THREE DIMENSIONAL ANALYSIS OF HOUSES ON EXPANSIVE SOILS

ETUDE TRIDIMENSIONEL DE MAISONS SUR SOLS EXPANSIFS

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SYNOPSIS The analysis of houses with shallow footings resting on expansive soils is a complex task. It is necessary to define the free field deformation profile of the soil, which can be asymmetric below the house plant and variable with time. Besides, due to analytical difficulties, the three dimensional nature of the soil-structure interaction is commonly omitted in many engineering analysis. This work presents a 3-D analysis using an elastic finite element approach for economic houses damaged by soil expansions. Different free field deformation profiles of the soil were investigated to end up with a relatively good comparison between predicted and observed crack patterns in the house walls. The effect on the crack patterns of some structural elements of the house are also pointed out.

INTRODUCTION

When dealing with economic dwellings on expansive soils the use of piles or other special solutions to prevent detrimental movements are precluded by cost. Alternatively, reinforced strip footings posses advantages since local experience and expertise can be used as they are natural extensions of conventional wall footings (Ramaswamy and Abu-El-Sha´r, 1987).

Figure 1 illustrates a design process for strip footings under a condition of differential hogging, but it can be applied for a condition of differential uplift. The procedure can be summarized as follows:

- A maximum soil differential hogging below the footing, y_h, is defined along with the shape of the soil without external loads (free field deformation, FFD). The free field deformation can be expressed as:

$$y = y_h \; f(L,X) \tag{1}$$

- The lack of support e_1 and e_2 is assumed and the footing is analyzed as a beam on elastic foundation with an effective length of support $L-(e_1+e_2)$. The modulus of subgrade reaction, k, can be obtained as $k = \sigma/\rho$ where σ is the average contact stress at the foundation level and $\rho = \rho_o - \rho_\sigma$; ρ_o is the vertical heave due to active layers between the foundation depth, D_f, and a depth equals to D_f+2B (B is the footing width) and ρ_σ is the heave due to active layers between D_f and D_f+2B when the contact stress, σ, is acting (induced vertical stresses due to σ within D_f and $D_f + 2B$ can be computed using Boussinesq charts). In order to compute the average contact stress, σ, the total footing length, L, can be used without to much error (Fernández, 1993).

- Vertical movements, ρ_σ and ρ_σ, due to heave are obtained from laboratory tests on undisturbed samples, as a function of the vertical confinning pressure and the initial and final degree of saturation of the soil, following a procedure outlined by Retamal and Ortigosa (1992). When using this procedure, the maximum variation of the degree of saturation for the active layers between D_f and $D_f + 2B$ is introduced to define initial and final values of the saturation degree. For engineering purposes it is not really necessary to specify the initial and final absolute values of the degree of saturation, but only their difference.

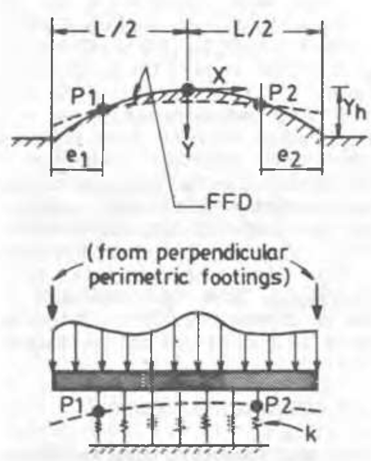

Fig.1. Design Model for Hogging

Vertical displacements for the beam on elastic foundation are superposed to the FFD and the intersection points P_1 and P_2 are defined; this points give new e_1 and e_2 values which are compared with the assumed values. The procedure is repeated until the assumed and calculated magnitudes agree.

The maximum angular distortion for the final shape of the footing must be compared with the allowable distortion for the specific structure. Alternatively, induced stresses on the structure are compared with the allowable stresses.

FREE FIELD DEFORMATION (FFD)

According to Lytton and Meyer (1971), eq.(1) can be written as:

$$y = y_h \left[\frac{X}{L/2}\right]^m \tag{2}$$

with m ranging between 2 and 4 (m = 2 gives maximum curvature for the FFD, so the stresses induced on the structure will be encreased).

On the other hand, Lytton and Meyer suggest a design FFD with a shape shown in Fig. 2, where L_m is the penetration distance. Along this distance changes on the degree of saturation will produce vertical differential movements in the soil covered by the house plant. According to McKeen and Johnson (1990) the penetration distance ranges between 0 (inactive soils) to a maximum of 2.4m. Taking L_m = 2m as a design value, the FFD in Fig. 2 can be expressed by the following equations:

$$y = 0 \qquad \text{if } |X| \leqslant a \tag{3a}$$

$$y = y_h \left[\frac{X - a}{L/2 - a}\right]^2 \qquad \text{if } a < |X| \leqslant L/2 \tag{3b}$$

with $a = L/2 - L_m$ and L_m=2m.

Values of the maximum differential hogging, y_h, depend on the soil type and the profile of the degree of saturation below the house plant. Actually this profile is influenced by climatic factors, surface vegetation, topography and soil stratigraphy. In order to obtain design values for y_h, direct measurements were undertaken by means of plastic covers installed at six different sites, to simulate surface conditions of houses without including external loads. The house perimetric footings were simulated by extending the plastic sheets 0.60m allaround the perimeter. Figure 3 shows typical results and Fig. 4 the time variation of the ıaximum hogging, y_{hmax}, and the maximum uplift, y_{umax}. According to these results, hogging is the most detrimental FFD pattern to be used in design.

MODULUS OF SUBGRADE REACTION

As pointed out before, the modulus of subgrade reaction, k, for a hogging pattern where the footing central area heaves, can be obtained using the procedured outlined by Retamal and Ortigosa (1992). However, values of k must be modified due to the "contact problem" as shown in Fig. 5. Then, the final value of the modulus of subgrade reaction, k_c, is obtained by means of the following equation:

$$k_c = \left[\frac{\delta - y}{\delta}\right] k \tag{4}$$

where y is given by eqs. (3a) and (3b).

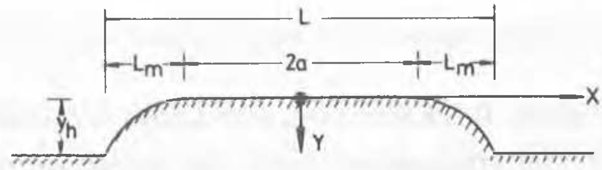

Fig.2. Free Field Soil Displacements used in the Analysis

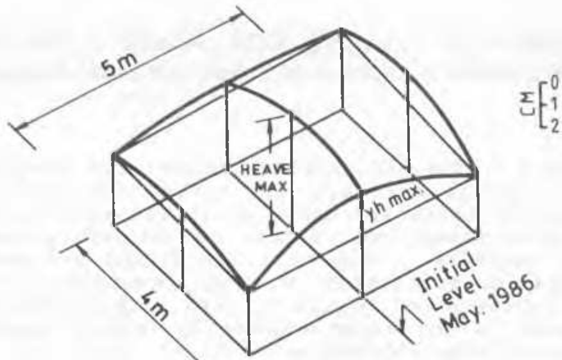

Fig.3. Vertical Movements below Plastic Cover at La Dehesa in January 1987 (Retamal and Ortigosa, 1992)

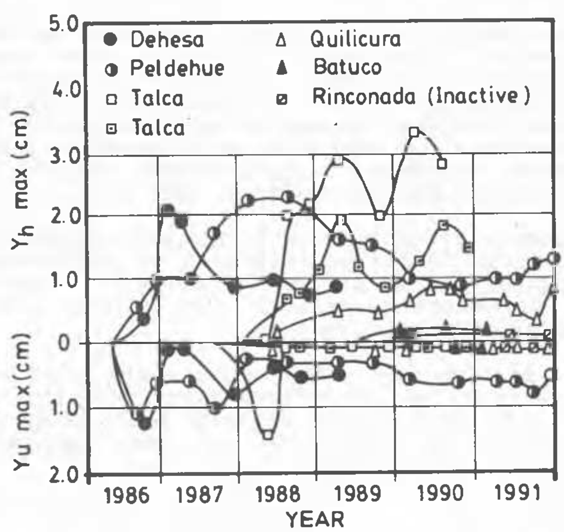

Fig.4. Uplift and Hogging measured with Plastic Covers (Retamal and Ortigosa, 1992)

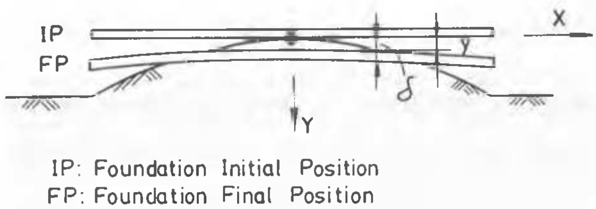

Fig.5. Contact Problem due to Hogging

When hogging is produced by shrinkage at the ends of the foundation, all the previous procedures applies. However, the modulus of subgrade reaction, k, must be obtained using the classical procedures for computing vertical settlements in foundations resting on fine grained soils.

THREE DIMENSIONAL ANALYSIS

Figure 6 shows an isometric view of houses which were damaged due to soil movements with a hogging FFD. A typical pattern of the measured cracks is included in that figure. A theoretical analysis of the house behaviour was performed using three dimensional finite elements and a FFD given by eqs.(3a) and (3b) with y_h=3cm (maximum value measured in the field covered areas as shown in Fig. 4). Both symmetric and asymmetric FFD were included in the analysis as shown in Fig. 7. For the middle wall an additional heave, Δ, was considered according to the field measurements, with $\Delta \approx 0.65 y_h = 1.95$cm. For a hogging heave pattern and the average contact pressure of 20.5 kPa, the modulus of subgrade reaction was $k=0.46 kg/cm^3$; for a hogging pattern due to shrinkage at the house corners the modulus of subgrade reaction was 1.46 kg/cm^3 (Fernandez, 1993).

Failure criteria for the concrete masonry and the mortar joints were taken from Drysdale and Hamid (1982, 1984):

Shear failure in the horizontal joints
$$C_1 = \left| \frac{\tau_{xy}}{\nu_h - \mu\sigma_y} \right| \quad (5)$$

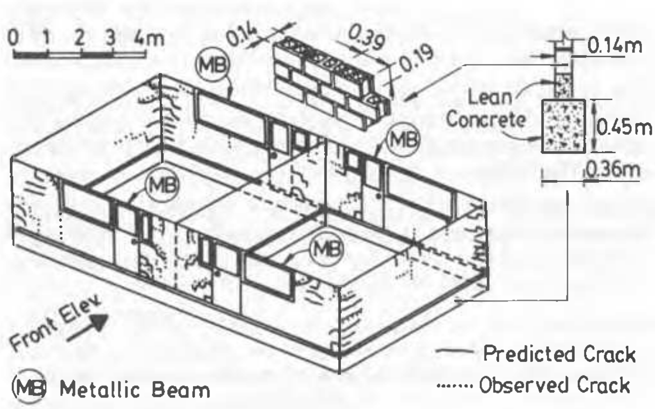

Fig.6. House Isometric View and Predicted Cracks for Type A Free Field Displacements

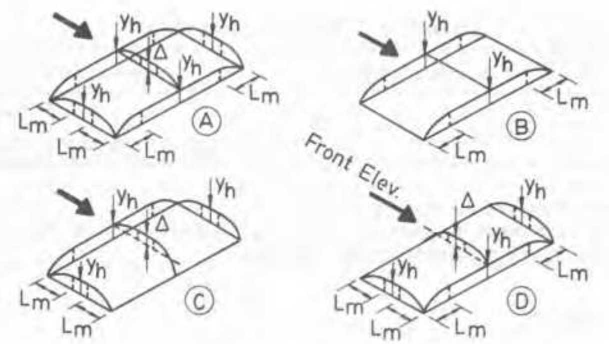

Fig.7. Three Dimensional Free Field Displacements used in the House Analysis

Shear failure in the vertical joints
$$C_2 = \left| \frac{\tau_{xy}}{\nu_v - \mu\sigma_x} \right| \quad (6)$$

Tension failure:
$$C_3 = \left| F_1\sigma_x + F_2\sigma_y + F_3\sigma_x^2 + F_4\sigma_y^2 + F_5\sigma_x\sigma_y + F_6\tau_{xy}^2 \right| \quad (7)$$

where τ_{xy} = shear stress in the horizontal and vertical joints; ν_h = adherence shear strength in the horizontal joints; ν_v = adherence shear strength in the vertical joints; μ = friction coefficient; σ_y = normal stress to the horizontal joints (positive for tensile stress) and σ_x = normal stress to the vertical joints (positive for tensile stress). Values of F_i are given as a function of f'_{mn}, f_{tn}, f'_{mp} and f_{tp}, where f'_{mn} = compressive strength normal to the horizontal joints; f_{tn} = tensile strength normal to the horizontal joints; f'_{mp} = compressive strength normal to the vertical joints and f_{tp} = tensile strength normal to the vertical joints.

For the concrete elements failure criterion was expressed as follows:

Tension failure
$$C_4 = \left| \frac{\sigma_{max}}{\sigma_t} \right| \quad (7)$$

Shear failure
$$C_5 = \left| \frac{\tau_{max}}{\tau_c} \right| \quad (8)$$

where σ_{max} = maximum tensile stress acting in the concrete; τ_{max} = maximum shear stress acting in the concrete; σ_t = concrete tensile strength for flexural failure and τ_c = concrete shear strength.

Equations (5) through (8) will predict failure (cracks) on those elements of the 3-D mesh where $C_i \geq 1.0$. Due to difficulties in solving the 3-D soil-structure interaction problem, linear stress-strain behaviour was assumed for the house materials, without taking into account changes in the structural rigidity due to cracks. Table I presents the strength properties used in the analysis and the shear modulus, G, for concrete and concrete masonry.

TABLE I MATERIAL PROPERTIES

Concrete Masonry ($kPa \times 10^3$)							Concrete ($kPa \times 10^3$)		
f'_{mn}	f'_{mp}	f_{tn}	f_{tp}	ν_h	ν_v	G	σ_t	σ_c	G
2.29	1.2	0.09	0.23	0.11	0.9	1060	0.53	1.1	5520

For concrete masonry μ = 0.54
All strength properties were multiplied by 0.5 to take into account construction defects.

RESULTS

Figure 6 shows a typical crack pattern predicted using a symmetric FFD typified by Case A in Fig. 7 and $k=0.46 kg/cm^3$ representing a central hogging due to soil heave. Comparisons with the measured crack pattern is fairly good, in spite of introducing a linear stress strain behaviour for the house materials. Results using $k=1.46 kg/cm^3$ (central hogging due to corner shrinkage) do not show too much differences when using symmetric FFD patterns. However, for asymmetric FFD the increase in the modulus of subgrade reaction predicts a more severe crack pattern.

As regards to the cracks distribution, symmetric FFD typified by Case B in Fig. 7 was the most detrimental for the front and rear walls, while asymmetric FFD typified by Case C and D in Fig. 7 were the most detrimental for the middle wall.

Additional predictions were performed introducing reinforced concrete columns 0.15x0.20m in the wall intersections and horizontal beams 0.15x0.20m in the top of the walls (confined masonry). Footing height was increased from 0.45m to 1.0m using a better quality concrete, ending with a more rigid foundation system. Figure 8 compares the predicted crack pattern for confined and unconfined masonry using a symmetric FFD typified by Case B and $k=0.46kg/cm^3$. A drastic crack reduction is observed; besides, failure coefficients in the critical elements of the confined masonry were of the order of 50% of those obtained for the original house (unconfined masonry).

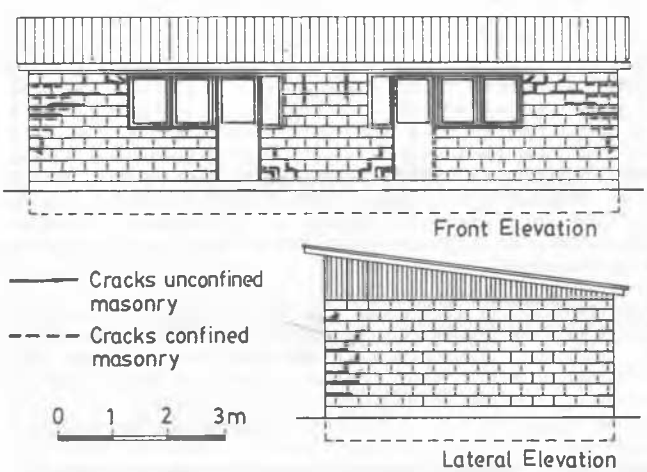

Fig.8. Predicted Crack Pattern for Type B Free Field Displacements

CONCLUSIONS

For predicting free field vertical soil displacements (FFD) due to shrinkage or heave below a foundation system it is necessary to define a maximum design value for the differential hogging, y_h, or uplift, y_u. Experimental measurements in Chile suggest hogging to be more detrimental than uplift, with a desing value y_h=3cm. On the other hand, FFD can be mathematicaly expressed by means of eqs.(3a) and (3b) with a moisture penetration length L_m=2m.

For hogging due to central heave, the modulus of subgrade reaction used in the analysis must be computed using soil data from heave tests on undisturbed samples. For hogging due to end or corner shrinkage, the modulus of subgrade reaction must be obtained using the classical methods for computing settlements of footings resting on fine grained soils. Final modulus of subgrade reaction must be modified due to the "contact problem" as pointed out by eq.(4).

The three dimensional finite element analysis proved to be a powerful tool to understand the crack pattern for houses resting on expansive soils. The analysis show a better structural behavior when using confined masonry along with more rigid footings.

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