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CONSTRUCŢII. ARHITECTURĂ

INDIRECT ESTIMATION OF SWELLING PRESSURE FROM ROUTINELY DETERMINED GEOTECHNICAL PARAMETERS

BY

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Abstract. The light weight structure built over potentially expansive soils may suffer damage due to the uplift pressure exerted by the soil after moisture increase. The measurement of the swelling pressure can be made in laboratory using direct methods based on the oedometer tests. This test is long time consuming and implies high costs. There is an increasing trend in predicting the value of swelling pressure based on routinely determined geotechnical parameters like dry unit weight, initial water content, clay content, Atterberg limits, cation exchange capacity. This article presents the results of correlation and regression made with the Statistica V.13 software, on 50 soil samples collected from nine countries. The analyses show a high coefficient of correlation (R) of swelling pressure with the plasticity index followed by the liquid limit and clay content. Also, this paper provides empirical equations for indirect estimation of swelling pressure based just on a single soil parameter (PI, LL) or two parameters (PI and LL, PI and Cl).

Keywords: expansive soils; swelling pressure; statistical study; empirical correlation; empirical method.

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1. Introduction

The swelling of soils is a process that occurs in fine soils that are rich in hydrophilic minerals (*i.e.*, montmorillonite), which modify their volume with change in water content. A proper design of a structure on such soils needs a proper identification and estimation of swelling characteristics. The geotechnical engineers use the oedometer test to evaluate the swelling characteristics. In this test, the geotechnical engineer measures the increase in volume with time on soaked samples, the swelling pressure being equal with the pressure needed to bring the soil specimen to its initial void ratio (Kayabali and Demir, 2011). This test has some disadvantages, like long time consumption, extra care with sample preparation and relatively high costs if there is a high number of soil specimen to be tested (Elbadry, 2015). During preliminary site investigation the soil swelling characteristics like swelling pressure and prediction of swelling potential can be evaluated using different correlation existing in the literature. There is an increasing interest in proposing new correlation between swelling pressure and soil index properties determined by routine tests (*i.e.*, dry unit weight, initial water content, clay content, Atterberg limits, cation exchange capacity). The problem is to find which soil index will correlate the best with the swelling properties of an expansive soil. The correlation can be made using one to three soil indexes. The most common used empirical equations which are concern with the prediction of swelling pressure are summarized in Table 1.

Table 1
Summary of the Empirical Methods

Equation propose by	Empirical equation	References
Komornik and David (1969)	$logp_s = -2.132 + 0.0208 \cdot LL +$ $+0.00665\gamma_d - 0.0269 \cdot w_i$ [kgf/cm^2]	Al-Rawas *et al.*, 2006
Vijayvergiya and Gazzaly (1973)	$logp_s = 1/19.5 \cdot (\gamma_d + 0.65 \cdot LL - 139.5$ [tons/ft^2]	Al-Rawas et al., 2006
Nayak and Christensen (1974)	$p_s = 2.50 \cdot 10^{(-1)} \cdot PI^{1.22} \cdot Cl^2 / (w_i^2) + 25$ [kN/m^2]	Elbadry, 2015
Popescu (1974)	$p_s = 0.5735 \cdot PI - 10.9196$ [kN/m^2]	Elbadry, 2015
Brackely (1975)	$logp_s = 5.3 \cdot [147 \cdot e / PI]$ [kN/m^2]	Elbadry, 2015
El-Sharief (1987)	$logp_s = 2.6386 \cdot \gamma_d + 1.3922 + 10^{(-2)} \cdot LL - 2.4755$	Elbadry, 2015
LL – liquid limit; PI – plasticity index; Cl – clay content; e – void ratio; w_i – natural moisture content; γ_d – dry unit weight		

Soil scientist agreed that there isn't a correlation equation that estimates the swelling potential or swelling pressure accurately for all soils.

The main objectives of this study were: (i) to investigate the influence of routinely determined geotechnical parameters like LL, PI and clay content on swelling pressure using the correlation analysis, and (ii) based on regression analysis, to establish a relationship between the geotechnical parameters that have the highest influence on the swelling properties of soils for indirect estimation of swelling pressure.

2. Materials and Methods

2.1. Soil Sample Collection

The data consists in 86 sets of values out of which 50 values were used for the learning stage and 36 for validating the results. The geotechnical data for the selected soil set of values were collected from the literature, from nine countries (Australia: 5 samples; India: 36 samples; Sudan: 5 samples; Egypt: 1 sample; Greece: 3 samples; Turkey: 3 samples; U.S.A.: 4 samples; Saudi Arabia: 15 samples; Pakistan: 12 samples; other countries: 2 samples). The samples were chosen that the swelling pressure test to be conducted on soil specimens compacted at optimum moisture content. The ranges in geotechnical properties of the soils used in the learning stage are (Table 2): the clay content ranged from 0.9 to 100% by weight; a liquid limit of 7.1 to 176% and a plasticity index of 7.1 to 150%.

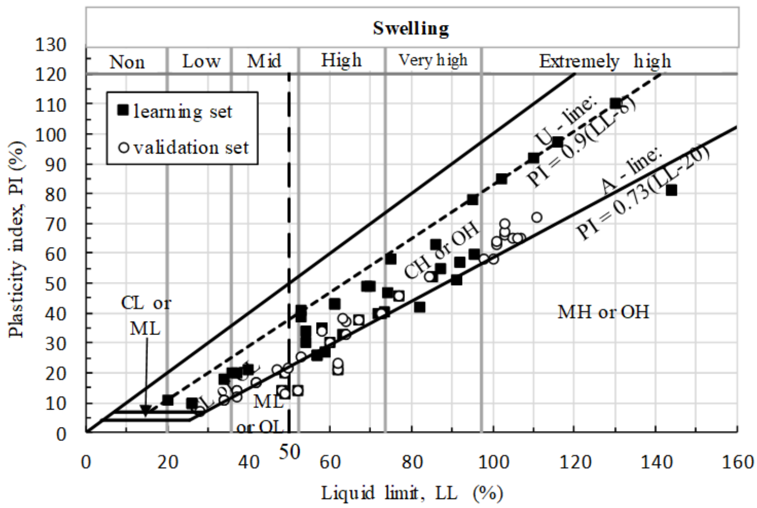


Fig. 1 − Plasticity chart of the soil samples.

The plasticity chart of the soil samples (Fig. 1) shows that the variation domain of the swelling potential of the samples is from low to very high. Also, it can be observed that the position of the majority of soil samples on plasticity chart is above the A line, indicating that they belong to the inorganic clay varieties (Fekerte *et al*., 2011).

Table 2

Summary of Geotechnical Results for Soil Samples that was Used for Learning Stage

Clay (%)	*LL* (%)	*PI* (%)	p_s (kPa)	References	
		Sample area	Australia	No. of samples:	5
0.9÷93.3	49÷91	12÷51	80÷263	Mirzababaei *et al*., 2017; Alazigha *et al*., 2018; Jayalath *et al*., 2016; Tehrani, 2016; Hasan *et al*., 2016	
		Sample area	India	No. of samples:	36
26 ÷ 100	7.1 ÷ 100	7.1 ÷ 81	0 ÷ 466.7	Sri Rambabu *et al*., 2016 Sathyapriya and Arumairaj, 2016; Sudha Rani, 2013; Shingade *et al*., 2016; Radhakrishnan *et al*., 2014; Patil *et al*., 2016; Parimala *et al*., 2017; Tripathy *et al*., 2009; Sridharan and Gurtug, 2004; Ramesh *et al*., 2012; Pruska *et al*., 2015	
		Sample area	Sudan	No. of samples:	5
61	47 ÷ 72.46	21 ÷ 39.9	52.5 ÷ 217	Zumrawi *et al*., 2017; Elarabi, 2005; Shingade *et al*., 2016	
		Sample area	Egypt	No. of samples:	1
68.54	95.3	59.6	450	Husain *et al*., 2014	
		Sample area	Greece	No. of samples:	3
70.4 ÷ 9.2	82 ÷ 87	42 ÷ 63	335 ÷ 820	Markou, 2013	
		Sample area	Turkey	No. of samples:	3
37 ÷ 55	37 ÷84.6	20÷52.3	165.2÷454.4	Güneyli, 2017; Kilic *et al*., 2016	
		Sample area	U.S.A.	No. of samples:	4
50 ÷ 66	54 ÷ 92	27 ÷ 57	75 ÷ 263	Lin and Cerato, 2012	
		Sample area	Saudi Arabia	No. of samples:	15
40.9 ÷ 55.1	101 ÷ 114	63 ÷ 74	420 ÷ 470	Seif, 2015	
		Sample area	Pakistan	No. of samples:	12
29.2 ÷ 98.3	34 ÷ 176	18 ÷ 150	94 ÷ 928.6	Israr *et al*., 2014	
		Sample area	-	No. of samples:	2
	170; 63	120; 38.06	400; 182.72	Bose, 2012; She *et al*., 2019	

2.2. Statistical Analysis

The statistical analysis was performed using the Statistica V.13 software. The statistical evaluation of the studied samples is given in Table 3.

Analyzing the data from Table 3, we can observe that the we have a large standard deviation, meaning that the data are more spread out. In this case, when standard deviation is larger than the mean value, we have a preponderance of low values, the sample data distribution has a spread of extreme values.

Table 3
Statistical Data for Physical Parameters of the Soil Samples

Variable	Nr. of samples	Mean	Minimum value	Maximum value	Standard deviation
Clay content (%)	50	53.94	0.90	100.00	21.80
Liquid limit (%)	50	72.85	20.00	176.00	33.67
Plastic limit (%)	50	27.69	6.00	63.00	12.09
Plasticity index (%)	50	46.51	10.00	150.00	30.50
Swelling pressure (kPa)	50	241.07	0.00	928.60	218.66

2.3. Correlation Analysis

The purpose of the correlation analysis is to quantify the interrelationship between two variables (*e.g.*, between the swelling pressure and the main physical geotechnical parameters). The dependence between swelling pressure and the geotechnical parameters using the correlation analysis can be measured using the correlation coefficient. This coefficient can achieve a value in the open interval (− 1, 1). If the correlation coefficient is closer to 1 means that there is a stronger correlation between the variables, a coefficient close to zero means that the degree of relationship between the two variables is weak or none (Witten and Frank, 2005).

Using the Statistica V.13 software we can obtain dependency between the geotechnical parameters used in this study. The aim of this evaluation was to find out the variables which has good correlation with swelling pressure. The relationship between these parameters, clay content, plasticity index, liquid limit, plastic limit and swelling pressure is given in Table 4.

The swelling pressure row in Table 4, offers the level of regression between the swelling pressure and geotechnical parameters used in this study. The clay fraction, liquid limit and plasticity index are positively correlated with the swelling pressure meaning that if these geotechnical parameters will increase the value of swelling pressure will increase. The plasticity index, PI, is highly positively correlated to swelling pressure, p_s, having a correlation coefficient of 0.82, followed by liquid limit, LL and clay content with a coefficient of 0.71 and 0.42 respectively.

Table 4

Correlation matrix (R) for the properties of soils used in the learning set

Variable	Clay content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Swelling pressure (kPa)
Clay content (%)	1.00				
Liquid limit (%)	0.28	1.00			
Plastic limit (%)	-0.09	0.29	1.00		
Plasticity index (%)	0.30	0.93	0.05	1.00	
Swelling pressure (kPa)	0.42	0.71	-0.18	0.82	1.00

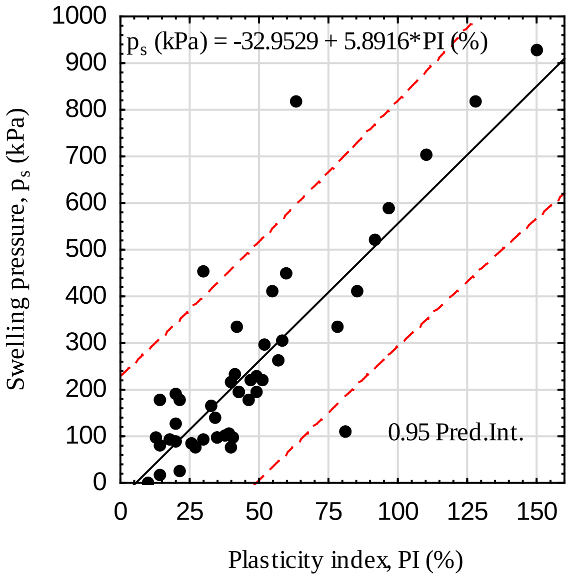
The lowest correlation is shown with the plastic limit, PL, for which the correlation coefficient is -0.18, meaning that the degree of relationship between the two variables is weak or none (Witten *et al*., 2005). A higher correlation with the plasticity index and liquid limit compared with the clay content, indicates a strong influence of clay mineral composition on soil behaviour (Fekerte *et al*., 2011).

2.4. Regression Analysis

The regression analysis is a function that allows us to make prediction about one parameter using the information that is known about another parameter. Using the information from Table 4, we can choose the variables that have good correlation with the swelling pressure and those parameters will be chosen as independent variables.

Due to the low value of the correlation coefficient of the clay content and plastic limit, these variable parameters will be rejected as independent variables. The chosen variables were used as single independent variables in a linear empirical model.

The linear regression model was developed using Statistica V.13, the graphical results being presented in Fig. 2, with a prediction level of 0.95. We can conclude that the plasticity index and liquid limit are the most important factors that influence the swelling pressure. Therefore, these two parameters were selected in a multiple linear regression to build up a regression equation (Fig. 3). The data used in this research was compiled from different research papers (Table 2), having results for compacted soil at optimum moisture content.



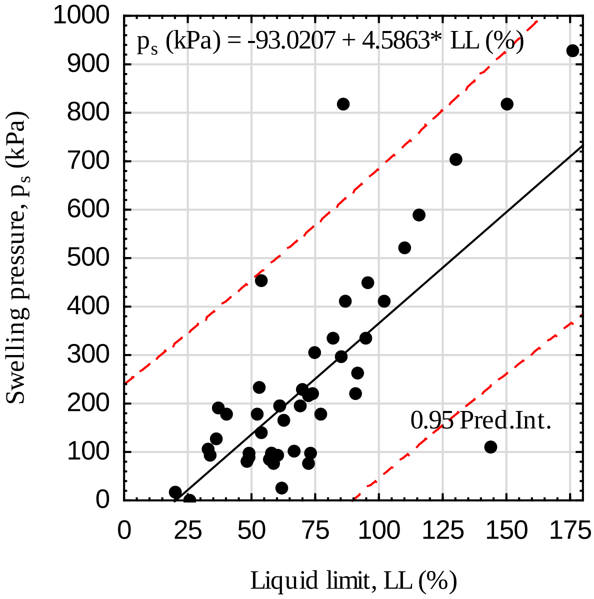


Fig. 2 − Independent correlations between the plasticity index, PI (%), liquid limit LL (%) and measured swelling pressure, p_s (kPa).

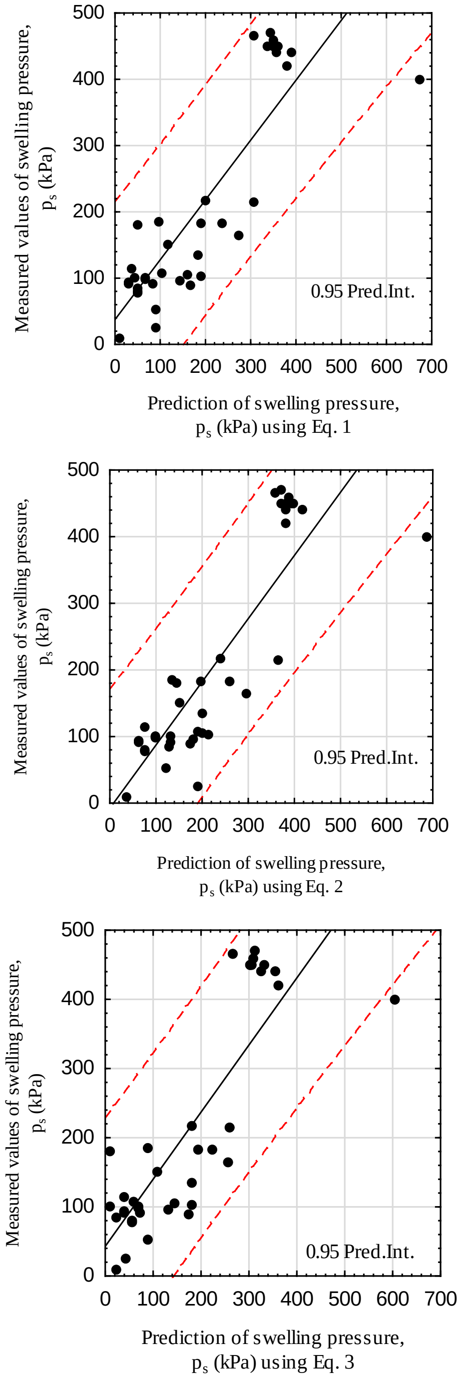


Fig. 3 − Measured versus predicted values of swelling pressure for validation set.

The prediction equations that exist in the literature correlate the swelling pressure with one, two or three number of variables. Usually, the number of variables is limited to two (Table 1).

Using the linear regression between the plasticity index (PI) or liquid limit (LL) with the measured swelling pressure (p_s) (Fig. 2), the following equations were obtained:

$$p_s\ [\text{kPa}] = 5.88 \cdot PI - 32.95 \tag{1}$$

$$p_s\ [\text{kPa}] = 4.59 \cdot LL - 93.02 \tag{2}$$

where: p_s – the swelling pressure in kPa; PI – plasticity index (%); LL – liquid limit (%).

Based on a graphical correlation between the plasticity index (*PI*) and liquid limit (*LL*) as the predictors (of the swelling pressure, p_s), the swelling pressure, (p_s) can be calculated using the following equation:

$$p_s = 9.21 \cdot PI - 3.21 \cdot LL + 46.79 \tag{3}$$

where: p_s – the swelling pressure in kPa; PI – plasticity index (%); LL – liquid limit (%).

3. Verification of the New Swelling Pressure Equations

From the total number of geotechnical data 36 values sets were used for validation the results. Applying the new proposed equations, the predicted values of swelling pressure as a function of measured values are shown in Fig. 3.

The prediction capacity of the proposed equations is illustrated in Table 5. Using the value of the correlation coefficient R, the correlation between two variables can be classify as strong for R > 0.8, medium for 0.8 < R < 0.2, and week for R ⩽ 0.2 (Güneyli, 2017; Smith, 1986). The R^2 coefficient give us the amount of variation from the mean explained by the model (Güneyli, 2017). The other coefficient "p" gives us measure of how far is the estimated value from the hypothesized value to its standard error. If "p" value is less than 0.05, then each variable from the equation is representative in the final result (Güneyli, 2017; Fekerte *et al*., 2011).

Table 5
Summary of Statistics of Each Proposed Equation

Eq.	R	R^2	p
1	0.85	0.72	0.018
2	0.85	0.72	0.019
3	0.83	0.69	0.023

Table 5 shows that the proposed equations for the swelling pressure are all relevant. The differences between the correlation coefficients are very small, the equations indicating a strong correlation (R > 0.8).

4. Conclusions

The database of this research consists of 86 data sets containing the Atterberg limits (PL, LL) clay content (Cl) and swelling pressure (p_s). The data sets have been used to investigate the influence of routinely determined geotechnical parameters like PL, LL, PI and Cl upon the swelling pressure value.

The current study was divided in two steps, first was the learning step and second the validation step. In the learning step a number of 50 data sets was used to study the influence of Atterberg limits and clay content on swelling pressure. The analysis was performed using the Statistica V.13 software, and the influence of the selected parameters on swelling pressure was statistical studied using the correlation analysis. The conclusion was that the plasticity index and liquid limit have a strong correlation (R > 0.8), the correlation coefficient being equal with R = 0.82 and R = 0.71 respectively. The correlation between the swelling pressure with the clay content (d < 0.002 mm) is classify as a medium one (0.8 < R < 0.2). The plastic limit shows very week correlation with the swelling pressure (R ⩽ 0.2), for these reasons this parameter was eliminated from further studies. From these correlations four prediction equations were derived which can provide reliable prediction of swelling pressure for compacted, expansive soils.

The second step, the proposed equation was used to predict the swelling pressure on 36 data sets, different from the sets used in learning step. The results from these equations were compared with the measured values of swelling pressure. The conclusion drawn after statistical analysis between the predicted and measured values was that all equations have a high prediction performance.

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ESTIMAREA INDIRECTĂ A PRESIUNII DE UMFLARE PE BAZA PARAMETRILOR GEOTEHNICI OBȚINUȚI DIN ÎNCERCĂRI STANDARD DE LABORATOR

(Rezumat)

Structurile ușoare construite pe pământuri cu potențial de umflare pot suferi degradări importante datorită presiunii de umflare exercitată de terenul de fundare ca urmare a creșterii umidității. Măsurarea presiunii de umflare se poate face în laborator folosind metode directe bazate pe încercarea edometrică. Această încercare consumă mult timp și implică costuri ridicate. Există o tendință în creștere în prezicerea valorii presiunii de umflare pe baza parametrilor geotehnici determinați de rutină, cum ar fi greutatea volumică în stare uscată, umiditatea naturală, conținutul de argilă, limitele Atterberg, capacitatea de schimb cationic. Acest articol prezintă rezultatele corelației și regresiei realizate cu software-ul Statistica V.13, pe 50 de probe de pământ colectate din nouă țări. Analizele arată un coeficient ridicat de corelație (R) între presiunea de umflare și indicele de plasticitate urmat de limita superioară de plasticitatea și masa procentuală a fracțiunii de argilă. De asemenea, în această lucrare se propun două ecuații empirice pentru estimarea indirectă a presiunii de umflare, ecuații bazate doar pe un singur indice geotehnic (PI, LL) sau pe doi indici geotehnici (PI și LL, PI și Cl).