Applicability of Hyperbolic Method for the Prediction of Shear Strength Parameters from Multistage Direct Shear Tests

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ABSTRACT: Measurement of shear strength through a conventional direct box shear test involves the requirement of at least three identical soil specimens. The collection of samples and carrying out a number of tests is very expensive and time consuming. Multistage shear strength test provides a faster method for the determination of shear strength parameters of a soil through tests on a single sample. Earlier studies conclusively proved the effective use of multistage triaxial compression test to predict the shear strength of soils. In this paper an attempt is made to study the possibility of using multistage box shear tests on a single soil sample instead of the conventional box shear tests to predict the shear strength. Undrained direct shear tests conducted on three different soil types - medium sand, air dried Cochin marine clay and red earth showed very good agreement between the results of multistage and conventional box shear tests. It has been brought out that the stress-strain curve in the shear box test follows the hyperbolic form throughout the test. Hence, it is possible to predict the failure shear stress, knowing the stress-strain relationship for the initial portion only. Making use of this behavior, multistage tests were carried out on single sample changing the normal load after obtaining initial portion of stress- strain behaviour. It has been brought out that the conventional box shear test could be approximated to multistage box shear test using only one soil sample, avoiding the variability between three or four soil samples used in a conventional test. The test procedure has the distinct advantage of requiring only one sample coupled with large saving in time without much compromise on the accuracy.

KEYWORDS: Box shear test, Multistage test, Shear strength, Medium sand, Marine clay, Red earth.

1. INTRODUCTION

The conventional method of measurement of shear strength involves testing of at least three identical soil specimens in the laboratory through triaxial compression test or direct shear test. It has been proved already that in situations where there is shortage of soil specimens, multistage test conducted on single soil specimen can give reasonably good values. De Beer (1950) was the first to apply the multistage principle to measure the shear strength characteristics of saturated soils in triaxial shear test. To obtain maximum amount of information from a limited number of tests and to eliminate the effect of soil variability, a multistage testing procedure was attempted by Kenny and Watson (1961) and Lumb (1964) in triaxial shear test.

Sridharan and Rao (1972) have shown that the pore pressure-strain relations also obey the rectangular hyperbola relations in the same way as the deviator stress- strain relations in a multistage triaxial shear test. The stress- strain as well as the pore pressure-strain relationships in multistage testing also shows essentially linear relationships on the transformed plot.

Kovari and Tisa (1975) have proposed a test method, designated as the multiple-stage triaxial test (MST) which is capable of deducing more sets of strength parameters from a single specimen and comprehending the full range of strength envelopes by using a few specimens. It has been proved that their MST method is a suitable substitute for the conventional single- stage triaxial test (SST) when a dry and hard rock specimen such as marble and sandstone is used. However, their test procedure may not be adequate for a saturated porous soft rock.

The triaxial test has usually been employed to characterize the mechanical properties of rock-like materials in a laboratory. This conventional method, called the single-stage triaxial test (SST) provides only a pair of peak and residual strengths from a single specimen. Therefore, it is very inconvenient in achieving the whole spectrum of mechanical characteristics of rock specimens whose amount is so limited due to geological conditions, etc. as reported by Akai et al. (1981). They have proved that MST (multistage test) method is a suitable substitute for the SST when dry and hard rock specimen such as marble or sandstone is used.

A series of multistage consolidated drained triaxial tests on unsaturated, residual soils from Hong Kong were carried out by Ho and Fredlund (1982).

The direct box shear test results on saturated glacial till specimens reported by Gan and Fredlund (1988) exhibit essentially linear failure envelopes with respect to the normal stress axis. The failure envelopes also show close agreement between the single-stage and multistage direct shear test results. According to them, this would indicate an acceptability of the multistage direct shear test technique for Indian head glacial till.

Nam et al. (2011) through his studies on undisturbed soil samples presented a comprehensive evaluation of the validity of using the multistage direct shear test as a rapid and practical method to determine the shear strength of unsaturated soils. Shear strength parameters obtained from the multistage tests were compared with those from conventional direct shear tests using multiple soil specimens. Results of drained direct shear test carried out by Hormdee et al. (2012) using the multistage technique demonstrate that it is possible and convenient to perform multistage shear test on compacted soil to measure shear strength.

Gan & Fredlund (1996) reported the use of single stage as well as multistage shearing in the triaxial and direct shearing tests. They found that multistage tests have some advantages over single stage shear tests because of the highly heterogeneous nature of the soils. Eventhough there are some limitations in direct shear test, some modification to the conventional test by multistage test has been suggested. This paper is an attempt to verify the possibility of using the results of multistage direct shear test conducted on a single specimen to predict the shear strength of a soil, since conducting a box shear test is much simpler and faster compared to the triaxial test.

2. MATERIALS AND METHODS

In the present study, three different types of soils were used - sand, air dried Cochin marine clay and red earth. River sand of medium fraction (425µm – 2mm) - as per the ASTM D 2487 - 11 and IS 1498-1970 classifications was used in the present study. Marine clay was collected from Kadavanthara in the Greater Cochin area on the Western coast of India, from bore holes advanced by shell and auger method. Air dried marine clay was prepared by spreading the representative samples of moist clay in large trays and dried by exposing it to sunlight. The lumps formed during drying were broken by a wooden mallet and passed through 425 µm sieve without any loss of material and then preserved in polythene bags.

Red earth soil, collected by open excavation, was dried, sieved through 425 µm sieve and was stored in polythene bags. The grain size distribution curves of these three different soil types are shown in Figure 1. The physical properties of the air dried Cochin marine clay and red earth are presented in Table 1.

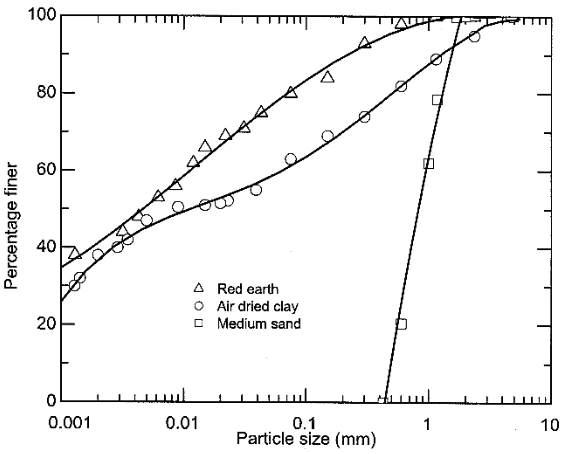

Figure 1 Grain size distribution curves

Table 1 Properties of air- dried marine clay and red earth

Properties		Air dried Cochin marine clay	Red earth
Liquid limit	(%)	50.0	55.0
Plastic limit	(%)	27.0	30.0
Plasticity index	(%)	23.0	25.0
Shrinkage limit	(%)	15.8	26.0
Optimum moisture content	(%)	23.8	24.0
Maximum dry unit weight	(kN/m^3)	15.3	16.0
Grain size distribution			
Sand 0.075 – 4.75 mm	(%)	41	19
Silt 0.002 – 0.075 mm	(%)	23	40
Clay <0.002 mm	(%)	36	41

3. PRINCIPLE OF MULTISTAGE SHEAR BOX TEST

Kondner (1963) has analysed the results of the consolidated–undrained triaxial compression tests conducted at various overconsolidation ratios under various rates of strain and shown that in terms of the hyperbolic stress-strain, it takes the form

$$\frac{\epsilon}{\sigma} = a + b\epsilon \quad \dots\dots\dots.(1)$$

and solving for the stress σ

$$\sigma = \frac{\epsilon}{a+b\epsilon} \dots\dots\dots\dots(2)$$

In terms of the deviator stress, the hyperbolic stress-strain relation for the tests analyzed takes the form of

$$\sigma_1 - \sigma_3 = \frac{\epsilon}{a+b\epsilon} \dots\dots\dots\dots.(3)$$

Where

σ_1 and σ_3 - the major and minor principal stresses

ϵ - the axial strain; and

a and b - constants whose values must be determined experimentally.

It can be transformed into the linear form

$$\frac{\epsilon}{\sigma_1-\sigma_3} = a + b\epsilon \dots\dots\dots\dots\dots\dots(4)$$

which is experimentally verified with a high degree of accuracy.

The ultimate values of the stresses, $\sigma_1$and σ_3, can be obtained by taking the limit of Eq. 3 as ε becomes very large or

$$(\sigma_1 - \sigma_3)_{ult} = \lim_{\epsilon\to\infty}(\sigma_1 - \sigma_3) = \frac{1}{b} \dots\dots(5)$$

The graphical representation of $\epsilon/(\sigma_1 - \sigma_3)$ versus ϵ yields a straight line and the slope of the line give the value of b. This procedure of linearization enables the prediction of the peak value of shear resistance when the slope of the transformed plot of the stress – strain curve is known. It was also found by Kondner (1963) that the predicted and observed values show good relation.

4. TEST PROCEDURE

Direct shear box tests were conducted as per the procedure given in IS 2720-13 on air dried marine clay/red earth samples prepared at optimum moisture content and maximum dry unit weight (Table 1) and, in case of medium sand, at maximum dry unit weight of 16.2 kN/m^3. The conventional shear box tests were conducted on identical samples, at normal loads of 50, 100, 150 and 200 kN/m^2.

In the multistage shear test conducted in the standard shear box, the normal load is applied on the specimen prepared at the maximum dry unit weight, determined as per ASTM D 698-12. As the shear force is applied and the test is in progress, a plot between horizontal displacement and strain divided by shear stress is made, so that a straight line is obtained. Once the straight line is clearly established, next increment of normal load is applied and continued till the $\epsilon/(\epsilon/\sigma))$ plot gives a straight line. The process is repeated for subsequent normal loads also.Hence a single sample is sufficient to carry out four to six stages (with different normal loads) in the case of a direct shear test also.

5. RESULTS AND DISCUSSIONS

Figure 2 shows a typical shear stress – shear strain curves of single stage box shear tests (conventional test) on four identical samples of medium sand at dense state (unit weight of 16.2 kN/m^3). These stress-strain plots can be approximated to a rectangular hyperbola.

The same set of experimental data, if plotted between ϵ and $\epsilon/_{\sigma}$ results in four different straight lines as shown in Figure 3. This procedure of linearization enables the prediction of peak value of shear resistance when the transformed plot of stress- strain curve is known.

In the multistage shear test an identical sample of medium sand was placed in the shear box apparatus and the first normal load of 50 kN/m^2 was applied. The horizontal strain was applied upto 10% shear strain of conventional shear box test and the corresponding shear stress was obtained. Then the second normal load of 100 kN/m^2 was applied after releasing the shear stress keeping the residual shear

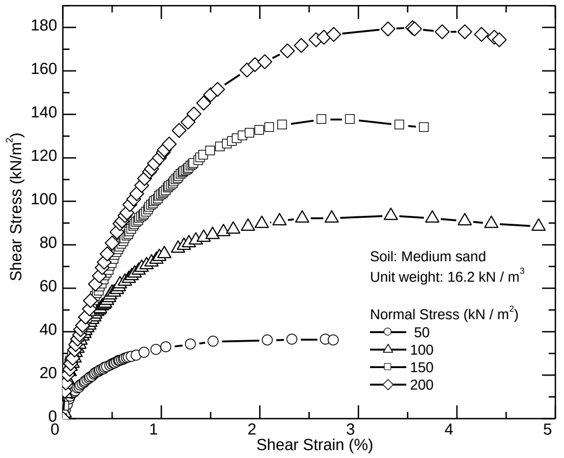

Figure 2 Shear stress – shear strain curves from conventional box shear test (medium sand)

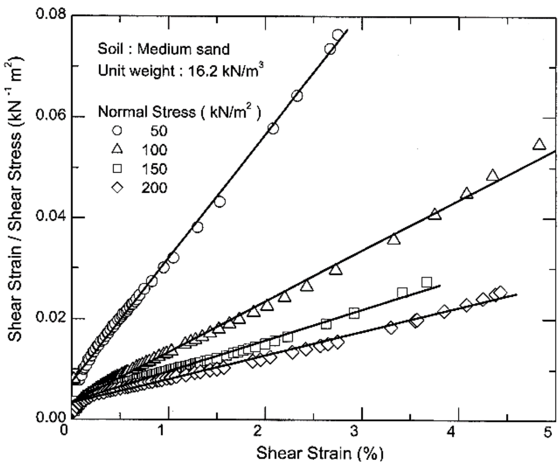

Figure 3 Transformed stress-strain curves for medium sand from conventional box shear test

strain present while releasing the shear stress. The procedure was repeated for different normal loads and the corresponding shear stress was obtained. The shear stress - shear strain plot was made ignoring the residual strain during each stage of the multistage test, and presented as Figure 4. It is seen that at every stage, the stress – strain plot shows a hyperbolic relationship. Figure 5 shows the transformed hyperbolic stress- strain plots for the same data given above (Figure 4).

To verify the validity of this technique, tests were also conducted on two other soils, namely, air-dried Cochin marine clay and red earth. Figure 6 shows the stress – strain curves obtained by the conventional shear box tests on Cochin marine clay (air dried) and the corresponding transformed hyperbolic stress-strain plots are presented in Figure 7. Figure 8 represents the stress- strain curves for the multistage test conducted on the air dried Cochin marine clay. Experimental data of Figure 8 are plotted in the transformed form (Eq. 4) and is given in Figure 9.

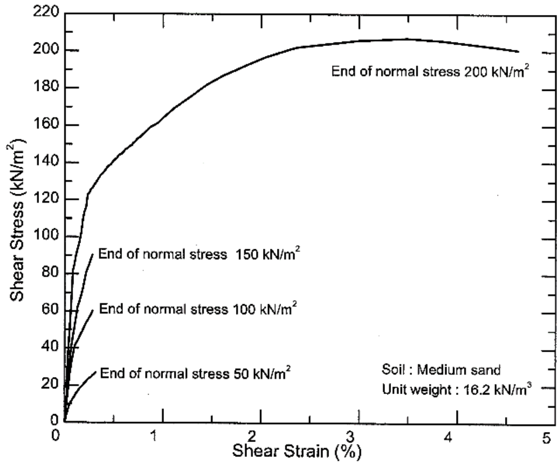

Figure 4 Shear stress – Shear strain curves from multistage box shear test (medium sand)

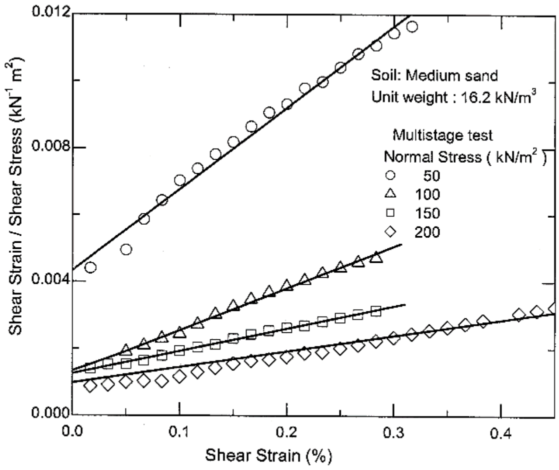

Figure 5 Transformed stress-strain curves from multistage box shear test (medium sand)

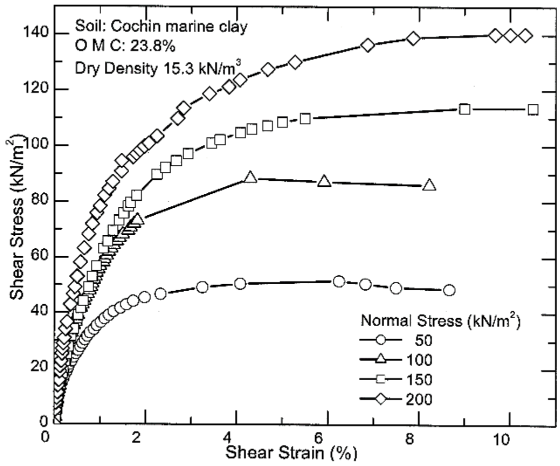

Figure 6 Shear stress – Shear strain curves from conventional box shear test (Cochin marine clay)

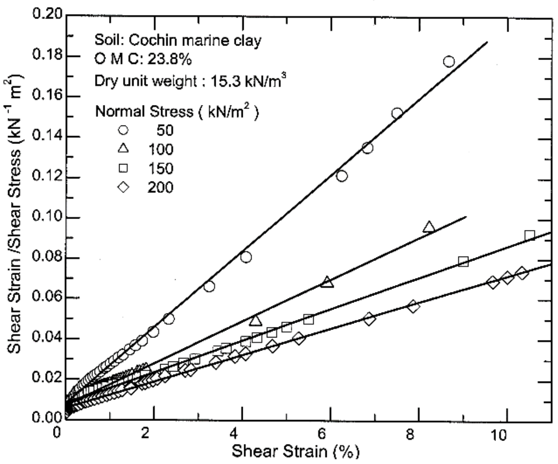

Figure 7 Transformed stress-strain curves from conventional box shear test (Cochin marine clay)

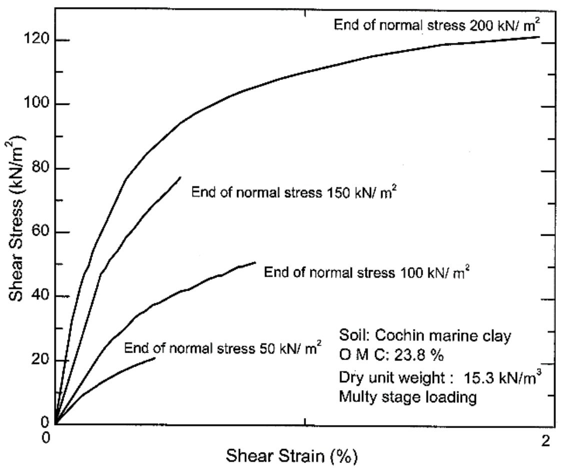

Figure 8 Shear stress – Shear strain Curve from multistage box shear test (Cochin marine clay)

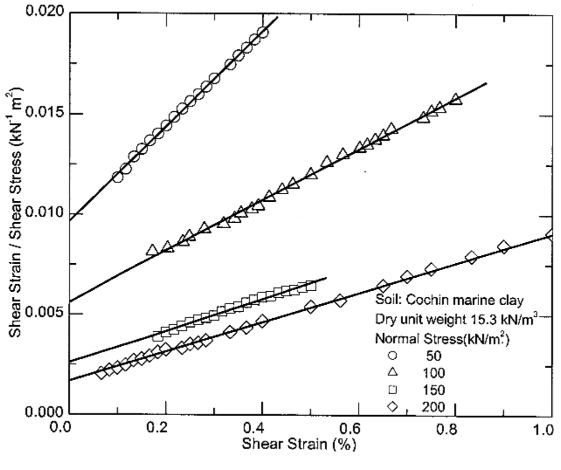

Figure 9 Transformed stress-strain curves from multistage box shear test (Cochin marine clay)

The same set of tests was repeated for a third soil ie, red earth. Figure10 shows the stress – strain curves obtained by the conventional shear box tests on red earth and the corresponding transformed hyperbolic stress-strain plots are presented in Figure 11.

Figure12 represents the stress- strain curves for the multistage test conducted on the same red earth and its transformed plots given in Figure 13.From the results of the conventional and multistage box shear tests on the above three soils - medium sand, air dried Cochin marine clay and red earth, it can be concluded that hyperbolic relations are valid for soils of different geological origin.

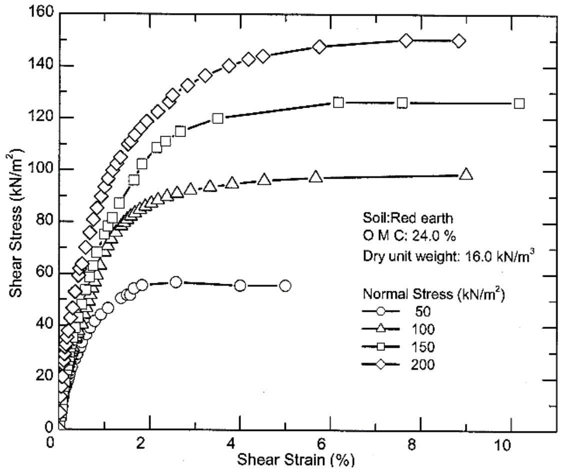

Figure 10 Shear stress – Shear strain Curves from conventional box shear test (red earth)

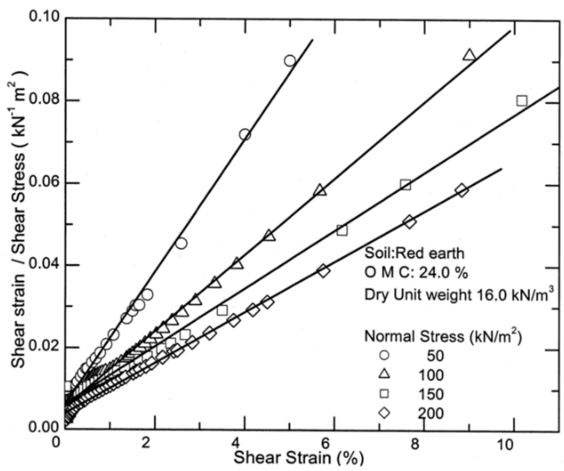

Figure 11 Transformed stress-strain curves from conventional box shear test (red earth)

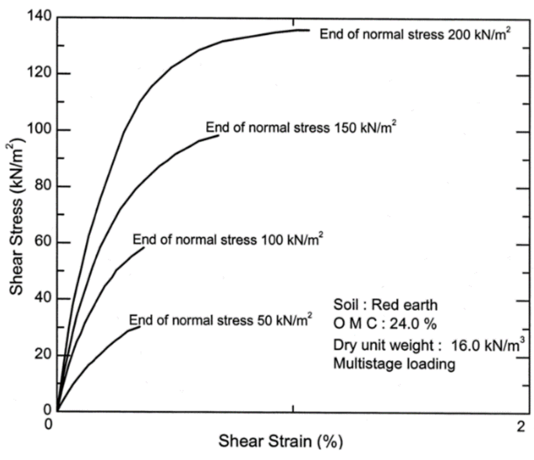

Figure 12 Shear stress – Shear strain curves from multistage box shear test (red earth)

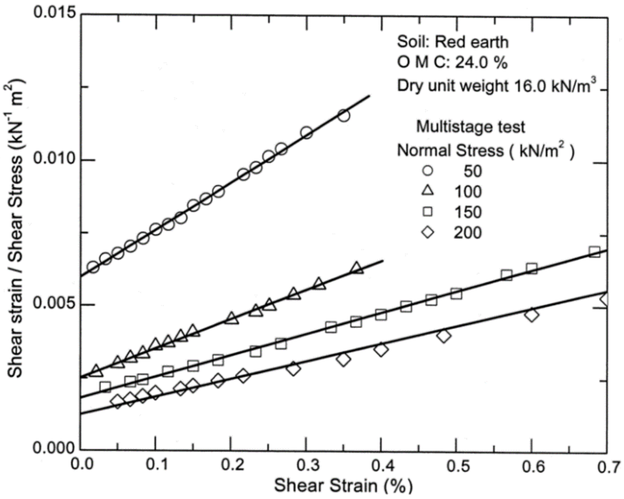

Figure 13 Transformed stress-strain curves from multistage box shear test (red earth)

Figure 14 shows the relation between actual shear stress and predicted shear stress (from hyperbolic stress – strain plots) obtained from conventional box shear tests conducted on the three soil types ie, medium sand, air dried Cochin marine clay and red earth. The relationship yields a straight line plot given by the equation $\sigma_{ph} = 1.12\ \sigma_a$ with a very high correlation coefficient of 0.99

where σ_{ph} = predicted shear stress from conventional hyperbolic stress-strain relations and

σ_a = actual shear stress from conventional shear tests

Similarly Figure 15 presents the plot between actual failure shear stress and predicted stress from hyperbolic stress-strain relationship, obtained from results of multistage test conducted on single samples in the case of all the above three soil types. Again it is seen that the correlation is very good. The equation for the straight line relationship is obtained as $\sigma_{mh} = 1.05\ \sigma_a$ with a very high correlation coefficient of 0.98 where σ_{mh} = predicted shear stress from multistage hyperbolic stress-strain relations.

The above discussions validate the usefulness of multistage shear test for the prediction of shear stress at failure with a single sample.

6. CONCLUSIONS

Prediction of shear stress at failure in the box shear test using multistage test procedure has been presented. Three different soil types namely - medium sand, air dried Cochin marine clay and red earth of varying geological origin has been used in the experimental investigation. It has been brought out that the stress strain curve in the shear box test follows the hyperbolic form throughout the test.

Hence, it is possible to predict the failure shear stress, knowing the stress-strain relationship for the initial portion only. Making use of this behavior, multistage tests were carried out on single sample changing the normal load after obtaining initial portion of stress strain behaviour. It has been brought out that the conventional box shear test could be approximated to multistage box shear test using only one soil sample, taking care of the variability between three or four soil samples used in a conventional test. The test procedure has the distinct advantage of requiring only one sample coupled with large saving in time without much compromise on the accuracy.

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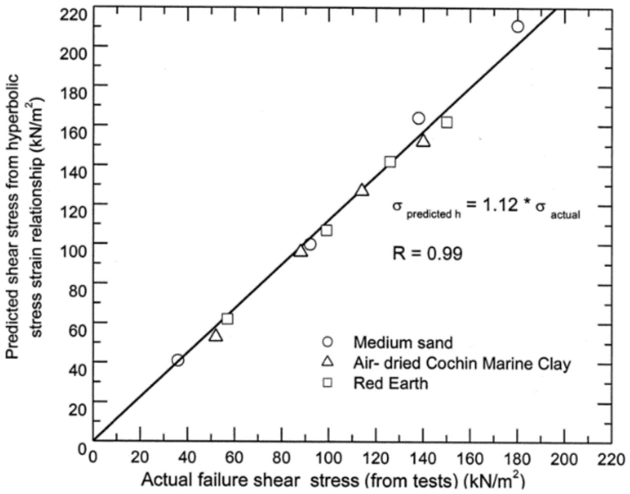

Figure 14 Relationship between actual shear stress and predicted shear stress obtained from hyperbolic stress strain curve (obtained from conventional box shear test)

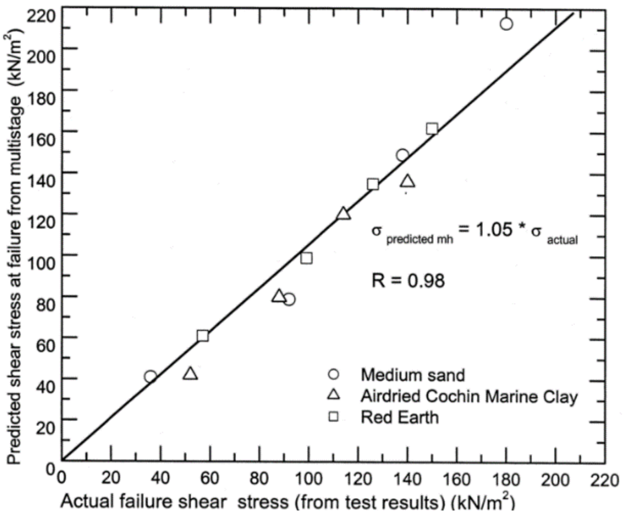

Figure 15 Relationship between actual shear stress from conventional and predicted shear stress obtained from multistage test

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