauges affixed on the triaxial sample, which is under vacuum confinement. During the test, both on-sample strain measurements and the external strain measurements were made using the strain gauges and external dial gauge, respectively. The testing procedures are exactly same as that explained in the previous section with the exception that in this series strain measurements were made using on-sample strain gauges in addition to external measurements.

In order to evaluate the validity of the strain measurements using strain gauges, a comparative study was performed between the strains measured using strain gauges with the on sample strain measurements using on-sample LVDT, supplied by M/s Wykeham Farrance, UK, which is similar that reported by Atkinson (2000). The LVDT was of submersible type that can resolve the deformation in the linear range of ± 5 mm.

Results and Discussions

Validation of Vacuum Confinement Technique

Figures 3 to 5 compares the stress-strain and volume change-strain curves obtained when the effective confining stress was applied by vacuum and cell pressure for Ennore sand under drained condition and for Kaolinite clay under drained and undrained conditions, respectively.

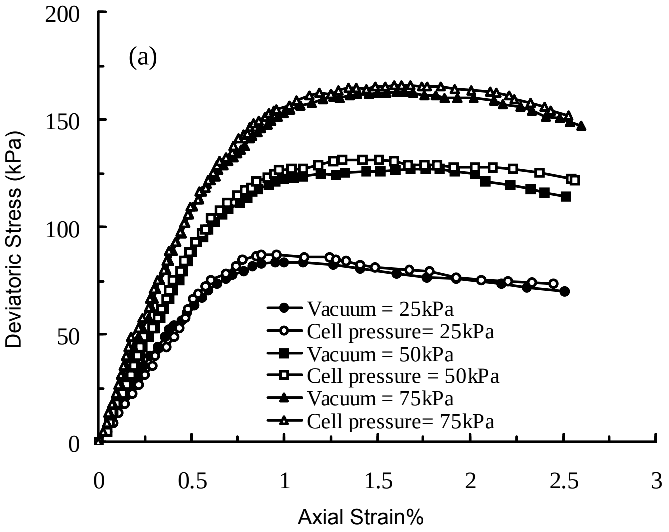


Fig. 3 (a) Comparison of Stress-Strain Curves for Ennore Sand Confined with Vacuum and Cell Pressure under Drained Condition

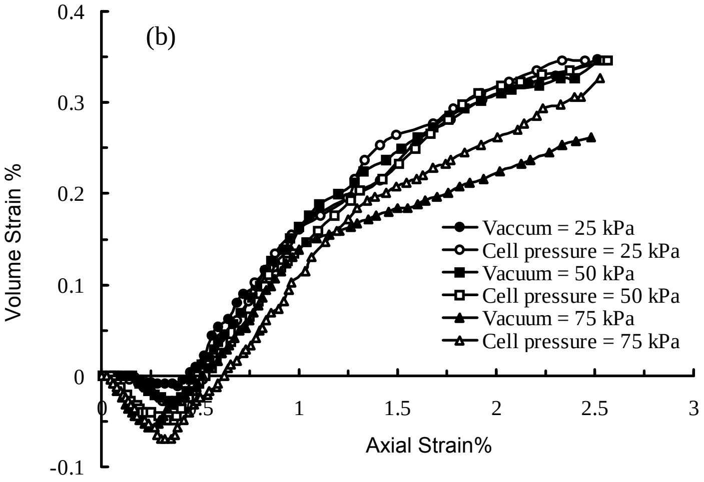


Fig. 3 (b) Comparison of Volume Change-Strain Curves for Ennore Sand Confined with Vacuum and Cell Pressure under Drained Condition

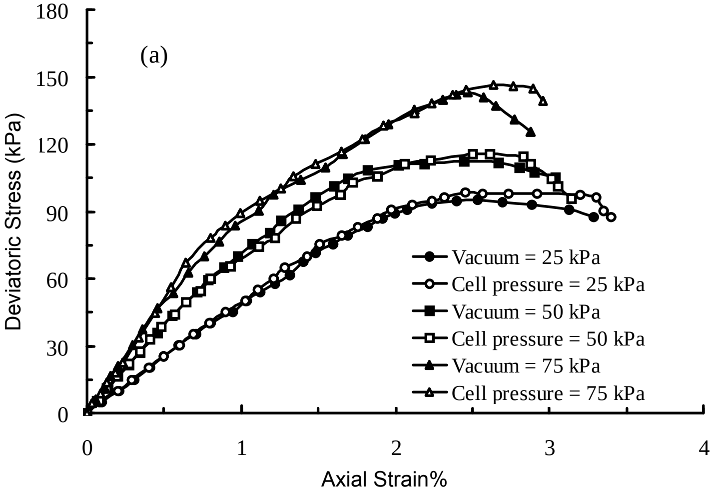


Fig. 4 (a) Comparison of Stress-Strain Curves for Kaolinite Clay Confined with Vacuum and Cell Pressure under Drained Condition

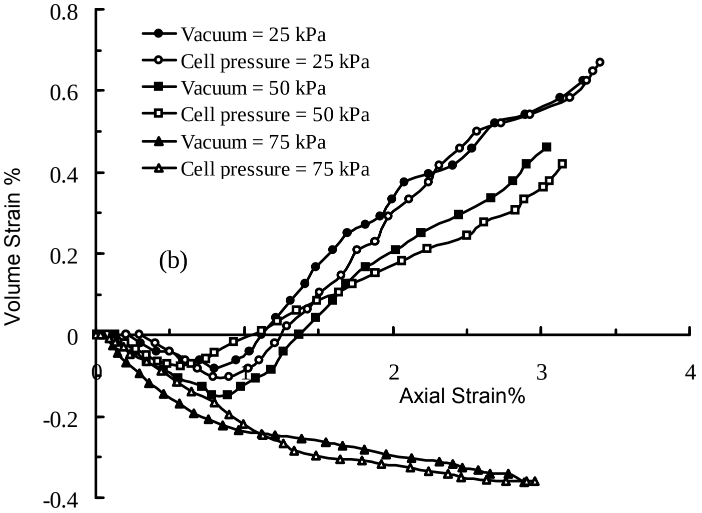


Fig. 4 (b) Comparison of Volume Change-Strain Curves for Kaolinite Clay Confined with Vacuum and Cell Pressure under Drained Condition

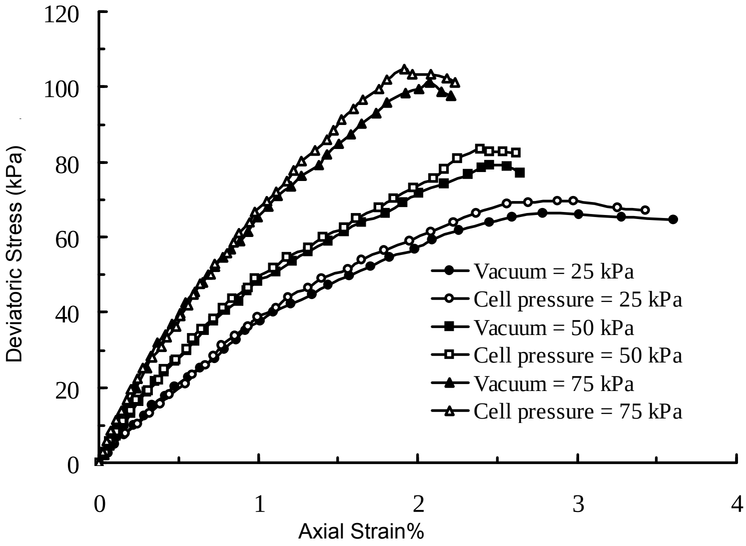


Fig. 5 Comparison of Stress-Strain Curves for Kaolinite Clay Confined with Vacuum and Cell Pressure under Undrained Condition

The plots clearly show that the stress-strain curves are practically identical for different confining pressures. The agreement between the volume change-strain curves is also excellent. This is possible only if the effective stress induced to the sample by both the methods is the same. From the above observations, it can be concluded that the application of negative pressure to the pore phase of the soil sample has the same effect of applying a positive cell pressure in triaxial testing, after consolidation.

However, it is essential to evaluate the small strain behavior of soils when the vacuum is used for confinement. Guided by this, further investigations were carried out to evaluate the stress-strain behaviour in the small strain region using on-sample measurements of strain and the results are reported in the subsequent sections.

Results of On-sample Strain Measurements

Typical stress-strain curves obtained by on-sample strain measurements using strain gauges and by external strain measurements using dial gauge on Ennore sand and Kaolinite clay under different drainage conditions are shown in the Figure 6 (a, b and c) for different confining pressures using vacuum confinement technique.

From the figure, it can be seen that the external dial gauge records much larger strain compared to the strain gauges mounted on the sample for the same deviatoric stress. This is attributed to the accumulation of various errors involved in external strain measurements (Baldi *et al.* 1988; Atkinson and Sallfors, 1991).

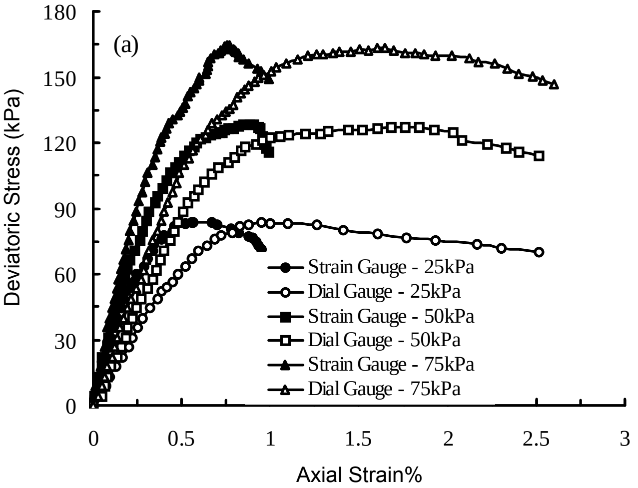


Fig. 6 (a) Stress-Strain Curves Obtained from On-Sample Strain Measurements using Strain Gauges and External Strain Measurement using Dial Gauge at Different Confining Pressures for Ennore Sand under Drained Condition

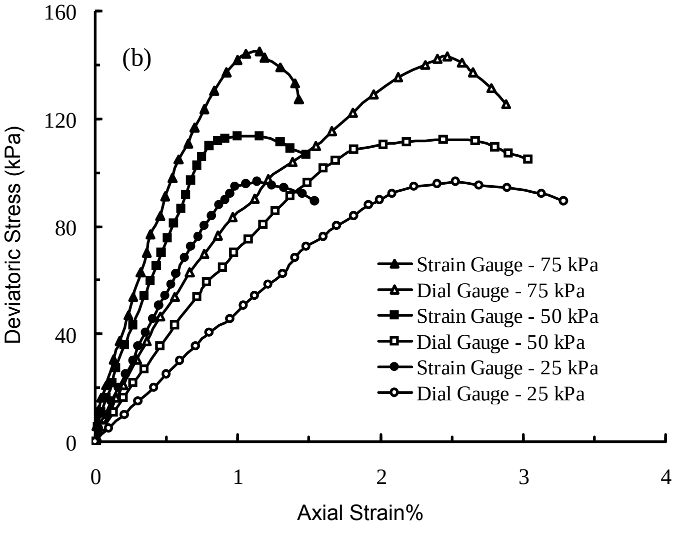


Fig. 6 (b) Stress-strain Curves Obtained from On-sample Strain Measurements using Strain Gauges and External Strain Measurement using Dial Gauge at Different Confining Pressures for Kaolinite Clay under Drained Condition

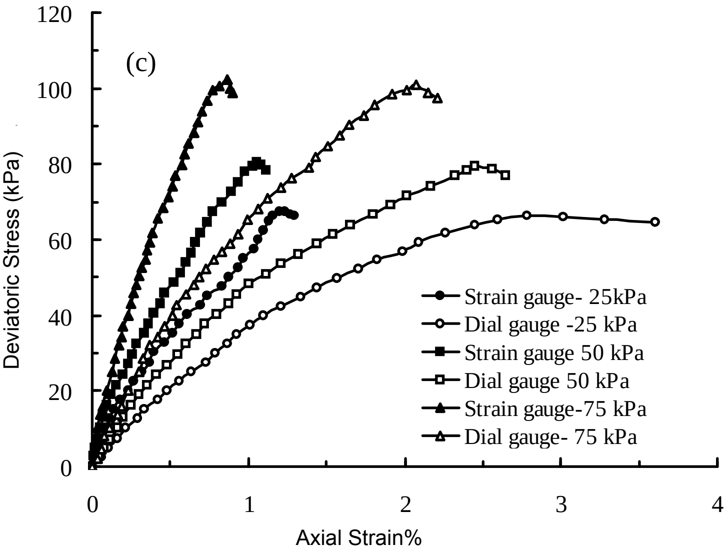


Fig. 6 (c) Stress-Strain Curves obtained from On-Sample Strain Measurements using Strain Gauges and External Strain Measurement using Dial Gauge at Different Confining Pressures for Kaolinite Clay under Undrained Condition

Table 2 Initial Tangent Modulus Computed based on Measurements from On-sample Strain Gauge and External Dial Gauge

Soil	*Drainage condition*	*σ_3' (kPa)*	*E_i (MPa)*	
			Strain gauges	*Dial gauge*
Ennore Sand	Drained	25	31.3	14.2
		50	36.4	18.2
		75	41.7	21.6
Kaolinite Clay	Drained	25	11.9	5
		50	17	7.6
		75	22.5	10.7
	Undrained	25	9.7	4
		50	15	6.8
		75	20	8.8

The Initial Tangent Modulus values (E_i) calculated for the Ennore sand and Kaolinite clay are tabulated in Table-2.

It can be seen that the E_i value calculated using the strains measured by the strain gauges are about 2 to 2.5 times higher than those calculated using external measurements. Similar results were reported in the literature (Lo Presti *et. al*. 1993; Burland 1989), which is consistent with the present study. Typical plot showing the variation of secant modulus with axial strain is shown in Figure 7. As expected the secant modulus values computed using the dial gauges mounted externally underestimate the values of secant modulus.

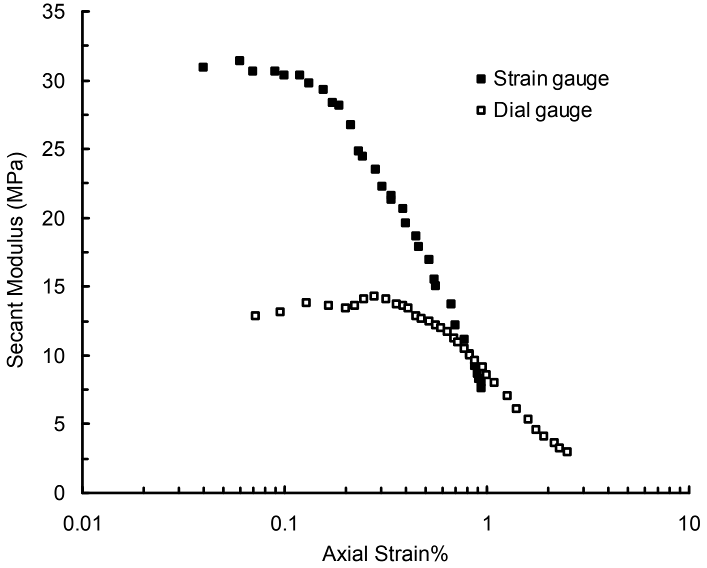


Fig. 7 Typical Variation of Secant Modulus with Axial Strain Computed Based on Measurements from On-Sample Strain Gauge and External Dial Gauge for Ennore Sand at Confining Pressure 25 Kpa

Comparison of Results with On-sample LVDT

Figure 8 shows the stress-strain curves obtained for Ennore sand under vacuum confinement of 50 kPa, during both loading and unloading stages. The strains were measured concurrently on the same sample using the on-sample LDVT and the on-sample strain gauge. The results agree very well suggesting that the strains measured using the strain gauges are reliable.

Figure 9a shows the stress-strain curves obtained on Ennore sand under a confining stress of 50 kPa that was achieved by vacuum confinement in one sample and by cell pressure application in the other sample. The strains developed on the sample confined with vacuum were measured by on-sample strain gauges where as those developed on the other sample was measured by on-sample LVDT. The stress-strain curves are very well comparable both in the loading and un-loading phases. Similar results are obtained for the Kaolinite clay under both drained and undrained conditions as can be seen in Figures 9b and 9c respectively. The initial tangent modulus values computed based on on-sample LVDT and strain gauges are compared in Figure 10. The values of initial tangent modulus from on-sample strain gauges and on-sample LVDT are very well comparable.

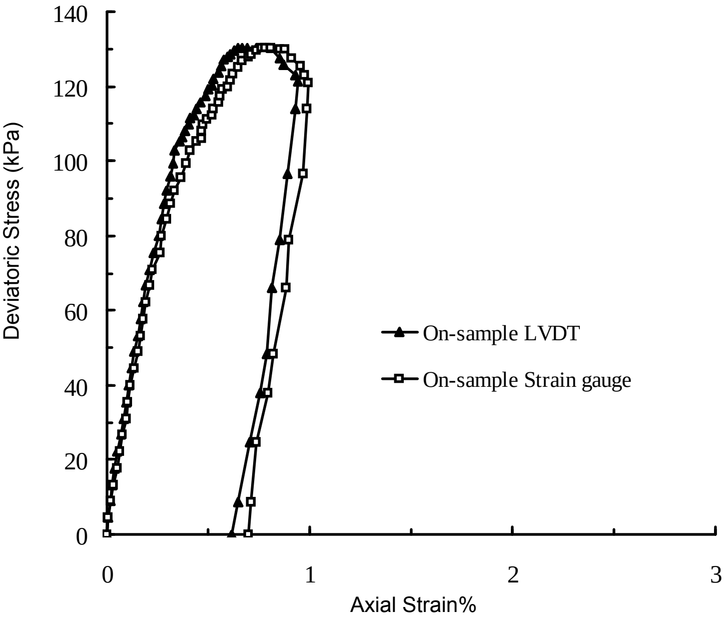


Fig. 8 Comparison of Stress-Strain Curves obtained based on Measurements using On-Sample Strain Gauges and On-Sample LVDT on Ennore Sand under Vacuum Confinement

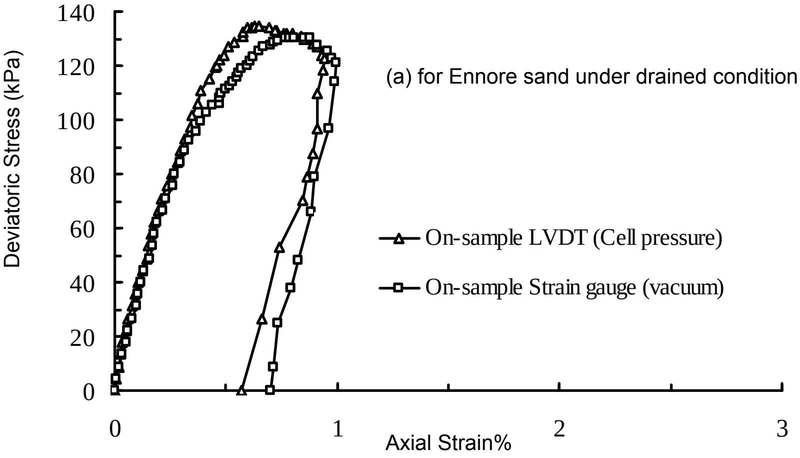
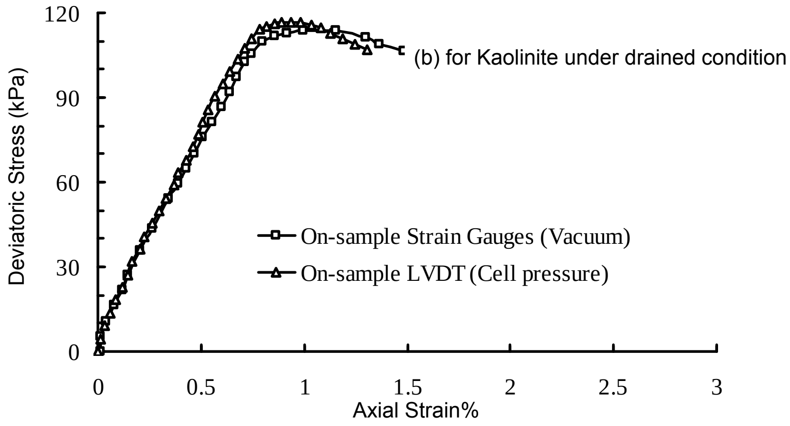


Fig. 9 Comparison of Stress-Strain Curves Obtained from On-Sample Strain Gauges and On-Sample LVDT on Samples Confined with Vacuum and Cell Pressure



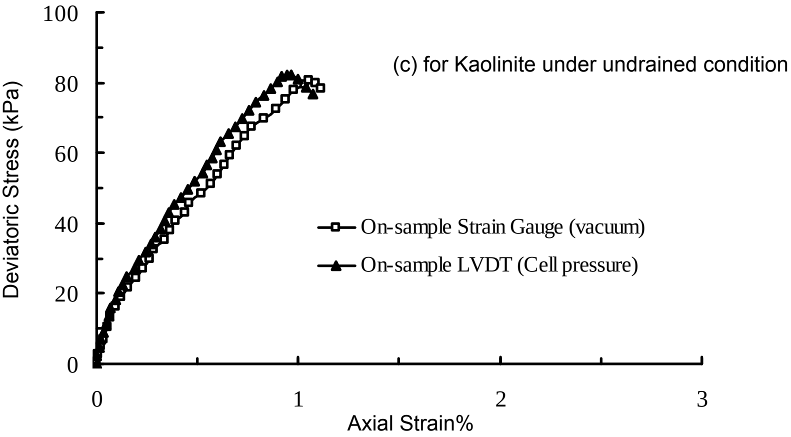


Fig. 9 Contd.. Comparison of Stress-Strain Curves Obtained from On-Sample Strain Gauges and On-Sample LVDT on Samples Confined with Vacuum and Cell Pressure

The above results proves that the strains developed in triaxial samples in the small strain range can be measured by fixing strain gauges after inducing the effective confining stress by applying negative pressure in the pore space. Though the suggested method has the limitation that a maximum confining stress of only 100 kPa could be achieved by vacuum, the method has the following advantages:

(i) As this technique requires no cell pressure application by water for the confinement of triaxial sample, the strain measurements are free from the effect of water pressure.

(ii) The fixing mechanism is very simple and sample disturbance due to fixing is eliminated. Therefore, the method can be adopted for soft clays which otherwise would undergo disturbance if heavy on-sample transducers are mounted.

(iii) The technique is simple and inexpensive when compared to many other devices.

(iv) As the strain gauges are fixed only after the consolidation is over, problems due to reduction in size of sample due to consolidation do not arise.

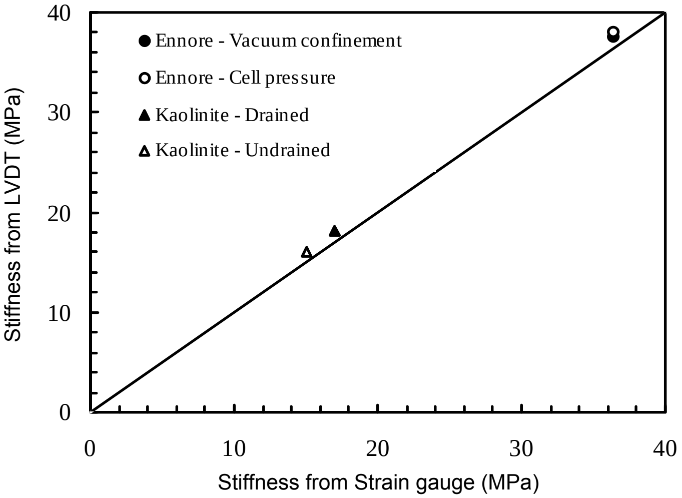


Fig. 10 Comparison of Initial Tangent Modulus obtained based on Measurements from On-Sample Strain Gauges and On-Sample LVDT

Conclusions

A new technique is proposed in this paper to measure the strains in triaxial samples using strain gauges. The stress-strain curves obtained by vacuum confinement technique are practically the same as those obtained by conventional cell pressure application for both sand and clay under different drainage conditions. As the sample under vacuum confinement is free to access, any sort of on-sample instrumentation can be made. In the present study, strain gauges were mounted on the sample for measuring the axial strains. Comparison with the on-sample strain measurement using the sophisticated state-of-the-art on-sample LVDT proves the validity of the proposed technique. The limitation of the proposed method is that an effective confining stress of only 100 kPa can be achieved by the vacuum confinement. Therefore, the method is suitable for practical situations where the effective overburden pressure in the ground is less than 100 kPa.

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