

3D Analysis of an irregular- geometry foundation under the effects of an expansive soil

J. Horta Rangel, A. Zepeda Garrido, E. Rojas Gonzalez, T. Lopez Lara, L. Perez Rea and Hernandez J. Zaragoza
 Engineering Graduate Department, Autonomous University of Queretaro, Queretaro, Mexico, Z.C. 76010
 jaimehorta@prodigy.net.mx

Abstract

The expansive soil effect generates, first of all volumetric variation which causes changes in the soil's profile. The expansion pressure starts on the inside of the expansive soil mass as humidity increases, and, as a consequence, the tendency to increase its volume also increases. A 3-D analysis of an irregular-geometry plate foundation subject to expansive effects is presented. The analysis involves the soil's response and is represented by link bearings. The expansion effects are transmitted by the links to the foundation based on prescribed displacements with the shape of a paraboloid. The study herein developed considers the 3-D behavior of an irregular slab foundation; it focuses on the structural implications over the plate foundation due to expansive phenomenon. Commonly the solutions developed do not cover the 3-D implications of the whole phenomenon and the stiffness properties of an irregular plate foundation. The treatment covered in this study allows us to get more realistic results of the stress-strain state of plate foundations than the ones obtained through 2D models. The expansion effects generally have a random character because the place where they will occur cannot be certainly predicted, the proposed procedure It has the feasibility of rapidly studying cases of expansion occurring in the plate foundation, generating a versatile interaction with the user of the program developed for this purpose.

Keywords: Expansive soil, Computer modeling, Finite element analysis, Winkler Model, Contact pressure.

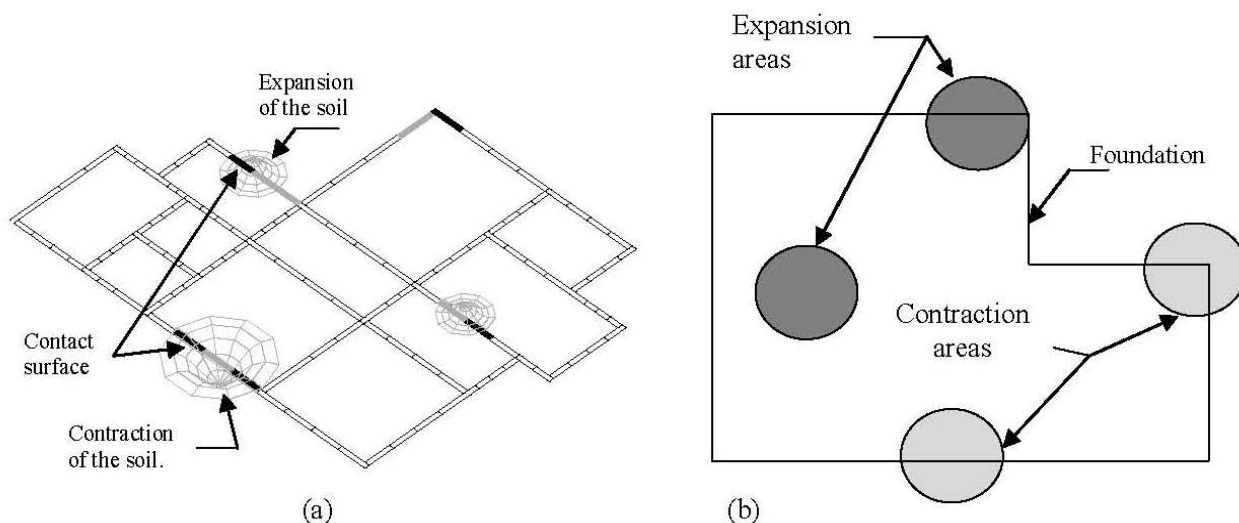
Introduction

As a certain increase in the volume of the soil's mass takes place, it can affect the surrounding area; however, the most relevant effect takes place in the vertical direction. At the same time, the loss of humidity in the soil makes its volume contraction, due to the increase in matric suction. This way, settlements can occur in the foundation as well as changes in the soil-structure contact pressures. Fig.1 shows the soil-foundation contact surface, which can experience a lift due to the expansion of the soil's mass or a settlement due to the volumetric contraction of the soil. All this is directly transmitted to the foundation whose displacements, depending on the extent to which they are generated, can cause structural damages to the dwelling.

One of the factors which identify the expansive

activity of a soil is its expansion due to saturation. Experimental tests in the odometer allow us to determine the expansion of clay under loads. This information is used to determine the surface expansions of the platform according to the estimated affected area of humidity inside the soil (Fredlund *et al.*, 2006). The results tend to show that as surface pressure increases due to applied external loads, the possible superficial expansive effect over the platform is more likely to be lower. One of the most vulnerable constructions, due to the scarce loading that it provokes on the soil, is the popular dwelling, with pressures lower than 1.5 T/m^2 . There are several solutions that can be applied to this phenomenology. One of them, of great practical interest, is Lytton's proposal (Lytton, 1984) which considers the expansion and/or contraction effects of soil, assuming that the foundation's

Fig.1. Effects of expansion and/or contraction over: (a) a grid foundation (b) over a slab foundation



behavior is like a simply supported beam or a cantilever. He also suggests a parabolic shape for the geometric conformation of the expansive effect. There are other solutions which fit the foundation's behavior into the soil expansion, considering the saturation and associated suction effects, there are 2-D solutions for this case (Fredlund & Li 2006) none of these approaches cover the 3-D implications of the whole phenomenon and the stiffness properties of an irregular plate foundation. The study herein developed considers the 3-D behavior of an irregular foundation; it focuses on the structural implications over the plate foundation due to expansive phenomenon. The program generated has been written in APDL language for Ansys environment (Ansys Inc., 2009).

Analytical model

The general physical model associated with the contact problem between two deformable means involves the following Lagrangean expression (Gurtin, 1981):

$$\int_{vol} S \cdot E \, dv = \int_{\partial\Omega} t \cdot u \, d\Omega + \int_{vol} b \cdot u \, dv + \int_{s_{ij}} \delta u_i^{ij} f_i^{ij} \, ds^{ij} \quad (1)$$

S: Piola-Kirchoff stress tensor; E: Infinitesimal deformation tensor; t: surface traction field; b: body forces field; u: displacement field; f_i: Contact forces

The first integral corresponds to the strain energy. The load potential (expression at the right side of the equation) is made up of three integrals: the surface tractions, the body forces, and the contact forces f_i. The problem covered in this paper sets out a particular case, the structure's interaction with a stratified means with expansibility characteristics that can randomly appear. The mechanical-equivalent models represent one of methodologies for the solution to this problem, one of them, Filonenko-Borodish model which couples both the vertical response of the soil and the shear stress. This approach applies elements such as vertical springs in the nodes such an element with shear capability in the soil's support plane. The differences of this model in relationship with the Winkler model are small (Zepeda A 2004), which is why a relatively simple way of approaching the problem expecting a smaller processing time is using the Winkler model. The discrete model corresponding to the analogue mechanical Winkler model is expressed with the next equation (Cook, 1988):

$$\left\{ \int_B [B]^T [D] [B] \, dv + \int k [N]^T [N] \, da \right\} [U] = \int_B [N]^T \begin{Bmatrix} b_x \\ b_y \\ b_z \end{Bmatrix} \, dv + \int_{\partial B} [N]^T \begin{Bmatrix} p_x \\ p_y \\ p_z \end{Bmatrix} \, d\partial B + \begin{Bmatrix} P_x \\ P_y \\ P_z \end{Bmatrix} \quad (2)$$

[B]: shape function derivatives matrix; [D]: elastic constant matrix; [N] : shape function matrix; b_x, b_y, b_z : body forces p_x, p_y, p_z : pressures acting over the body surface; P_x, P_y,

P_z : punctual forces applied on the discrete model's nodes. k : soil stiffness module.

If we consider only the diagonal elements of the stiffness matrix, it is the same as considering the response of the supporting means through normal springs to the foundation's plane. The essential characteristic of this model is the spring's stiffness. In our case, the supporting means is constituted by strata, including the base or platform on which the foundation rests. One way of including the stiffness of the stratified soil is through a parallel model (Selvadurai, 1979), with the following expression:

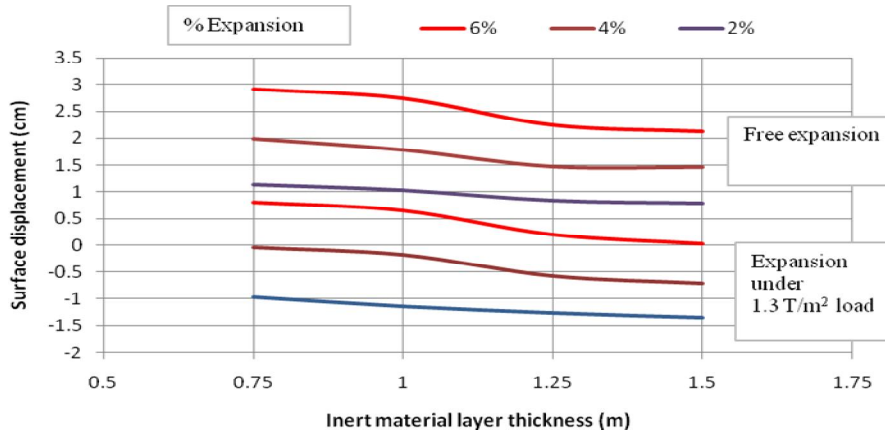
$$K = \frac{H}{\frac{H_1}{K_1} + \frac{H_2}{K_2} + \dots + \frac{H_r}{K_r}} \quad (3)$$

K: Global stiffness of the stratified means; H: Total strata thickness; H_i: Thickness of stratum I; K_r: Stiffness of stratum r.

There are two effects to consider: Soil expansion due to humidity increase and soil contraction due to loss of humidity, situation which commonly occurs in surface strata close to the free boundary (Mills, 2000). Surface expansion assessment of the soil is complex and depends on several factors and parameters, such as the depth of the expansion area inside the soil, on the shape of the expansion area, on the expansive potential of the soil, on the constituent properties of the participating strata, on the saturation and the source which causes it, among others. There are many works which punctually analyze this effect. For example, the works of (Mitchell, 1980; Hung, 2000), which talk about non-saturated soils, report the surface expansion considering the suction effects according to the soil's saturation. In general these effects are associated with a surface stratum on which the foundation rests. Generally, complex cases which involve stratigraphy, total area of expansion and irregular foundations in a 3-D context are not covered. Many times simpler solutions are sought; however, they are solutions with feasibility in their practical implementation. Such is the case of the works of (Lytton, 1984), which consider practical solutions for foundation grids and plates over soils with expansive potential. The case of irregular foundations is not reviewed here, nor is the surface effect or the surface area of influence of the expansion discussed.

An approach to the surface effects of the expansion can be seen in the paper produced by the author (Horta *et al.*, 2010). Fig.2 reproduces these results obtained in a particular case corresponding to a soil made up of three strata, analogous to the case study developed in the present work. One of the strata, the upper one, corresponds to the platform. That result is in no way a general solution; it does not cover all the cases, but it gives an idea of the surface effect according to many of the variables involved. Fig.2 relates the soil's surface expansion at the interface level with the plate foundation according to the soil's expansive potential as well as the thickness of the inert material layer of the platform. Two

Fig.2. Surface movements values of the soil at platform level vs. thickness of the inert layer and expansion potential of the soil in layer 2 (Horta J., et al., 2010).



cases are considered, one under free expansion and another one of expansion under a load of 1.3 T/m² which corresponds to a one-story dwelling. This last case, which is the most common one, tells us, for example, that for a deformation due to a 6% soil expansion and an inert material layer of 1.0 m, the expected surface expansion will be 0.7 c.m. The design of this graph has considered an area of expansion inside the second soil stratum (Fig. 3) in such a way that the effects for other similar cases could be not so favorable, this would be the case if the first stratum were the one with expansive activity.

Table 1. General data of the analyzed cases

Parameter	Proposed Values
Strength of concrete F'c	250 Kg/cm ²
Soil strength at platform level	10.0 T/m ²
Foundation Plate stiffness	0.15 m
Depth of the foundation beams	0.30m
Foundation beam anchor	0.20
Live load over foundation	0.17 T/m ²
Uniform load over beam	0.8 T/m
Analysis mesh module	0.20 m
Surface expansion of soil	0.02 m
Surface expansion radius	1.2 m

Methodology case study

The plate foundation with an irregular geometry is shown in Fig. 4. The purpose of this study is to assess the behavior of the foundation subject to expansion effects in accordance with the next data. In Tables 1 and 2 the data corresponding to the problem analyzed are shown. We assessed the global stiffness of the strata in accordance with the relation (3):

$$K = \frac{4.75}{\frac{0.75}{5000} + \frac{1.0}{1200} + \frac{3}{1600}} = 1661.8 \text{ T/m}^3 \quad (4)$$

The soil's response in accordance with Winkler's equivalent mechanical model is represented through springs that correspond to the global stiffness of the stratified means. In our study we use links type short concrete bars that withstand tension or compression, exclusively. The length of these bars located under foundation are suggested to be L_c= 0.50 m. The area of

these bearings is assessed according to the following relation: (K_{soil})(a²) = K_{link}, here parameter "a" is the width of the chosen mesh. On the other hand, the stiffness of the link elements are assessed through: K_{link} = A_c E_c / L_c So, based on these relations, the area required by the link bearings are as follow:

$$(A_{link})_i = (K_{soil})(a^2/E_c)L_{link}; \quad (A_{link})_e = (K_{soil})(a^2/2E_c)L_{link}; \quad (5)$$

Relations applicable depending on the link's location: inside, edge, corner, inside corner, respectively. For the study being performed, a modular mesh separation is applied a = 0.20 m; The concrete's elasticity module is obtained through Mexican Standars (NTCRCDF 2010)

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$$E = 14000 \sqrt{F'c} = 221,360 \text{ Kg/cm}^2$$

The areas of applicable resulting bearings for our study are:

$$(A_{link})_{in} = 15 \times 10^{-6} \text{ m}^2; \quad (A_{link})_{edge} = 7.5 \times 10^{-6} \text{ m}^2; \quad (A_{link})_{in.corner} = 3.75 \times 10^{-6} \text{ m}^2 \quad (6)$$

Numerical mode

The plate foundation is modeled with a finite element "shell63" (Ansys nomenclature) with 6 degrees of freedom per node, 3 linear displacements and 3 rotations; foundation beams are finite elements 3D beam44. The resulting discrete model is shown in the Fig.5. The lower nodes of the link bearings affected due to the expansion are displaced according to the expansion values. Next Fig.6 illustrates this procedure. There are two main characteristics which are important in this step, the radius of the surface expansion and the way in which the vertical expansion effect will vary. The links' lower nodes are displaced upwards at the same magnitude than the expansion occurring in the soil, which leaves the upper nodes free to displace and deform depending on the action generated over them. The shape of the expansion is adopted like a quadratic shape (y=β + η x²) similar to the one suggested by (Lytton, 1984).The plate foundation subject to service loads (dead + live loads) is analyzed. The 3D link bearings relate 3 linear degrees of

Table 2. Data corresponding to soil strata

Characteristic or Parameter	Proposed values
Thickness of the foundation support platform	1.0 m
Thickness of stratum 1	1.0 m
Thickness of stratum 2	3.0 m
Platform stiffness module k	3000 T/m ³
Stratum 1 stiffness module k	1200 T/m ³
Stratum 2 stiffness module k	1600 T/m ³
Support length	0.5 m
No. of corner link bearings	6
No. of inside corner link bearings	2

Fig. 3. Set-up of the soil stratified area

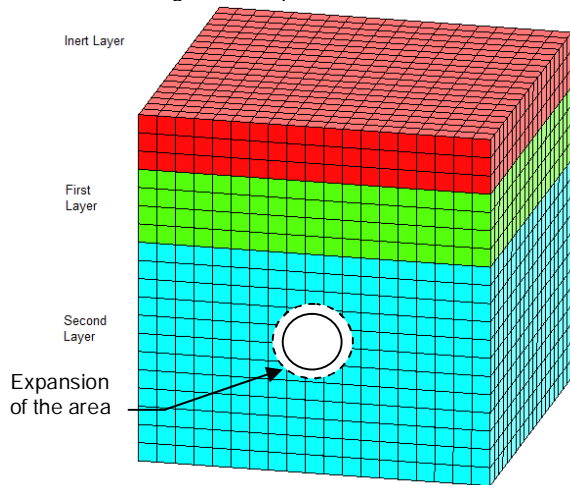


Fig. 4. Expansion soil effects inside slab foundation. (Dead +Live) concentrated loads are shown in circles.

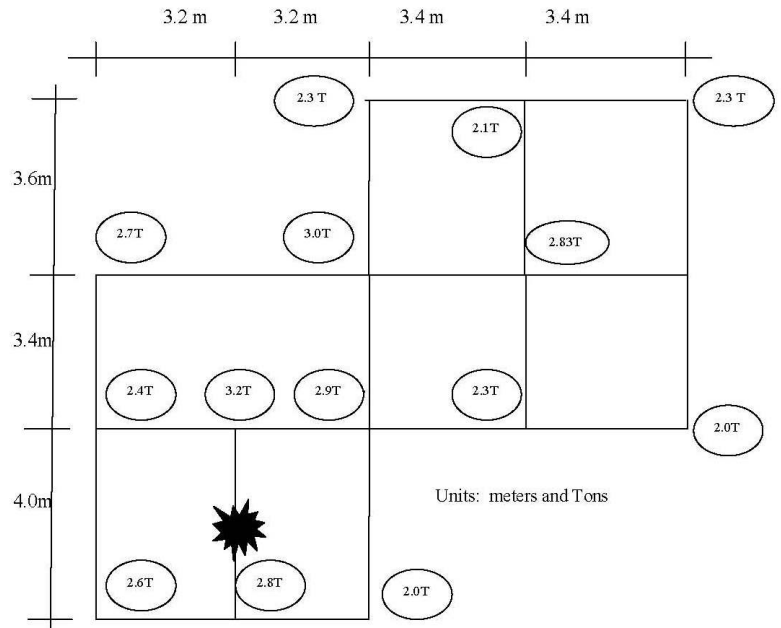


Fig. 5. Discrete model for the slab foundation

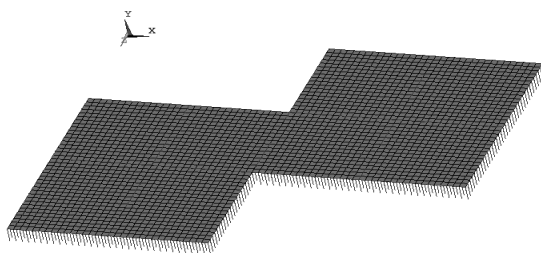


Fig. 6. Deformed Links representing the soil response under slab foundation

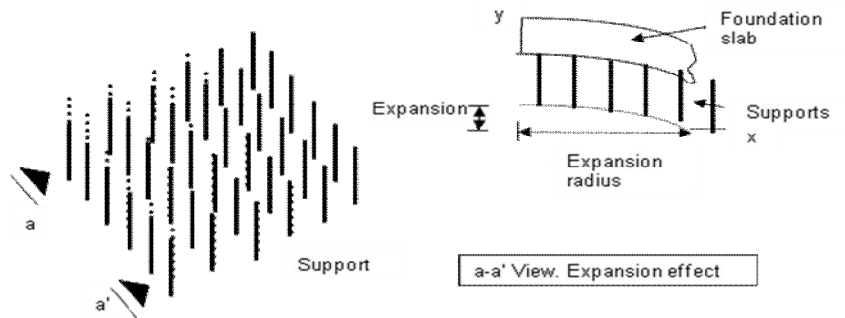


Fig. 7 Displacements on foundation. Maximum value: 5.38 mm

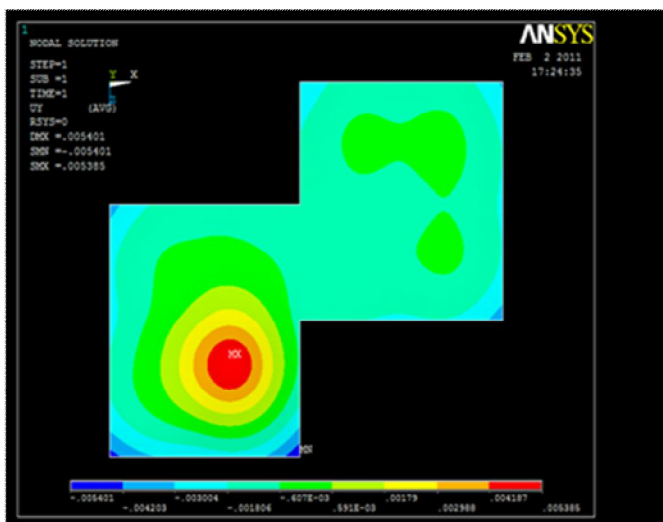
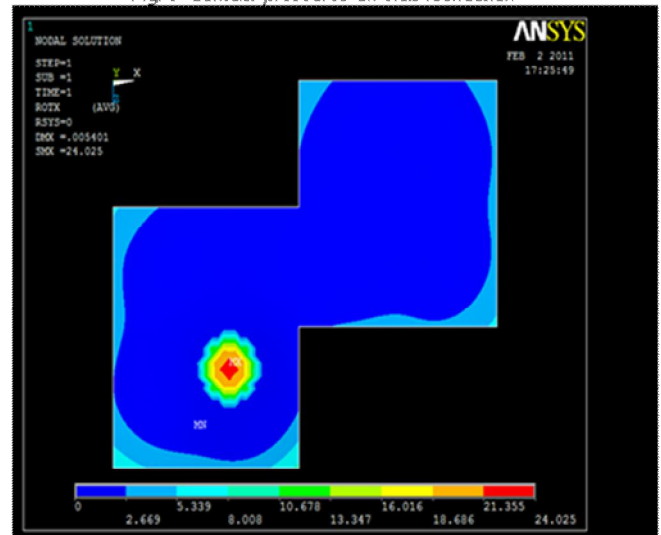


Fig. 8 Contact pressures on slab foundation



freedom and they couple to the degrees of freedom corresponding to the shell63 plate. The lower degrees of freedom of all the links are restricted. Furthermore, with the purpose of guaranteeing the stability of the plate, restrictions are added in the plate's plane only in 3 edge nodes. Fig. 7 shows the resulting displacement; the greatest one reported is a 5.38 mm located inside slab in the area with expansion soil effects. According to this result, differential displacements are smaller than what is allowed by the standards. Fig.8 shows the contact pressures values with a maximum of $24.0 \text{ T/m}^2 > 10.0 \text{ T/m}^2$ (maximum value allowed). Contact pressure is high in the area of maximum expansion effects, but very low in other areas.

Conclusions

The analysis of foundations over expansive soils involves a contact problem between two deformable means, which is a non-linear problem. Additional implications come up when including non-linear constitutive properties like viscoelastic properties of the soil. The expansive effect generated inside soil mass produces effects which tend to modify contact stresses and displacements. In this context, the inert material layer on which the foundation rests plays a very important role in the behavior of the soil-structure system. The expansive energy dissipation property of this layer and its constituent properties are relevant in the integral study of the foundation's analysis.

The approach of the analysis suggested in this paper is based, partly on the results obtained by (Horta, 2010) when studying the transmission of the expansive effect of the inside to the interface with the foundation. The present study has focused on the assessment of the foundation subject to expansive effects in different areas of the foundation, comparing the results with regard to the foundation without expansive effects. In both cases with expansive effects, we can see that the stresses are much higher when they occur in an inner area than when they occur in a corner, partly because in this last case, the effect does not cover the whole area but only part of it. The stresses in the foundation caused by expansive effects are high and even though no significant angular distortions were found in the analyses performed, the stresses in the expansion area are excessively high, even though limited, in a relatively small area compared to the rest of the foundation. An aspect that can be emphasized of the study performed is that in the case of an analysis without an expansive effect, the sizing of the plate and the properties of the inert material layer can be minimum, however, when the expansion effects occur, even the small ones like the one considered here, the contact pressures and the foundation stresses grow significantly. Therefore, the sizing terms of a plate foundation and the platform properties according to the possible expansion effects to which the foundation would be subject to, must be revised. In these terms, changes in the factors that can significantly affect the expansion effects have been raised. An aspect that must be considered here is the character of the scope desired to carry out in this type of analysis. The study carried out herein shows us the undesired effects which could occur over a foundation in terms of the occurring stresses. The creep effect in the

concrete is also valid in any moment due to the character of the loads applied. This leads to the degradation of the material's constitutive properties over time, which could increase the distortions in the foundation, thus, increasing the risks of generating faults due to angular distortion.

Remarks

The steel amount herein obtained is for a feasible expansion effect on the inside of the plate; however, due to the uncertain character of the expansive effect, it can occur in other areas, which could suggest the need to properly assemble in other areas similarly; this could lead to having plates with significant steel amount. Analogous analysis could be taken when analyzing the soil's contraction, which would lead to having effects in the front face of the plate. Thus, a subject which would still be of interest would be the scope of the analyses that must be raised on the matter.

The 3D analysis performed in this study allows us to get more realistic results of the stress-strain state of plate foundations than the ones obtained through 2D models. On the other hand, the expansion effects generally have a random character because the place where they will occur cannot be certainly predicted; thus, the foundations over expansive soils must be analyzed with all the implications of this phenomenon. Here we have covered the problem with the purpose of coming up with a feasible and practical solution for plate foundations with an irregular geometry.

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