A Rational Method of Predicting Swelling Potential for Compacted Expansive Clays

Méthode rationnelle permettant de prédire le potentiel de gonflement pour les argiles compactes expansibles

B. V. RANGANATHAM, B.E. (HONS) (MADRAS), D.I.C. (LOND.), M.SC. (LOND.), PH.D. (LIVERPOOL), A.M.I.H.E., A.M.I.C.E., *Assistant Professor in Soil Mechanics, Indian Institute of Science, Bangalore, India*

B. SATYANARAYANA, B.E.(HONS) (ANDHRA), M.E. (I.I.SC.), *Senior Research Fellow, Civil and Hydraulic Engineering Department, Indian Institute of Science, Bangalore, India*

SUMMARY

Though considerable progress has been made in explaining the mechanism of swelling in soils, there is no satisfactory method for predicting the swelling characteristics. In this paper a method is evolved for this purpose in terms of shrinkage index and swell activity. The range of water content between the liquid limit and shrinkage limit, which is an important measure of volume change is called the shrinkage index. The swell activity is defined as the change in shrinkage index divided by the corresponding change in clay fraction.

A number of soils, both natural and artificially prepared, have been successfully classified as having low, medium, high, or very high swelling potential by means of shrinkage index values. It is further shown that the qualitative as well as quantitative evaluation of the swell characteristics of a compacted expansive soil is possible by the use of shinkage index.

SOMMAIRE

Quoique de considérables progrès aient été réalisés en approfondissant le mécanisme du gonflement des sols, aucune méthode n'a pu clairement prédire les caractéristiques du gonflement. Dans cet article une méthode employant l'indice de retrait de l'argile et l'activité du gonflement est expliquée. La variation de la teneur en eau entre le seuil du liquide et celui du retrait, mesure importante dans le changement de volume, se nomme indice de retrait. L'activité de gonflement est définie comme le changement de l'indice de retrait divisé par le changement correspondant de la fraction argileuse.

Des échantillons de sols, naturels et préparés artificiellement, ont été classifiés avec succès avec un potentiel de gonflement bas, moyen, élevé ou très élevé, en utilisant des valeurs d'indice de retrait. Il est démontré que l'évaluation qualitative et quantitative des propriétés de gonflement d'un sol compact expansible est possible par l'emploi de l'indice de retrait.

DURING THE PAST FEW YEARS numerous studies have been conducted to investigate the swelling characteristics of compacted expansive soils. The problem of identifying those soils which are likely to possess undesirable expansive characteristics has not met with any considerable progress, however, because of the limited understanding of the numerous complex factors involved.

Holtz and Gibbs (1956) have made an extensive study of this problem and recommended an empirical method for both identifying and predicting the expansive characteristics of compacted clays. The method is based on the measured expansion of soils from the air-dry to the saturated condition, clay fraction, plasticity index, and so on. The volumenometer method of estimating the potential expansiveness of the soil (Bruijin, 1961) is based on the initial moisture content, moisture content changes governed by the permeability characteristics, and the boundary conditions of the soil body. The double oedometer test (Jennings and Knight, 1958) for estimating the heave of a structure is based on the degree of dessication, the activity of the soil, overburden, and applied loading. Seed, *et al.* (1962) have extended the study, conducting a number of tests on artificial soils prepared by mixing commercially available clay minerals with different proportions of sand. A well-defined relationship was established between the clay fraction, activity of the soil, and swelling potential (defined as the percentage of swell under a 1-psi surcharge of a sample compacted at optimum moisture content to maximum dry density in the standard AASHO compaction test). A simplified method for the prediction of swelling potential based on the plasticity index gives values within ± 33 per cent error.

It can be easily discerned from this review that most of the approaches are empirical in that they are unrelated to the physics of the problem. A logical parameter for correlation with the swelling potential would be the shrinkage index—the range of water content between the liquid limit and the shrinkage limit—for this is a direct measure of volume change of significance in engineering practice. A new method presented in this paper for predicting the swelling potential of a compacted expansive soil is thus based on the shrinkage index. The method is developed on the basis of test results on black cotton soils, conducted by the authors, as well as those reported by Seed, *et al.* (1962).

SCOPE OF THE INVESTIGATION

The efforts of the present experimental investigation are concentrated on the determination of swell characteristics of black cotton soils obtained from different tracts in southern India. The properties of these soils are reported in Table I which shows that a good range of free swell is covered. Also shown in the same table are the values of the swelling potential calculated by the empirical methods of Seed, *et al.* The difference (30 to 65 per cent) between the experimental and the calculated values is considerable. This exceeds the limits (± 33 per cent) claimed by the authors thereby indicating the necessity for a more rational approach.

TABLE I. PROPERTIES OF THE SOILS INVESTIGATED

Properties	Soil A	Soil B	Soil C	Soil D
Liquid limit	54.4	49.5	69.6	74.4
Plastic limit	24.7	20.2	39.2	37.8
Plasticity index	29.7	29.3	30.4	36.6
Shrinkage limit (per cent)	8.0	10.9	12.4	13.2
Clay content (per cent)	28	15	18	38
Optimum moisture content (per cent)	15	12.6	25	20
Max. dry density (lbs/cu. ft.)	112.5	117	98.5	105.0
Free swell (per cent)	133.5	126	193	209
Shrinkage index	46.4	38.6	57.2	61.2
Swelling potential				
Experimental	14.9	11	17.2	20.2
Empirical*	6.43	5.4	6.04	12.8
Error (per cent)	57	51	65	37
Empirical†	8	7.9	9.5	14
Error (per cent)	47	30	45	30

*Calculated by the relationship (Seed, *et al.*, 1962) $SP = 3.6 \times 10^{-5} \times A^{2.44} \times C^{3.44}$.
†Calculated by the relationship (Seed, *et al.*, 1962) $SP = K.60.(PI)^{2.44}$.

SHRINKAGE INDEX

It is well known that many plastic clays under zero confining pressure will imbibe water until they reach an equilibrium water content approximating the liquid limit. This is also corroborated by the test results shown in Fig. 1. By

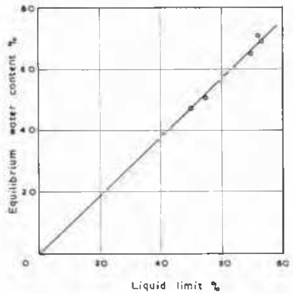

FIG. 1. Relationship between liquid limit and equilibrium water content under zero confining pressure.

the very definition, there will not be any decrease in volume on drying the soil below the shrinkage limit. Obviously these form the upper and lower limits of volume changes, the lower limit (shrinkage limit) below which there is no decrease in volume on drying, and the upper limit (liquid limit) above which soils are not generally met in civil engineering practice. The range of water content between these two limits, called shrinkage index, is thus considered appropriate for the prediction of volume change characteristics.

SWELL ACTIVITY

The potential expansiveness depends on many factors, the most important being the type and amount of clay fraction of the soil. The shrinkage index is already shown to be another important factor. For all the artificially prepared soils (Seed, *et al.*, 1962) the clay fraction is plotted against the shrinkage index in Fig. 2. It will be seen that the points define a series of straight lines relating shrinkage index to

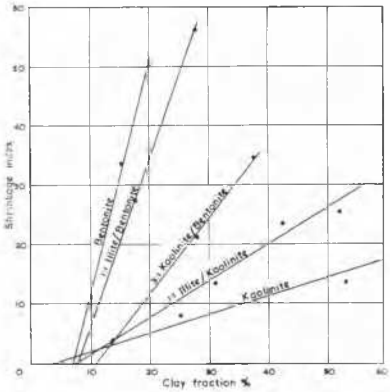

FIG. 2. Relationship between shrinkage index and clay fraction.

clay fraction. The slope of line is defined as the swell activity of the soil which can be expressed as: Swell activity (SA) = Change in shrinkage index/Corresponding change in clay fraction = $\Delta(SI)/\Delta C$.

RELATIONSHIP BETWEEN SWELL ACTIVITY, CLAY FRACTION, AND SWELLING POTENTIAL

As already established (Seed, *et al.*, 1962), the amount of swelling potential for any clay increases in accordance with that of the clay fraction, which when stated mathematically is

$$SP = KC^x \tag{1}$$

where SP is the swelling potential, C is the clay fraction ($< 2\mu$), x and K are constants depending on the type of clay. The values for K and x for each clay are determined by plotting log SP *versus* log C (see Fig. 3). Thus equation (1) becomes

$$\log SP = \log K + x \log C. \tag{2}$$

The exponent x is determined by the slope of the line and the coefficient K by the value of SP when $C = 1$. It was observed that x would be close to 3.44 for any type of clay and the coefficient K is the only factor differentiating one from the other which is a characteristic index of the swelling potential of any given type of clay. The values (Seed *et al.*, 1962) of K so determined are reported in Table II.

The coefficient K differentiating each type of clay is believed to be related to the swell activity which denotes the expansive capability. In order to see the possibility of such a relationship, values of K are plotted against the corresponding values of swell activity (obtained from Fig. 2 and reported in Table II) in Fig. 3 on log-log scale. It will be

TABLE II. VALUES OF K AND SWELL ACTIVITY FOR THE ARTIFICIAL SOILS

Type of clay	K (after Seed *et al.*)	Swell activity
Bentonite	152×10^{-5}	3.9
1:1 illite/bentonite	78×10^{-5}	2.84
6:1 kaolinite/bentonite	31.6×10^{-5}	—
3:1 illite/bentonite	5.5×10^{-5}	1.29
1:1 illite/kaolinite	1.12×10^{-5}	0.6
Kaolinite	0.28×10^{-5}	0.3

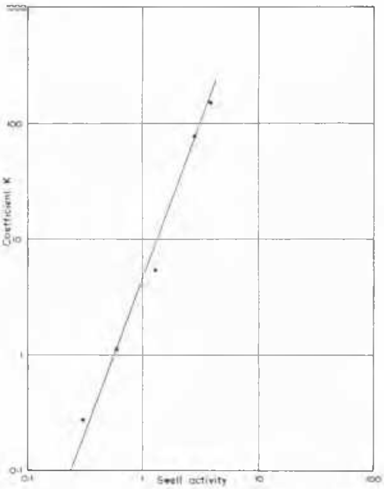

FIG. 3. Relationship between coefficient K and swell activity for experimental soils.

seen that a relationship of the form

$$K = \alpha(\mathrm{SA})^{y} \qquad (3)$$

can be established between the coefficient K and the corresponding swell activity (SA) where α, y are constants. The values of α and y defining the above relationship are (from Fig. 3) 4.57×10^{-5} and 2.67 respectively. Thus it may be concluded that for the artificial soils investigated,

$$K = (4.57 \times 10^{-5}) \times (\mathrm{SA})^{2.67}. \qquad (4)$$

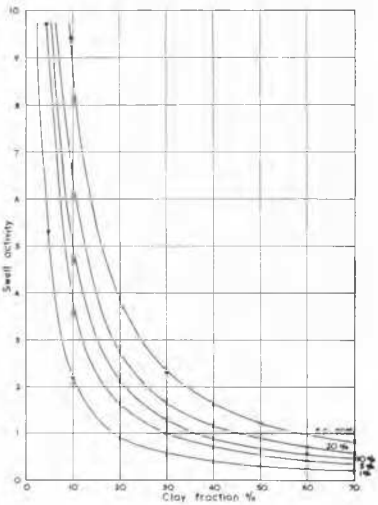

FIG. 4. Relationship between swelling potential, swell activity, and clay fraction.

As the soils used in this investigation covered a wide range of clay minerals, it seems reasonable to expect this to be generally applicable to all expansive soils in a satisfactory manner.

EVALUATION OF SWELLING POTENTIAL

As seen from equation (1), the swelling potential is a function of clay fraction and a coefficient which in turn is a function of swell activity. Combining equations (1) and (4) we get

$$\mathrm{SP} = (4.57 \times 10^{-5}) \times (\mathrm{SA})^{2.67} \times (C^{3.44}). \qquad (5)$$

showing that the expansion characteristics can be quantitatively evaluated in terms of clay fraction and the swell activity. A family of curves is drawn in Fig. 4, from which the swelling potential can be evaluated readily by plotting the position of the soil in the curves.

USE OF SHRINKAGE INDEX TO PREDICT THE SWELLING POTENTIAL

It is shown that the swelling potential is a function of clay content and swell activity

$$\mathrm{SP} = \alpha(\mathrm{SA})^{2.67} \times (C^{3.44}). \qquad (5a)$$

From the definition of the swell activity,

$$\mathrm{SA} = \Delta(\mathrm{SI})/\Delta C \qquad (6)$$

or swell activity can also be expressed as

$$\mathrm{SA} = \mathrm{SI}/(C-n) \qquad (7)$$

where n is the intercept of the curve (Fig. 2) on the axis representing clay fraction, and the n-values vary from 4 to 22 for the soils included in the study. Substitution of equation (3) in equation (5) gives

$$\begin{aligned}\mathrm{SP} &= \alpha[\mathrm{SI}/(C-n)]^{2.67} \times C^{3.44}\\ &= \alpha(\mathrm{SI})^{2.67}[C^{3.44}/(C-n)^{2.67}]\\ &= \alpha(\mathrm{SI})^{2.67}N \qquad (8)\end{aligned}$$

in which $N = C^{3.44}/(C-\mathrm{n})^{2.67}$. The accuracy of the value of swelling potential depends on the value of N in equation (8).

Values of N can be readily computed for different values of C and n. A family of 'C–n–N' curves are shown in

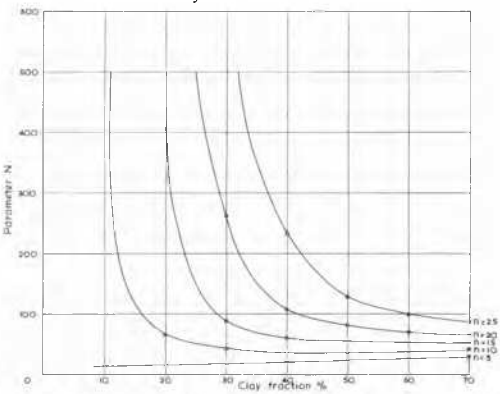

FIG. 5. Relationship between clay fraction and parameter N.

Fig. 5, from which the values of N could be read for any set of C and n values. It may be seen that for $n = 13$, which represents the average value for the soils included in the study, the value of N ranges from 45 to 70 (mean value of 57.5) for soils with the clay fraction between 30 and 70. Thus for soils with clay fraction lying in this range, a direct relationship between the swelling potential and shrinkage index could be expressed as

$$SP = (263 \times 10^{-5}) \times (SI)^{2.67}. \quad (9)$$

This gives values of swelling potential accurate within ± 22 per cent.

From the results of laboratory tests on natural soils, a value of 9 for N has been arrived at. The values of swelling potential calculated on this basis and those experimentally determined are given in Table III. It can be seen that even

TABLE III. COMPARISON OF EXPERIMENTAL AND CALCULATED VALUES OF SWELLING POTENTIAL

	Soil type			
	A	B	C	D
Experimental values	14.9	11	17.2	20.2
Calculated by shrinkage index factor	11.7	7.2	20.2	24.3
Error (per cent)	21.5	34	17.5	20

for the natural soils the values of swelling potential could be evaluated quantitatively within ± 34 per cent. Hence for natural soils:

$$SP = (41.13 \times 10^{-5}) \times (SI)^{2.67}. \quad (9a)$$

DIRECT RELATIONSHIP BETWEEN SWELLING POTENTIAL AND SHRINKAGE INDEX

Fig. 6 shows a relationship between swelling potential and shrinkage index plotted on a log-log scale. It is seen that the relationship for natural and artificial soils is similar but not identical. It is of the form

$$SP = \beta(SI)^{p} \quad (10)$$

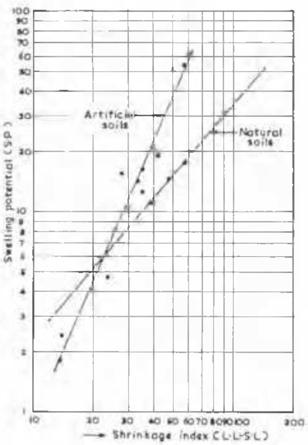

FIG. 6. Direct relationship between swelling potential and shrinkage index.

where β and p are constants. The constants evaluated from Fig. 6 are: for artificial soils $\beta = 1/256$ and $p = 2.37$; for natural soils $\beta = 1/6.3$ and $p = 1.17$. This relationship (Eq 10) is in conformity with the relationship (Eq 8) arrived at from shrinkage index and swell activity. A direct relationship between swelling potential and shrinkage index is thus established.

CLASSIFICATION OF SOILS USING SHRINKAGE INDEX

To enable a soil engineer to identify and spot an expansive soil which might need further detailed investigation regarding the swell characteristics under actual field conditions, it is desirable to establish a classification system based on shrinkage index.

Table IV gives the limits of the shrinkage index for low, medium, high, or very high swelling potential in accordance with the USBR classification. Using these limits of shrinkage index, thirty-three out of thirty-eight soils (Seed *et al.*, 1962) agree with the USBR classification (Fig. 7).

TABLE IV. CLASSIFICATION OF EXPANSIVE SOILS WITH THE SHRINKAGE INDEX AS BASIS

Classification	Range of shrinkage index
Low	0–20
Medium	20–30
High	30–60
Very high	>60

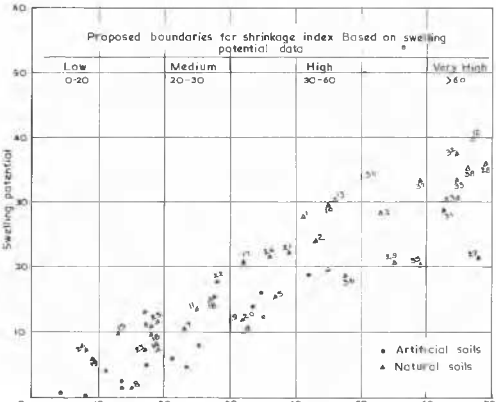

FIG. 7. Classification of expansive soils based on shrinkage index.

CONCLUSIONS

From the data on artificial soils, a relationship is obtained between the swelling potential, shrinkage index, and swell activity. It is shown that by using the shrinkage index, which is a rational index for volume changes of clays, qualitative as well as quantitative evaluation of the swelling potential of expansive soils is possible.

A classification system based solely on the shrinkage index is developed for predicting the degree of swell potential.

Among the methods developed for predicting the swelling potential, the one now proposed predicts values which are closer to the experimental values.

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