Proceedings of the 24th European Young Geotechnical Engineers Conference (EYGEC), Durham, UK
Osman, A.S. & Toll, D.G. (Eds.) 2015
ISBN 978-0-9933836-01

Indirect estimation of the swelling pressure of active clay based on a new activity coefficient (C_A)

M. Aniculaesi*[1]

[1] *"Gheorghe Asachi" Technical University of Iaşi, România*

ABSTRACT Active clays, in some in situ soil condition, can be classified as difficult foundation soil layer. Thus, it is necessary to estimate the swelling potential of these clays, based on which the possible degradation of light weight engineering structure can be anticipated (small buildings, roads, runways, parking lots, etc). In this paper, the activity coefficient (C_A) computed using the "soil chart", unifies in the same representation Casagrande's plasticity chart, Seed's chart and the grain size distribution. Based on the value of C_A the soils were grouped into four shrink–swell potential risk categories. The activity coefficient (C_A) has been correlated with the swelling pressure using a multiple regression function and a very high determination coefficient (R^2 = 0.74) resulted. There have been used the experimental results from 104 active clays worldwide, collected from the scientific literature. The proposed equation offers for the preliminary stage of site investigation a rapid evaluation of the swelling potential and swelling pressure.

1 INTRODUCTION

The problem of the expansive soils derives from the volume variation due to the variation in their moisture content. These volume variations can lead to significant damage to the construction structures. The damage due to the existence of expansive soils within the active zone of the foundations can be avoided/minimized by the proper identification and classification of the foundation soil layers, the quantification of the swelling pressures, and adopting an appropriate design approach (Erzin et al. 2013; Das et al. 2010).

Currently there is a constant interest in simple investigations of expansive soil behavior, leading to various forms of empirical equations, which relates the swelling pressure to certain physical properties of soils (Holtz et al., 1956; Seed et al., 1962; Ranganatham et al., 1965; Komornik et al., 1969; Nayak et al., 1970; Yilmaz, 2006; Erzin et al., 2013). For the assessment and therefore the classification of the swelling potential, in the scientific literature, there are swelling potential classifications by correlating the swelling potential with either one geotechnical index: colloidal clay fraction ($C_{2\mu}$), plasticity index (PI) or the liquid limit (LL); or with two geotechnical indices in charts like the ones proposed by Casagrande, Seed, Van der Merwe, etc. (Seed et al., 1962; Van Der Merwe, 1964).

The simultaneously use of these classifications and charts for the same soil, can lead to a different assessment of the swelling potential. To eliminate these shortcomings and finding a satisfactory solution, in this paper the classification of the swelling potential is proposed by using a composite index named activity coefficient (C_A) (Stanciu, et al., 2011).

2 PREVIOUS INVESTIGATIONS IN SWELLING POTENTIAL CLASSIFICATION

The swelling potential is defined by Holtz, as being the volume variation of an undisturbed soil sample dried in natural condition, and according to Seed, the soil potential is defined as the soil volume variation for remolded soils dried in natural condition.

Based on the swelling potential classified qualitatively into four categories (Table 1), it is possible to anticipate the damage level that the active soils can create to building structures.

Table 1. The swelling potential classification in correlation with anticipated damages to building structures

Swelling potential	Characteristic surface movement (mm) (AS 2870-2011)	Structural degradation type (Jahangir, 2011)
Low	0 – 20	Small cracks in the windows of length, on the intersection of the wall and ceiling, etc.
Medium	20 – 40	Large cracks in the plaster, around the doors and windows;
High	40 – 75	Large cracks due to shear diagonal of the wall, or large cracks in the joints between structural elements, cracks in the foundations, etc.
Very high	> 75	The structure can suffer permanent lateral displacement, or reach the structural collapse situation. It also records the cracks in the foundation.

Finding a representative geotechnical index in the swelling potential estimation is a continuous challenge for geotechnical researchers. The first association with the swelling potential was made using the clay content and Atterberg limits, these physical parameters being considered as the most representative indicators of the swelling potential assessment (McCormack et al., 1975; Snethen et al., 1977; Parker et al. 1977). Other researchers showed that there is no significant correlation between these indices and the swelling potential of the soil (Yule et al., 1980; Gray et al., 2002).

Therefore, it is essential to establish some methods to use these geotechnical indices in a unique standard swelling potential classification. There was a need to combine these indices either in mathematical correlations or by adopting classification charts, from which, the most used in the literature are the ones proposed by Casagrande (Casagrande, 1932), Seed (Seed et al., 1960), Van Der Merwe (Van Der Merwe,1964), etc.

In 1980, Silvan Andrei proposed for the first time the unification of Casagrande's chart, Seed's chart and the grain size distribution in a single representation called the "soil chart" (Andrei et al. 1980).

This representation is considered as being unique for each soil (Andrei, 1980; Andrei, S. et al., 1997) (Figure 1).

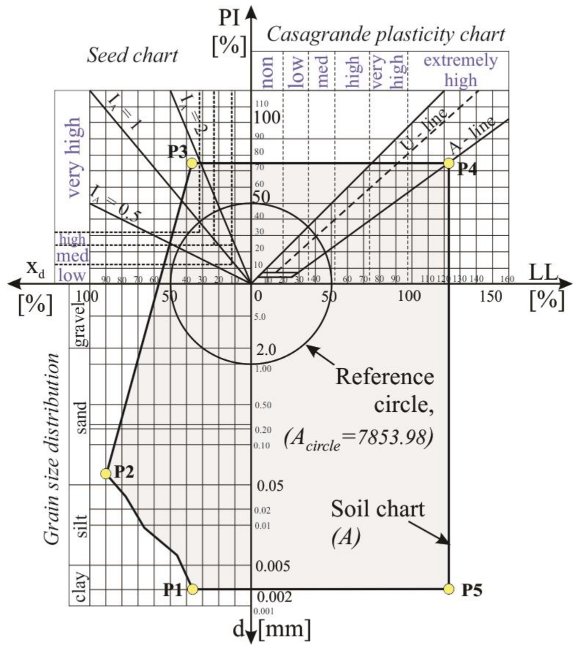

Figure 1. Typical soil chart

The shape and the size of the "soil chart" represent a first criterion of the soil characterization. The higher the soil chart is, the higher the soil activity is considered. The resemblance between shape and dimension of various soils charts leads to the conclusion of similar properties for the compared soils (Andrei, 1980).

The reference circle introduced in the soil chart representation has the role of scaling the drawing (Figure 1), and to make easier the observation of the chart shape and dimension modification, defining a normalized soil chart area (A^n) (N.E. 0001-1996):

$$A^n = \frac{A}{A_{circle}} \quad (1)$$

where: A^n - the normalized soil chart area; A - the soil chart area; A_{circle} - the reference circle area.

The resemblance of two soils charts, one with a fully identified behavior (A_i^n) and the second one with unknown behavior (A_j^n) can be evaluated using an analogy coefficient (A_n) (N.E. 0001-1996):

$$A_n = \frac{A_i^n - A_j^n}{2 \cdot (A_i^n - A_j^n)} \qquad (2)$$

If $A_n > 10$, the two compared soils can have similar behavior when their moisture content and density are also similar.

For a qualitative evaluation of the swelling potential, using the soil chart, Stanciu defines a new coefficient, named the activity coefficient (C_A). In the equation of the activity coefficient, Stanciu introduced the maximum and minimum normalized soil chart areas, which have been identified for two Romanian soils: sodium montmorillonite and kaolinite (Figure 2) (Stanciu, et al., 2011; Stanciu, et al., 2013).

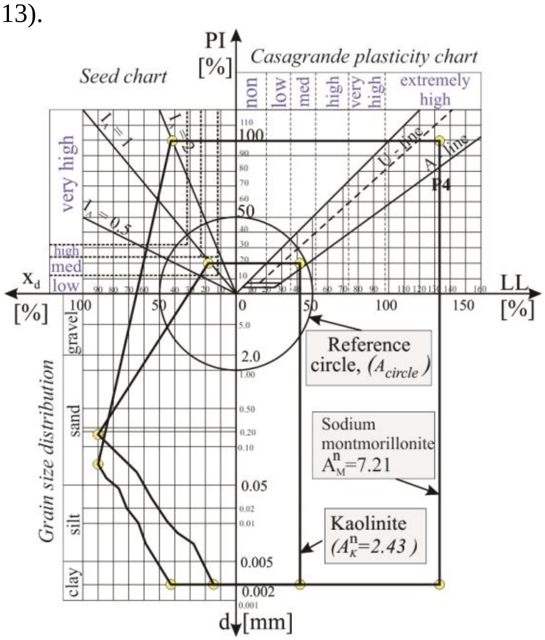

Figure 2. The minimum and maximum soil charts (Stanciu et. al., 2013).

The activity coefficient for an investigated soil is evaluated using these extreme chart areas:

$$C_A = (A_O^n - A_K^n) / (A_M^n - A_K^n) \qquad (3)$$

where: C_A - activity coefficient; A_O^n - normalized soil chart area for the studied clay; A_K^n - normalized soil chart area for the kaolinite; A_M^n - normalized soil chart area for the sodium montmorillonite.

The values of the normalized soil chart areas for these two extremes soils behavior from Romania, sodium montmorillonite and kaolinite are given in Table 2.

Table 2. The normalized soil chart areas for sodium montmorilonite and kaolinite (Stanciu, et al., 2011; Stanciu, et al., 2013)

Soil	Reference circle area A_{circle}	Normalized area A^n *(eq.1)*	Activity coefficient C_A *(Eq.3)*
Sodium montmorillonite	7853.98	$A_M^n = 7.212$	1
kaolinite	7853.98	$A_K^n = 2.433$	0

Based on the value of the activity coefficient, Stanciu divided the swelling potential of an active soil in four categories, from low to very high swelling potential (Table 3).

Table 3. Swelling potential classification using the activity coefficient (Stanciu, et al., 2011; Stanciu, et al., 2013)

Activity coefficient C_A	Swelling potential
0 ÷ 0.24	low
0.25 ÷ 0.49	medium
0.50 ÷ 0.74	high
0.75 ÷ 1.00	very high

3 THE GENERALIZATION USE OF THE ACTIVITY COEFICIENT

The activity coefficient for an active soil is calculated using the soil chart area of that soil relatively to two extreme areas (sodium montmorillonite and kaolinite) (Figure 2). The samples have been collected from Medieşu-Aurit area – the sodium montmorillonit, and the kaolinite samples from Șuncuiuș area, Romania.

3.1 Swelling potential classification using the activity coefficient

For 104 clays from all around the world: England: 1; Saudi Arabia: 1; Canada: 2; China: 9; Cyprus: 1; Finland: 4; Jordan: 13; India: 9: Italy: 1; Iran: 3; Japan:

6; Malaysia: 2; New Zealand: 1; Nigeria: 3; Romania: 25; USA: 18; Turkey: 4; Thailand: 1, the soil charts have been represented and the normalized areas of these soils were calculated.

The minimum value of normalized soil chart was obtained for Atoka clay, Oklahoma, SUA (Miller et al., 2000), and the maximum value for the Isahaya clay, Japan (Onitsuka et al., 2003) (Figure 3).

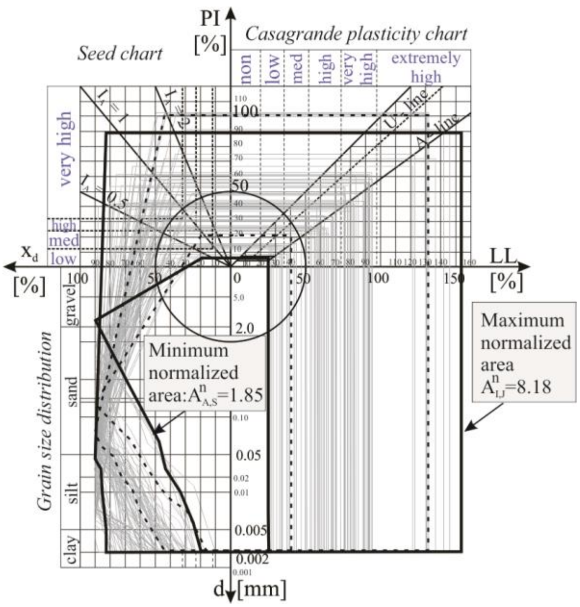

Figure 3. Minimum and maximum normalized areas of the soil charts for 104 reported clays

The normalized soil chart areas of these two soils are given in Table 4.

Table 4. The normalized soil chart areas for Isahaya clay, Japan (maximum area) and Atoka clay, Oklahoma, SUA (minimum area)

Active clays	Reference circle area, A_{circle}	Normalized area A^n *(Eq.1)*
Isahaya clay, Japan	7853.98	$A^n_{I,J} = 8.18$
Atoka clay, USA	7853.98	$A^n_{A,S} = 1.85$

Therefore, by having the minimum and maximum value of the normalized area of soil charts, this paper proposes the generalization use of the activity coefficient, by replacing in Eq. 3 the values of the normalized soil chart extremes initially proposed by Stanciu (A^n_K and A^n_M) with the normalized ones for the Atoka clay, USA ($A^n_{A,S}$) and Isahaya clay, Japan ($A^n_{I,J}$). The activity coefficient for a new clay under investigation can be computed using the relation:

$$C_A = (A^n_O - A^n_{A,S}) / (A^n_{I,J} - A^n_{A,S}) \quad (4)$$

where: $A^n_{A,S}$ - normalized soil chart area for Atoka clay - USA; $A^n_{I,J}$ - normalized soil chart area for Isahaya clay, Japan.

3.2 *Correlation between the swelling pressure and the activity coefficient*

By multiple linear regressions the swelling pressure was correlated with the activity coefficient, colloidal clay fraction and natural moisture content, and the following relation is proposed:

$$S_p[kPa] = (C_{2\mu} - w_n) \cdot C_A \cdot 10 \quad (5)$$

where: S_p - swelling pressure [kPa]; C_A - activity coefficient; $C_{2\mu}$ - colloidal clay fraction [%]; w_n - natural moisture content [%]

The comparison between the experimental data of the swelling pressure and the predicted ones based on Eq. 5 is shown in Figure 4.

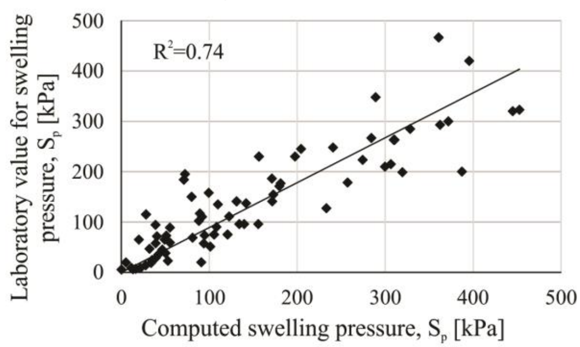

Figure 4. The correlation between the calculated values of the swelling pressure using the proposed equation and the values resulted from laboratory testing

In order to compare the obtained results based on the proposed equation (Eq. 5), and those using other equations from literature which use for the swelling pressure evaluation the combined effect of at least three geotechnical indices, the equation of Nayac

(Eq. 6) and the one proposed by Sabtan (Eq. 7) (Nayak et al., 1971; Sabtan, 2005) have been selected:

$$S_p[kPa] = 6.89\left\{3.5817\left[10^{-2}\left(PI\right)^{1.12}\left(C_{2\mu}^2 / w_n^2\right)\right]+3.7912\right\} \quad (6)$$

$$S_p[kPa] = 135 + 2\left(C_{2\mu} + PI - w_n\right) \quad (7)$$

The comparison between the experimental data of the swelling pressure and the predicted ones based on the equations proposed by Nayac (Eq. 6) and Sabtan (Eq. 7) is shown in Figure 5 and Figure 6.

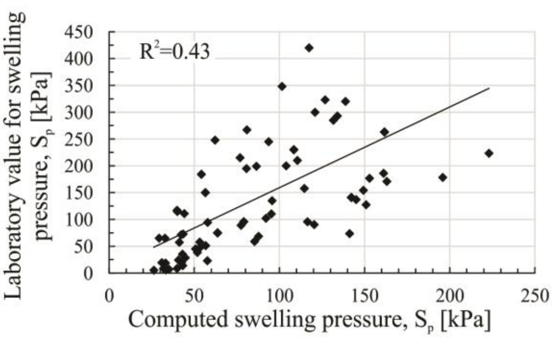

Figure 5. The correlation between the calculated values of the swelling pressure using Nayac's equation, and the values resulted from laboratory testing

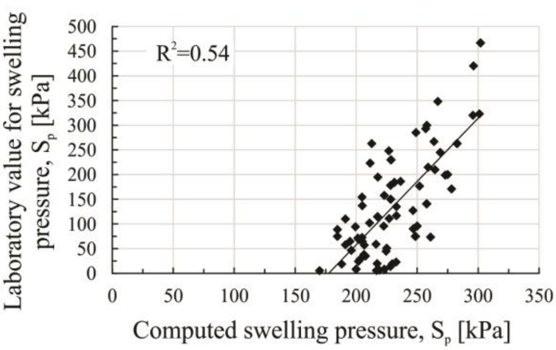

Figure 6. The correlation between the calculated values of the swelling pressure using the Sabtan's equation and the values resulted from laboratory testing

The cross-correlation between predicted and experimental data represents a very good indicator for the verification of an equation performance.

The verification of the equation capacity in offering the results closed to the ones obtained by laboratory testing can be made using the performance indices like R^2 (determination coefficient) and RMSE (root mean square error) (Eq. (8)):

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (y_i - \overline{y}_i)^2} \quad (8)$$

where: y_i - experimental values; $\overline{y}_i$ - calculated values; N – number of values.

If R^2 is 1 and RMSE is 0, the prediction model is accepted as excellent (Yilmaz, 2006).

The values the determination coefficient and the RMSE for the proposed equation (Eq. 5) have been compared with the values obtained using the Nayac's (Eq.6) and Sabtan's (Eq.7) equations, and the results are centralized in Table 5.

Table 5. Performance indices (R^2, RMSE)

	R^2	RMSE
Eq. (5)	0.74	0.15
Eq. (6) Sabtan	0.54	18.33
Eq. (7) Nayac	0.43	0.59

The proposed equation (Eq. 5) exhibited a high performance for predicting the swelling pressure of the soils according to the R^2 and the RMSE values as 0.74 and 0.15 (Table 5). By comparison, the indices obtained above make it clear that the predictive equation proposed in this paper can be considered a good proposal.

4 CONCLUSIONS

The soil chart can be used as a new way to estimate the soil swelling potential. The chart unifies in a single representation the main geotechnical indices used in expansive soil classification.

By multiple linear regression it is possible to obtain a sound correlation equation between the swelling pressure and the activity coefficient (C_A), defined based on the soil chart, colloidal clay content ($C_{2\mu}$) and the natural moisture content (w_n).

It was found that the values of the swelling pressure obtained using the proposed equation are much closer to the experimental ones, by comparison with those resulted from using the other equations described above.

Thus, the proposed equation is simpler, it has a higher precision of the results then those obtained using Nayac's and Sabtan's equations, which until now are considered being the most representative equations for the indirect estimation of the swelling pressure.

REFERENCES

Andrei, S. & Antonescu, I. 1980. *Geotechnical and foundation*, Vol. I. Construction Institute Bucharest – in Romanian

Andrei, S. Manea, S. & Ciocalteu, A. 1997. La systématisation, le stockage et la reutilization des informations géotechniques. Principe d'organisation d'une banque de données géotechniques. *Revue Française de Géotechnique*, **78**, 51-61

Australian Standard AS 2870-2011 - Residential slabs and footings

Casagrande, A. (1932), Research on the Atterberg limits of soil, *Public Roads* **13**, 121-130.

Das, S.K., Samui, P., Sabat, A.K. & Sitharam, T.G. 2010. Prediction of swelling pressure of soil using artificial intelligence techniques. *Environmental Earth Sciences* **61**, 393–403

Erzin, Y. & Gunes, N. 2013. The unique relationship between swell percent and swell pressure of compacted clays, *Bulletin of Engineering Geology and the Environment* **72**, 71-80

Gray, C.W., Allbrook, R., 2002. Relationships between shrinkage indices and soil properties in some New Zealand soils. *Geoderma* **108** (3-4), 287-299

Holtz, W. G. & Gibbs, H. J. 1956. Engineering properties of expansive clays. *Transactions, ASCE **121***, 641-677.

Jahangir, E. 2011. *Phénomènes d'interaction sol-structure vis-à-vis de l'aléa retraitgonflement pour l'évaluation de la vulnérabilité des ouvrages*, Institut National Polytechnique de Lorraine, These.

Komornik, A. & David, D. 1969. Prediction of swelling pressure of clays. *J. ASCE, Soil Mechanics and Foundation Division*, SM No. **1**, pp. 209-225.

McCormack, D.E., Wilding, L.P., 1975. Soil properties influencing swelling in Canfield and Geeburg soils, *Soil Science Society of America Journal* **39**, 496 - 502

Miller, G.A. & Azad, S. 2000. Influence of soil type on stabilization with cement kiln dust. *Construction and Building Materials* **14**, 89-97

Nayak, N.V. & Christensen, R.W., 1971. Swelling characteristics of compacted, expansive soils. Clays and Clay Minerals, **19**, 251-261.

N.E. 0001-96, Foundation design and execution code on expansive soils, 1996, in Romanian

Onitsuka, K. & Modmoltin, M. & Kouno, M. & Negami, T. 2003. Effect of organic matter on lime and cement stabilized Ariake clay, *J. Geotech Eng., JSCE*, No. 729/III-62, pp. 1-13.

Parker, J.C., Amos, D.F., Kastner, D.L., 1977. An evaluation of several methods of estimating soil volume change. *Soil Soc. Am. J.* **41**, 1059-1064

Sabtan, A.A., 2005. Geotechnical properties of expansive clay shale in Tabuk, Saudi Arabia. *Journal of Asian Earth Sciences* **25**, 747 - 754

Seed, H. B., Mitchell, J. K. and Chan, C. K., 1960, The strength of compacted cohesive soils. *Proceedings, ASCE Research Conference on Cohesive soils, Boulder, American Society of Civil Engineers*, New York, 877-964.

Seed, H. B., Woodward, R. J., Jr. & Lundgren, R. 1962. Prediction of swelling potential for compacted clays. *J. ASCE, Soil Mechanics and Foundation Division,* **88**, No. SM-3, Part I, pp. 53-87.

Snethen, D.R., Johnson, L.D., Patrick, D.M., 1977. An evaluation of expedient methodology for identification of potentially expansive soils. *Soil and Pavements Laboratory, U.S. Army Eng. Waterway Exp. Sta., Vickburg, MS*, Rep. No. FHWA-RE-77-94, NTIS PB-289-164

Stanciu, A. & Lungu, I. 2006. *Foundations*, Technical Editure, Bucuresti, in Romanian

Stanciu, A., & Lungu, I., & Ciobanita, L., & Aniculaesi, M. 2011. A new concept to identify and characterize active clays, *Proceedings of the of the XVth European Conference on Soil Mechanics and Geotechnical Engineering*, Athens, Greece, 381 - 386

Stanciu, A., Aniculaesi, M. & Lungu I. 2013. Soil chart, new evaluation method of the swelling-shrinkage potential, applied to the Bahlui's clay stabilized with cement, *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, 1191 – 1194

Van Der Merwe, D. H., 1964. The prediction of heave from the plasticity index and percentage clay fraction of soil. *South African Institute of Civil Engineers* **6**. 103-107.

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

Yule, D.F., Ritchie, J.T., 1980. Soil shrinkage relationships of Texas vertisols: 1 small cores. *Soil Sci. Soc. Am. J*. **44**, 1285 – 1291.