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EVALUATION OF SHRINK-SWELL POTENTIAL OF SOILS BY TWO PROCEDURES

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A b s t r a c t. The swelling potential (S) values of fifteen topsoil samples from northcentral Italy estimated from their plasticity indices were compared with their volumetric shrinkage potential (VS) computed from measured coefficient of linear extensibility (COLE) data. The absolute values from the two methods were different but the relative order of shrink-swell potential produced by them was the same for all soils. Hence both methods give the same information on the potential of these soils to change volume with changes in moisture content. Since it is easier and less time-consuming to measure COLE than plasticity index, computation of volumetric changes from linear shrinkage data is a better method than prediction from measured Atterberg's consistency limits. However, an univariate model of the form VS=3.28 (PI)-33.48, (r^2=0.99), adequately predicted VS in all five test soils and shows that below a PI of 10 % volumetric change due to moisture stress is not expected on these soils.

INTRODUCTION

Information on the shrink-swell potential of soils when subjected to changes in moisture stress is needed by civil, agricultural, foundation and geotechnical engineers for understanding and solving problems related to the bearing capacity of soils, differential settlements in foundations, and the susceptibility of soils to frost-induced alterations in stability. For this reason detailed soil survey reports include data that can be used to make inferences on this soil property, such as the Atterberg's consistency limits, moist and dry bulk densities and the coefficients of linear extensibility (COLE) [3].

Shrink-swell potential can be estimated from the plasticity index, clay content and the plasticity activity of soils. In this paper values from such estimates are compared with measured data.

THEORY

The shrink-swell potential of soils can be evaluated from measurements of any of the following: (i) the percent swell of samples (*S*), (ii) coefficient of linear extensibility (COLE), and (iii) percent volume change or volumetric shrinkage (*VS*). In geotechnical studies *S* is commonly estimated from either of the following linearized empirical relationships [5]:

$$\log S = \log z + a \log (PI) \qquad (1)$$

$$\log S = \log k + a \log A + b \log C \qquad (2)$$

where *A* - percent activity, *C* - percent clay and *PI* - plasticity index and *k*, *a*, *b* and *z* have the respective values: 0.000036, 2.44, 3.44 and 0.00216. Activity is defined as the ratio of *PI* to *C* (mm), where *PI* is the difference between liquid limit (*LL*) and plastic limit (*PL*).

COLE is defined as:

$$\text{COLE}=(L_m-L_d)/L_d=(L_m/L_d)-1 \qquad (3)$$

where L_m - length of moist soil samples and L_d - length of dry samples. Equation (3) is used for computing COLE when the length measurements are made on the < 2 mm (fine-earth) soil fractions. When COLE is calculated from natural clods, volume rather than length changes are used.

If it is assumed that dimensional changes per unit length in Eq. (3) are equal along the X, Y and Z axes [6], then:

$$\text{COLE} = (V_m/V_d)^{1/3} - 1 \quad (4)$$

where V_m - volume of moist clod and V_d - volume of the dry clod. But volume measurements of soils are used mainly to compute bulk density values and in fact COLE was developed as an application of bulk density data [7], using the dry (D) and moist (D') density values where:

$$D = M_d/V_d \quad (5)$$

$$D' = M_d/V_m \quad (6)$$

and M_d - mass of dry soil clod.

By substituting the reciprocals of D and D' for the respective volumes in Eq. (4) we obtain:

$$\text{COLE} = (D/D')^{1/3} - 1. \quad (7)$$

It is important to emphasize that D is the oven-dry bulk density and D' is the bulk density at the 0.03 MPa or other defined water retention. The use of Eq. (7) to measure COLE on natural clods has been described in detail by Franzmeier and Ross Jr. [4] and Holmgreen [8].

Volumetric shrinkage (VS) on the other hand is defined as:

$$VS = [(V_m/V_d) - 1] \cdot 100. \quad (8)$$

If Eq. (8) is rewritten as:

$$VS = [(V_m - V_d)/V_d] \cdot 100 \quad (9)$$

then VS can be related to dry and moist bulk densities if we substitute the reciprocals of D and D' from Eqs (5) and (6),

$$VS = [(D/D') - 1] \cdot 100 \quad (10)$$

or by substituting from Eq. (7),

$$VS = [(\text{COLE} + 1)^3 - 1] \cdot 100. \quad (11)$$

Equation (11) gives the basic relationship between VS and COLE. According to Hallberg [7], volumetric shrinkage gives a more easily understandable rating of the shrink-swell potential of a soil than its corresponding COLE value.

MATERIALS AND METHODS

This study was conducted with fifteen natural soil samples collected from different parts of north central Italy. The samples were air-dried and passed through a 2 mm sieve. The pertinent properties of the 2 mm fraction are given in Table 1. Particle size distribution was determined by the pipette method, mineralogical analyses by X-ray diffractometry and cation exchange capacity (CEC) by the sodium acetate method. These techniques are described in detail in American Society of Agronomy (ASA) Monograph No. 9 [1].

Two methods were used to determine liquid limit. The first was the Casagrande method [14] and the second was the cone penetrometer technique [15] using a standard laboratory penetrometer (Seta Model, 1970). The second method is less time-consuming and the values obtained are less operator-dependent than the first but the first method is the conventional procedure. So a comparison of the liquid limit values obtained by the two methods was thought necessary. Plastic limit was obtained by the Casagrande technique whereas plasticity index was obtained as the difference between the cone penetrometer liquid limit and the plastic limit.

The method used to estimate shrink-swell potential is that given above in Eq. (1). Values from this procedure (known as S_1) were compared with estimates obtained from Eq. (2)

Table 1. Some characteristics of the soil samples used for model development

Soil No.	Particle size fractions (%)			Texture[1]	CEC2 (me/100 g)	Clay mineralogy[3]
	Sand 0.02-2.0 mm	Silt 0.002-0.02 mm	Clay <0.002 mm			
1	12.2	41.4	46.4	C	31.5	IL, K, S
2	13.1	40.1	46.8	C	29.9	IL, K, S
3	56.8	25.1	18.1	SL	21.7	IL, S, K
4	54.2	21.7	24.1	SL	23.9	IL, S, K
5	51.6	28.7	19.7	SCL	22.8	INT, K+I+,IL
6	54.1	28.1	17.8	SCL	22.8	INT, K+H, IL
7	26.0	36.6	37.4	CL	22.3	K, IL, CH
8	28.9	34.1	37.0	CL	28.3	K, IL, CH
9	22.2	34.0	43.8	C	22.8	K, IL, CH
10	52.0	28.3	19.7	SL	21.3	V+S, INT, K+H
11	59.1	24.9	16.0	SL	22.3	V + S, INT, K + H
12	66.1	19.3	14.6	SL	16.9	V + S, IL, K+ H
13	64.6	22.1	13.3	SL	20.7	V + S, IL, K + H
14	49.2	29.9	20.9	SCL	21.7	IL, K + H, INT
15	46.4	36.0	17.0	SCL	25.0	IL, K + H, INT

1. C - clay, SL - sandy loam, SCL - sandy clay loam; 2. CEC - cation exchange capacity; 3. IL - illite, K - kaolinite, H - halloysite, S - smectite, CH - chlorite, V - vermicullite, INT - intergrade (CH-S-V).

(known as S_2). The volumetric shrinkage (VS) was computed from measured COLE values using Eq. (11). The method used to determine COLE is that described by Schafer and Singer [13] for measurements on 2 mm sieved soil samples. Moist length was measured after equilibration at 0.03 MPa tension whereas dry length was measured after oven-drying the moist sample for 24 h at 105 °C.

Simple correlation and regression models were used to evaluate the relationship between estimated and measured shrink-swell potential data. The measured shrink-swell potential were also related to particle size fractions and the consistency limits by simple models. The model with the highest coefficient of determination (R^2) and the smallest standard error (S.E) was chosen as the best.

To validate the best-fit model five other soils (see Table 2 for characteristics) were sampled, air-dried, sieved and used to determine the shrink-swell potential and the other independent variable. The predictive ability of the model was evaluated by how close the estimated values were to the measured ones.

RESULTS

The liquid limit values obtained by the cone penetrometer and Casagrande techniques are shown in Table 3. Consistently the cone penetrometer (P) over-estimated the values obtained from the Casagrande (C) method by between 4 and 10 %. The standard deviation values of 9.2 and 9.8 and the coefficients of variation of 20.6 and 23.7, for the P and C values respectively, indicate, however, that both methods gave closely related liquid limits. The correlation coefficient r=0.997, significant at $P \leq 0.001$ also confirms this. A similar observation was made on some lateritic soils by Queiroz de Carvalho [11], who proposed the cone penetrometer method as an alternative to the classical Casagrande technique. The overestimation was lower for the clayey than for the more sandy soils.

Measured and estimated shrink-swell potential values are shown in Table 4. On each soil the per cent swell estimated from the plasticity index alone (S_1) was higher than that estimated from the plasticity activity and per cent clay contents (S_2). The high

Table 2. Some properties of the test soils used for model validation

Soil No.	Particle size fractions (%)			Texture	CEC (me/100g)	Atterberg's limits*		
	Sand	Silt	Clay			LL %	PL %	PI %
01	12.5	31.4	56.1	Clay	33.7	61.1	31.8	29.3
02	12.1	32.3	55.6	Clay	33.7	60.6	31.4	29.2
03	26.2	46.5	27.3	Clay loam	19.6	41.9	21.6	20.3
04	26.4	36.7	36.9	Clay loam	20.7	42.1	20.9	21.2
05	41.0	37.5	21.5	Loam	22.8	38.7	24.8	13.9

* LL - liquid limit; PL - plastic limit; PI - plasticity index.

Table 3. Atterberg's limits (%) and activity of the soil samples

Soil No.	Liquid limit (penetrometer)	Liquid limit (Casagrande)	Percent over-estimation	Plastic limit	Plasticity Index	Activity[1]
1	62.1	60.3	2.9	31.1	31.0	0.67
2	61.1	58.2	4.7	31.2	29.9	0.64
3	40.0	36.2	9.4	23.2	16.8	0.93
4	40.5	36.0	10.9	25.1	15.4	0.64
5	35.9	32.1	10.6	23.1	12.8	0.65
6	33.8	30.0	11.3	21.9	11.9	0.67
7	53.2	50.9	4.2	25.9	27.3	0.73
8	50.1	48.1	4.0	22.7	27.4	0.74
9	53.5	51.0	4.6	25.0	28.5	0.65
10	36.8	34.0	7.5	21.3	15.5	0.78
11	42.3	38.1	10.0	27.6	14.7	0.92
12	33.7	30.4	10.0	23.4	10.3	0.71
13	43.8	39.5	9.8	27.8	16.0	1.20
14	41.3	37.6	8.9	25.9	15.4	0.74
15	42.9	38.6	10.0	27.6	15.3	0.87

1. Activity (A) - $\frac{\text{Plasticity index}}{\text{\% Clay}}$

Table 4. Measured and estimated shrink-swell potential of the soils

Soil No.	Measured		Estimated swelling potential (S)		
	COLE	Volumetric shrinkage, %	(1)	(2)	Shrink-swell hazard
1	0.189	68.09	9.41	7.32	Very severe
2	0.176	62.64	8.61	6.75	Very severe
3	0.063	20.12	2.11	0.64	Severe
4	0.060	19.10	1.71	0.69	Moderate
5	0.028	8.64	1.09	0.36	Slight
6	0.021	6.43	0.91	0.27	Slight
7	0.165	58.12	6.90	4.30	Very severe
8	0.165	58.12	6.96	4.28	Vere severe
9	0.170	60.16	7.66	5.58	Very severe
10	0.059	18.76	1.73	0.56	Moderate
11	0.038	11.84	1.52	0.41	Moderate
12	0.013	3.95	0.64	0.16	Slight
13	0.045	14.12	1.87	0.41	Moderate
14	0.053	16.76	1.71	0.60	Moderate
15	0.047	14.77	1.68	0.49	Moderate

1. $S - 0.00216\ (PI)^{2.44}$; 2. $S - 0.000036(A)^{2.44}, (C)^{3.44}$; where PI - plasticity index; A - activity; C - clay %.

correlation (r=0.99) between both estimates shows that they are very closely related and therefore, give the same information on the relative swelling potentials of these soils.

A comparison between volumetric shrinkage (VS) and per cent swell (S_1) is depicted graphically in Fig. 1. The regression equation between both values:

$$VS = 2.15 + 7.41\,(S) \qquad (12)$$

has a coefficient of determination (R^2) of 0.98 (significant at $P \leq 0.001$) and a standard error (S.E) of 0.70. This figure shows a close relationship between observed and predicted VS values which again indicates that both values give the same information on the relative shrink-swell potential of these soils even though their absolute values are different. This potential ranges from slight (for the sandy soils) to very severe (for the clay soils).

Regression models depicting the relationships between VS and other soil properties are shown in Table 5. With the exception of the plastic limit which correlated poorly with VS, the other physical parameters were closely related to this property with coefficients of determination (R^2) that ranged from 80 to 99 %. This shows that VS is related more to the liquid than plastic limits of soils. In terms of the magnitudes of R^2 and the standard error of estimates, the best predictive model is:

$$VS = 3.28\,(PI) - 33.48 \qquad (13)$$

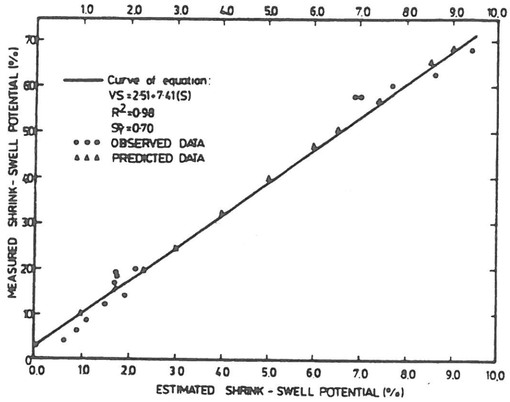

Fig. 1. Relationship between measured and estimated shrink-swell potential of soils.

which is also plotted in Fig. 2. This supports earlier findings that the plasticity index (PI) can be reliably used to predict soils that may pose problems of expansion [9]. Equation (13) shows that below a PI value of 10 % these soils will not show any appreciable changes in volume with changes in moisture contents.

In Table 6 it is shown that Eq. (13) is a reliable predictor of the volumetric change capacity (VS) of the five test soils. Analysis of the coefficients of variability showed that the measured and predicted VS values were very close, varying by less than 3 % only.

DISCUSSION

Shrinkage-susceptible soils pose serious problems to agriculturalists and engineers. Vertical shrinkage cracks on agricultural soils act as channels through which rapid

Table 5. Relationship between soil volumetric shrinkage (VS) and some physical properties

Soil No.	Independent variable	Regression equation	Standard error (SE)	R^2
1	Percent sand (PSD)	VS = 66.07-0.71 (PSD)	3.02	0.86*
2	Percent silt (PSI)	VS = 2.81 (PSI) - 54.96	4.11	0.80*
3	Percent clay (PC)	VS = 1.88 (PC) - 19.79	1.39	0.94*
4	Liquid limit (LL)	VS = 2.43 (LL) - 79.38	2.21	0.88*
5	Plastic limit (PL)	VS = 3.67 (PL) - 64.36	5.37	0.22NS
6	Plasticity index (PI)	VS = 3.28 (PI) - 33.48	0.65	0.99*

* Significant at P=0.001; NS - not significant.

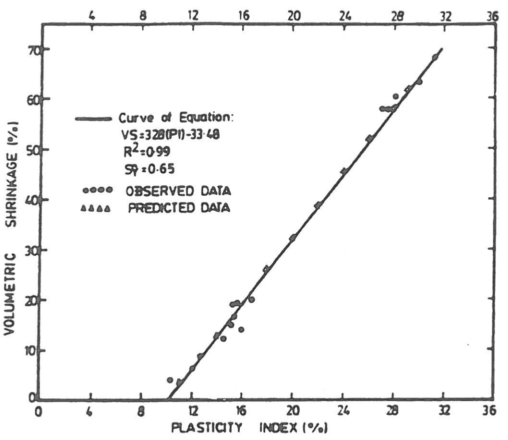

Fig. 2. Relationship between volumetric shrinkage and plasticity index of soils.

alone (Eq. 1) gives the same information on the relative shrink-swell potential of these soils as the percent volumetric shrinkage (*VS*) obtained from measured linear shrinkage data (COLE). Since measurement of COLE is easier, less time-consuming and generally more reliable than that of *PI*, calculation of *VS* from COLE values offers a good alternative method for evaluating the shrink-swell potentials of these soils.

The highly correlated linear relationship between *VS* and *PI* is consistent with literature [9]. This relationship is not surprising since COLE, from which *VS* was calculated and the plasticity index values are parameters depicting differences at higher and lower moisture contents. Noteworthy is also the a high positive correlation between

Table 6. Comparison between measured and estimated volumetric shrinkage of the test soils

Soil No.	Measured		Volumetric shrinkage (VS) estimated from VS = 3.28 (PI)-33.48
	COLE	Volumetric shrinkage	
01	0.178	63.47	62.62
02	0.172	60.90	62.30
03	0.103	34.19	33.10
04	0.108	36.03	36.06
05	0.039	12.16	12.11
SD		21.23	21.46
CV%	-	51.35	52.04

loss of irrigation water can occur. If used for foundations for buildings and dams without adequate anti-shrinkage treatment, cracks will frequently occur on the walls as the soils contract during dry periods. For these reasons several studies have been carried out to evaluate the expansion-contraction potential of soils from more easily determined soil properties.

Even though attempts have been made to relate this property to some chemical properties like the percent base saturation of the exchange complex [2,12]. The most common approach is to relate it to particle size distribution and Atterberg's consistency limits. From the results of this study it is evident that the percent swell (*S*) of these soils estimated from the plasticity index (*PI*)

VS and clay content. A highly significant positive correlation (r=0.96) was also obtained between *PI* and the clay contents. It appears therefore, that clay in these soils, through its effects on *PI*, influences their shrinkage susceptibility. This is not always the case with all soils. Mbagwu [10], on some alluvial soils in Nigeria, obtained an in significant positive correlation (r=0.3506) between COLE and the amount of clay. Franzmeier and Ross Jr. [4] made also similar observations in the United States of America. It was concluded that the type and amount of adsorbed cations, type and amount of clay and fabric arrangement interactively influence COLE values and hence, the shrinkage potential of soils.

The linear model relating *VS* to *PI*, shown in Eq. (13) was able to adequately predict volumetric shrinkage in all the five test soils because of the close similarity between the properties of these test soils and those from which the model was developed. But it is easier to measure *VS* by the method used in this study than to compute *PI* for *VS* prediction. The usefulness of Eq. (13) is, however, that if the Atterberg's limits of similar soils are already known or are the characteristics that can only be determined, this model can be used for a rapid evaluation of their shrinkage potential.

CONCLUSIONS

The results of this study show that the relative order of expansion-contraction potential of the soils studied from estimates by the non-linear model, $S=2.16 \cdot 10^{-3}\,(PI)^{2.44}$, is the same as that obtained from calculations with measured coefficient of linear extensibility (COLE) using the Eq. 11.

Since it is easier and less time-consuming to measure COLE than plasticity index, evaluation of the shrinkage potential of soils from COLE is a better alternative method. However, on similar soils where plasticity index data are already available, it is possible to estimate *VS* from the simple model, $VS = 3.28\,(PI) - 33.48$, ($r^2=0.99$).

This model shows that below a plasticity index value of 10 %, volumetric changes in these and similar soils due to changes in moisture contents should not be expected.

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