IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Evaluation of the swelling pressure for expansive soils

To cite this article: M Aniculaesi and I Lungu 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **586** 012012

IOP Conf. Series: Materials Science and Engineering **586** (2019) 012012 doi:10.1088/1757-899X/586/1/012012

Evaluation of the swelling pressure for expansive soils

M Aniculaesi[1] , I Lungu[2]
[1] "Gheorghe Asachi" Technical University of Iaşi, Bd. Dimitrie Mangeron nr. 67, 700050 Iaşi, România,
[2] "Gheorghe Asachi" Technical University of Iaşi, Bd. Dimitrie Mangeron nr. 67, 700050 Iaşi, România

E-mail: aniculaesi.mircea@gmail.com

Abstract. The interaction between light structures and expansive soils as mainly active clays was studied since the 1950's. The first stage in foundation design on this problematic soil is the evaluation of the swelling potential, based on which one identifies the clay's activity and its correlation with the value of the swelling pressure (p_s) for the decisional support of the geotechnical design ($p_{effective} > p_s$). In the literature there are many formulas that can be used to predict the swelling pressure based on the correlation between various geotechnical parameters. This paper provides the swelling pressure as correlation with the consistency index (CI) and the liquid limit (LL), by linear regression of the experimental results for the 56 active clays from seven countries. Using the analytical methods, one can predict the total heave of a floor slab founded on expansive clay. The validity of the proposed correlation has been tested in the prediction of the total heave in the centre of a floor slab for a light industrial building in North-Central Regina, Saskatchewan, Canada.

1. Introduction
It is a well-known phenomenon that unsaturated expansive clays change their volume with the change of their water content. The water content variation at shallow depth is mainly due the seasonal climate change. As it triggers activity of expansive soils, the depth up to which the water content variation is influenced by the seasonal climate change is called the active zone. This depth can be approximated following the guidelines given in the Engineer Manual EM 1110-1-1904 [1].
When the soil heave is impeded by an engineering structure, the soil develops a swelling pressure against the contact structural element, foundation or slab. Many light weight constructions founded on these soils disregarding the swelling pressure occurrence can suffer structural degradations with limitations on the functionality and additional costs for their rehabilitation. Consequently, it is very important to accurately estimate the swelling potential and the correlated swelling pressure in order to select and implement the optimum measures to minimise the soil heave.
The evaluation methods of the swelling pressure can be divided in two categories: direct or indirect ones [2]. The direct methods are based on the oedometer test, using the readings from the vertical swell of a sample after saturation [3][4]. The indirect methods relate the swelling pressure and swelling potential to one or several physical soil parameters such as liquid limit, clay content, plasticity index, natural water content. In table 1 the typical empirical correlations between the physical properties and the swelling pressure are presented.
When focusing on the light weight constructions interacting with expansive soils one can separate them in three categories such as: (a) road infrastructures; (b) slabs for outdoor parking spaces; (c) houses. Although all of them are founded within the active zone, the first two categories benefit from large budgets for soil improvement to reduce its heave, the third category owners seldom accept such costs. For houses, the interest stays with counteracting the swelling pressure of the natural soil with net pressure from the house itself hence an efficient foundation design represents the main aim. The task becomes the estimation of the swelling pressure at reasonable geotechnical investigation costs. Following that task, the prediction of the total heave against measurements from documented case studies may reinforce the confidence of practitioners in controlling the heave effect.

IOP Conf. Series: Materials Science and Engineering **586** (2019) 012012 doi:10.1088/1757-899X/586/1/012012

This paper proposes a new correlation between the swelling pressure and two geotechnical indices: liquid limit and consistency index. The values obtained with the new empirical correlation were compared with the measured values from direct tests for 56 samples from seven countries (table 2).
The values obtained using the proposed empirical equation have been used to predict the total heave, by replacing the swelling pressure values derived from the basic formula for the constant volume oedometer test based method [1] [5]. The results were verified using the data collected by the Prairie Regional Station of the Division of Building Research (DBR), in Western Canada, for a light industrial building in North-Central Regina, Saskatchewan [6].

Table 1. Prediction equations for the swelling pressure value based on empirical correlations.

Equation	*Author*
$logp_s = -2.132 + 0.0208 \cdot LL + 0.000665 \cdot \gamma_d - 0.0269 \cdot w_0\ [daN/cm^2]$	Komornik and David [5]
$p_s = 2.5 \cdot 10^{-1} \cdot PI^{1.12} \cdot C^2/w_0^2 + 25\ [kN/m^2]$	Nayak and Christensen [5] [7]
$p_s = -227.27 + 2.14 \cdot w_O + 1.54 \cdot LL + 72.49 \cdot \gamma_d\ [N/cm^2]$	Erguler and Ulusay [5]
$logp_s = -4.812 + 0.01405 \cdot PI + 2.394 \cdot \gamma_d - 0.0163 \cdot w_0\ [daN/cm^2]$	Erzin and Erol [5]
$logp_s = -5.02 + 0.01383 \cdot PI + 2.356 \cdot \gamma_d\ [daN/cm^2]$	Erzin and Erol [5]
$p_s = 135 + 2 \cdot (C + PI - w_O)\ [\mathrm{k}N/m^2]$	Sabtan [5]
$log_{10}p_s = (0.4 \cdot LL - w_O - 0.4)/12$	Vijayvergiya and Ghazzaly [7] [19]
$log_{10}p_s = (\gamma_d + 0.65 \cdot LL - 139.5)/19.5$	Vijayvergiya and Ghazzaly [7]

Notes: p_s – swelling pressure; LL – liquid limit; PI – plasticity index; w_0 – water content; γ_d – dry unit weight; C – clay content

2. Indirect correlation of the swelling pressure with index properties

Using the physical properties of soil samples collected from the literature (table 2) an indirect equation for the swelling pressure has been proposed. This equation correlates the liquid limit (LL) and the consistency index (CI) with the swelling pressure, indirectly but clearly correlated with the initial water content:

$$p_s = (3.71 \cdot \mathrm{LL} - 125)/CI \tag{1}$$

where: p_s - swelling pressure [kPa]; LL – liquid limit (%); CI – consistency index

Table 2. Physical properties and swelling pressures of the samples used in correlation.

	No. of samples	Liquid limit (%)	Consistency index (%)	Natural moisture content (%)	Swelling pressure (kPa)	References
Ethiopia	12	96 ÷ 110	0.87 ÷ 1.15	32 ÷ 42.1	199 ÷ 420	[8]
Turkey	7	50 ÷ 67	0.86 ÷ 1.42	14.4 ÷ 32.7	18.8 ÷ 72.7	[9]
Iraq	6	35 ÷ 51	1.3 ÷ 3.7	16 ÷ 19.7	5.5 ÷ 19.5	[10]
Brazil	5	51.5 ÷ 55	1.38 ÷ 2.1	12.2 ÷ 15.8	24.4 ÷ 45	[11]
USA	4	54 ÷ 92	0.93 ÷ 1.21	20.6 ÷ 27.1	75 ÷ 263	[12]
India	1	64	1.24	18	135	[13]
Jordan	1	83	1.38	25	245	[14]
Other soils	20	41.4÷ 129.2	0.99 ÷ 1.34	14 ÷ 23.3	46.54 ÷ 223.4	[15] [16] [17]

The comparison between the experimental data of the swelling pressure and the predicted values based on equation 1 is shown in figure 1. The equation capacity in offering the results closed to the ones obtained by laboratory testing can be made using the performance index like R^2 (determination coefficient). The value of R^2 using the linear regression between the predicted and measured data indicated a strong coefficient of correlation (0.70). If R^2 is 1 the prediction model is accepted as excellent [18]. The proposed equation for the swelling pressure evaluation exhibited a high performance for predicting the swelling pressure of the soils according to the R^2 value.

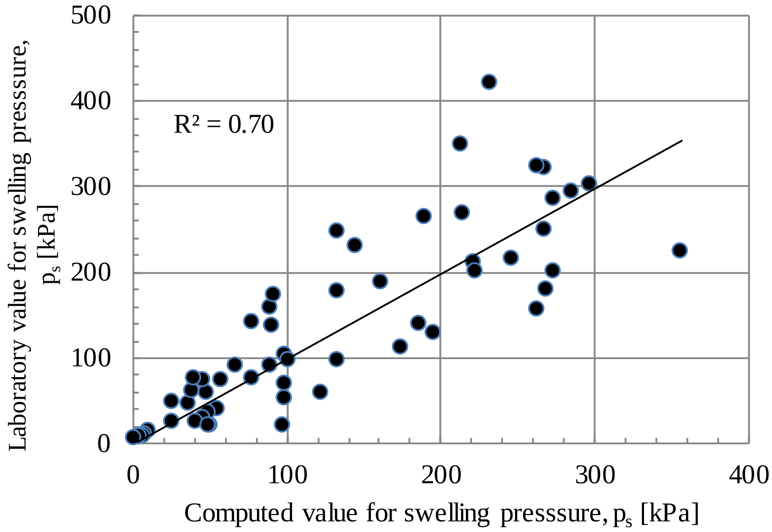

Figure 1. The linear regression as correlation between computed values of the swelling pressure and laboratory test values.

3. Soil heave analysis

The anticipated heave can be calculated using the equation presented in [1], [5]:

$$S_{max} = \sum_{j=1}^{n} \frac{C_{sj}}{1+e_{0j}} \cdot log_{10} \frac{p_{sj}}{\sigma'_{fj}} \cdot H_j \tag{2}$$

where: S_{max} - maximum potential vertical heave [m]; n - number of strata within the depth of heaving soil; c_{sj} – swelling index of stratum j, as the slope of the *e-log(σ-u)* loading line; p_{sj} – swelling pressure of stratum j [kPa]; σ'_{fj} – final or equilibrium average effective vertical pressure of stratum j [kPa]; e_{0j} – initial void ratio of stratum j.

The total vertical heave is calculated using the summation of heave on each sublayer (n) up to the active zone limit (or critical depth). The swelling pressure p_{sj} in each stratum can be obtained using the direct methods (oedometer tests) or by introducing the swelling pressure obtained from the indirect equation.

By replacing the swelling pressure as from equation 1 in equation 2 the maximum potential heave can be evaluated by:

$$S_{max} = \sum_{j=1}^{n} \frac{C_{sj}}{1+e_{0j}} \cdot log_{10} \frac{(3.71 \cdot \mathrm{LL} - 125)/CI}{\sigma'_{fj}} \cdot H_j \tag{3}$$

3.1. Estimating of total heave for a slab on grade floor on Regina clay, Canada

In 1961 a light industrial building was constructed in the North of the city of Regina, Saskatcewan, Canada, and in 1962 the building owner noticed heave and cracks in the floor slab. The average values of geotechnical parameters for this soil are [5] [6]: clay content = 50%; liquid limit = 77%; plastic limit = 33%; average water content = 29%; unit weight = 18.88kN/m^3; initial void ratio = 0.962; swelling index = 0.09; swelling pressure = 325kPa. In analyses, a surcharge of 5.75kPa is applied, which represents the weight of the concrete slab and the weight of the fill under the slab. The measured heave under the center was 105mm. Yoshida et al. [6], estimates the soil heave of Regina clay considering different situation for the final pore water pressure: case 1 – final pore water pressure equal to zero; case 2 - final pore water pressure is negative, and case 3 - final pore water pressure is hydrostatic. For the benefit of testing the validity of the simple estimation of the swelling pressure with the new proposed correlation, the predicted values of heave are given in table 3, only for the assumption of final pore-water pressure as zero and thus considering that initially negative pore-water pressure increase to zero as water content increases during the wet season.

Table 3. Prediction of heave assuming final pore-water pressure is zero (case 1) [6].

Depth (m)	0.15	0.45	0.75	1.05	1.35	1.65	1.95	2.25
w_f (%)	40.1	39.2	38.5	37.9	37.3	36.7	35.9	34.6
S_{max} (mm)	118	92	70	51	35	21	10	2

Notes: $e_0 = 0.962$ – initial void ratio; $C_s = 0.090$ – swelling index; $S = 100\%$ – degree of saturation

The estimated values obtained with the equation 3 were compared with laboratory tests results for the expansive clay from the city of Regina. Assuming that the final pore water pressure will be equal with zero, as the case 1 from Yoshida et al [6], the final equilibrium average effective vertical pressure will be $\sigma'_{fj} = \sigma_{\gamma zj} + \Delta\sigma_j$. The soil heave under the slab was calculated using equation 3, assuming different values for the swelling pressure with the depth due to the water content variation (table 4).

Table 4. Prediction of heave using equation 3 assuming final pore-water pressure is zero.

Depth (m)	0.15	0.45	0.75	1.05	1.35	1.65	1.95	2.25
w_f (%)	40.1	39.2	38.5	37.9	37.3	36.7	35.9	34.6
S_{max} (mm)	109.5	99.7	82.9	68.7	56	44.8	34.5	25.4

Notes: $e_0 = 0.962$ – initial void ratio; $C_s = 0.090$ – swelling index; $S = 100\%$ – degree of saturation

Figure 2 present the variation with depth of the measured swell, calculated by Yoshida et al. [6], and by the proposed equation (equation 3).

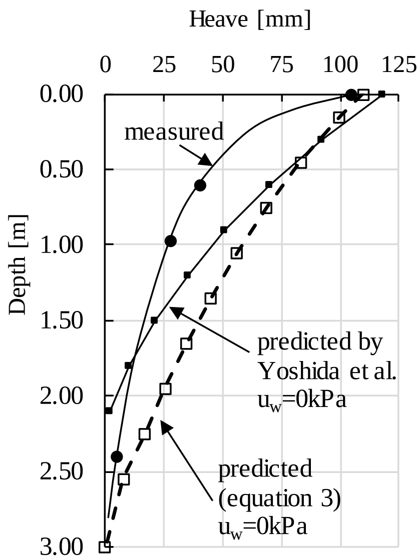

Figure 2. Predicted and measured ground heave under the centre of the slab

The maximum value of heave computed by the proposed equation is 109.5mm, which is very close to the measured one 105mm. As one compares the values of the heave at different depths up to the active zone (z_a = 3m), the calculated values differ from the measured ones (figure 2). The same trend can be noticed also in the paper published by Yoshida et al. [6] for the case 1 (final pore-water pressure equals zero) as in figure 2.

4. Conclusions

Soil improvement techniques for expansive soils to reduce the swelling potential and consequently the swelling pressure for the benefit of undamaged light constructions during their service time have been proved efficient based on extensive research for many years. As every construction together with its site conditions represent a unique situation, generalizations of simpler approaches for the estimation of the swelling pressure should be applied with caution. However, the budget allocated to proper geotechnical investigations in such cases plays a very important role. In case of houses, especially ground-floor only structures are light weight and their foundation should be geotechnically designed to balance the swelling pressure. Its estimation is essential since the final pore-pressure can be safely assumed to increase from a negative value up to zero. This paper proposes a new equation which correlates the swelling pressure with the liquid limit and consistency index. By comparing the computed results with the measured ones, the R^2 performance indices was found to be equal with 0.7, which mean that there is a relatively good correlation between the measured and predicted values. The validation has been made by predicting a total heave of the floor slab from a well-documented case for a light industrial building in North-Central Regina, Saskatchewan, Canada. The proposed correlation for the swelling pressure resulted in a total maximum heave of 109.5mm, which is with only 4% higher than the measured one (105mm) and thus in good accordance with the practical evidence.

5. References

[1] U.S. Army Corps of Engineers 1990 *Engineering and Design. Settlement analysis* Engineer Manual No. 1110-1-1904
[2] Al-Shamrani M A and Dhowian A W 2003 Experimental study of lateral restraint effects on the potential heave of expansive soils *Engineering Geology 69 (2003) 63–81*
[3] ASTM D 4546 – 03 *Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils*
[4] STAS 1913/12-88 *Soil foundation. The evaluation of physical and mechanical properties of expansive soils (in Romanian)*
[5] Arafat H and Ebid A M 2015 Optimum Replacement Depth to Control Heave of Swelling Clays *International Journal of Engineering and Innovative Technology (IJEIT) Volume 4, Issue 9*
[6] Yoshida R T, Fredlun D G and Hamilton J J 1983 The prediction of total heave of a slab-on-grade floor on Regina clay *Canadian Geotechnical Journal 20: 69-81, NRC Research Press*
[7] Al-Rawas A and Goosen M F A 2006 *Expansive Soils: Recent Advances in Characterization and Treatment* CRC Press ISBN 9780415396813 - CAT# SW6816
[8] Teklu D 2003 Examining the Swelling Pressure of Addis Ababa Expansive Soil *A Thesis Submitted to The School of Graduate studies of Addis Ababa University*
[9] Ozer R, Ulusay R and Isik S N 2012 Evaluation of damage to light structures erected on a fill material rich in expansive soil *Bulletin of Engineering Geology and the Environment* Volume 71, Issue 1, pp 21–36
[10] Al-Khashab M N and Abdulnafaa M T 2008 Treatment of Expansive Clayey Soil with Crushed Limeston *Engineering & Technology Journal*. 26. 376-386
[11] Lew B 2010 Structure Damage Due to Expansive Soils: a Case Study *Electronic Journal of Geotechnical Engineering*. 15. 1317-1324
[12] Lin B and Cerato A B 2012 Prediction of expansive soil swelling based on four micro-scale properties *Eng Geol Environ* 71:71–78

IOP Conf. Series: Materials Science and Engineering **586** (2019) 012012 doi:10.1088/1757-899X/586/1/012012

[13] Ramesh P, Rao N A V and Murthy K N 2012 Efficacy of sodium carbonate and calcium carbonate in stabilizing a black cotton soil *International Journal of Emerging Technology and Advanced Engineering* ISSN 2250-2459, Volume 2, Issue 10, pp 197-201

[14] Nusier O Kh and Alawneh A 2007 Micropiles Reinforcement for Expansive Soils: Large-Scale Experimental Investigation *Ground Improvement* 11(2):55-60

[15] Nayak N V and Christensen R W 1971 Swelling characteristics of compacted, expansive soils *Clays and Clay Minerals*, Vol. 19,pp. 251-261. Pergamon Press

[16] Abdullah W N and Alsharqi A S 2011 Rehabilitation of Medium Expansive Soil Using Cement Treatment *Jordan Journal of Civil Engineering*, Volume 5, No. 3 pp 343-356

[17] Tripathy S and Rao K S S 2009 Cyclic Swell–Shrink Behaviour of a Compacted Expansive Soil *Geotechnical and Geological Engineering 27(1):89-103*

[18] Yilmaz I 2006 Indirect estimation of the swelling percent and a new classification of soils depending on liquid limit and cation exchange capacity *Engineering Geology, 85, 295-301*

[19] Elbadry H 2017 Simplified reliable prediction method for determining the volume change of expansive soils based on simply physical tests *Housing and Building National Research Center Journal 13, pp 353-360*