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SWELLING CHARACTERISTICS OF COMPACTED, EXPANSIVE SOILS

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Abstract—The limitations of existing methods for the prediction of swelling behavior of compacted soils are examined. Both the purely theoretical approach and the purely empirical approach are found to be inadequate. The present study is based on a semi-empirical approach in which a model of swelling behavior is developed leading to equations relating swelling potential or swelling pressure of a compacted soil to its plasticity index, clay content and initial molding water content. The model is based on the concepts of the diffuse double layer, modified by introducing empirical constants to account for elastic swelling effects and other limitations involved in the direct application of double layer theory to real soils. The empirical constants are evaluated from the results of experimental investigations carried out on a large number of soil samples representing a wide variation of clay content as well as consistency limits.

It is shown that the predicted values of the swelling potential and swelling pressure based on the proposed model agree closely with the experimental results of this study and those reported in the literature. Furthermore, the equations developed in this study are of a more general nature and appear to be applicable to a larger range of soil types than those previously published.

INTRODUCTION

CONSIDERABLE research has been done in an attempt to understand the basic mechanisms involved in swelling of expansive soils. Theories based on physico-chemical considerations have been developed to explain swell or swell pressure characteristics of pure clay suspensions. To a certain extent experimental verification of these theories has been obtained (see for example Bolt, 1956; Yong *et al.*, 1962). However, there are certain important limitations in applying these theories to natural or compacted soils. For example, these theories fail to account for the complexities of natural or compacted soils because of several simplifying assumptions made in them. Also, in spite of the simplifying assumptions these theories are still mathematically complex and difficult to apply to engineering practice.

Recently greater attention has been given to empirical investigations of the swelling behavior of compacted and natural soils (Holtz and Gibbs, 1956; Ladd, 1960; Seed *et al.*, 1962; Ranganatham and Satyanarayan, 1965; Nalezny and Li, 1967; Sowers and Kennedy, 1967; Komornik and David 1969). As a result of these investigations, various forms of empirical equations have been proposed which relate swelling behavior to certain physical properties of soils, such as consistency limits, clay content, initial moisture content and density, which are well understood by engineers. These empirical equations are easy to apply and give satisfactory results when applied to the particular soils for which they were developed. However, the empirical approach also has its limitations. For example, the equations are based purely on the results of the experimental investigations conducted on a limited number of soil samples; it remains to be seen whether these equations give satisfactory results when applied to other soils. Furthermore, there is no theoretical basis to support the validity of the particular form of equation used.

In the present investigation semi-empirical relationships are developed to predict swelling behavior of compacted, expansive soils. The basic forms of the relationships are derived from theoretical considerations of the diffuse double layer and the osmotic pressure for parallel clay plates. To bridge the gap between the idealized soil system used in the theoretical considerations and the real soil system, empirical constants are introduced as modifications to the basic theoretical relationships. These empirical constants are evaluated from experimental investigations carried out on a large number of soil samples representing a wide variation in clay content and consistency limits. The resulting semi-empirical equations relate swelling behavior of a compacted soil to its clay content, plasticity index and initial molding water content.

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PREVIOUS INVESTIGATIONS

The analytical approach to the prediction of swelling pressure in soils is based on the osmotic pressure developed between clay plates (Bolt, 1956; Nalezny and Li, 1967; Mitchell, 1969). However, in soils, osmosis occurs without the physical existance of a semipermeable membrane and the conditions inducing osmosis are different than the "ideal" conditions assumed in deriving the equation for osmotic pressure (Ruiz, 1962). Furthermore, in order to estimate the osmotic pressure it is necessary to determine the cation concentration at the mid-plane between the particles. Solutions for cation concentration at the mid-planes between the clay plates are available for some simple cases only, and, at any rate, it is difficult to evaluate the cation concentration accurately for natural or compacted soils.

In equating the osmotic pressure to the swelling pressure of a soil, the effects of elastic rebound, pressure in entrapped air bubbles, and the forces of attraction are neglected. In some soils, including compacted clays, swelling due to these effects can be significant. Although there have been attempts to account for the attractive forces (Ruiz, 1962; Nalezny and Li, 1967), in general, these theoretical equations for the prediction of swelling or swelling pressure are far from satisfactory for use with natural or compacted soils.

Recently there have been several attempts to develop empirical relationships to predict swelling or swelling pressure of soils. Extensive experimental investigation by Seed *et al.* (1962) on artifically prepared, compacted soils indicated that, for a given type of clay mineral, the swelling potential* of a soil, S, is related to its activity, A, and clay content, C, by the equation,

$$S = k(A^{2\cdot44})(C^{3\cdot44}) \qquad (1)$$

where,

k = a constant for all types of clay mineral $\approx 3\cdot6\times10^{-5}$.

Seed *et al.* also report that plasticity index (PI) is the single best factor to predict swelling potential of soils. The form of the equation in terms of plasticity index is,

$$S = (k)(M)(PI^{2\cdot44}) \qquad (2)$$

where,

M = constant
= 60 for natural soils
= 100 for artificial soils.

*Per cent vertical strain under 1 psi surcharge.

Equation (1) provides a more accurate prediction of swelling potential of compacted soils than equation (2) but Seed *et al.* suggest that equation (2) may be best suited for practical purposes because it relates the single parameter, plasticity index, to swelling potential. The authors show that the loss of accuracy involved in using equation (2) instead of equation (1) will not exceed ±33 per cent for natural soils with clay contents ranging from 8 per cent to 65 per cent. They also found that shrinkage limit cannot be correlated with the swelling potential.

Ranganatham and Satyanarayan (1965) who carried out swelling potential studies on four natural soils found that either swell activity (ratio of change in shrinkage index to the corresponding change in clay content) and clay content or shrinkage index alone correlate better with swelling potential of compacted soils. Thus, Ranganatham and Satyanarayan (1965) propose an equation of the form,

$$S = m_1(SI)^{2\cdot67} \qquad (3)$$

where,

m_1 = constant
= 41·13, for natural soils
SI = shrinkage index (liquid limit-shrinkage limit) as a percentage.

Ranganatham and Satyanarayan report that equation (3), predicts swelling potential within ±34 per cent. However, when equation (3) is applied (by the writers) to soils studied by Seed *et al.*, the errors in the calculated values of swelling potential are found to be quite large, indicating that equation (3) as proposed by Ranganatham and Satyanarayan is also not applicable to compacted soils in general.

Sowers and Kennedy (1967), who studied the swelling behavior of undisturbed natural soils, indicate that swell pressure and swelling potential can best be related to the water plasticity ratio which is defined as the ratio of water content minus plastic limit to plasticity index. However, in the case of swelling pressure versus water plasticity ratio, there is a wide scatter of the data points.

Komornik and David (1969) carried out swelling pressure tests on a number of natural (undisturbed) soil samples and, on the basis of statistical (regression) analysis, developed the following relationship:

$$\log(P) = \bar{2}\cdot132 + 0\cdot0208(LL) + 0\cdot000665(\gamma_d) - 0\cdot0269(w) \qquad (4)$$

where,

P = swelling pressure in kg/cm²

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LL = liquid limit
γ_d = dry density of soil sample in kg/m^3
w = water content.

Komorik and David obtained a coefficient of correlation of 0·60 for log (P) with the parameters in equation (4); i.e. liquid limit, density and moisture content. However, the coefficient of correlation decreased to 0·51 when log (P) was related to only two quantities, i.e. liquid limit and density. The coefficient of correlation was further reduced to 0·16 when log (P) was related to liquid limit alone. Nevertheless, the authors state that liquid limit is best as a single variable in the prediction of swelling pressure of soils.

The preceding empirical equations give reasonably good results when applied to the particular soils for which they were developed. Furthermore, they are easy to apply as they relate the swelling behavior to simple physical characteristics of soils which can be easily determined in any soil engineering laboratory. Consequently, these equations are received more favorably in practice than the theoretical equations discussed earlier. However, as may be noted in the preceding discussion, they apparently lack the generality necessary to cover a broad range of soil types.

A MODEL TO PREDICT SWELLING BEHAVIOR

Previous investigations of swelling behavior have revealed that the following factors influence swelling potential and swelling pressure:

(i) type and amount of clay
(ii) initial placement conditions
(iii) stress history
(iv) nature of pore fluid
(v) temperature
(vi) volume change permitted during swelling pressure measurements
(vii) shape, size and thickness of the sample, and
(viii) time.

If the experimental method is standardized, the type and amount of clay along with certain initial placement conditions of the samples are the basic parameters influencing swelling behavior of soils. In order to develop quantitative expressions for swelling behavior of soil, the type of soil may be replaced by its consistency limits and the initial placement conditions can best be represented by the initial placement moisture content of the sample. In treating consistency limits, clay content and initial placement moisture content of the soil as the basic parameters influencing swelling behavior, it is assumed that the structure of expansive soils compacted to maximum dry density and optimum moisture content corresponding to the standard AASHO compaction test is relatively constant.

As a first approximation the swelling pressure may be equated to its osmotic pressure as expressed by the van't Hoff equation with the concentration of cations at the central plane between particles as predicted by the Langmuir equation (Yong and Warkentin, 1966):

$$*P = P_{os} = RTc_c = \frac{RT\pi^2}{z^2\beta(d+x_0)^2(10^{-16})} \qquad (5)$$

where,

P = swelling pressure
P_{os} = osmotic pressure
R = universal gas constant
T = temperature, Kelvin units
c_c = concentration of cations at mid-plane between clay particles
z = valence of cations
β ~ dielectric constant of the pore fluid; a constant for constant temperature
d = half-distance between clay particles
x_0 = a correlation factor for plate spacing whose value depends upon surface charge density; its value varies from 1 to 4 Å (Bolt, 1956) which is generally small compared to d.

Assuming constant temperature, and $x_0 \ll d$, the swelling pressure can be represented in the form

$$P \sim \frac{1}{z^2d^2}. \qquad (6)$$

For a soil containing both clay and non-clay fraction, the half-distance between particles may be approximated by (Nalezny and Li, 1967)

$$d = \frac{(10^4)w}{CS_S} \qquad (7)$$

where,

w = water content, as a percentage, based on total weight of soil
C = clay content, by weight, of soil as a percentage
S_s = specific surface of the soil in m^2/g.

Combining equations (6) and (7) gives

$$P \sim \frac{C^2S_s^2}{z^2w^2}. \qquad (8)$$

*Pore fluid assumed to be distilled water.

It is well known that the liquid limit or plasticity index can be used as an indicator of the specific surface of soil (Yong and Warkentin, 1966; Komornik and David, 1969). Furthermore, for an expansive soil, the liquid limit or plasticity index decreases with increasing valence of cations adsorbed on the clay surface. Accordingly, the quantity (S_s^2/z^2) in equation (8) is replaced by an expression of the form,

$$\frac{S_s^2}{z^2} \sim E^{2j} \tag{9}$$

where,

$E =$ liquid limit, plasticity index or shrinkage index

$j =$ a constant.

Equation (9) is an attempt to give a simple mathematical representation to the relationship between the consistency limits of a soil and its specific surface and valence of the adsorbed cations. Better results may be obtained if the quantity (S_s^2/z^2) is represented as a power series in E. However, lacking precise knowledge of the behavior of E with respect to (S_s^2/z^2), such refinement seems inappropriate. Substituting equation (9) into equation (8),

$$P \sim \frac{C^2E^{2j}}{w^2} \tag{10}$$

or equivalently,

$$P = K_n' \frac{E^nC^2}{w^2} + K_n''. \tag{11}$$

Equation (10) describes the form of the expected relationship for swelling pressure as a function of clay content, water content and consistency limits. Then equation (11) can be regarded as a regression function with parameters K_n', K_n'', and n to be determined by applying the principle of least squares to experimental data on swelling pressure.

The swelling potential, S, defined as the percent increase in the vertical height is given by

$$S = \left[\frac{d_f}{d_i} - 1\right] 100 \tag{12}$$

where d_f and d_i refer to the final and initial half-spacing between particles respectively. From equation (6) it may be seen that, for a given soil,

$$d \sim \frac{1}{\sqrt{P}} \tag{13}$$

Then, combining equations (10), (12), and (13) the following equation is obtained for the swelling potential with a surcharge loading of one psi:

$$S \sim \left[\frac{E^jC}{w} = 1\right] \{\text{surcharge} = 1 \text{ psi}\} \tag{14}$$

or

$$S = K_m' \frac{E^mC}{w} + K_m'' \tag{15}$$

where equation (14) represents the expected form of the relationship for swelling potential and equation (15) is a regression equation with parameters K_m', K_m'' and m to be determined from least squares analysis of experimental data on swelling potential.

Several approximations were introduced in deriving the equations for the prediction of swelling behavior due to osmotic effects. In addition, it may be mentioned that the swelling pressure and swelling potential due to mechanical effects may or may not be related to each other in the same manner as that due to osmotic effects. At present there are no mathematical equations available relating elastic swelling behavior to physical properties of soils. But it seems reasonable to assume that the stored elastic strain energy due to bending of particles must be related, in some way, to the surface area. As previously discussed, the parameter E is an indicator of the surface area and hence it is probable that swelling behavior related to elastic effects is also a function of the parameter E. Thus, the basic form of equations (11) and (15) is believed to be adequate for the prediction of swelling behavior due to both osmotic and mechanical effects.

In the equations for the prediction of swelling behavior, the parameter E is an indicator of the soil type. It has been previously noted that the type of soil can be represented by liquid limit, plasticity index or shrinkage index. The selection of the best of these three parameters to represent the term E is to be determined on the basis of experimental results.

EXPERIMENTAL WORK

In order to obtain a sufficient variation in the clay content, consistency limits and moisture content within a few soil samples, the soils were prepared by mixing silica sand and commercially available clays, viz. kaolinite, grundite and bentonite in various proportions. In all 18 different soils as listed in Table 1 were tested.

The swelling potential and swelling pressure tests were conducted on soil specimens compacted to a moisture content close to the optimum and the corresponding density of the standard AASHO compaction test. Prior to compaction, the soil was mixed with the desired amount of distilled water

Table 1. Test results

Soil type	% sand/clay	Basic clay materials	Liquid limit (%)	Plasticity index (%)	Shrinkage limit (%)	Clay content (%)	OMC* (%)	Swelling potential: Initial moisture content, w_i (%)	Swelling potential: Measured per cent swell, S_m	Swelling pressure: Initial moisture content, w_i (%)	Swelling pressure: Measured swell pressure, P_m (psi)
GB-11-1	70 30	Grundite &	48·0	29·0	21·2	24·6	15·2	15·5	10·10	15·5	8·39
GB-11-2	60 40	bentonite	63·6	42·1	18·1	32·8	16·1	16·3	15·95	16·6	14·80
GB-11-3	50 50	in ratio 1:1	84·5	57·8	14·3	41·0	17·0	17·0	25·00	17·7	27·00
GB-21-1	65 35	Grundite &	41·4	23·0	16·3	27·2	14·9	15·1	7·85	15·2	6·75
GB-21-2	50 50	bentonite	61·0	39·7	12·5	38·8	16·1	16·1	16·10	15·8	22·90
GB-21-3	35 65	in ratio 2:1	75·6	48·1	10·3	50·5	19·2	19·5	21·80	19·4	25·65
GB-41-1	50 50	Grundite &	45·4	26·8	12·6	37·1	15·1	15·1	10·60	15·6	8·55
GB-41-2	35 65	bentonite	55·9	31·3	10·8	48·3	16·5	17·0	13·30	16·5	13·10
GB-41-3	20 80	in ratio 4:1	66·8	35·9	11·7	59·3	18·6	18·7	17·90	18·8	24·80
KB-11-1	70 30	Kaolinite &	84·3	65·0	19·7	23·1	14·4	14·3	26·70	14·5	16·00
KB-11-2	60 40	bentonite	107·8	86·9	17·2	30·8	16·8	16·8	37·40	17·2	22·40
KB-11-3	50 50	in ratio 1:1	129·2	110·5	13·7	38·5	18·8	19·0	46·60	19·0	32·40
KB-21-1	65 35	Kaolinite &	57·9	43·5	13·5	24·4	14·1	14·0	20·30	14·3	12·90
KB-21-2	50 50	bentonite	83·9	67·0	14·9	34·8	16·5	16·7	27·70	16·3	19·88
KB-21-3	35 65	in ratio 2:1	107·2	85·1	16·6	45·3	20·8	20·8	35·80	20·9	25·85
KB-41-1	50 50	Kaolinite &	61·1	43·0	15·2	32·3	16·8	16·8	18·80	16·9	9·95
KB-41-2	35 65	bentonite	70·7	49·4	17·3	42·0	19·5	19·5	23·40	19·9	13·90
KB-41-3	20 80	in ratio 4:1	89·9	62·5	20·6	51·7	23·3	23·3	28·20	23·2	18·48

*OMC = optimum moisture content corresponding to maximum dry density of standard AASHO compaction test.

and allowed to equilibrate for 4 days in a closed container kept in a room maintained at a constant temperature near 75°F. The compaction test was carried out in a specially designed Proctor mold which is divided into 3 parts. The portion of the specimen in the central part which is exactly 1 in. high was used for swelling potential and swelling pressure tests.

The sample in a swelling potential test was permitted to swell in the vertical direction under a surcharge of 1 lb/in². In the swelling pressure test the sample was restrained from swelling, with the restraint provided through a load cell or a proving ring which permitted the measurement of the vertical force on the sample. For all the samples the maximum vertical strain allowed was less than 0·1 per cent which is negligible for all practical purposes.

The results of the various tests, i.e. consistency limits, compaction, swelling potential, and swelling pressure tests, are given in Table 1.

DISCUSSION OF TEST RESULTS

The constants and the parameter E in equations (11) and (15) were evaluated from the test results by using regression analysis. It was found that E in those equations can best be represented by the plasticity index rather than the liquid limit or shrinkage index.

The soils of the present investigation can be grouped broadly into two categories: i.e. one group containing the soils with grundite and bentonite clay minerals (GB soils) and the other group representing the soils with kaolinite and bentonite clay minerals (KB soils). The constants of equations (11) and (15) were evaluated both separately and combined, for the soils of these two groups. The following equations were obtained by the method of least squares.

(i) *For swelling pressure*

$$P_P = (5{\cdot}05\times 10^{-3})(PI)^{1{\cdot}66}\frac{C^2}{(w_i)^2}+4{\cdot}1239\ \{\text{For GB Soils}\} \quad (16)$$

$$P_P = (6{\cdot}982\times 10^{-4})(PI)^{1{\cdot}92}\frac{C^2}{(w_i)^2}+9{\cdot}1191\ \{\text{For KB Soils}\} \quad (17)$$

$$P_P = (3{\cdot}5817\times 10^{-2})(PI)^{1{\cdot}12}\frac{C^2}{(w_i)^2}+3{\cdot}7912\ \{\text{For all soils}\} \quad (18)$$

where P_P is the predicted value of swelling pressure, in psi, at the initial moisture content, w_i, of the sample.

(ii) *For swelling potential*

$$S_P = (1{\cdot}3548\times 10^{-2})(PI)^{1{\cdot}59}\frac{C}{w_i}+4{\cdot}8046\ \{\text{For GB Soils}\} \quad (19)$$

$$S_P = (4{\cdot}4938\times 10^{-3})(PI)^{1{\cdot}74}\frac{C}{w_i}+14{\cdot}722\ \{\text{For KB Soils}\} \quad (20)$$

$$S_P = (2{\cdot}29\times 10^{-2})(PI)^{1{\cdot}45}\frac{C}{w_i}+6{\cdot}38\ \{\text{For all soils}\} \quad (21)$$

where S_P is the predicted value of swelling potential, as a percentage, at the initial moisture content, w_i, of the sample.

In each of the six cases the coefficient of correlation, r, of the fitted regression lines is very high as can be seen by the comparison between the predicted and the measured values shown in Figs. 1–4. Of course the correlation is better when separate equations are fitted for GB and KB soils.

COMPARISON OF RESULTS WITH PREVIOUS INVESTIGATIONS

Many investigators have conducted swelling pressure and/or swelling potential tests on compacted expansive soils (Ladd, 1960; Seed *et al.*, 1962; Parcher and Liu, 1965; Ranganatham and Satyanarayan, 1965; Nalezny and Li 1967). Unfortunately, in most cases, either the testing conditions differ greatly from that adopted in the present investigation (Ladd, 1960; Parcher and Liu, 1965; Nalezny and Li, 1967), or the given data are insufficient to apply the proposed equations to their soils (Seed *et al.*, 1962). However, some comparisons of the various proposed methods are possible. These are summarized in Fig. 5 and Table 2.

Figure 5 shows a comparison of the ratios of predicted to measured values of swelling potential and swelling pressure using the methods previously reviewed, as well as the writers equations. Figure 5a applies to the soils studied by the writers, while Fig. 5b applies to the soils studied by Seed *et al.* The results of these comparisons are summarized in Table 2.

The relative success of the various prediction methods can be evaluated in terms of (a) the scatter of the data points and (b) the mean value of the ratio of the predicted to the measured values. In Fig. 5, the scatter of the data is manifested in the slope of the curves; i.e. the flatter the slope, the greater the scatter. Of course, the mean value of S_P/S_m or P_P/P_m should, ideally, be as close to unity as possible. In Table 2, the relative amount of scatter in the various methods can readily be seen

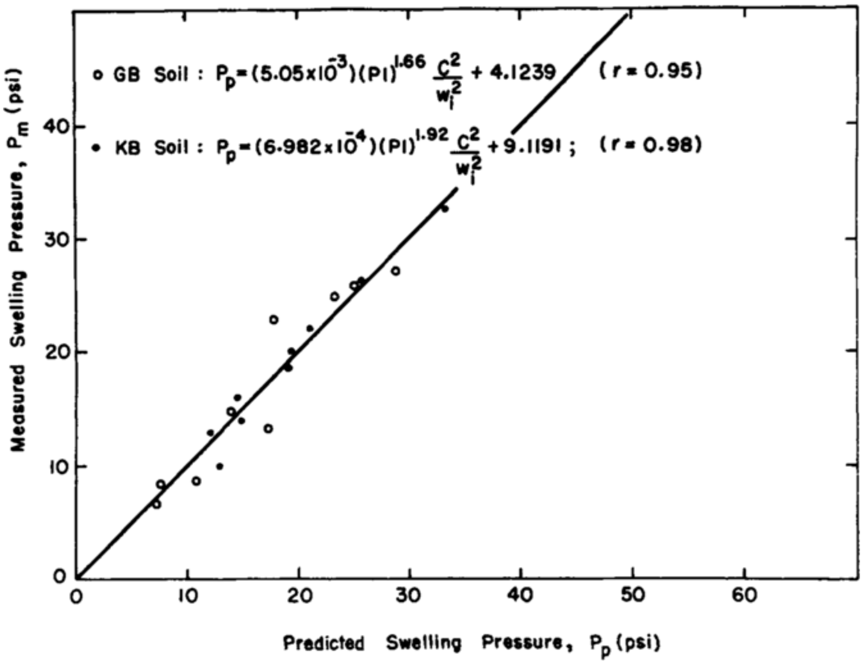

Fig. 1. Measure vs. predicted values of swelling pressure.

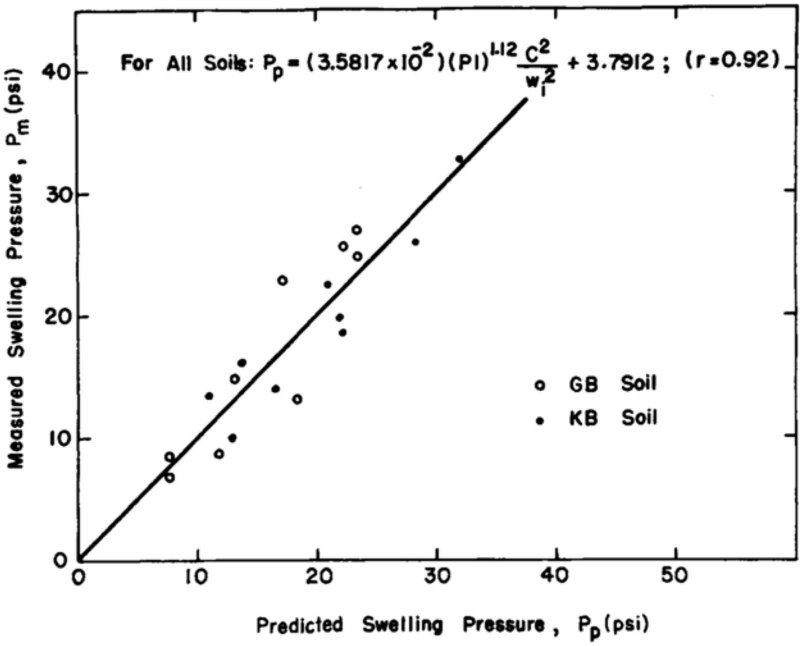

Fig. 2. Measured vs. predicted values of swelling pressure.

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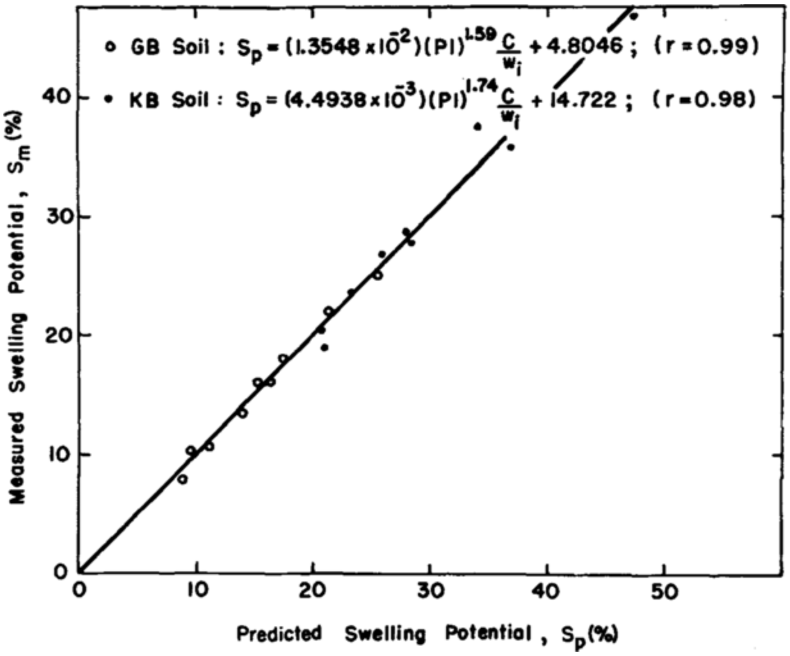

Fig. 3. Measured vs. predicted values of swelling potential.

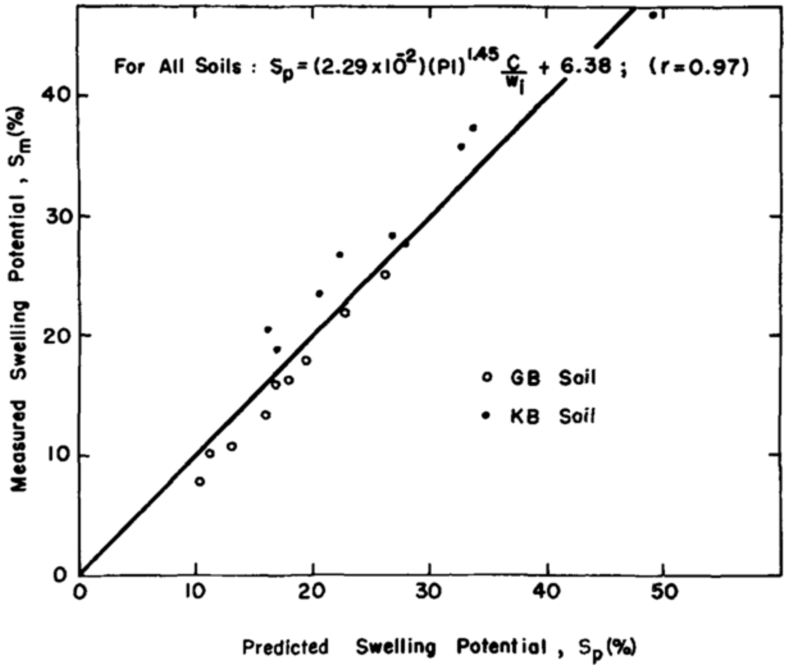

Fig. 4. Measures vs. predicted values of swelling potential.

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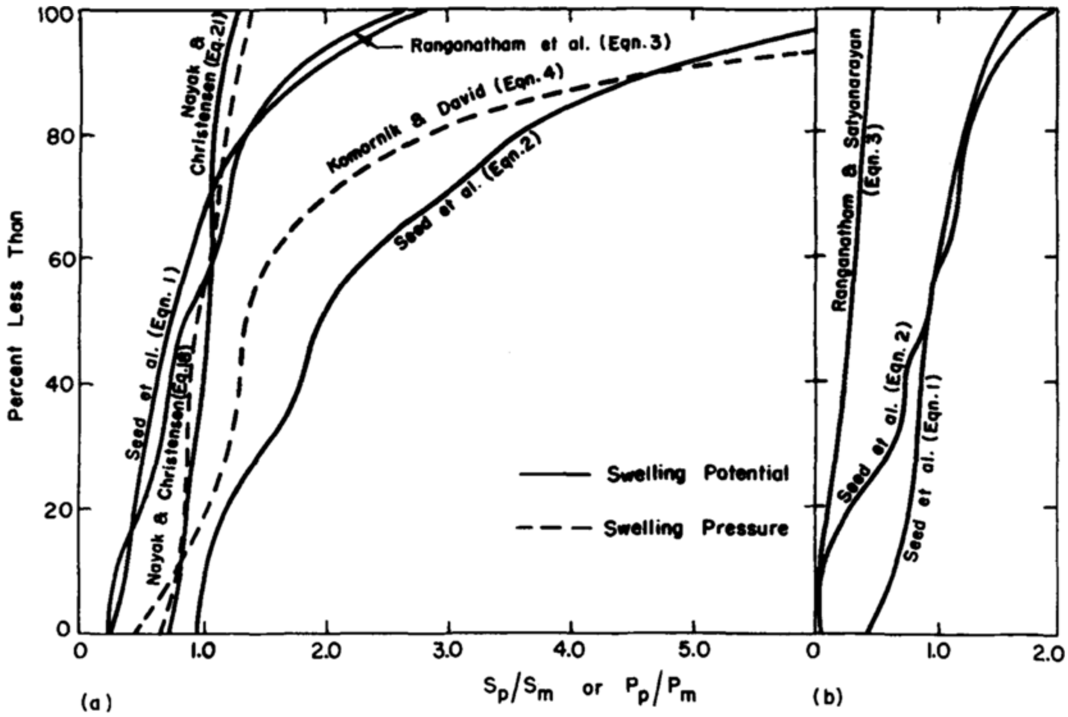

Fig. 5. Comparison of prediction methods for swelling potential and swelling pressure (a) soils of the present study (b) soils studied by Seed *et al.*

Table 2. Comparison of prediction methods for swelling potential and swelling pressure

Method	Soils of the present study			Soils studied by Seed *et al.*		
Swelling potential	$(S_p/S_m)_{10}$	$(S_p/S_m)_{50}$	$(S_p/S_m)_{90}$	$(S_p/S_m)_{10}$	$(S_p/S_m)_{50}$	$(S_p/S_m)_{90}$
Nayak and Christensen equation (21)	0·82	1·05	1·17			
Seed *et al.* equation (1)	0·35	0·77	1·92	0·65	0·92	1·35
Seed *et al.* equation (2)	1·02	1·97	4·73	0·07	0·92	1·45
Ranganatham and Satyanarayan equation (3)	0·28	0·86	1·75	0·05	0·30	0·45
Swelling pressure	$(P_p/p_m)_{10}$	$(P_p/p_m)_{50}$	$(P_p/p_m)_{90}$	$(P_p/p_m)_{10}$	$(P_p/p_m)_{50}$	$(P_p/p_m)_{90}$
Nayak and Christensen equation (18)	0·80	0·96	1·30			
Komornik and David equation (4)	0·80	1·36	4·70			

$(S_p/S_m)_{10}$, $(S_p/S_m)_{50}$ and $(S_p/S_m)_{90}$ designate that 10 per cent, 50 per cent and 90 per cent of the observations are smaller than the reported values.

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by comparing the differences between the 90 per cent and 10 per cent values and the approximate mean value is given by the 50 per cent value.

For the soils of the present study, the writers equation (equation 21) clearly gives the most accurate predictions for swelling potential followed by Ranganatham and Satyanarayan (equation 3) and Seed *et al.*'s equation involving activity (equation 1). The equation recommended by Seed *et al.* for practical use (equation 2) produces large errors, particularly for soils of high plasticity. For swelling pressure, the writers equation 18 gives the best results. The only other method available for comparison, that of Komornik and David (equation 4) is comparatively inaccurate when applied to the soils of the present study.

Figure 5b shows a comparison of the methods of Ranganatham and Satyanarayan (equation 3) and Seed *et al.* (equations 1 and 2) for the soils studied by Seed *et al.* The writers method could not be included in this comparison because the molding water content for these soils is unknown. For these soils the method of Seed *et al.* (equation 1) appears to give the best results. However, it may be noted that Ranganatham and Satyanarayan's method gives comparatively little scatter and by suitable adjustment of the constant m_1, the agreement would be better than that obtained from either of the equations proposed by Seed *et al.* Therefore, it would appear that for the soils studied by Seed *et al.*, the shrinkage index is a slightly better indicator of swelling potential than is the activity and considerably better than the plasticity index alone. In the case of the writers' soils (Fig. 5a), these two approaches (equations 1 and 3) appear to give nearly the same degree of accuracy.

The writer's equation for swelling potential (equation 21) was also applied to the soils tested by Ranganatham and Satyanarayan (1965). However, the results of this comparison are not included in Fig. 5 or Table 2 because of the small number of tests (4) reported. The accuracy of the writers predictions is roughly equivalent to that of Ranganatham and Satyanarayan (maximum error equals 49 per cent for the writers predictions as compared to 36 per cent for Ranganatham and Satyanarayan) for the tests reported. It must be noted, however, that this comparison is not very meaningful from a statistical point of view due to the small size of the (statistical) sample.

CONCLUSIONS

(1) A set of semi-empirical equations has been derived for the prediction of swelling behavior of compacted, expansive soils. The proposed equations are based on consideration of osmotic and mechanical swelling phenomena and have been found to give accurate predictions of swelling pressure and swelling potential for a wide range of soil types.

(2) The application of the proposed equations in practice is simple as they contain only parameters which can be determined from routine classification tests; namely, plasticity index, clay content and initial molding water content.

(3) Comparison with other methods reported in the literature indicates that the proposed equations give considerably better accuracy, at least for the soils tested by the writers. The other methods appear to be most inaccurate in the ranges of high plasticity (for swelling potential) and high activity (for swelling pressure) where the tendency is for the swelling potential or swelling pressure to be greatly overestimated. On the other hand, the writers' equations do not seem to suffer any loss of accuracy in these ranges.

(4) Since the molding water content is included as one of the variables in the writers' equations, they have a wider range of applicability than those previously proposed. Although the writers' equations assume constant soil structure, and, therefore, similar conditions of compaction, a range of water contents near the optimum can be accommodated without seriously violating the assumptions. This is an important advantage since some variation from the optimum water content is inevitable in field compaction.

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Résumé—Les limitations des méthodes existantes pour la prédiction du gonflement de sols compactés sont examinées. On trouve que l'approche purement théorique et l'approche purement empirique sont toutes deux inappropriées. L'étude présente est fondée sur une approche semi empirique dans laquelle on développe un modèle de comportement gonflant qui conduit à des équations reliant le potentiel de gonflement ou la pression de gonflement d'un sol compacté, à son indice de plasticité, sa teneur en argile et sa teneur initiale en eau lors du moulage. Ce modèle est fondé sur les concepts de la double couche diffuse, modifiée en introduisant des constantes empiriques qui tiennent compte des effets de gonflement élastique et d'autres limitations inhérentes à l'application directe de la théorie de la double couche à des sols réels. Les constantes empiriques sont évaluées à partir des résultats de recherches expérimentales effectuées sur un grand nombre d'échantillons de sols représentant une large gamme de teneurs en argile et de limites de cohésion.

On montre que les valeurs prédites pour le potentiel de gonflement et la pression de gonflement fondées sur le modèle proposé sont en accord étroit avec les résultats expérimentaux de ce travail et avec ceux de la littérature. En outre, les équations développées ici sont d'une nature beaucoup plus géné ale et semblent applicables à une plus grande varié é de types de sols, que celles qui avaient été publiées antérieurement.

Kurzreferat—Es werden die Begrenzungen bestehender Methoden für die Voraussage von Quellungsverhalten verdichteteter Böden untersucht. Es gestgestellt, dass sowohl die rein theoretische Methode als auch die rein empirische Methode ungenügend sind. Die gegenwäartige Untersuchung basiert auf einer half-empirischen Methode, bei welcher ein modellmässiges Quellungsverhalten entwickelt wird um Gleichungen zu erhalten, die das Quellungspotential oder den Quellungsdruck eines verdichteten Bodens in Beziehung zum Plastizitätsindex, Tongehalt und anfänglichem Formwassergehalt desselben bringen. Das Modell gründet sich auf die Begriffe der diffusen Doppelschicht theorie, abgeändert durch Einführung empirischer Konstanter zur Berücksichtigung der elastischen Quellwirkungen und anderer Begrenzungen, die eine unmittelbare Anwendung der Doppelschichttheorie auf wirkliche Böden mit sich bringt. Die empirischen Konstanten werden aus den Ergebnissen versuchsmässiger Untersuchungen, die mit einer grossen Zahl von Bodenproben, die einen weiten Bereich von Tongehalten und Kosistenzgrenzen darstellen, ausgeführt wurden, abgeschätzt.

Es wird gezeigt, dass die auf Grund des vorgeschlagenen Modells vorausgesagten Werte des Quellungspotentials und des Quellungsdrucks eng mit den Versuchsergebnissen dieser Untersuchung und den Literaturdaten übereinstimmen. Darüber hinaus sind die in dieser Untersuchung entwickelten Gleichungen von einer allgemeineren Art und scheinen auf einen weiteren Bereich von Bodenarten anwendbar zu sein als die bisher veröffentlichten.

Резюме — Рассмотрены ограничения методов прогнозирования разбухания компактных почв. Установлено, что результаты использования чисто теоретического и чисто эмпирического подходов не являются равноценными. Исследование основано на полуэмпирическом подходе, в котором развито представление о процессе разбухания, приводящее к уравнениям, связывающим потенциал разбухания или давление разбухания компактных почв с их коэффициентом пластичности, содержанием глинистой компоненты и начальным содержанием воды. Подобное моделирование основано на концепции диффузного двойного слоя, несколько измененной введением эмпирических констант для учета эффектов эластичного разбухания и других ограничений, обусловленных прямым применением теории двойного слоя к реальным почвам. Эмпирические константы оценены по результатам экспериментальных исследований большого количества образцов почв с широкими вариациями как содержания глинистого компонента, так и плотности грунта.

Показано, что предсказанные на основе предложенного метода значения потенциала разбухания и давления разбухания хорошо согласуются с экспериментальными результатами проведенного исследования и литературными данными. Кроме того, уравнения, предложенные авторами, имеют более общее значение и, по всей вероятности, применимы к более разнообразным почвам, чем ранее разработанные методы.