Influence of Failure Strain on Shear Strength of Soil

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Abstract: Strain is an important parameter measured to understand the stiffness characteristics of soil structure. Stress-strain graph obtained from triaxial compression test is widely being used as one of the precise method to measure the shear strength of soil. Soil is known for its poor tensile strength and derives it compressive strength mainly from its shear strength. Hence, the shear strength of soil is employed in designing the foundation of all the civil engineering structures, stability analysis of slopes, designing earth retaining walls, embankments and man-made excavation etc. The soil failures like landslides, differential settlement and earthquake induced liquefaction etc., causes dislocation and considerable changes in the strain. During laboratory triaxial compression test, some of the samples has shown strain hardening behavior (continuous taking load without fail). To understand the importance of strain when peak stress has not reached, two different failure strain conditions (i.e., 15 % and 20 %) were assumed for analysis. Shear strength parameters for both the failure conditions are evaluated and reported in this study.

Index Terms: **Strain, Shear Strength, Soil, Triaxial Test.**

1. INTRODUCTION

The shear strength is an internal resisting force to arrest movement of the soil particles. The shear stress is developed both by applied load and overlying soil load. Thus the shear failure of a soil mass occurs when the shear stresses induced due to the compressive loads exceed the shear strength of the soil. The soil resist external load by its shear resistance in terms of cohesion *'c'* (cementing or bonding between particles) and angle of internal friction 'ϕ' (interlocking of particles). The shear strength can be evaluated in terms of total stress and effective stress. In consolidated drained test, effective stress result is obtained because during shearing pore water is released. Whereas in consolidated un-drained test with measurement of pore water pressure the drainage valve is closed during shear and pore water pressure is noted, in which total and effective strength parameters can be obtained. The stresses induced in soil due to applied loads depend upon its stress-strain characteristic. The stress-strain behavior of soils is extremely complex and it depends upon a large number of factors, such as drainage condition, water content, void ratio, rate of loading and the stress path. However, simplifying assumptions are generally made in the analysis to obtain stresses. It is generally assumed that the soil mass is homogeneous and isotropic. The stress-strain relationship is assumed to be linear. The theory of elasticity is used to determine the stresses in the soil mass

The stress-strain relationship decides the shear strength of soil which may vary depending on density, mineralogy, grain size, shape of particle and drainage condition. Failure strain may vary with type of test and soil type.

Mohr-Coulomb failure theory is a valuable tool in analysis of the shear strength of soil. According to Mohr, the failure is caused by a critical combination of the normal and shear stress. Figure 1 shows the Mohr's graphical representation of stresses when a soil element is subjected to principal stresses (σ_1 and σ_3).

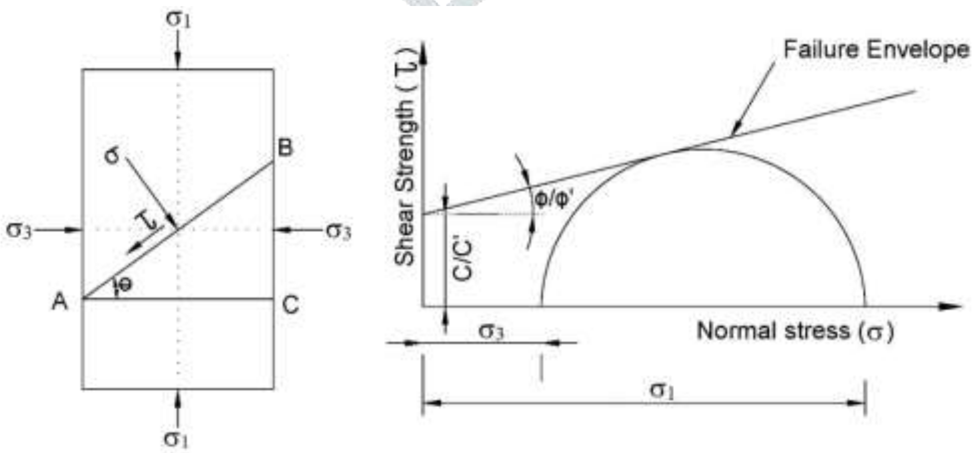


Fig. 1. Mohr's graphical representation of stresses

The Mohr-Coulomb failure envelope is represented by a straight line. It represents shearing resistance of soil linearly related with 'σ'. Here *'c'*, equals to the intercept on τ-axis and 'ϕ' is the angle which the envelope makes with σ-axis. The effective stress can be calculated by deducting the pore water pressure from the total stress.

Total shear strength, $\tau = c + \sigma \tan\phi$

Effective stress, $\sigma' = \sigma - u$

Effective shear strength, $\tau' = c' + \sigma' \tan\phi'$

Where,
c/c' = Cohesion for total and effective stress
ϕ/ϕ' = Angle of internal friction for total and effective stress
σ_3 = Minor principle stress
σ_1 = Major principle stress
σ_d = Deviator stress ($\sigma_d = \sigma_1 - \sigma_3$)
u = Pore water pressure

During shearing of soil samples in a triaxial test the deviator stress-strain graph may vary depending on the type of soil. Sandstone/cemented soil follows brittle failure and shear stress attains a peak value at a small strain, thereafter follows strain softening and reaches residual state. In case of loose or normally consolidated soil, the shear stress increases gradually and finally attain a residual strength. However, when the specimen is compacted more, strain hardening occurs at an early strain and shearing resistance of the soil increases upto the maximum resistance i.e., peak shear strength. In compacted soil after attaining the peak shear strength, specimen losses its dense state and follows strain softening behavior to reach at residual state. Figure 2 shows the deviator stress-strain curve for different soil.

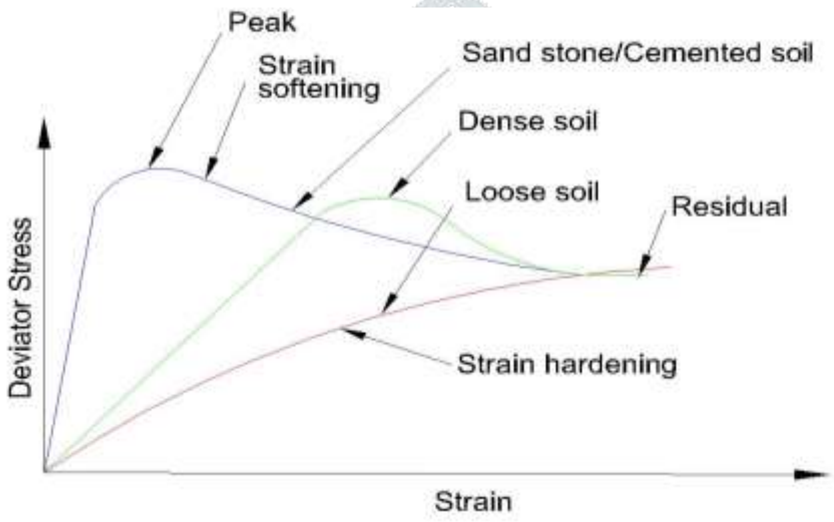


Fig. 2. Deviator stress- strain curve for different soil

2. STRAIN MEASURIMG INSTRUMENTS

Strain is a measure of deformation, and is defined as the change in length divided by its original length. Its unit is represented in percentage. In laboratory triaxial testing, the observation of the strain during loading is usually measured by any of the below mentioned instruments.

2.1 LVDT (Linear variable differential transformer)

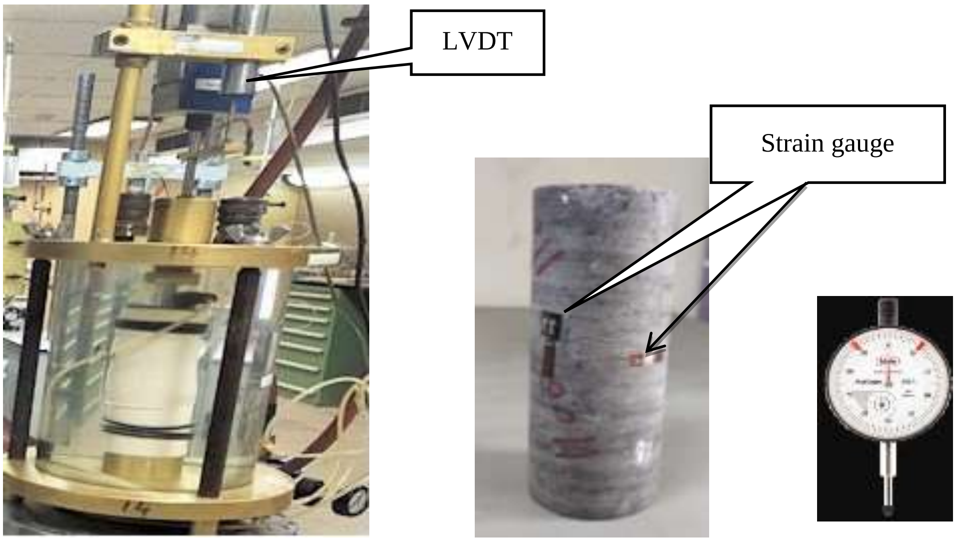
Linear Variable Displacement Transducers (LVDT) is an absolute measuring device that converts linear displacement into an electrical signal through the principle of mutual induction. It precisely measures the longitudinal strain of soil samples during triaxial tests. LVDT image is shown in Fig. 3(a). Least count is in the order of 0.001 mm and its measurement range varies from 0 to 40 mm. The device is connected with a data acquisition system (DAS). DAS is interfaced with a computer system along with software which displays the deformation parameters and graphs.

2.2 Strain Gauge

A strain gauge is a device which is used to measure longitudinal and lateral strain. The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. In a Wheatstone bridge circuit, the gauge is attached directly to the test specimen by a suitable adhesive. As the specimen is deformed, the foil is deformed, causing its electrical resistance to change. The strain experienced by the test specimen is transferred directly to the strain gauge with a linear change in electrical resistance. Strain gauge image is shown in Fig. 3(b)

2.3 Dial Gauge

Dial gauge is a mechanical instrument which is used to measure the axial deformation. The contact point of the spindle is placed outside the triaxial cell. While loading, spindle moves accordingly. From the main and revolution counter scale reading is noted at required intervals. Dial gauge image is shown in Fig. 3 (c).



(a) LVDT (b) Strain gauge (c) Dial gauge

Fig. 3. Strain measuring instruments

3. MATERIALS AND PREPARATION OF SPECIMENS

3.1 MATERIALS

To study the effect of strain on the shear strength of soil, a series of triaxial tests were conducted on MI and CI types of soil. Two different samples for each types of soil was considered. Four specimens for each samples were packed at respective saturated moisture content and 98 % of MDD with utmost care. Packed dry density measured after the test corroborates with the initial 98 % of MDD. The test results of soil classification, specific gravity, maximum dry density (MDD) and packed dry density in triaxial test are shown in Table 1.

Table 1. Basic properties of soil samples

Sample no.	BIS Soil Classification	Specific gravity (G)	MDD (g/cc)	Packed dry density (g/cc)
1	MI	2.71	1.552	1.52
2	MI	2.66	1.584	1.55
3	CI	2.68	1.687	1.65
4	CI	2.72	1.67	1.64

3.2 PREPARATION OF SPECIMENS

The nominal diameters of the specimens prepared are 38 mm and 76 mm in height as per IS-2720 (Part 12). It is also ensured that the ratio of diameter of specimen to maximum particle size should not be less than 5. Cylindrical specimen along with filter paper and porous stone is placed between pedestal and rigid cap, covered with latex membrane and secured with rubber O-ring. Transparent perspex cylinder is then secured on a triaxial cell apparatus which is filled with water (see Fig. 4).

Fig. 4. Preparation of specimen in triaxial cell apparatus

4. TESTING MACHINE AND TEST METHOD

To evaluate the shear strength of soil, a series of triaxial tests were conducted as per IS-2720 (Part 12) in semi-automatic triaxial compression testing machine. In doing so consolidated undrained (CU) test were carried out, with measurement of pore water pressure (u).

4.1 TESTING MACHINE

Semi-automatic triaxial compression testing machine consist of a strain controlled loading machine, a triaxial cell apparatus, and pressure chambers. Machines is attached with readout devices like load cell, LVDT and pressure transducer for measuring load, strain and stress respectively. Load cell has a least count of 0.01 kgf, its capacity varies from 0 to 250 kgf, LVDT (Linear variable differential transformer) with least count of 0.001 mm, its measuring range varies from 0 to 40 mm and pressure transducer with least count of 0.001 psi, its pressure range varies from 0 to 200 psi. All the three readouts devices are connected with a data acquisition system (DAS). DAS is interfaced with a computer system along with software which displays test parameters, graphs and diagnostic messages etc. Figure 5 shows the semi-automatic triaxial machine setup. Triaxial laboratory consists of four machines in one row to test the specimen at four different confining pressures to model the appropriate field condition.

Fig. 5. Semi-automatic triaxial machine setup

4.2 TEST METHOD

Total four numbers of specimens are tested for each sample at incremental confining pressures. Triaxial test involves four process 1) Preparing of specimen at desired density in a mould and packing of specimen in triaxial cell apparatus, 2) Checking the degree of saturation by B-parameter co-efficient, degree of saturation is preferably at 100% but should not be less than 90% for saturated condition (if needed assistant of back pressure system may be taken to saturate the specimen), 3) Consolidation at varying confining pressures (σ_3) and 4) Shearing the specimen using strain control compression machine.

Specimen in the triaxial cell apparatus is subjected to the confining pressure (σ_3) by applying pressure to water in the cell through air compressor. During the CU test condition, the specimen is allowed to consolidate in the first stage and drainage is permitted until the consolidation is completed. In the second stage, no drainage is permitted and specimen is sheared by operating strain controlled machine. Shear stress develop due to compressive loads exerted on the secured specimen due to movement of machine at desired strain rate. Deviator stress ($\sigma_d = \sigma_1 - \sigma_3$) is recorded in the DAS with the help of pressure transducer until the specimen fails (see Fig. 6).

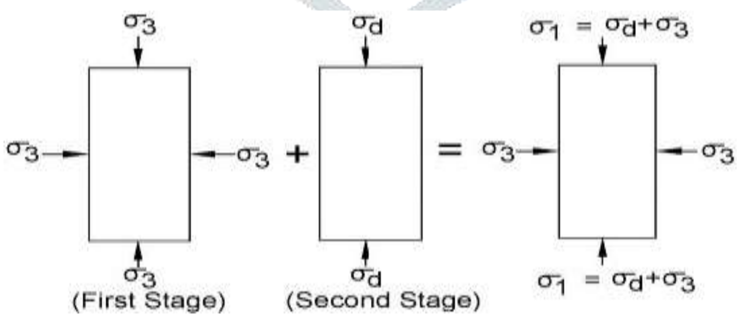


Fig. 6. Cylindrical specimen subjected to stresses in CU test

Here,

σ_1 = Major principle stress acting on major principle plane

σ_3 = Minor principle stress acting on minor principle plane (confining pressure)

σ_d = Deviator stress ($\sigma_d = \sigma_1 - \sigma_3$)

For obtaining a failure envelope or strength envelope, tests are performed on minimum three or more number of identical specimens at incremental confining pressure in the stress range of interest and deviator stress is recorded until the specimen fails. We get peak stress in all the specimens at incremental confining pressure before failure. Results are plotted and '*c*' and 'ϕ' are determined from the best fit line of modified failure envelope.

5. CALCULATIONS

The raw data is extracted from data acquisition system to plot the deviator stress-strain graph at incremental confining pressures (σ_3) as shown in Fig. 7. The maximum deviator stress is picked from stress-strain graph and 'p-q' graph is plotted to obtain a straight line, represented as modified failure envelope. The coordinates of the top point of the Mohr circle corresponding to the maximum stresses, are represented as 'p' and 'q'.

$$\text{Where,}\quad p = \frac{(\sigma 1+\sigma 3)}{2} \text{ and } q = \frac{(\sigma 1-\sigma 3)}{2} \qquad \text{... (1)}$$

A line is drawn through theses points to make an angle 'α' with the p-axis and an intercept 'a' on the q-axis and has the line equations as $q = a + p \tan\alpha$. Comparing with the coulomb equation of $\tau = c + \sigma \tan\phi$, the values of shear strength parameters 'c' and 'ϕ' are obtained from the intercept 'a' and slope 'α', using below equations.

$$c = a/\cos\phi \text{ and } \phi = \sin^{-1}(\tan\alpha) \qquad \text{... (2)}$$

Modified failure envelope can be drawn either in terms of total stresses or in terms of effective stresses. The equation obtained from the 'p-q' plot of total stresses and effective stresses are shown in Fig. 9 and Fig. 10. The two envelopes (total and effective) will give different values of 'a' and 'α', which help to evaluate the shear strength parameters (c, c', ϕ and ϕ').

6. RESULTS AND DISCUSSION

Four different samples whose peak stress has not reached were selected in this study. All the selected samples exhibited strain hardening behavior (continuous taking load without fail). Deviator stress (σ_d)-strain (%) graph, pore water pressure (u)-strain (%) graph and stress ratio (σ_1/σ_3)-strain (%) graph are presented only for sample no. 1 in Fig. 7, as similar profile were obtained for other sample no. from 2 to 4. For sample no. 1, it is observed that with an increase in strain, deviator stress increases and maximum pore water pressure attains at an early strain and decreases marginally thereafter. Similar results are also detected for other samples. Readings of deviator stress, pore pressure, maximum stresses (p/p′ and q/q′) for sample no.1 are tabulated in Table 2 and Table 3.

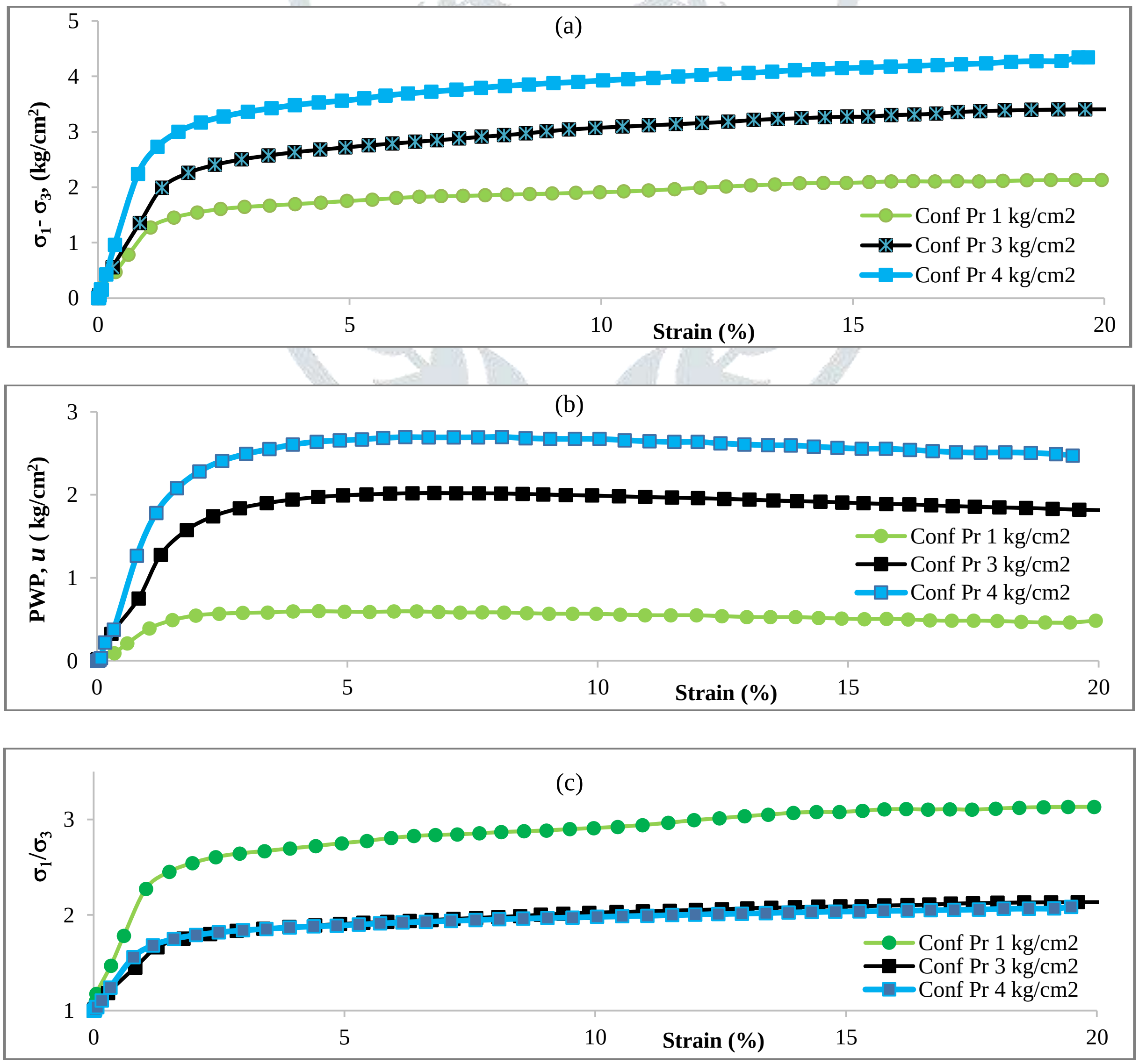


Fig. 7. (a) Deviator stress (σ_d) - strain (%) graph, (b) Pore water pressure (u)-strain (%) graph and (c) Stress ratio (σ_1/σ_3) -strain (%) graph for sample no. 1.

To understand the importance of strain when peak stress has not reached, two different strain conditions were analysed. Condition-A when failure strain considered is at 15 % and condition-B when failure stain considered is at 20 %. Four different samples whose peak stress has not reached were selected in study. Calculation of shear strength parameters (c, c', ϕ and ϕ') from 'p-q' plot (see Fig. 8 and Fig. 9) for both the conditions are presented in detail for sample no. 1 (see Table 2 and Table 3). Shear strength parameters for remaining samples no. from 2 to 4 are calculated in same line and tabulated in Table 4 and Table 5.

Table 2. Shear strength parameters obtained at 15 % strain for sample no. 1.

σ_3 (kg/cm^2)	Dev. stress, σ_d (kg/cm^2)	Strain (%)	PWP, u (kg/cm^2)	p	p'	q=q'
1.00	2.08	15	0.51	2.04	1.53	1.04
3.00	3.27	15	1.91	4.63	2.73	1.63
4.00	4.15	15	2.57	6.07	3.51	2.07
Obtain from Fig. 8 and Eq. 2	a (kg/cm^2) = 0.506 a' (kg/cm^2) = 0.234	c (kg/cm^2) = 0.524 c'(kg/cm^2) = 0.274	$\tan\alpha$ = 0.2531 $\tan\alpha'$= 0.5209		ϕ (Deg.) =14.70 ϕ'(Deg.) =31.39	

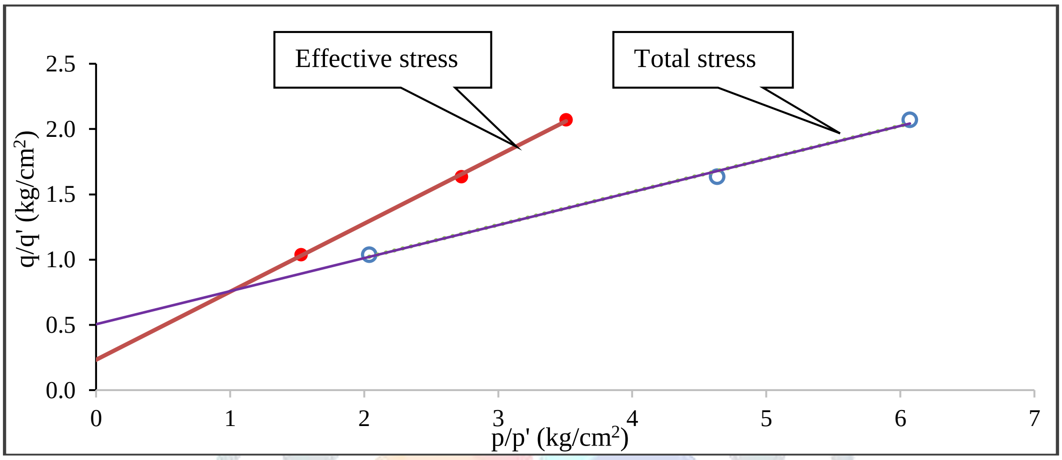


Fig. 8.'p-q' plot with strength envelop obtained at 15 % strain for sample no. 1

Table 3. Shear strength parameters obtained at 20 % strain for sample no. 1.

σ_3 (kg/cm^2)	Dev. Stress, σ_d (kg/cm^2)	Strain (%)	PWP, u (kg/cm^2)	p	p'	q=q'
1.00	2.13	20	0.48	2.07	1.58	1.07
3.00	3.40	20	1.82	4.70	2.88	1.70
4.00	4.34	20	2.47	6.17	3.70	2.17
Obtain from Fig. 9 and Eq. 2	a (kg/cm^2) = 0.499 a'(kg/cm^2) = 0.233	c (kg/cm^2) = 0.518 c'(kg/cm^2) = 0.273	$\tan\alpha$ = 0.2659 $\tan\alpha'$= 0.5194		ϕ (Deg.) =15.40 ϕ'(Deg.) =31.29	

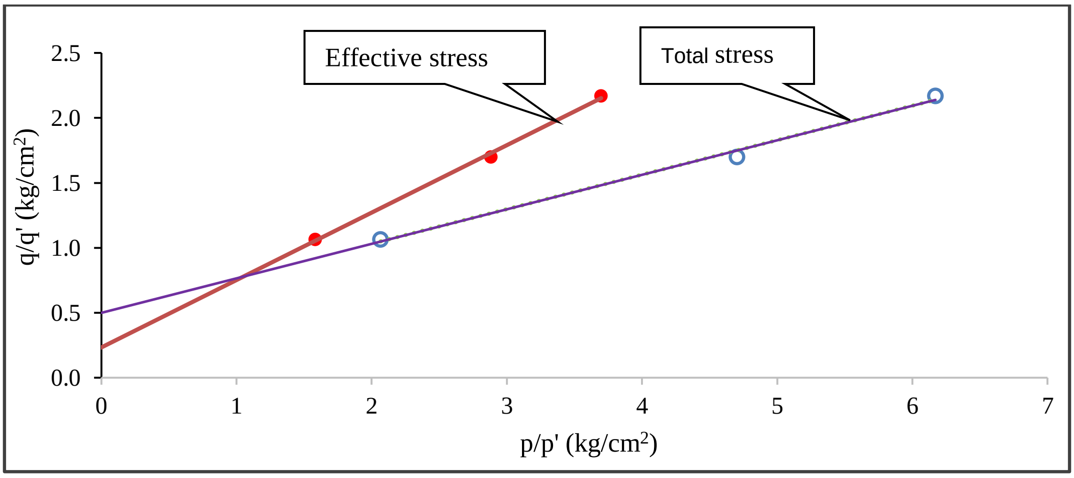


Fig. 9. 'p-q' plot with strength envelops obtained at 20 % strain for sample no. 1.

Assuming normal stress as 4 kg/cm^2 in all the samples the total and effective shear strength (τ & τ'), are calculated from shear strength parameters (c, c', ϕ and ϕ') obtained at two different strain conditions and their results are tabulated in Table 4 and Table 5. The difference in results between two different strain conditions are presented in Table 6.

Table 4. Total and effective shear strength calculated at 15 % strain, assuming normal stress as 4 kg/cm^2

Sample no.	Total shear strength			Effective shear strength		
	c (kg/cm^2)	ϕ (Deg)	τ (kg/cm^2)	c' (kg/cm^2)	ϕ' (Deg.)	τ' (kg/cm^2)
1	0.524	14.7	1.573	0.274	31.39	2.715
2	0.688	15.4	1.790	0.107	39.66	3.423
3	0.364	15.9	1.503	0.152	35.29	2.983
4	0.257	17.5	1.518	0.115	34.75	2.890

Table 5. Total and effective shear strength calculated at 20 % strain, assuming normal stress as 4 kg/cm^2

Sample no.	Total shear strength			Effective shear strength		
	c (kg/cm^2)	ϕ (Deg)	τ (kg/cm^2)	c' (kg/cm^2)	ϕ' (Deg.)	τ' (kg/cm^2)
1	0.518	15.4	1.620	0.273	31.29	2.704
2	0.698	15.6	1.815	0.101	39.42	3.389
3	0.395	15.6	1.512	0.168	34.90	2.958
4	0.294	17.2	1.532	0.170	33.68	2.836

Table 6. Difference in shear strength at 15 % and 20 % strain, assuming normal stress as 4 kg/cm^2

Sample No.	Total strength, τ (kg/cm^2)				Effective strength, τ (kg/cm^2)			
	At 15% strain	At 20% strain	Difference	Difference (%)	At 15% strain	At 20% strain	Difference	Difference (%)
1	1.573	1.620	-0.046	-2.9	2.715	2.704	0.011	0.4
2	1.790	1.815	-0.025	-1.4	3.423	3.389	0.034	1.0
3	1.503	1.512	-0.008	-0.6	2.983	2.958	0.025	0.8
4	1.518	1.532	-0.014	-0.9	2.890	2.836	0.054	1.9

Difference in the deviator stress obtained between 15 % and 20 % strain is found to be marginal at each confining pressures. Considering failure at 15 % axial strain, and comparing them with 20 % strain, the total shear strength gets reduced in the range of 0.6 % to 2.9 % and effective shear strength increased in the range of 0.4 % to 1.9 % when normal stress assumed is 4 kg/cm^2.

7. CONCLUSIONS

From the triaxial test conducted it is observed that the maximum pore water pressure attained at an early strain in comparison to deviator stress and decreases marginally thereafter. Difference in the deviator stress obtained between 15 % and 20 % strain is found to be marginal at each confining pressures. Considering failure at 15 % axial strain, and comparing them with 20 % strain, the total shear strength reduced marginally and effective shear strength increased marginally. Difference in deviator stress is marginal between 15 % and 20 % of axial strain and therefore considering maximum deviator stress (when sample has not reached peak stress) in either of the strain condition has minimal impact on the shear strength of soil. The shear stresses at failure depends upon the normal stresses on the potential failure plane. Failure occurs by critical combination of the normal and shear stresses. Cohesion is independent of normal stress and angle of internal friction between the particles is directly proportional to the normal stress.

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