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Generalised State Parameter for Strength Behaviour of Partially Saturated Soils

by

N.S. Pandian*

T.S. Nagaraj**

G.L. Siva Kumar Babu***

Introduction

Partial saturation is an important aspect in fine grained soils. Many of the phenomena such as heave, collapse, swelling pressure and, variation of shear strength upon inundation are due to partial saturation and pose considerable difficulties, particularly in the design and construction of foundation Structures and earthen embankments. Partial saturation is encountered wherein weather conditions induce alternative drying and wetting. During drying, beyond shrinkage limit air enters the soil pores and generates capillary stresses. The capillary stresses increase the effective stresses in soils (Bishop and Blight 1963, Sridharan 1968, Ho and Fredlund, 1982). This results in many natural soils in arid and semi-arid regions being partially saturated most of the time. Quantification of effective stresses in partially saturated soils is still a matter of research. It gets reflected in higher strength values compared to fully saturated soils and consequently higher factors of safety. During rewetting, the capillary stresses get reduced and the effects are reflected in reduced strength values.

In addition to natural soils in arid and semi arid zones, compacted soils, the bulk material in the construction of earthen structures such as dams, subgrades of highways and runways are also essentially partially saturated in their as compacted state. In some cases even if the construction is using essentially gravel or rockfill, there are important zones such as cores which are constructed of fine grained soils. Now a days, earthen dams of unprecedented height and size are being designed and constructed. Highway and airport pavements capable of sustaining heavy loads are being built

*Assistant Professor, Dept. of Civil Engrg, Indian Institute of Science, Bangalore-560 012, India.

**Professor, Dept. of Civil Engrg, Indian Institute of Science, Bangalore- 560 012, India.

***Scientist, Central Road Research Institute, New Dehli (formerly Scienctific Officer, I.I. Sc Bangalore)

and heavy structures are being located in areas formerly considered unsuitable based on the characteristics of the underlying soils. The overall performance of these earthen structures depends to a large extent upon the shear strength of the fine grained soils used. Therefore the construction of large earth structures requires continuous investigations on the strength characteristics of fine grained soils that are normally encountered in practice. When construction activities are to be taken up on a large scale, a preliminary of the soil properties is necessary before large scale detailed investigations are planned for execution. Literature review shows that, no such guiding information is available for partially saturated soils. Hence, an approach in this direction, based on phenomenological considerations will go a long way in providing the necessary preliminary design inputs for engineering in partially saturated soils. The study reported in this paper is essentially towards this goal.

Earlier Work Done

Rutledge (1947) prepared a critical review of the shearing resistance of partially saturated soils. According to him, for partially saturated soils the four major variables which affect the strength are minor principal stress dry density, water content and degree of saturation. In 1955, Leonards (1955), showed that for two soils of differing plasticity characteristics (liquid limits being 70 and 37) tested within the range of water contents 17.5 to 25.7, for void ratios 0.51 to 1.01 and degrees of saturation 51% to 97.8%, it is possible to represent the strength variation by a relationship between the void ratio at failure and the logarithm of the principal stress difference or compressive strength. For a specified set of initial conditions this relationship is independent of confining pressure, amount of drainage permitted, water content and the degree of saturation. It was also suggested that this uniqueness would exist even for a soil consolidated and then allowed to rebound to a lower confining pressure.

Lambe (1958) has shown that the structure of soil is an important factor which controls the strength and deformation behaviour of compacted soils for a given type of soil and compaction method used. The structure is governed by the molding water content and the compactive effort which is reflected in void ratio. Subsequently, Seed et al (1960) presented considerable data which confirmed and extended the concept that the shear strength, deformation and other properties of partially saturated soil are greatly dependent on the structure of soils, water content and density.

It is generally considered that (Henkel, 1960) for normally consolidated soils, the state of the soil can be specified by the state of stress and the void ratio or water content. However, in the case of partially saturated soils, additional parameters are required to describe the state of partial saturation and the interactions between the different soil components. These additional parameters are degree of saturation and soil structure (Matyas and Radhakrishna, 1968).

DaCruz (1963) based on the experimental data at failure conditions showed that there is a direct dependence of void ratio and degree of saturation on the strength of the soil in the form, "void ratio (degree of saturation)1/2" and "logarithm of shear strength of the soil". This functional form indicates that void ratio is a controlling factor of higher degree than the degree of saturation. The degree of saturation is a function of void ratio, water content and the specific gravity of the soil. The void ratio depends on the equilibrium between external and internal forces applied to soil structure, and the water content is a measure of the water holding capacity in the voids. According to him $e/\sqrt{S_r}$ is a measure of soil structure and is related to strength.

Bolt and Bruggenwert (1976) and Nagraj and Srinivasa murthy (1985) explained the physico-chemical state of a partially saturated soil considering the degree of truncation in a diffuse double layer. Nagaraj and Srinivasa Murthy (1985) from consideration of truncated diffuse double layer theory, have shown that the parameter $(e/e_L)\sqrt{S_r}$ is related to the externally applied pressure.

The above discussion suggests that $e\sqrt{S_r}$ is a soil state parameter for partially saturated soils. When different types of soils are involved, identification of a reference state is necessary. For saturated soils, liquid limit state is identified to be reference state and is used for the normalisation of engineering behaviour of saturated soils (Nagaraj and Srinivasa Murthy, 1983 and, Srinivasa Murthy et. al 1988). Olsen and Langfelder (1965) measured the values of pore water tension in partially saturated soils and related them to surface area. The results indicate that larger negative pore water pressures are associated with larger specific surfaces and, liquid limit of soils is essentially a reflection of surface area (Nagaraj and Jayadeva 1981). Further, this is a state, at which stress history effects and cementation bonds are absent, since, the soil is fully remoulded. Thus, with reference to this state, in situ cemented or prestressed states in partially saturated condition can also be examined. This suggests that liquid limit state can be the reference state for partially saturated soils also. This aspect is the axiom of a series of investigations in this direction. The cardinal aim of these investigations is to establish new meaningful correlations between scattered facts and hence uncover new patterns so as to result in a holistic approach to analyse and predict the soil behaviour.

Based on the above reasoning, in order to study the shear strength behaviour of partially saturated soils using this approach, an equation of the form

$$(e/e_L)\sqrt{S_r} = a - b \log q \qquad (1)$$

is considered in the present investigation. In the above equation, e represents the equilibrium void ratio, S_r, the degree of saturation and e_L, the void ratio at liquid limit. These parameters are lumped in the form of $(e/e_L)\sqrt{S_r}$ and related to the shear strength. The term, $(e/e_L)\sqrt{S_r}$ is called the generalised state parameter for partially saturated soils. Now, the problem reduces to the determination of soil states at failure in shear testing, eliminating the ordeal of measuring the true effective stress or pore water tension in partially saturated state. This is in tune with Kirby's (1989) contention that for partially saturated soils, an approach based on total stresses offers practical advantages over those based on effective stresses.

In the present investigation, unconfined compression tests were performed on three soils having different plasticity characteristics. In this paper, results of unconfined compression tests are discussed and the relationship between unconfined compressive strength and the generalised state parameter $(e/e_L)\sqrt{S_r}$ is obtained. The relationship so obtained is combined with exhaustive published data to result in a more general form.

Results and Discussion

Figures 1,2 and 3 show the unconfined compressive strength test results for red soil, brown and black cotton soil respectively, at four different water contents for each soil, in the e — log q space. Even though the points show a definite trend of variation, there is considerable scatter, showing that void ratio is not uniquely related to unconfined compressive strength. For the same results, figures 4, 5 and 6 show the relationships between $e\sqrt{S_r}$ and unconfined compressive strength, clearly demonstrating that $e\sqrt{S_r}$ is a better parameter to analyse strength behaviour than the void ratio or water content alone. Figure 7 shows the relationship between $e\sqrt{S_r}$ and strength for all soils for all water contents studied. Upon normalisation with void ratio at liquid limit, the plots reduce to a band which can be represented by an equation of the form

$$(e/e_L)\sqrt{S_r} = 1.03-0.23 \log q \quad (2)$$

with a correlation coefficient of 0.89 and is shown in fig. 8.

The above relationship shows that unconfined compressive strength of a compacted soil is clearly related to the generalised state parameter. This relationship is valid within the range of water contents used and the soils studied. This relationship also implies that changes in unconfined compressive strength due to changes in soil states are compatible, and such changes can be predicted using this approach, particularly when different types of soils are involved.

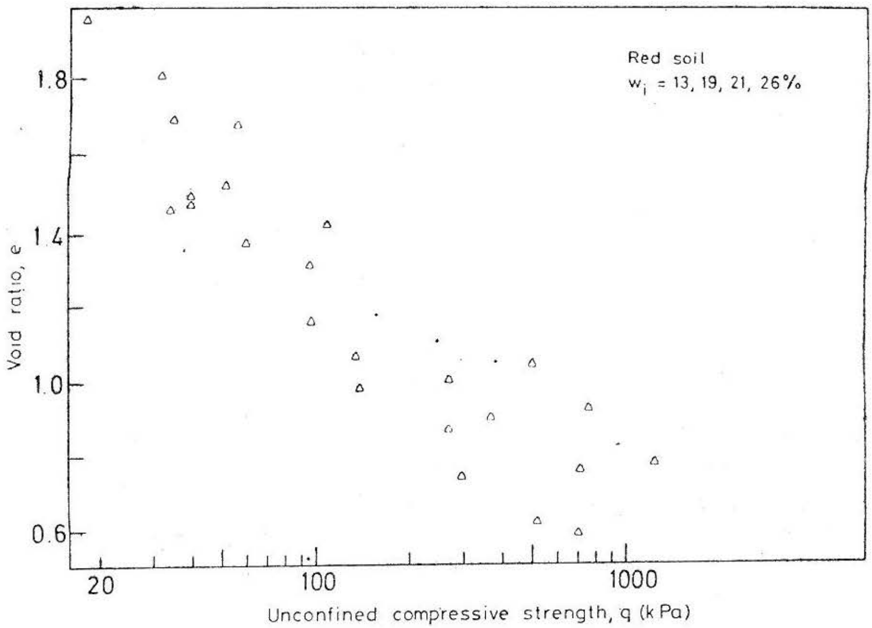

FIGURE 1 Void ratio-unconfined compressive strength for red soil at different water contents

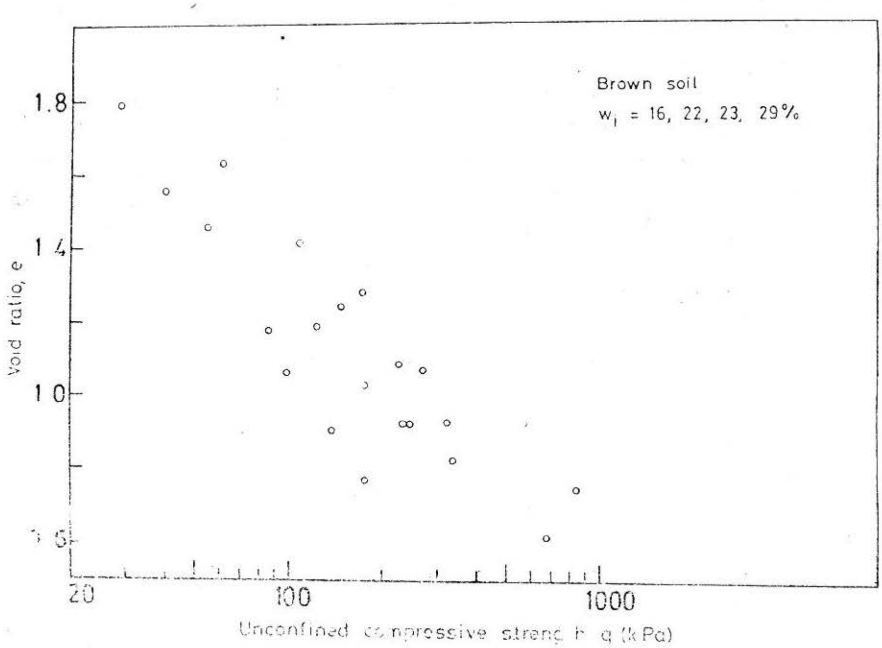

FIGURE 2 Void ratio—unconfined compressive strength for brown soil at different water contents

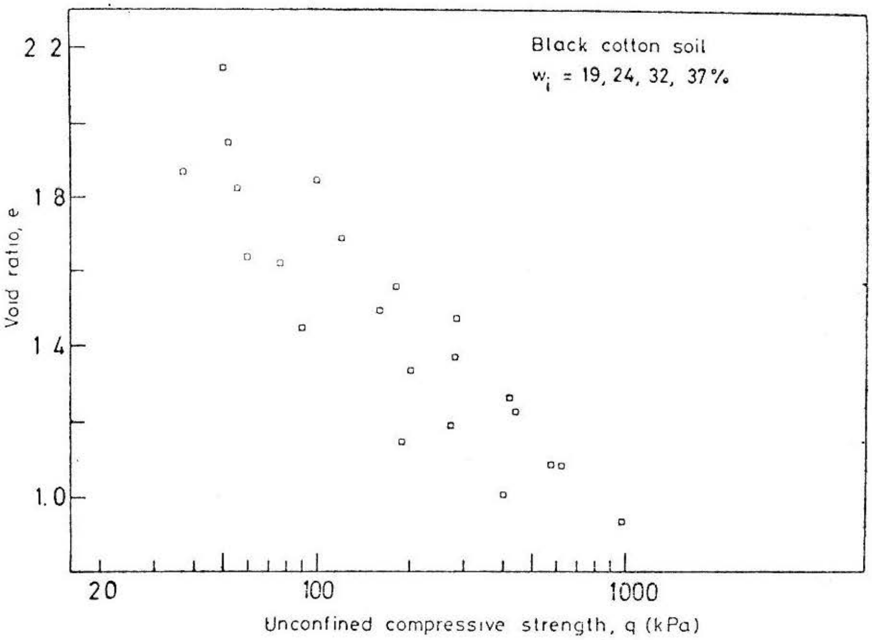

FIGURE 3 Void ratio—unconfined compressive strength for black cotton soil at different water contents

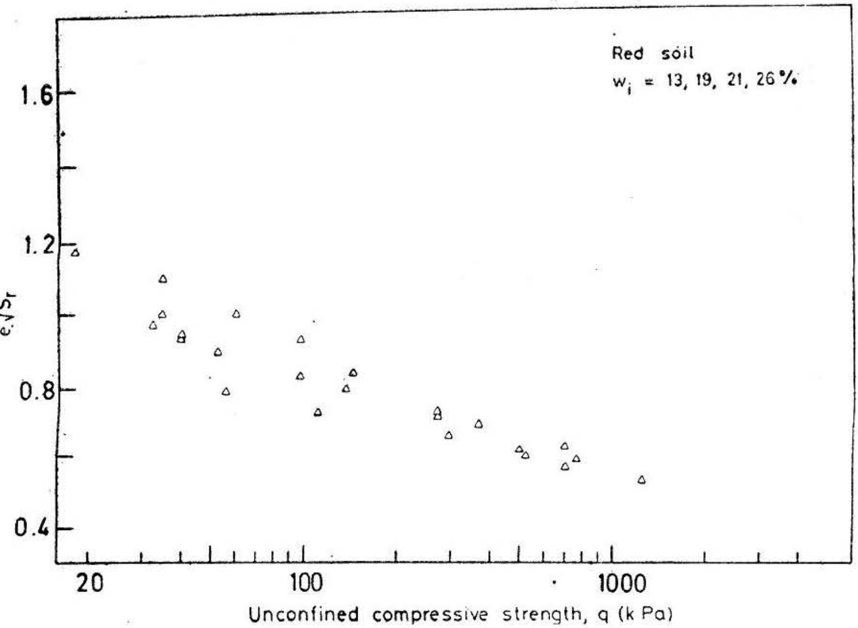

FIGURE 4 $e\sqrt{S_r}$—unconfined compressive strength for red soil

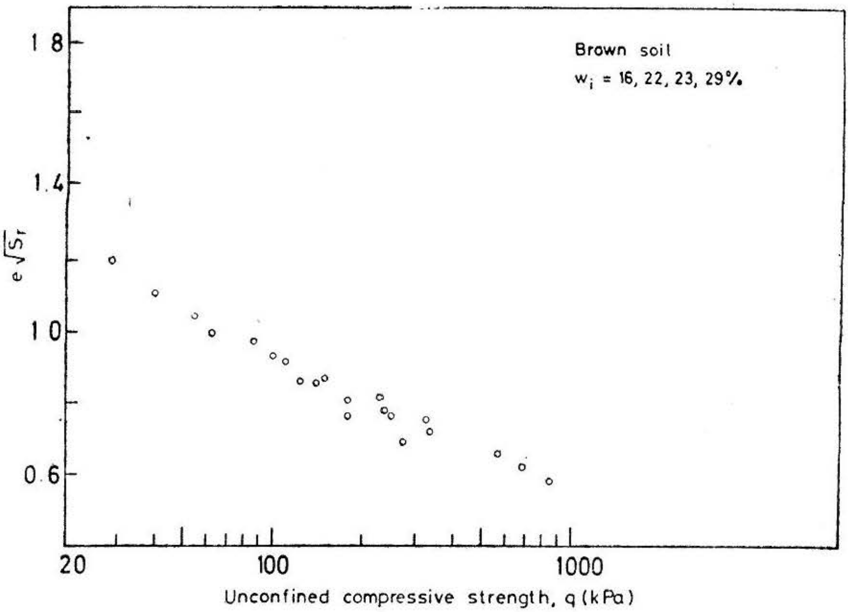

FIGURE 5 $e\sqrt{S_r}$—unconfined compressive strength for brown soil

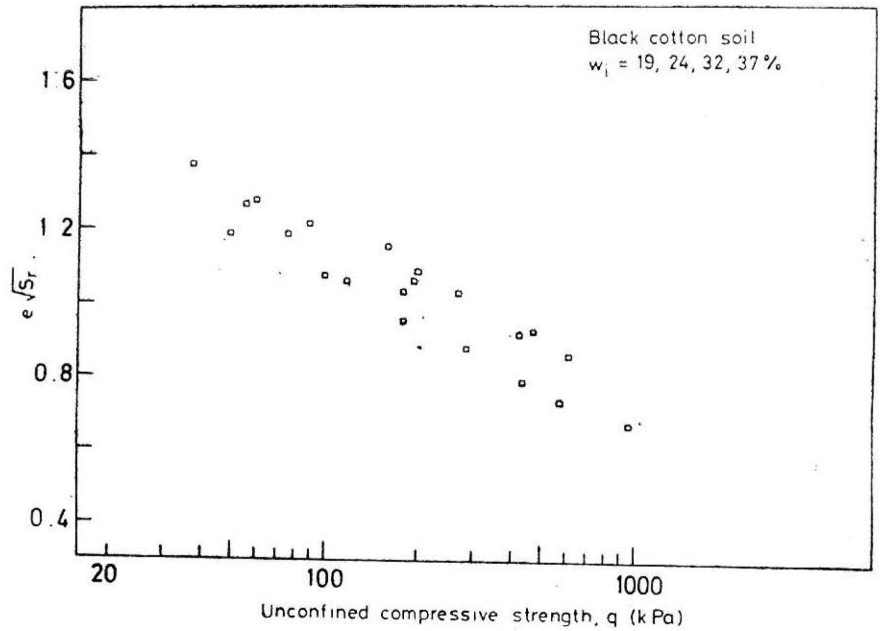

FIGURE 6 $e\sqrt{S_r}$—unconfined compressive strength for black cotton soil

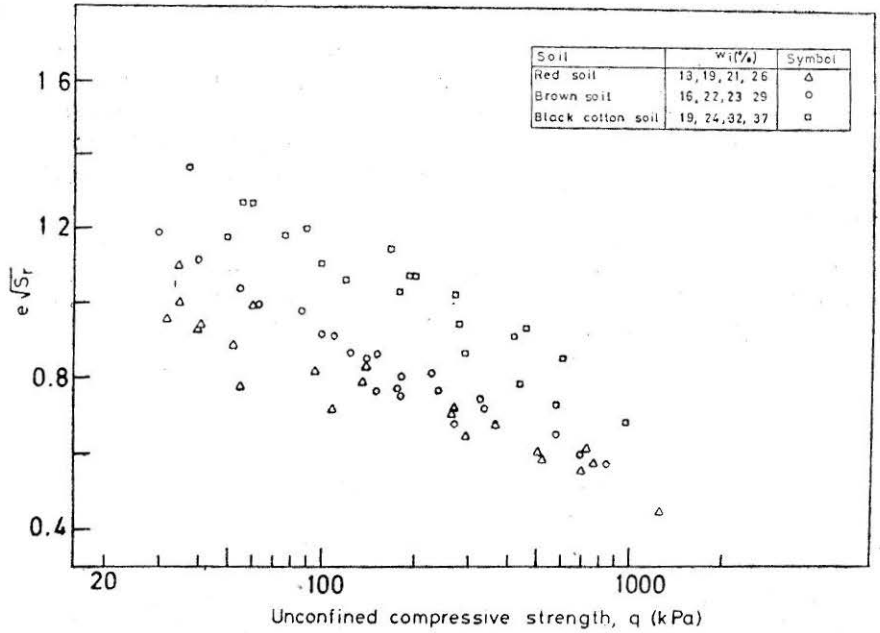

FIGURE 7 $e\sqrt{S_r}$—unconfined compressive strength for all the soils

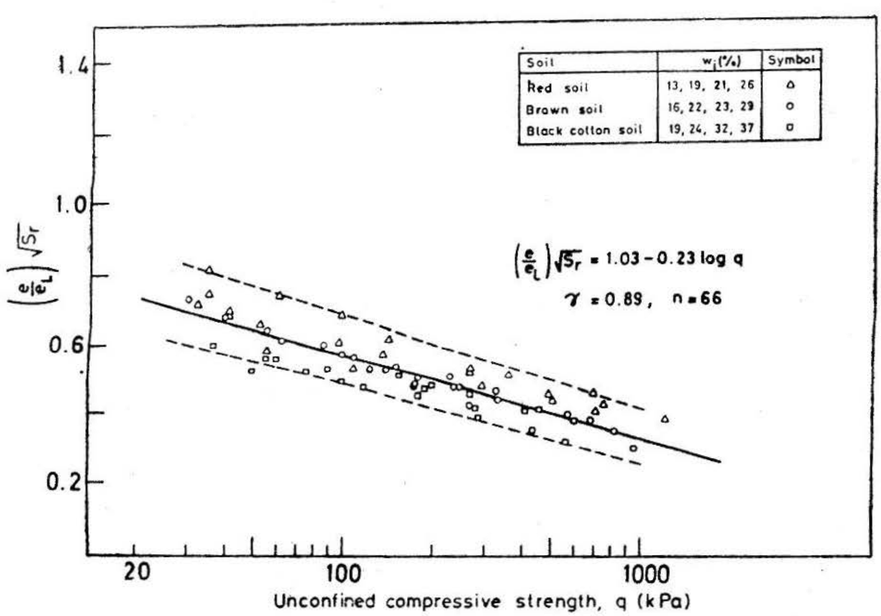

FIGURE 8 Generalised state parameter—unconfined compressive strength

Comparison with Published Literature

Test results of Mitchell (1955), DaCruz (1963), Ajaz and Parry (1975), Weitzel and Lovell (1979) and Liang and Lovell (1983) are available in literature regarding strength of compacted soils. Weitzel and Lovell (1979) and, Liang and Lovell (1983) conducted extensive tests in Indiana area, USA as part of a study sponsored by Indiana department of Highways and the US Federal Highway Administration.

As a part of the analysis, the shear behaviour of these clays were examined in terms of $e\sqrt{S_r}$ versus $q/2$ relationships. The test conditions include different degrees of compaction (modified, standard and lower energy proctor) and different confining pressures (69, 138, and 27 kPa). The generalised relationship is in the form of a band and can be represented by the equation

$$(e/e_L)\sqrt{S_r} = 0.84 - 0.16 \log q \tag{3}$$

with a correlation coefficient of 0.82 (Pandian et al 1992).

The experimental data from this investigation as well as the published data of DaCruz (1963), Ajaz and Parry (1975), Weitzel and Lovell (1979) and Liang and Lovell (1983) when normalised with corresponding void ratios can be represented by an equation

$$(e/e_L)\sqrt{S_r} = 0.97 - 0.20 \log q \tag{4}$$

with a correlation coefficient of 0.89 and is shown in the Fig. 9.

Mitchell (1955) conducted unconfined compression tests on samples (Liquid limit, 45%) obtained from kneading compaction. His data, normalised with the corresponding void ratio at liquid limit results in a relationship which can be represented by

$$(e/e_L)\sqrt{S_r} = 0.95 - 0.21 \log q \tag{5}$$

with a correlation coefficient of 0.89. This equation compares very well with equation (4). This can be considered to give support to the approach proposed in this investigation.

It is possible that in all the above cases involving published data, where the information is given in the form of graphs, there are small errors involved while abstracting the values. In addition, it is known that shear behaviour is a complex phenomenon; but each shear strength value is considered irrespective of the failure strain and rate of shearing as well as the non-homogeneity in the samples themselves. These factors themselves could be responsible for a band. Nevertheless, it suffices to indicate that the shear strength behaviour of partially saturated soil can be examined by using the generalised state parameter approach.

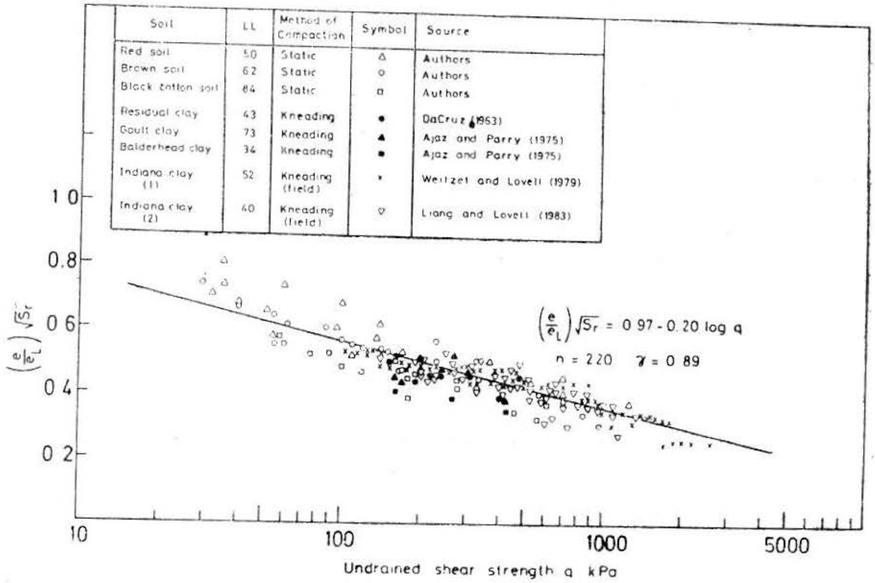

FIGURE 9 Generalised state parameter—undrained shear strength relationship for the experimental data as well as published data.

The published data analysed in this paper contain soil states obtained from different confining pressures and different efforts of compaction. Still, all the results lie along the same line. This is useful in the design of slopes of earthen embankments and compacted soil structures that are primarily based on predicted strength values. The variation of shear strength can be estimated during and at the end of construction, as well as on the long term basis, if the initial soil states are known.

Concluding Remarks

In this paper, shear strength behaviour of partially saturated soils are examined in terms of generalised state parameter approach. It has been shown that the strength behaviour of these soils can be examined with liquid limit as the reference state. The relationship obtained in this investigation for unconfined compressive strength is a convenient form in considering the changes in soil states due to external stress conditions and the associated changes in strength, particularly when different types of soils are involved. In soil engineering practice connected with partially saturated soils there are no approaches connecting soil states with stress conditions. This approach and the form of relationship proposed definitely fits into such scheme.

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