LOCAL STRAIN MEASUREMENTS IN TRIAXIAL TESTS USING ON-SAMPLE TRANSDUCERS

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ABSTRACT: Conventional triaxial tests mostly use external LVDTs attached to the actuator of automated triaxial system so as to measure the strain. However, these LVDTs measure the external strain applied and not the strain developed in the sample during shearing. This paper presents the use of on-sample transducer to measure localized strain in a soil sampled subjected to triaxial tests. Specimens prepared at two relative densities (30% and 90%) and three effective confining pressures (50, 100 and 150 kPa), were tested with displacement rates of 0.005 mm/min and 1.2 mm/min. It has been observed that the slower rate of loading poses significantly higher secant stiffness of soil. The use of on-sample transducers provide a wide range of strains i.e. from low strain (~ 1×10^{-3}%) to high strain (> 1%) and can be used to evaluate the modulus reduction curve over the investigated wide range of strain. The capability of on-sample transducers can be effectively harnessed to evaluate the maximum shear modulus of a soil.

Keywords: Local strain, triaxial tests, on-sample transducer, cohesionless soil

1 Introduction

The response of soils subjected to static and dynamic loading are highly dependent on the strains induced in the soils. The range of these strains caused by various sources such as earthquake, machine vibration and traffic, can be categorized into two sections namely low strain (i.e. from 0.0001% to 0.001%) and high strain (i.e. from 0.01% to 0.1%). The variations of soil stiffness over such a wide range of shear strain are generally represented by the modulus (stiffness) degradation curve (Fig. 1).

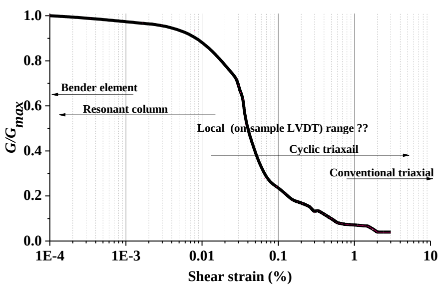

Fig. 1 Typical range of strain properties measured in laboratory (after Likitlersuang *et al*. 2013)

In soil dynamics and earthquake engineering, the small strain shear modulus (G_{max}), secant modulus (G) and the damping ratio (D) are important parameters in soil characterization (Likitlersuang *et al*. 2013). The small strain shear modulus of the soil is very important parameter to normalize the secant modulus obtained at different shear strains. To obtain the initial shear modulus, researchers have used resonant column and bender element tests. Recently, researchers have used on-sample linear variable differential transducers (LVDTs) to measure the local strain mobilized on the soil specimens (Cuccovillo and Coop, 1997; Santagata *et al*. 2005). Some studies on small strain stiffness of cohesive soil using on-sample LVDTs were reported, but, the same on cohesionless soil are limited. In this study, the small strain shear modulus of cohesionless soil was determined in laboratory using on-sample LVDTs. The soil specimens prepared at relative densities (D_r) of 30% and 90%, and confining pressures of 50, 100, 150 kPa were sheared at displacement rates of 0.005 mm/min and 1.2 mm/min.

2 Previous studies

Burland and Symes (1982) initially introduced and used the electrolytic liquid levels as horizontal inclinometers in a triaxial test apparatus for the measurement of local displacements and strains on soil specimens. Further, Symes and Burland (1984), Jardine *et al*. (1984; 1985), Cuccovillo and Coop (1997) and Santagata *et al*. (2005) have used different types of on-sample LVDTs on clay and sandy soil triaxial specimens, and reported undrained shear stiffness at a very small axial strain. Present study investigates the local strain (or, small strain) mobilized on the soil specimen during monotonic shearing.

3 Experimental Investigation

3.1 Soil characteristics

Brahmaputra sand (BS) obtained from Guwahati region

(Assam, India) has been used for the study. Particle size of BS (Fig. 2) was determined by conducting dry sieve analysis (IS: 2720, part-4) and classified them as poorly graded sand as per relevant standards (ASTM D2487; IS: 1498). It can be observed that the soil belongs to the category of severely liquefiable soils (Tsuchida, 1970; Xenaki and Athanasopoulos, 2003). Index properties of the soil such as minimum and maximum dry unit weight, specific gravity, Coefficient of curvature (C_c), Uniformity coefficient (C_u) were determined as per relevant standards (IS: 2720, part-3; IS: 2720, part-14) and are enlisted in Table 1.

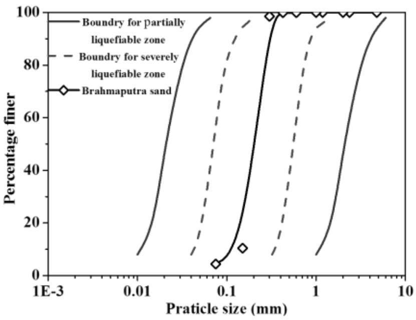

Fig. 2 Particle size distribution

Table 1 Physical properties of collected Brahmaputra sand

Unit weight (kN/m^3)		Specific Gravity	D_{10} (mm)	C_u	C_c
γ_{max}	γ_{min}				
16.84	13.85	2.7	0.13	1.47	1.09

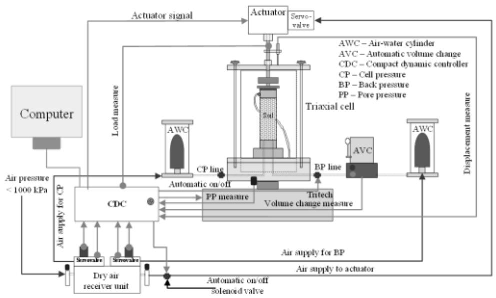

Fig. 3 Layout of cyclic triaxial test setup

3.2 Testing apparatus

An automated pneumatic controlled cyclic triaxial apparatus also facilitating monotonic triaxial tests, shown in Fig. 3, was used for the experimental investigations. It consists of a 100 kN capacity loading frame fitted with an actuator (±15 mm displacement range) operating over a frequency range of 0.01-10 Hz; a triaxial cell having (2000 kPa capacity), and an air compressor having a maximum capacity of 800 kPa. During monotonic compression shear, the shearing was done with upward movement of Tritech while actuator was fixed. Instrumentations available with the apparatus are: Linear Variable Differential Transducers (LVDT) of measuring displacement 30 mm; one submersible load cell of capacity 25 kN; three pressure transducers of 1000 kPa capacity to measure cell pressure, back pressure and pore-water pressure, and one volume change measuring device. The testing is controlled by a Compact Dynamic Controller (CDC) unit, which conveys the instructions provided by software and record the data by data logger.

3.3 Sample preparation

Dry pluviation technique (ASTM D3999) was adopted to prepare the cylindrical specimens of BS having 70 mm diameter and 140 mm height. A nominal vacuum pressure of 15-20 kPa has been used to maintain verticality of the specimen (Ishihara *et al.* 1978). In order to achieve a quick saturation, carbon dioxide was flushed through the specimen, for 10-15 minutes, with a pressure lesser than the applied cell pressure (CP), followed by flushing with de-aired water. To attain the saturation, the CP and back pressure (BP) were then gradually increased in stages while maintaining an almost constant differential pressure of 10 kPa and checking the pore pressure parameter (*B*) after each CP increment. At a BP of 200 kPa, the *B*-value was obtained to be greater than 0.96 and then saturation process was terminated. The test specimens were consolidated to the targeted effective stress levels, before the application of monotonic loading.

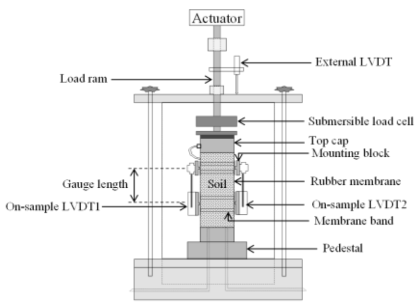

Fig. 4 Schematic diagram of the use of on-sample LVDTs

3.4 On-sample LVDTs

The local axial strain in a triaxial test specimen was measured using two linear variable displacement transducers (LVDTs), oriented vertically at the middle of the specimen as shown in Fig. 4. Each transducer was fixed on the specimens with two mounting blocks, which displaces relative to one another as the specimen deforms. The mounting block was fixed on the soil specimens with rubber band of the same stiffness as of membrane. The displacement recorded by transducers required to calculate the local axial strain uses the initial distance between mounting blocks i.e. the gauge length, rather than the initial specimen length.

4 Results and discussions

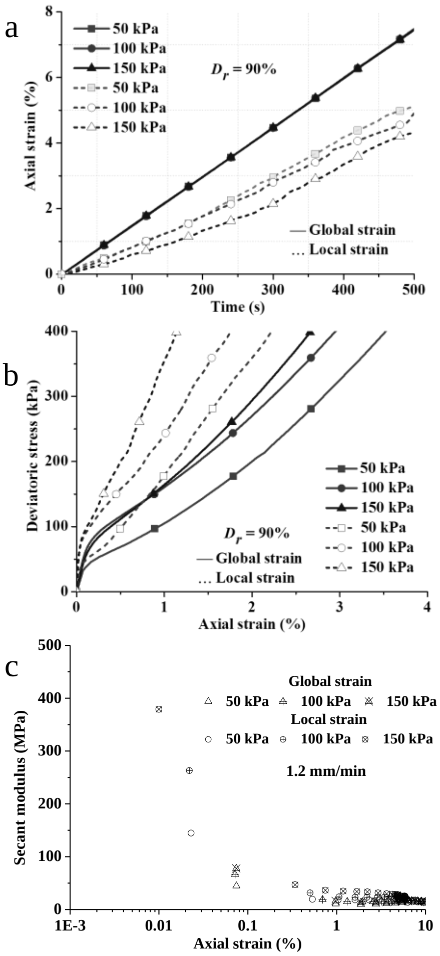

Fig. 5 Variation of (a) global and local strain (b) Stress-strain response and (c) soil stiffness with on-sample and external LVDTs

Static triaxial tests were performed on the sandy soil specimens to measure local strain using on-sample LVDTs. The specimens prepared at D_r = 30% and 90% was sheared at σ'_c = 50, 100, 150 kPa with displacement rate of 1.2 mm/min. For the sake of brevity, only the results for specimens with D_r = 90% are presented in this paper.

Local axial strain (based on the on-sample LVDTs) was evaluated and compared with the global axial strain (based on the external LVDT) as shown in Fig. 5. Figure 5a shows the variation of both global and local axial strain at D_r = 90% and at different confining pressures. It can be observed from Fig. 5a that the local axial strain varies nonlinearly in contrast to the global axial strain, the difference being approximately more than 50%. Figure 5a also hints that the axial strain applied at the top of the specimen does not get uniformly transferred throughout the length of the specimen. The stiffness evaluated at these local strains would be higher in comparison to the global axial strain, which can be represented as maximum stiffness of soil. Thus, of the measured local axial strain can be treated as small strain for the evaluation of maximum shear stiffness of the specimen. The local axial strain results have been evaluated based on the average of the records of both longitudinal deformation transducers LVDT-1 and LVDT-2, in order to eliminate any inaccuracy originating due to bedding error. The response of soil specimen during static compression shear has been depicted in Fig. 5b, which also indicates that the high deviatoric stress with on-sample (local strain) LVDTs results in higher initial soil stiffness than the global strain. Figure 5c shows secant shear modulus evaluated for different confining pressure at a displacement rate of 1.2 mm/min. It can be observed from Fig. 5c that the on-sample LVDTs capture relatively higher stiffness corresponding to local strain in comparison to the external LVDT.

Figure 6 presents the response of soil at two different displacement rates 0.005 mm/min and 1.2 mm/min. Figure 6a illustrate the stress-strain response of soil at two displacement rates, where significantly higher deviation of deviatoric stress was observed at lower displacement rate. It can also be observed from Fig. 6a that the deviatoric stress becomes higher from on-sample LVDT because of small local strain. Figure 6b depicts the secant modulus variation at two displacement rates which shows loading rate significantly affects the soil stiffness. Specimen sheared with low displacement rate shows higher shear stiffness using on-sample LVDTs, whereas the same showed by external LVDT are significantly lower value. Soil stiffness becomes higher at higher displacement rate (1.2 mm/min) which is reflected by external LVDT, whereas, with on-sample LVDTs the same shows higher values at low displacement rate (0.005 mm/min). Hence, it can be stated that on-sample transducer helps in more in-depth of measurement and understanding of the stiffness of the soil specimens.

4.1 Effect of rubber band attachment

Rubber band having identical stiffness as that of the rubber membrane was used for an effective attachment of the on-sample LVDTs with the soil specimen. In order to quantify the effect of the presence of rubber band on enhancing the stiffness of the soil specimen at the location of its attachment, a controlled test experiment was conducted in the absence of the rubber band attachment wherein the on-sample LVDTs were directly attached on the rubber membrane surrounding the soil specimen. Figure 7 shows that the deviatoric stress increased marginally by 3% in the presence of the rubber strip (sample prepared at 90% relative density). The specimens prepared at lower relative density and tested at lower confining stress may depict greater effect of rubber band attachment on the stress-strain response in comparison to the specimen prepared at higher relative density and higher confining stress which has to be further investigated.

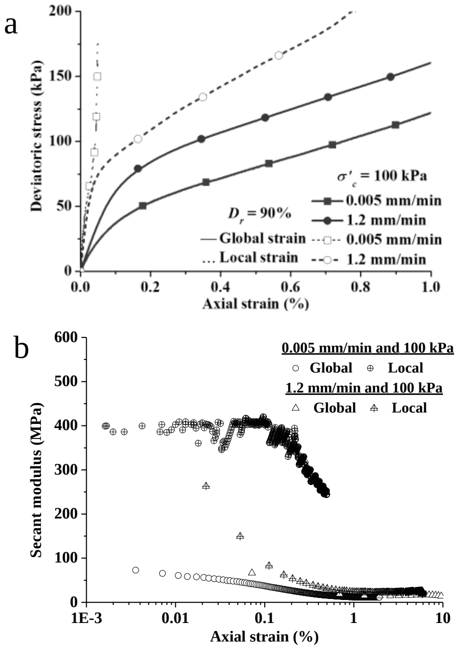

Fig. 6 Variation of (a) global and local stress-strain and (b) soil stiffness at two different displacement rates

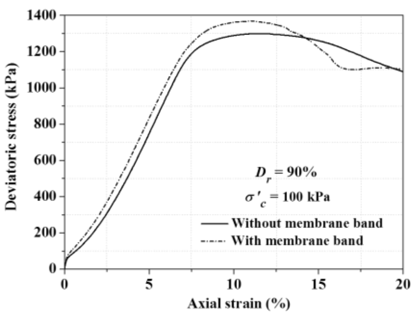

Fig. 7 Response of soil on the use of rubber strip

5 Conclusions

From the present study, it can be concluded that the on-sample transducers (LVDTs) play a significant role to eliminate the bedding error and to capture the small strain in term of local strain in the soil specimen. The use of on-sample LVDTs provide a wide range of strains i.e. from small strain (~ 1×10^{-3}%) to high strain (> 1%) and can be used to evaluate the modulus degradation curve over wide range of strain. The evaluated local strain (small strain) can be used to find out the maximum shear modulus. Membrane band used to hold the LVDTs reveal marginal effect on the stress response at higher relative density and confining pressure. Secant stiffness of soil is significantly affected by the rate of loading. Slower displacement rate of shearing exhibit significantly higher secant stiffness of soil specimens.

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