



Prediction of final settlements of buildings constructed on expansive soils

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Abstract

Because the action of the swelling pressure, the settlements caused by the transmitted load from the structure on expansive soils, and the settlements calculated by classic theories of soils mechanics are different. This swelling pressure acts in opposite direction to the weight of the building. In this paper, the authors propose the use of a volumetric strain coefficient by settlements a_{exp} , in a soil-structure interaction algorithm taking into account the expansive soil behavior in the reduction of the settlement magnitude when a building is placed above soil. It's necessary to know the initial properties of the expansive unsaturated soil and the load building conditions. A laboratory process is described for determining the a_{exp} coefficient.

Keywords: *Expansive Soils; Settlement; Soil Strain; Soil-Structure Interaction; Swelling Pressure.*

1. Introduction

Queretaro City is placed on a predominant clayey soil with a significant presence of montmorillonite, on the order of the 40% [1]. The region corresponds to a semiarid climate, which implies that the soil is subject to significant changes of humidity, having dehydration in spring and moisturizing in summer (figure 1).

In the United States, expansive clays are responsible for many damages in structures. Krohn and Slosson [2] reckoned in approximately 7,000 million dollars per year these affectations. The American Society of Civil Engineers estimates that 25% of all households in the United States have some damage caused by expansive soils [3].

Construction on expansive soils can usually be solved by using piles. When shallow foundations are used, the expansion pressure must be determined and foundation designed to provide enhanced to counter the pressure of expansion [4]. Still, these soils can create big problems for shallow and deep foundations [5].

The damage generated in the structures founded on these soils is due to that these are not adapted structurally to the answer mechanism taking into account the soil. Soil-structure interaction is an interdisciplinary field between soil mechanics and structural dynamics. Their origin date back to the late nineteenth century and has progressed due to the emergence of powerful computers and simulation tools, mainly to improve seismic safety [6]. Geotechnical performance of the foundation depends on the actions of the superstructure and the response of the soil in contact. The interdependence between the foundation and soil structure is called soil-structure interaction [7].

Because the problem of the soils with potential of volumetric change is, currently a prominent aspect to take into account in the projects of all kinds of constructions, this work attempts to present a methodology for considering the soil deformations in the settlement generated by a building, in which the loads originated by own weight surpass to the expansion forces. This is a problem of settlement diminished for the pressure of expansion. Utilization of a coefficient

of deformation that takes into account the expansive behavior of the soil, and that it can be measured with conventional laboratory equipment, facilitates the prediction of the actual settlements of the land.

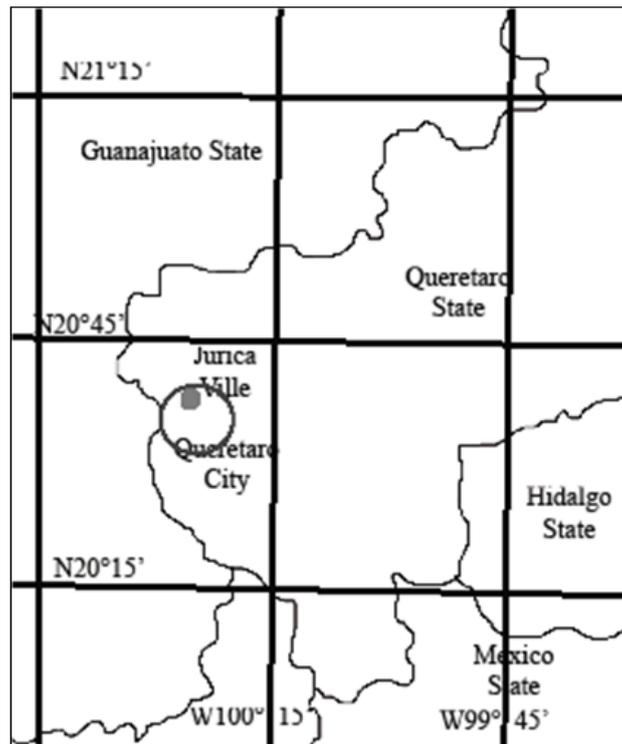


Fig. 1: Geographical Location of the Research Site.

1.1. Expansive soils

Expansive clays are those that are susceptible to undergo an appreciable increase of volume when increasing their humidity. The structures constructed on this type of clays are subject to the action of forces that cause up lifting, cracking, and rupture of foundations.

The expansion pressure is the maximum vertical stress that the soil can apply on the foundation in the limit of its expansion. If pressure on the ground is less than the expansion pressure, volume increase occurs, if the pressure of the building is greater than the expansion pressure causes compression volume [8]. The expansion pressure is not a constant and depends on the initial moisture; low initial moisture leads to higher expansive potential; then the expansion pressure for a soil is circumstantial [9].

The irrigation of gardens and the water leaking in pipes also will modify humidity of the original environment. Thus, the active zone (depth in a ground to which it happens periodic humidity changes) will be modified until obtaining another condition of balance where another regularity in the variations of water content is pronounced, which will be able to be repeated annually, whenever the new environmental condition prevails with time.

About the structure, the flocculated particles tend to be more expansive than dispersed clays, although in kneaded compaction, dispersed structures with a greater potential of expansion are created than statically compacted soils with low water contents [10]. The soil suction is an amount of energy that evaluates the capacity of the ground to retain water [11]. Said of another form, the soil suction is a state of negative pressure in the water of an unsaturated soil, which is related to the degree of saturation, the gravity, the size and the form of pores, the superficial tension and the electrical and chemical characteristics of particles of soil and water.

The initial state of stress and the magnitude of the overload also determine the amount of the change of volume. An external applied load acts to balance the repulsive interparticle forces and reduces the expansion [12]. The soil behavior influences in the structure behavior, therefore, the soil behavior is a fundamental part for the design and good operation of the structures.

2. Methods

2.1. Site characterization

For any project, when the design and construction is carried out is fundamental to realize a basic geotechnical site characterization in which are included the determination of the index and mechanical properties of the soil. For this work undisturbed samples of Jurica, Querétaro, México, were obtained, to a depth of 2,0 m. Subsequently, essays corresponding to properties index were made and the soil classification was obtained through plasticity chart. The measured expansion pressure was equal to seven Ton/m². The results of the soil characterization are summarized in table no. 1.

Table 1: Summary of the Geotechnical Properties of the Jurica's Soil.

Gravimetric humidity, ω	26%
Specific weight, γ_m	1.7 T/m ³
Specific gravity, S_s	2.54
Void ratio, e	0.87
Porosity, n	0.47
Saturation degree, $G\omega$	76 %
Volumetric gravity, $\theta\omega$	35%
Liquid limit, LL	78%
Plastic limit, LP	33%
Plastic index, IP	45%
Shrinkage limit, LC	7%
Linear shrinkage, CL	21%
Gravel content, G	3%
Sand content, S	14%
Fine soils content, F	83%

2.2. Analysis procedure

Classical geotechnical methods are traditionally used for determining the soil characterization focused upon the foundation design. This traditional approach to the soil behavior considers the saturated soil condition; therefore, the expansion pressure is not taken into account. However, an expansive soil will exert an uplifting pressure on the foundation structure reducing the settlements.

The authors are proposing a methodology that considers Zeevaert algorithms of interaction soil-structure (ISS) [13], using a new kind of coefficient associated with the expansive soil behavior [14]. The interaction between the foundation structure and the soil (ISS) consists of finding a system of reactions that applied to the foundation structure and to the soil mass simultaneously, both produce the same configuration of displacements between elements. In this, methodology is necessary to know the volumetric deformation value of the layers, which is determined of analogous way to the described by Zeevaert [13] to obtain the sexp coefficient in its recompression by load theory.

In a previous work, Perez y Cabrera [14] reported that the sexp varies with both the initial soil humidity and the moisture change. It is important when the soil is partially saturated and when the structural pressure on the soil is smaller than the expansive pressure and then the settlements are negatives (upward). Nevertheless, when the structural pressure on the soil is greater than the expansive pressure, the settlements will be positives but lesser than in a non-expansive soil. In this work, the last case is analyzed considering than the aexp coefficient depends of the initial structural pressure too.

2.3. Volumetric deformation coefficient due to settlements

For the determination of the volumetric deformation coefficient due to settlements was necessary to carry out laboratory tests to know vertical, initial and final stresses acting on the foundation soil.

The laboratory test was made in a mechanical oedometer in undisturbed samples of non-saturated expansive soils with natural humidity, taken of the same site from where the samples were taken to realize the characterization described in the previous section. Later, the overburden load was placed, and the specimen was saturated by capillarity until the expansion deformation was developed. This expansion obeys to the expansive soil property only and depends on the initial humidity. It is not considered that it involves stress relaxation by unloading during the expansion stage.

Once the soil was saturated, typical consolidation tests were carried out. Cycles of hysteresis in total load and unloading and similarly for partial stresses lightening are realized with the intention of obtaining the elastic and viscoplastic components of the deformation. The initial deformation by expansion of the soil is considered an important part of the elastic deformation of the material.

2.4. Calculation of the aexp coefficient

When a load due to the weight of the building is placed on the foundation (figure 2), the soil is recompressed in its elastic, plastic and visco-plastic components of the deformation [11]:

$$\Delta \varepsilon_c = \Delta \varepsilon_{eo} + \Delta \varepsilon_{po} + \Delta \varepsilon_{vpo} \quad (1)$$

For unloading and total recompression $\Delta \sigma_{oi}$ the secant module will be:

$$M_{co} = \frac{\Delta \varepsilon_{eo}}{\Delta \sigma_{co}} \left(1 + \frac{\Delta \varepsilon_{po}}{\Delta \varepsilon_{eo}} + \frac{\Delta \varepsilon_{vpo}}{\Delta \varepsilon_{eo}} \right) \quad (2)$$

Or

$$M_{co} = M_{eo} (1 + k_{po} + k_{vpo}) \quad (3)$$

In the same form for a partial lightening and recompression $\Delta \sigma_i$ it is had:

$$M_{ci} = M_{ei} (1 + k_{pi} + k_{vpi}) \quad (4)$$

And consequently the relation of these modules:

$$\frac{M_{ci}}{M_{co}} = \frac{M_{ei}}{M_{eo}} \cdot \frac{1 + k_{pi} + k_{vpi}}{1 + k_{po} + k_{vpo}} \quad (5)$$

But

$$\frac{M_{ei}}{M_{eo}} = \rho_{ei}$$

From

$$\frac{M_{ci}}{M_{co}} = \rho_{ei} \frac{1 + k_{pi} + k_{vpi}}{1 + k_{po} + k_{vpo}} \quad (6)$$

In an oedometric compressibility test, the terms $\Delta \sigma_{co}$, $\Delta \sigma_i$, $\Delta \varepsilon_{po}$, $\Delta \varepsilon_{eo}$ and $\Delta \varepsilon_{vpo}$ are obtained from the compressibility curve showed in figure 2. The terms M_{co} , k_{po} and k_{vpo} in equation (6) are calculated using the next equations:

$$M_{co} = \frac{\Delta \varepsilon_{eo}}{\Delta \sigma_{co}} ; \quad k_{po} = \frac{\Delta \varepsilon_{po}}{\Delta \varepsilon_{eo}} ; \quad k_{vpo} = \frac{\Delta \varepsilon_{vpo}}{\Delta \varepsilon_{eo}} \quad (7)$$

$\Delta \varepsilon_{vpo}$ Is a function of the time interval that the vertical pressure remain on the specimen.

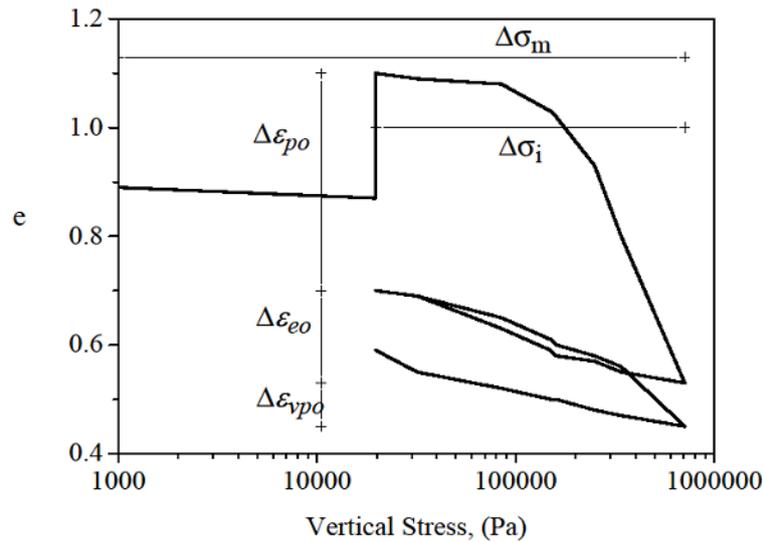


Fig. 2: Compressibility Curve for Jurica's Natural Soil.

The unknown quantities are k_{pi} and k_{vpi} since the M_{co} , k_{po} and k_{vpo} values are determined by laboratory tests in specimens of undisturbed soil for the maximum stresses lightening carrying out a hysteretic cycle (figure 2).

$$M_{co} = \frac{\Delta \varepsilon_{co}}{\Delta \sigma_{co}} \quad (8)$$

An approximated hypothesis can be done that the values k_{po} and k_{vpo} both are proportional at the level of stress of load applied for partial stress lightening to load applied for total stress lightening

$$\frac{k_{pi}}{k_{po}} \cong \frac{\Delta \sigma_i}{\sigma_{co}} \quad (9)$$

$$\frac{k_{vpi}}{k_{vpo}} \cong \frac{\Delta \sigma_i}{\sigma_{co}} \quad (10)$$

Replacing the equations (9) and (10) in the expression (6) it is obtained

$$\frac{M_{ci}}{M_{co}} = \rho_{ci} \frac{1 + (k_{po} + k_{vpo}) \Delta \sigma_i / \sigma_{co}}{1 + (k_{po} + k_{vpo})} \quad (11)$$

Where the recompression factor ρ_c is defined by the second term of the equation (10):

$$\rho_c = \rho_{ci} \frac{1 + (k_{po} + k_{vpo}) \Delta \sigma_i / \sigma_{co}}{1 + (k_{po} + k_{vpo})} \quad (12)$$

The strain secant module value for the recompression of the interesting layer will be

$$M_{ci} = \rho_{ci} \cdot M_{co} \quad (13)$$

And the volumetric compression coefficient α_{exp} for each one of the layers of thickness d_i in the soil mass is calculated:

$$\alpha_{exp} = M_{ci} * d_i \quad (14)$$

3. Results and discussion

In order to illustrate the practical way to obtain α_{exp} for an expansive soil, an expansion-compressibility-recompression essay was made in an oedometric device in soil from Jurica, which is widely known in the region because of its

expansive behavior. The investigated layer has a thickness of 2m. The results are shown in figure 2. Applying the suggested procedure the values for the deformations are obtained:

$$\Delta \varepsilon_{eo} = 0.172$$

$$\Delta \varepsilon_{po} = 0.4$$

$$\Delta \varepsilon_{vpo} = 0.089$$

$$\Delta \sigma_{co} = 689\,799.8 \text{ Pa}$$

$$\Delta \sigma_i = 673\,520.7 \text{ Pa}$$

Replacing the values obtained from figure 2 in the equations of (1) to (14), the strain secant module for the layer was initially calculated. After that, α_{exp} was calculated as it follows:

$$k_{po} = \frac{\Delta \varepsilon_{po}}{\Delta \varepsilon_{eo}} = \frac{0.4}{0.172} = 2.326 \quad (15)$$

$$k_{vpo} = \frac{\Delta \varepsilon_{vpo}}{\Delta \varepsilon_{eo}} = \frac{0.089}{0.172} = 0.517 \quad (16)$$

$$M_{ei} = \frac{\Delta \varepsilon_{eo}}{\Delta \sigma_i} = \frac{0.172}{673\,520.7 \text{ Pa}}$$

$$M_{ei} = 2.5537E - 07 / \text{Pa}$$

$$M_{eo} = \frac{\Delta \varepsilon_{eo}}{\Delta \sigma_{co}} = \frac{0.172}{689\,799.8 \text{ Pa}}$$

$$M_{eo} = 2.4935E - 07 / \text{Pa}$$

$$\rho_{ei} = \frac{M_{ei}}{M_{eo}} = \frac{2.5537E - 07 / \text{Pa}}{2.4935E - 07 / \text{Pa}} = 1.024 \quad (17)$$

$$\rho_c = \rho_{ei} \frac{1 + (k_{po} + k_{vpo}) \Delta \sigma_i / \sigma_{co}}{1 + (k_{po} + k_{vpo})} = 1.006 \quad (18)$$

$$M_{ci} = \rho_c \cdot M_{co} = 9.6399E - 07 / \text{Pa} \quad (19)$$

Therefore α_{exp} is:

$$\alpha_{exp} = M_{ci} * d_i = 9.6399E - 07 \text{ m} / \text{Pa} \quad (20)$$

The α_{exp} value thus obtained will have to be introduced in the equations of ISS of Zeevaert for the calculation of the final settlements.

When the external load on the soil stays constant, the coefficient of volumetric deformation varies with the initial humidity of the soil and with the humidity change [12]. The coefficient decreases when the initial humidity increases. In this work when the humidity stays constant the coefficient decreases when the initial external load increases, which indicates that the heave that will suffer the foundation structure is being affected by the magnitude of the expansion pressure. If the expansion pressure did not act, would have to hope that whichever greater it is the external load, the vertical settlements would have to be proportionally greater.

Is interesting to observe the graphic in figure 3 where the swelling percent decreases with de vertical pressure increment. It can see that after 300 kPa, the heave is reduced to zero and the settlements have started. For Jurica's soil then, it could be that a threshold of 300 kPa is the critical value for the vertical pressure between the heave and the settlement.

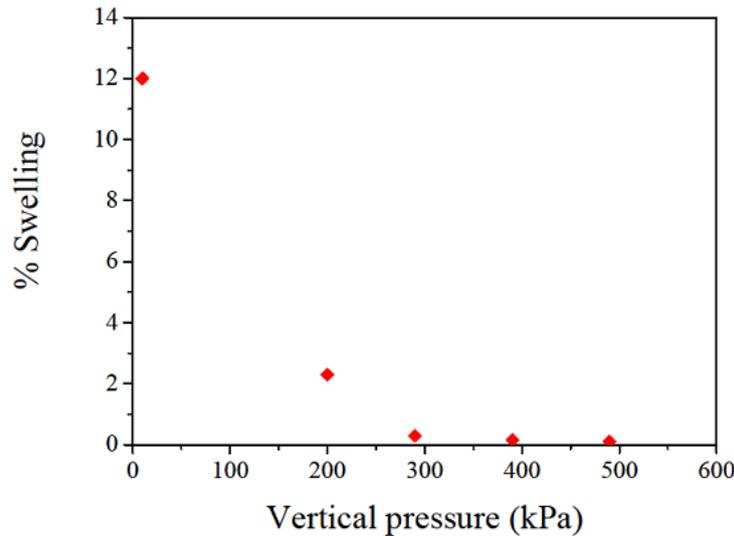


Fig. 3: Behavior of the Swelling Deformation of the Jurica's Natural Soil with the Vertical Initial Pressure.

In figure 4 the behavior of the α_{exp} versus the vertical pressure is presented. The graphic decreases exponentially with the vertical pressure increment. The threshold of 300 kPa is present herein again, when the α_{exp} is very close to zero.

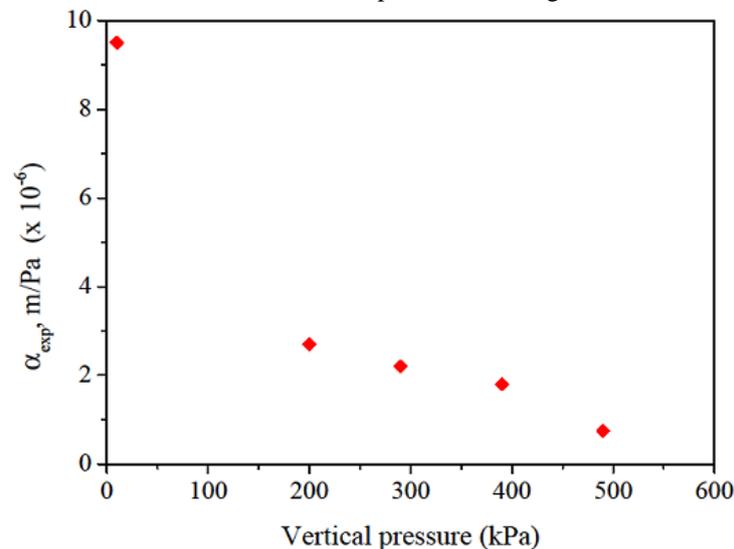


Fig. 4: Relationship between the Coefficient and the Vertical External Pressure for Jurica's Soil.

4. Conclusions

A methodology is presented for the calculation of the settlements of buildings constructed on expansive soils. The traditional methods for these problems use parameters obtained from oedometric tests realized with saturated soils. Although it is the surest way to analyze the problem, the final settlements in expansive soils are overestimated.

The coefficient of volumetric deformation determined here can be part of a methodology that includes soil-structure interaction algorithms, which take into account the behavior from the expansive soil for the prediction of final settlements in a building on which the soil expansion pressure acts. In the determination of the coefficient α_{exp} is necessary to know the initial conditions of the soil in the same way as the foundation structure that is going away to construct on since this one is function as much of the soil insitu property like of the external load.

Also, is interesting to observe from graphics in figures 4 and 5 that it can be concluded that for each kind of soil, it could exist a threshold of external pressure since it can be hoped settlements in an expansive soil.

This methodology must be carefully applied since the expansion pressure is developed only if the soil is hydrated, which doubtlessly will be reflected in a decrease of the bearing capacity of the ground. The diminution of the bearing capacity of the expansive soil when hydrating itself under a static pressure was not studied for this work and will be object of a next investigation.

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