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Application of a Physical Model of Soil-Structure Interaction in Static Condittions

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Abstract. This work has the objective of empirically reviewing the reasoning that is commonly carried out in the application of traditional theories in compatible events between coupled components, giving rise to the development of iterative calculation methods. In this case, a surface foundation beam subjected to uniformly distributed concentrated loads of equal magnitude was studied, for different rigidity conditions in the beam, with respect to the ground, between the limits of "totally flexible" to "totally rigid", That is, for an intermediate case that is an indeterminate system or semi-flexible foundation, without the presence of groundwater, trough the physical modeling of the foundation piece and the support soil.

Keywords. Soil-structure interaction, matrix equation of settlements, interaction matrix equation, foundation module.

1. Introduction

This work aims to confirm only the results in an elastic model without considering the transformation time. Which is justified when considered in the prototype, a soil little sensitive to time and a low level of stress used. In geotechnics, this acquires importance since we can establish a system of soil-structure interaction under known conditions and be able to verify the accuracy of the matrix method whit a practical model of experimentation.

An intermediate case was analyzed, where a semi-flexible foundation behaves according to the structural nature of the two participants, which in the best case should work in tandem, which if not, can generate future structural damage. For this work, only the case of superficial foundation such as strip footing or foundation slab in a semi-flexible state was tried.

Through the gravimetric and volumetric relations, were calculated, on initial conditions, the index properties of the soil, to typify it. Such index properties were; void ratio (e), saturation grade to water percentage (G_w%), porosity percentage (n%), the unit weight (γ_m) and the moisture content (w%)[1]. Later, was measured the displacement between soil and foundation piece contact. Such displacement, in general terms, under the state of efforts imposed in the model, can be expounded as:

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$$\delta = \alpha\sigma \tag{1}$$

where α is a deformation coefficient, delta is soil settlement or displacement and sigma is a normal effective effort. What can be expressed for a given point under the foundation piece of a stratified soil located on an axis "*i*" belonging to a stratum "*N*", such as:

$$\Delta\delta_{Ni} = \alpha_N \cdot \Delta\sigma_{Ni} \tag{2}$$

where $\Delta\delta_{Ni}$ is the increase of displacement in stratum "*N*" under the loaded strip "*i*", α_N is the deformation coefficient of the stratum "*N*", $\Delta\sigma_{Ni}$ is the increase of induced effort under the loaded strip "*i*", at the center of the stratum "*N*".

The foundation piece is solved by idealizing it in two superimposed conditions; "x_i=0", considering it a simply supported beam and "x_i=1", considering the reactions of the soil on the intermediate strips according to Maxwell's theorem.

2. General approach

Our work is based on the following hypothesis:

- Both the structure and the soil in their common border never lose contact, the soil is elastic, the soil is continuous, the soil is semi-infinite, the soil is uniform and isotropic, the foundation piece together with the soil are considered as a single body with respect to the stress-strain relationship, and the deformation energy is by gradual application of the loads, according to the consolidation effects of the soil and the construction times, for which the law of Clapeyron and the theorems of Betti and Maxwell are acceptable. [2].

2.1. Objective

Measure the deformations of the set under know stresses to revise the method of interaction proposed by Ph.D. Leonardo Zeevaert [3], in its simplest condition, that is, without considering changes in temperature, sub-pressure or neutral pressure and structural dynamics. In addition, applying point loads, "*P*", on the center of each ideal segment in which the foundation piece is divided. And, in this way, be in a position to solve the mechanical behavior of the piece or foundation structure when going from a hyperstatic problem to another one statically determined when the reactions of the soil, "*Xi*", are determined in the center of each strip.

2.2. Secondary objectives

- Promote the use of soil-structure interaction methods by means of a simple example based on the surface foundation of a structure under hyperstatic conditions, on the surface of a soil.
- Promote the idea that the greater the awareness of the mechanical behavior of the soil-structure system, the better use of the constructive resources available.
- Particularize the study trough the interaction method of L. Zeevaert, among other criteria of analysis. [3]

2.3. Variables

Quantitative, such as geometric dimensions, magnitude of loads, magnitude of stresses and deformations, as well as reactions modules, "*k*", which are the link between the terms of compatibility between soil and structure. And qualitative as are the stratigraphic characteristics and soil index, which mark the trends of the original mechanical parameters of the foundation soil.

3. Specific approach

The theme addressed in this work is to investigate from the real deformations in the interface or contact between the structure and the soil, and the phenomenological aspects considered by the iterative method used, whether or not, there is correspondence in the results as proposed the theoretical method. [4]

Experimentally, we only focus on the contraction, which is the cause of the feared settlements of the soil that differentially or totally can damage civil works, structurally, and functionally. The phenomenon implies a state of effective compression efforts. Thus for each stratum of the soil involved by the overload imposed by a structure, the volumetric compression of each stratum is a function of the unit deformation modulus, symbolized by "*Mc*" [4], and the increase in effective stresses , "$\Delta\sigma_z$", additional to those produced by nature at the average depth , "*z*", of each stratum, "*N*". This unit deformation module was determined in the laboratory and therefore must be corrected by means of a recompression factor, "*ρc*". Thus, for a stratum "*N*" of thickness "*d*", we have:

$$Mc^N = (\rho c \cdot Mc)_N \quad (3)$$

In this experimentally work, the instrumented soil was not subjected to recompression, therefore the value of "*ρc*" is unity, and the unit deformation modulus is simply:

$$\alpha_c^N = (Mc \cdot d)_N \quad (4)$$

4. Experimentation

To elaborate the experimental system, a wooden box was built, polished inside, to contain the experimental soil. The internal dimension of the box were; 41×47.5×100.3 centimeters. To determine the dimensions of the test box, the incidence of the walls or borders and the possible effects of friction that could arise were considered.

4.1. Characteristics of the experimental soil used

In general, the experimental soil corresponds to a common soil of the coastal area of the municipality of Veracruz, México, Belonging to medium to fine sands, poorly graded, grayish brown color.

The soil was classified according to the unified soil classification system (USCS) and its index properties were determined as shown in the following table:

Table 1. USCS classification and properties experimental soil index.

USCS classification	w%	e	n%	S_s	γ_m (gr/cm^3)	γ_d (gr/cm^3)	G_w%
SP	8.02-12.34	1.06-1.08	51.53-52.04	2.71	1.41-1.46	1.30-1.31	20.45-30.82

The experimental soil consisted of two layers or stratums, arranged in the test box, approximately 0.205 meters thick per layer, each compacted with a hand tamper whit a constant drop of the order of 20 centimeters.

4.2. Experimental foundation piece

With respect to the prototype foundation piece, a modulus of elasticity of 300,000 kg/cm^2 was determined. The moment of inertia with respect to the neutral axis is 30 cm^4. The stiffness (EI) was 9,000,000 kg*cm^2. The section had a thickness of 2.885 cm, width of the plate was 15 cm and its length was 75 cm.

For the analysis process, the prototype foundation piece was idealized by dividing it into five strips with the soil reaction under each one (R_b, x_1, x_2, x_3, R_a), as shown in the following figure:

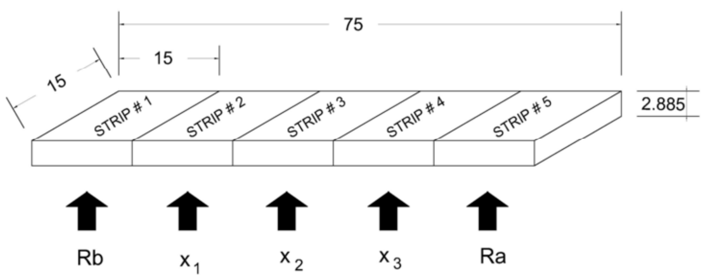

Figure 1. Idealization of the foundation piece by dividing it into five strips (all dimensions are in centimeters).

4.3. Load frame, uniform loads and measurement instrumentation

A rigid level load frame was built with respect to the horizontal, for the placement of the loads on the point contacts with the prototype foundation piece. At the same time, the prototype foundation piece make contact with the experimental soil contained on the wooden box.

Regarding the uniform loads, these were of the order of 7.097 kg each one, through the use of a known material (cast iron) in a closed PVC container. For each strip, the applied stress was of 3.04 kPa.

For the measurement of the deformations, five digital micrometers of the MITUTOYO brand were used with a reading resolution of 0.01 mm, a measuring range of 12.7 mm and a precision of 0.02 mm.

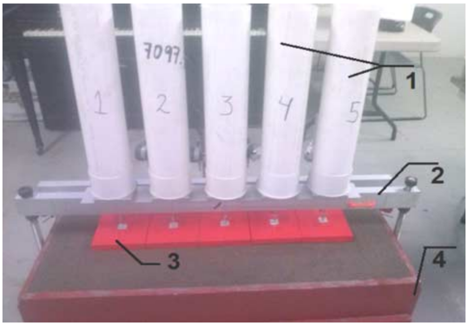

Figure 2. Full experimental model; uniform loads in PVC containers (1), level load frame (2), prototype foundation piece divided into five strips (3) and the wooden box with the experimental soil (4).

5. Application of the matrix method

Matrices of five columns and two lines were formulated in the matrix of settlements (EMA) and the interaction matrix (EMI) equations [5].

Thus, the EMA equation for the instrumented model is written:

$$\begin{vmatrix} \delta_1 & \delta_2 & \delta_3 & \delta_4 & \delta_5 \end{vmatrix} = \begin{vmatrix} I_{w11}q & I_{w21}q & I_{w31}q & I_{w41}q & I_{w51}q \\ I_{w12}q & I_{w22}q & I_{w32}q & I_{w42}q & I_{w52}q \end{vmatrix}^T \cdot \begin{vmatrix} (Mc \cdot d)_{N=1} \\ (Mc \cdot d)_{N=2} \end{vmatrix} \tag{5}$$

where I_w is the influence factor under a strip, δ is the settlement under each strip, M_c is the volumetric variation module, d is the stratum thickness, q is the induced loads, N=1, 2 is the number of order of the layers of the soil

$$\begin{vmatrix} \delta_1 & \delta_2 & \delta_3 & \delta_4 & \delta_5 \end{vmatrix} = \begin{vmatrix} I_{w11}q & I_{w12}q \\ I_{w21}q & I_{w22}q \\ I_{w31}q & I_{w32}q \\ I_{w41}q & I_{w42}q \\ I_{w51}q & I_{w52}q \end{vmatrix} \cdot \begin{vmatrix} (Mc \cdot d)_{N=1} \\ (Mc \cdot d)_{N=2} \end{vmatrix} \tag{6}$$

i= 1, 2,3,4,5, number of strips.

For the semi-flexible piece, where the structure as the soil, participate according to the relationship of rigidities, and merits the soil-structure interaction analysis, which is carried out in this case, with the method of Ph.D. Leonardo Zeevaert. [5].

We applied the EMA equations (matrix of settlements) and EMI (interaction matrix equation) in an iterative way. For this, we propose the equations in the following way:

$$EMA...........\delta_i = \left[\delta_{ij}\right]T \cdot \left[\frac{x_i}{\widetilde{a}}\right] \tag{7}$$

$$EMI...........\left[\delta_{ij}\right] \cdot \left[x_i\right] = \left[\Delta_{i0}\right] - \left[\delta_i\right] \tag{8}$$

These two equations are compatible if the values of "x_i" satisfy them. To carry out the iterations it is convenient to write EMI in the following way:

$$\left[\delta'_{ij}\right]+\left[\delta''_{ij}\right]+\left[\frac{1}{k_i}\right]D\cdot\left[x_i\right]=\left[\Delta_{fi0}\right]+\left[\Delta_{Ai0}\right] \tag{9}$$

where [x_i] is the columnar matrix of the unknowns reactions, [δ_{ij}'] is the symmetric matrix that represents the flexibility of the foundation structure for the conditions "x_i= +1". It is inversely proportional to the "EI" value. [δ_{ij}''] is the columnar matrix that represents the unitary vertical displacements of the foundation structure a a rigid element for the conditions "x_i =+1", at point "i". It is a function of the foundation module, "k_a" and "k_b" in supports "a" and "b". [$1/k_i$]D is the diagonal matrix that represents the unit vertical displacement of the soil for the conditions "x_i= +1", at point "i". [Δf_{i0}] is the columnar matrix that represents the displacements of the foundation structure in condition "x_i=0", of all the loads that act on it. It is inversely proportional to "EI" value. [Δ_{Ai0}] is the columnar matrix that represents the displacements of the foundations structure as a rigid element in condition "x_i=0", is a function of the foundation module in supports "a" and "b". [δi] is the columnar matrix with the values measured in the research prototype, which must coincide with the values measured in the prototype, after the iterative process.

6. Results

Below are the measurements of the deformations caused by the uniform loads, for the semi-flexible foundation piece during a test period of seven days:

Table 2. Deformations presented after the loading period in a semi-flexible piece.

Strip	Deformation (millimeters)
1	0.718
2	0.653
3	1.080
4	0.657
5	0.716

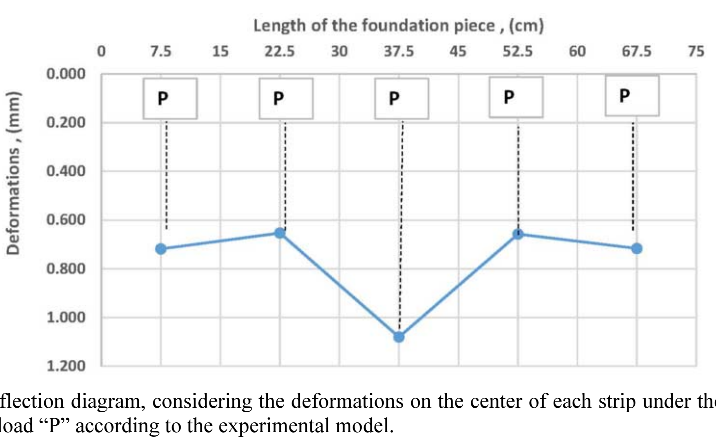

Figure 3. Deflection diagram, considering the deformations on the center of each strip under the application of a uniform load "P" according to the experimental model.

The results on the table show the accumulated settlements trough time (one week), under the strip "*i*", measured directly in the full experimental model. According to this, the maximum deformation was presented on the central strip under a system of uniform loads.

Calculation of the theoretical deformations and comparison with the deformations measured in the experimental model. To do this, each reactions is divided considering the influence of the five ideal stripes, between the final foundation modules, after iterative process.

Table 3. Calculated deformations with the Eq. (6).

$\delta 1$(cm)	$\delta 2$ (cm)	$\delta 3$(cm)	$\delta 4$(cm)	$\delta 5$(cm)
0.0721	0.0662	0.1120	0.0662	0.0721

The deformations calculated with the interaction matrix, described in the Eq. (6), are similar to the obtained on the experimental model, following the trend of maximum displacements on the central strip.

Table 4. Differences between the measured values, in millimeters and those calculated, are given in percentage, with respect to the values measured in the prototype and the reaction modules , k , calculated with the iterative process.

Strip	%	k (kg/cm)
1	0.418	225.73
2	1.375	92.45
3	3.704	50.89
4	0.761	92.45
5	0.698	225.73

With the two values o deformation for each strip, one calculated with the interaction matrix and the other obtained directly with the experimental model (Tables 2 and 3), we can establish a percentage of variation between them (Table 4).

Having a percentage variation less than the 5%, for this case, we can be safe of the accuracy of the interaction matrix, without forget the variable nature of a physical phenomenon.

7. Conclusions

According to the experimentation carried with the physical model built with a prototype foundation piece of intermediate rigidity and two layers of reconstituted soil of fine sand, the interactive method proposed by Ph.D. Leonardo Zeevaert [5], is an effective calculation tool, for this particular case, with a low range of variation with respect to direct measurements of a physical model. This this will be possible as long as the approximate tendency of the compressibility of the soil is previously known, that is, the index properties of the support soil.

If the developed procedure is applied in any other case of foundation by surface, the number, "n", of strips, must change according to the dimensions of the foundation piece and the degree of approach that is require.

The quality of the results obtained to procedures of this type, depends significantly on the representativeness of the index properties of the soil samples and the properties of the foundation piece.

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