The seismic response of embedded structures
Réponse séismique des structures enterrées

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ABSTRACT: Both inertial and kinematic effects of the dynamic soil-structure interaction according to the variation of many parameters such as layered soils, types and depth of foundations, height and planned dimensions of the structures are analyzed. Attention is given to the resulting shear forces on the embedded elements by using a calculation code which takes into account the dynamic soil-structure interaction (FLUSH) and a typical structural program (SAP).

RESUME: On analyse les effets d'inertie et les effets cinématiques de l'interaction dynamique terrain-structure en changeant plusieurs paramètres tels que la stratigraphie, la typologie et l'approfondissement des fondations, les dimensions des structures en élévation et en plan. On a donné une attention particulière aux différences qu'on obtient en ce qui conceme la contrainte de la structure en utilisant un code de calcul qui tient compte de l'interaction terrain-structure (FLUSH) et un programme de calcul typiquement structural (SAP)

1 INTRODUCTION

A realistic design for embedded structures under dynamic loads should involve the study of the soil-structure system. In the case of deeply embedded structures numerous factors should be taken into account, such as the variation of the seismic signal with depth, the variation of the deposit soil dynamic properties, the phenomena of loss of energy due to the soil (hysteretical dissipation) and to the soil-structure system (dissipation by radiation), the resistance of the soil to the motion of the structure (passive strain).

As it can be seen, the parameters involved are so numerous that a satisfactory study of soil-structure interaction in practical engineering is discouraging; on the other hand, it is not right to disregard the phenomena of interaction. In fact, many times there is the risk of an unsafe design, many other times an over size structure may be designed. In order to underline these problems, preliminary different cases of embedded structures which take in account the type of the soil, the structure dimension and the type of foundation are studied in this paper. The effect of adjacent structures is, moreover, analyzed.

The problem of dynamic soil-structure interaction is quite recent; nevertheless, several methods have already been proposed for the study of the dynamic behavior of soil-structure system. The aim of this paper is to provide not a method with new mathematic formulation, rather a guide for a straightforward study of not too simple embedded structures. Authors have wondered what an engineer needs to compute the stresses and strains on the whole embedded structure using the calculation codes on sale. The solution consists of the valuation of the stiffness coefficients applied locally to the soil-structure restraints.

These two values have been determined and tabled for different types of soil making it possible to take into consideration soil-structure interaction with simplicity and without great expenses of calculation.

2. INTERACTION PROBLEM FOR EMBEDDED STRUCTURE

If a system consisting of a soil and of a partially embedded foundation are considered and $\ddot{y}_0(t)$, $\ddot{y}_1(t)$, $\ddot{y}_b(t)$ are the acceleration recorded on the surface in the free field, the acceleration recorded on the surface with structure and the acceleration starting from bedrock respectively, it can be noticed that they are different one from another.

Essentially, these differences are due to two factors: the acceleration on the bedrock $\ddot{y}_b(t)$ is filtered by the soil gradually while it propagates towards the surface $\ddot{y}_0(t)$ (local amplification); once at the surface, the seismic wave is reflected into the soil $\ddot{y}_1(t)$ again, if it runs into a medium stiffer than the soil itself (amplification by radiation).

The latter is due to dynamic soil-structure interaction. In particular, two types of interaction, kinematic and inertial can be distinguished. The former is important when the foundation stiffness are very different from the soil stiffness: moreover they increase with foundation dimensions. On the contrary if the mass of the structure is not zero the initial motion of the structure creates some inertial forces which are transmitted into the soil through the foundation. Essentially, studying an embedded structure in a correct way means considering firstly the different values of accelerations to which structures are subjected, and expecially those values resulting from dissipated energy from the structure into surrounding soil during its oscillations.

In order to evaluate the mistakes of a typical design through calculation codes on sale several cases of embedded strucures have been analyzed. The involved parameters are: the structure dimensions, the embedment depth, the foundation typologies, the soil properties and the deformable layer heigth. Having considered different cases, the authors do not intend to propose a general method, but rather in order to understand what happens in the most frequent soil-structure conditions.

Three different types of soils have been considered with or without earth filling at the back of the structure:

- soft clay
- stiff clay
- dense sand

The dynamic characteristics of clays used in the calculations have been derived from the literature (Pane & Burghignoli, 1988).

For the sand the curves $(G/G_0)/\gamma$ e $(D/D_0)/\gamma$ are from Seed and Idriss (1970). The variation with depth of initial shear modulus G_0 has been obtained from a SPT test relating the N_{SPT} values to the values of G_0 according to the empirical formula proposed by Ohsaki & Iwasaki (1973)

$$G_0 = 120 N_{SPT}^{0.8} \qquad (1)$$

The analyzed situations are eight and are shown in Figure 1.

Each analysis has been performed according to the following calculation procedure:

- study of soil-structure system using the finite element program FLUSH. In this stage, the response spectra (with a

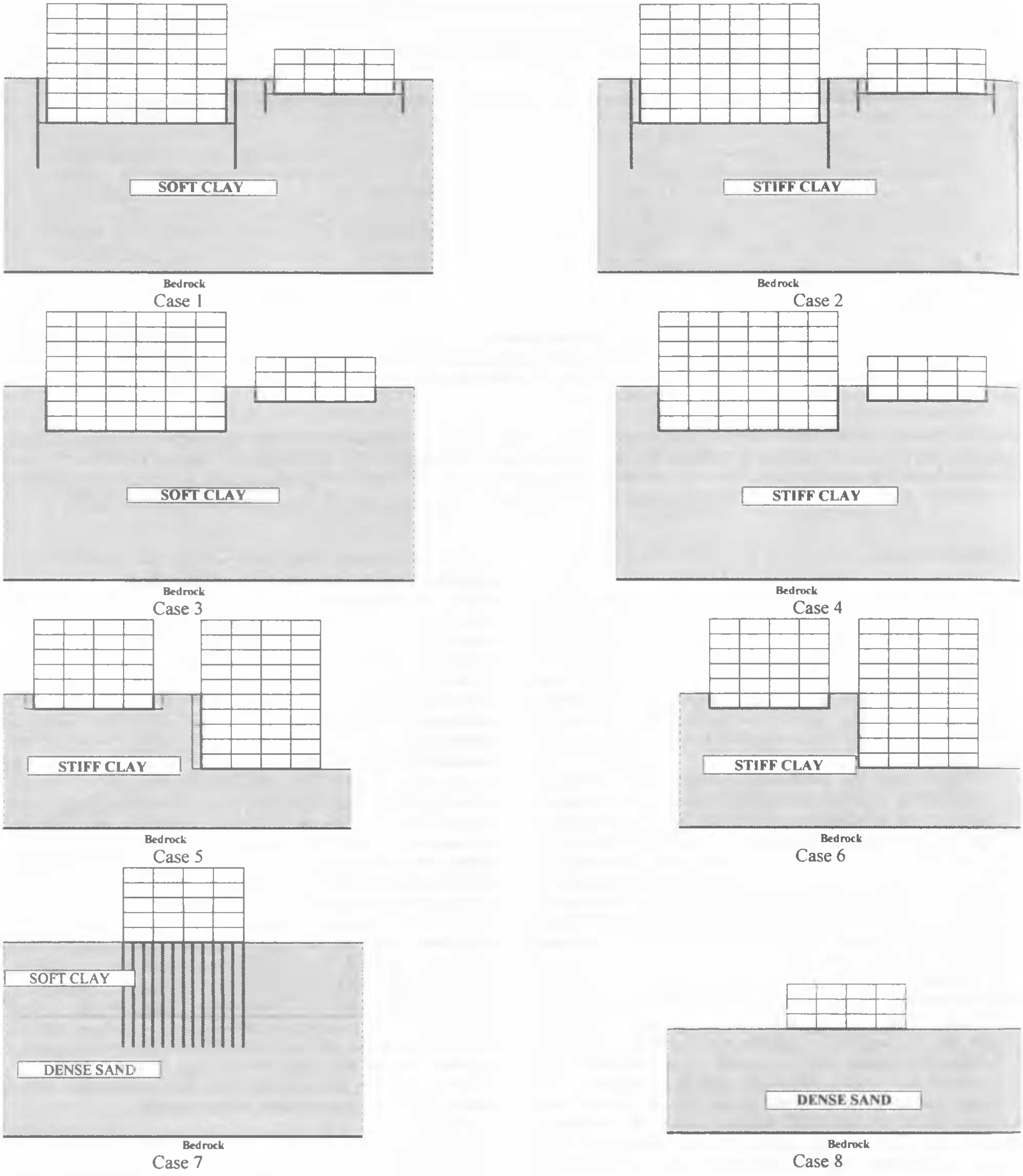

Figure 1. The analyzed situations.

damping of 5%) and the shear stresses in the structural embedded elements have been obtained;

- input of the obtained response spectra in a traditional structural finite elements program (SAP): in this case the shear stresses on the same elements quoted previously have been calculated.

The comparison between the two calculation code results has been made in terms of the total shear stress for each level in the structural embedded elements.

The studies of the proposed examples have underlined some interesting aspects.

For more consistent soils the analysis considering the total system provides smaller stresses than those obtained by SAP, in contrast with what happens for more deformable deposits. This behavior seems to be due to a more containing capacity of the soil, in the first case. For more deformable soils, the soil does not contain the action of the structure, but,on the contrary, it increases the stress level in the structure.

For adjacent structures a remarkable increase in the shear stress has been noticed especially on very consecutive structural elements. This behavior is not observed with a typical analysis using calculation codes SAP.

If the deposit consists of a very deformable soil, the effects derived from local amplification are stronger than those relevant to a very stiff soil. In fact, the amplification greater of the peak acceleration is recorded especially in the most superficial soil layers. Then, in these cases, great differences have been noticed in the stress values according to the response spectrum, one relevant to the free field ground level without structure and to the base of the structure.

For superficial structures or piles foundations the effects of soil-structure interaction are less evident.

3. LUMPED PARAMETERS SYSTEM

It has been demonstrated that from a general point of view the dynamic behavior of a foundation may be represented by a lumped parameters system. For a one degree of freedom system the equation that governs the motion is the following

$$m\ddot{z} + c\dot{z} + kz = Q(t) \qquad (2)$$

where z, $\dot{z}$, $\ddot{z}$ are displacement, velocity and acceleration of mass in the motion's direction, respectively; the coefficients *m*, *c*, *k* are the mass, the damping and the stiffness of the system, *Q(t)* is the external force. The values of these coefficients may be different varying the type of motions that is examined.

The frequency of a dynamic action can be defined as

$$f = \frac{\omega}{2\pi} \qquad (3)$$

on the contrary the natural frequency of the system is

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (4)$$

The maximum displacement of the system is governed by the damping coefficient c which is, generally, defined as the damping ratio D (ratio between c and critical damping c_c)

$$c_c = 2\sqrt{km} \qquad (5)$$

$$D = \frac{c}{c_c} \qquad (6)$$

3.1 *Choice of damping for lumped parameters system*

The dashpot of the lumped parameters system represents the soil damping.

There are two types of damping: one due to the loss of energy which follows the wave propagations near the foundation and one due to the hysteretical and viscous effects. Using viscous dashpots in the lumped parameters system it does not imply that the soil has viscous properties but it is useful only to obtain some simpler mathematical expressions.

3.2 *Damping due to radiation*

In order to evaluate the amount of the damping by radiation for a foundation in a lumped parameters system the theory of the elastic half space can be used.

The typical values of the damping ratio range between 0 and 60% (Whitman & Richart, 1967).

3.3 *Internal damping of the soil*

For soils subjected to a dynamic action the internal damping is due to hysteretical phenomena caused by loading and unloading cycles.

Damping curves for different soils are well known: a typical value for D which is common to sands and clay and thus selected for the SAP analysis is 5%.

3.4 *Choice of mass for an equivalent lumped parameters system*

The mass that should be used in a lumped parameters system consists of foundation block plus the structure mass. At first sight it seems that another mass (effective mass) should be considered to represent the inertia of the soil under the foundation block. Actually, the particles of soil move in different directions with different accelerations. This additional mass is justified only if its value is greater than the value of foundation plus structure. In any case, the simplest choice is to avoid considering the soil effective mass; in fact Richart and Whitman (1967) showed that for vertical oscillations, the lumped parameters system using zero effective mass had displacements similar to those one provided by tests on real foundations.

Table 1. Effective mass and mass moment of inertia of soil (Whitman & Richart, 1967)

Mode of vibration	μ=0	μ=1/4	μ=1/2
Vertical traslation	$0.5\rho r_0^3$	$1.0\rho r_0^3$	$2.0\rho r_0^3$
Horizontal traslation	$0.2\rho r_0^3$	$0.2\rho r_0^3$	$0.1\rho r_0^3$
Rocking	$0.4\rho r_0^5$		
Torsion	$0.3\rho r_0^5$	$0.3\rho r_0^5$	$0.3\rho r_0^5$

3.5 *Choice of stiffness coefficient*

The stiffness coefficient is the most important of three parameters; it is influenced by resonance frequency, by the amplitude of the motion for frequencies far from resonance frequency and for frequency of resonance itself.

Any method to determine the stiffness coefficient should consider the following factors: the partial embedment of the foundation, the dependence on initial conditions of stress and its increases, the distribution of stress in the contact areas and the dependence on shear modulus according to the depth and type of soil.

In Table 2 and Table 3 formulas of stiffness coefficients are provided for translational, rotational and torsional motions for circular and rectangular foundations on an elastic halfspace.

Table 2. Spring coefficients for circular base resting on elastic half-space (Whitman and Richart, 1967)

Motion	Spring coefficient	Reference
Vertical	$K_z = \frac{4Gr_0}{1-\mu}$	Timoschenko e Goodier (1951)
Horizontal	$K_x = \frac{32(1-\mu)Gr_0}{7-8\mu}$	Bycroft (1956)
Rocking	$K_\Phi = \frac{8Gr_0^3}{3(1-\mu)}$	Borowicka (1943)
Torsion	$K_\Theta = \frac{16Gr_0^3}{3}$	Reissner and Sagoci (1944)

Table 3. Spring coefficients for rectangular base resting on elastic half-space (Whitman and Richart, 1967)

Motion	Spring coefficients	Reference
Vertical	$K_z = \frac{G}{1-\mu}\beta_z\sqrt{BL}$	Barkan (1962)
Horizontal	$K_x = 2(1+\mu)G\beta_x\sqrt{BL}$	Barkan (1962)
Rocking	$K_\Phi = \frac{G}{1-\mu}\beta_\Phi BL^2$	Gorbunov and Possadov (1961)

The formulas for a stiffness coefficient for horizontal translational motions have been obtained using a uniform distribution of shear stress on the contact area betwen the foundation and the soil and evaluating the horizontal displacements in this area.

Soil Poisson's coefficient usually varies between 0.35 and 0.50 for dynamic stresses. In any case, uncertainties due to Poisson's coeffiecient cause conparative small mistakes in the determination of stiffness coefficients.

4. EVALUATION OF THE STIFFNESS COEFFICIENT VALIDITY

The calculation procedure used to evaluate the validity of stiffness coefficients to be applied to the structure restraints in the embedded part has been the following:

- calculation of the embedded structure by the calculation code FLUSH and determination of the shear modulus G(z) on the soil side of the soil structure contact area;
- use of the G(z) values through the Barkan's formula for vertical motions for calculating the stiffness K to apply to the structure restraints in the embedded part;
- finite element modelling of the structure and SAP analysis (Figure 2);
- comparison between the shear force on the vertical elements in contact with the soil obtained by FLUSH and by SAP (Figure 3)

Because for dynamic analyses SAP always provides positive values of the shear unlike FLUSH that provides the sign too, it was thought right to report the two both values positive and negative sign.

It results that for the examined cases the Barkan's values introduced in a SAP code provides value of shear force similar to those one obtained by considering the soil-structure system through the code FLUSH: the SAP analysis anyway gives conservative results.

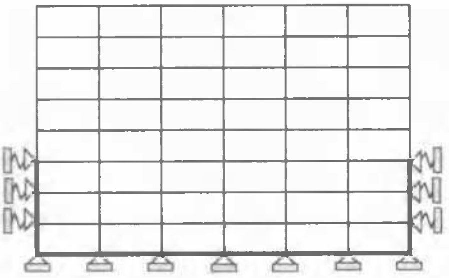

Figure 2. Modelling by SAP

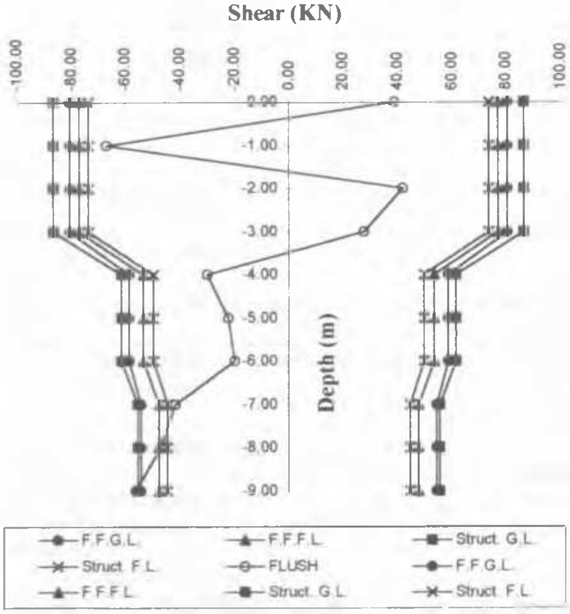

Figure 3. Comparison of shear calculated by SAP and by FLUSH.

The results of all cases cannot be reported. Only those concerning the case 2 will be graphed. In particular, the authors provide the values of stiffness to be applied to restraints as a function of the embedment depth (Figure 4) and the comparison between the values of the shear forces calculated by SAP and those one calculated by FLUSH.

5. CONCLUSIONS

The following preliminary conclusion may be drawn:

- the variables involved in a parametric study of the problem are very numerous: so, at the moment, in order to understand the importance each factor it has been preferable to examin selected particular cases;
- for geometrical configurations and for the type of soil which have been chosen, the values of stiffness obtained by Barkan's formula provide similar results, even if not equal to those ones calculated by considering soil-structure system through FLUSH.

For the present, that does not make the results thus obtained useful to pratical purpose.

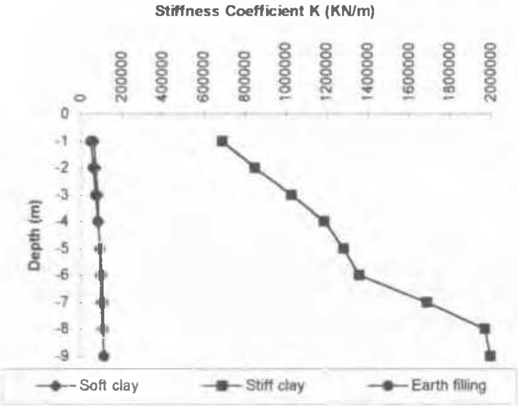

Figure 4. Stiffness values to be applied to the restraints.

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