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On the influence of the embedment of the foundation and the layered media

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ABSTRACT: The main objective of this paper is to contribute to determine the influence of both the embedment of the foundation and the layered media in the seismic response of building structures with prismatic rectangular foundations. A soil-structure interaction model was used for this purpose. A general beam formulation was adopted to represent the physical model of the structure and two lumped parameter models, were adopted to represent the soil and the interaction mechanisms. On the other hand, an equivalent halfspace model was added, that permits taking into account the layered elastic soil in the analysis.

The results obtained show that the embedment of the foundation is a fundamental parameter that cannot be neglected in the analysis because the structure forces could be significantly underestimated. In connection with the layered soil it can be stated that this is not an important factor because the differences with the halfspace results are not significant.

1 INTRODUCTION

The seismic analysis of buildings and other engineering structures is often based on the assumption that the foundation corresponds to a rigid semispace, which is subjected to a horizontal, unidirectional acceleration. Such model constitutes an adequate representation of the physical situation in case of average size structures founded on sound rock. Under such conditions, it has been verified that the free field motion at the rock surface, i.e., the motion that would occur without the building, is barely influenced by its presence. The hypothesis looses its validity when the structure is founded on soil deposits, since the motion at the soil surface, without the building, may be significantly altered by the presence of the structure. The latter, in turn, has its dynamic characteristics -vibration modes and frequencies- modified by the flexibility of the supports. Thus, there is a flux of energy from the soil to the structure, and then back from the structure into the soil, in a process that is loosely known in seismic engineering as soil-structure interaction.

In the specialized literature, many procedures are found to take into account these effects in the analysis, which are summarized by Wolf (1993). Among others, the books of Wolf (1985) and (1988), Richart et al. (1970) can be mentioned, as well as the contributions of Wong and Luco (1985) using impedance functions, Wolf and Somaini (1985) and Wolf and Paronesso (1992) using lumped-parameter models, Viladkar et al. (1992) the direct method and Hayashi and Takahashi (1992) the substructuring technique.

In spite of its importance, it has not been clearly established, when the influence of the embedment of the foundation and the layered media may be expected to be significant, nor the errors that may result from using incorrect values for the soil or foundation parameters. The main objective of this paper is then to contribute to a quantification of the effect of the embedment of the foundation and the layered media on the most important design variables in seismic problems, such as total base shear and overturning moment.

The study is confined to prismatic structures founded on similarly rectangular bases, located at an arbitrary plane under the ground level. The behavior of both soil and structure is assumed linearly elastic. In order to catch a glimpse on the effect of material nonlinearities, the concept of effective damping is resorted to. It is known that the concept is applicable for weak nonlinearities, which should be the case if damage to the system is limited.

2 DESCRIPTION OF THE MODELS

At this point, the structure and soil models used in the analysis, will be briefly described. Basically, this models were presented by Ambrosini (1994) and more details can be consulted in this work.

The physical model of the structure, presented by Ambrosini et al. (1995), is based on a general formulation of beams based on the Vlasov's theory of thin-walled beams, which is modified to include the effects of shear flexibility and rotatory inertia in the stress resultants, as well as variable cross-sectional properties. In addition, a linear viscoelastic constitutive law was incorporated. The load acting is constituted by a seismic loading introduced by a ground acceleration record.

The elements mentioned above lead to a system with three fourth order partial differential equations with three unknowns. Using the Fourier transform to work in the frequency domain, an equivalent system with twelve first order partial differential equations with twelve unknowns, is formed. The scheme described above is known in the literature as 'state variables approach'. Six geometric and six static unknown quantities are selected as components of the state vector v: The displacements ξ and η, the bending rotations ϕ_x and ϕ_y, the normal shear stress resultants Q_x and Q_y, the bending moments M_x and M_y, the torsional rotation θ and its spatial derivative θ', the total torsional moment M_T and the bimoment B.

(1) $$v(z,\omega) = \{\eta, \phi_y, Q_y, M_x, \xi, \phi_x, Q_x, M_y, \theta, \theta', M_T, B\}^T$$

The system is:

(2) $$\frac{\partial v}{\partial z} = Av + q$$

In which A is the system matrix and q the external load vector. In order to facilitate the numerical solution, the real and imaginary parts of the functions are separated, obtaining a final system of 24 first order partial differential equations with 24 unknowns.

After a review of the literature, and in view of the main objective of this work, two lumped-parameter models, based directly or indirectly on homogeneous, isotropic and elastic halfspace theory, were adopted to represent the soil and the interaction mechanisms. One model, presented by

Wolf and Somaini (1986), is used to model rectangular foundations embedded in the halfspace and can represent the coupling between horizontal and flexural vibration modes. The other model, presented by Clough and Penzien (1975), correspond to a circular foundation resting on the halfspace, which is greatly used in the professional practice. These models are formed by a set of masses, spring and dashpots, combined adequately with the purpose of represent the 'exact' solution within a wide range of frequencies and they are illustred in Figure 1, for horizontal and flexural vibration modes.

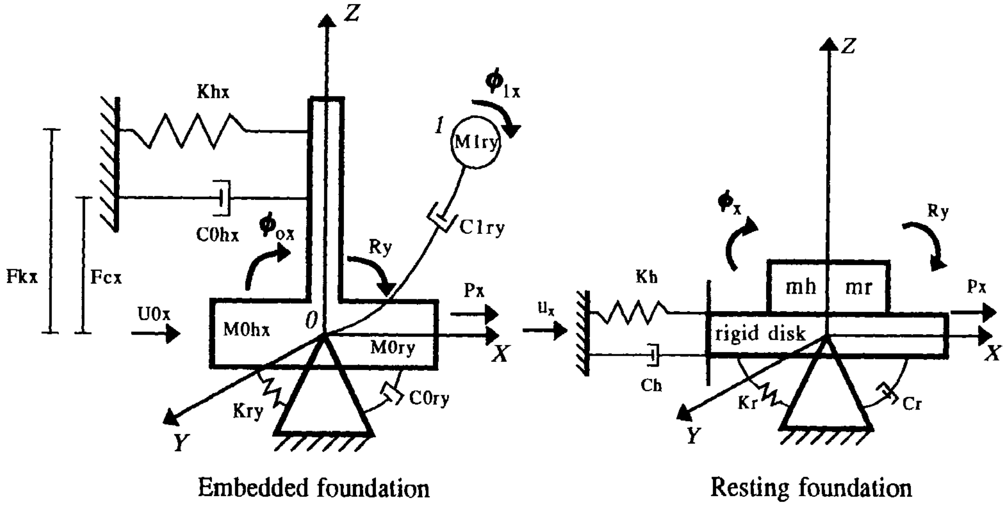

Figure 1: Soil models

The system (2) may be easily integrated using standard numerical procedures, such as the fourth order Runge-Kutta method, the predictor-corrector algorithm or other approaches. In order to solve the two-point value problem encountered, the latter must be transformed into an initial value problem as shown, for example, by Ebner and Billington (1968).

To incorporate the interaction model, described above, the boundary conditions, which for a fixed end are:

(3) $$\xi = \eta = \phi_x = \phi_y = \theta = \theta' = 0$$

must be replaced by motion equations of the soil model, except the condition $\theta' = 0$.

At this point, the soil models used were based, directly or indirectly, on the hypothesis of homogeneous, isotropic and elastic halfspace theory. However, in the situations found in the field, the soil is generally formed by a set of layers with different physical properties, such as the transversal soil moduli G_s or shear wave velocity v_S.

The basic idea of the model presented by Ishida (1985), which is used to take into account this effect, is to replace the layered soil by an equivalent elastic halfspace. The main characteristics of this halfspace are determined with the hypothesis of equal stress distribution in the layered soil and the halfspace. In addition, it must be pointed out that the model corresponds to a circular foundation resting on the halfspace.

3 NUMERICAL ANALYSIS AND RESULTS

The numerical analysis was performed using the program DAYSSI (Ambrosini (1994)) that was developed incorporating the models described above. A set of three structures, defined in Table 1, and three ground acceleration records, defined in Table 2, will be used.

Table 1: Structures used

Building	Description	H^* m	T_1^{**} sec	Reference
B1	Central core building	57.2	0.60	Liaw et al (1978)
B2	Torres del Miramar	55.9	1.03	Wallace et al (1990)
B3	Core and walls building	48.0	0.87	Coull (1973)

* = Total height of the building
** = Fundamental period determined by DAYSSI

Table 2: Ground acceleration records used

Ground Acceleration	Earthquake	Record	Δt^* seg	Duration* seg
A1	Caucete 1977	Córdoba	0.04	10
A2	Viña del Mar 1985	Viña del Mar S20W	0.017	35
A3	Loma Prieta 1989	Santa Cruz	0.02	20

* = Used by DAYSSI

With the purpose of comparing both models of soils, the program DAYSSI was run for several sets of data The results, in terms of maximum base shear stress resultant Q^i_{mb} and bending moment M^i_{mb}, are in Table 3. The model of rectangular foundations embedded presented by Wolf and Somaini (1986) is denoted by M1 and the model of circular foundation resting on the halfspace (Clough and Penzien (1975)) is denoted by M2.

4 DISCUSSION AND CONCLUSIONS

Based on the results obtained above, the following observations and conclusions can be mentioned:

- The model of foundation resting on halfspace overestimate the soil-structure interaction effects due to the neglect of the stiffness of the embedment of the foundation. Obviously the depth of the foundation is a fundamental parameter, and can be seen in Table 3 that for the building E2, with the greater depth (6 m), the differences are greater. The extensive use of the models of foundation resting on the halfspace leads to the wrong conclusions that the soil-structure interaction always produce reduction into the efforts and this reduction is very important. Hence, except in special cases such as offshore platforms, it is recommended the use of models of embedded foundation, otherwise significant and incorrect

Table 3: Influence of embedment of the foundation

Alternative	Q^i_{mb} MN		M^i_{mb} MNm		Differences	
	M1	M2	M1	M2	$\frac{Q_2}{Q_1}$	$\frac{M_2}{M_1}$
B1A1 G_s=35	1.922	1.427	37.580	23.582	0.743	0.628
B2A1 G_s=35	14.749	6.907	274.949	205.863	0.468	0.749
B3A1 G_s=35	12.038	11.761	334.332	195.647	0.977	0.585
B1A3 G_s=35	3.714	3.036	35.297	32.006	0.817	0.907
B2A3 G_s=35	24.488	17.961	528.529	176.646	0.733	0.334
B3A3 G_s=35	24.552	20.498	616.259	274.625	0.835	0.446
B3A1 G_s=85	19.316	11.553	473.257	264.965	0.598	0.560

In connection with the influence of the layered media, two soils with three layer each one, were considered. The characteristic of the soils are summarized in Table 4, and the results obtained with DAYSSI are in Table 5.

Table 4: Characteristics of the soils

Soil	*i*	G_{si}/G_1	z_i/r_0
SOIL1	1	1.0	0.5
	2	1.5	1.5
	3	2.5	3.0
SOIL2	1	1.0	1.0
	2	2.0	2.0
	3	4.0	3.0

Table 5: Influence of layered soil

Alternative	Q^i_{mb} MN			M^i_{mb} MNm		
	Halfspace	SOIL1	SOIL2	Halfspace	SOIL1	SOIL2
B1A1 G_s=35	1.427	1.429	1.373	23.582	28.459	27.052
B2A1 G_s=35	6.907	8.994	7.733	205.863	205.923	217.605
B3A1 G_s=35	11.671	12.244	12.780	195.647	228.896	222.707
B2A2 G_s=90	25.677	27.675	26.319	1026.548	992.211	1011.394
B1A3 G_s=35	3.036	3.269	3.161	32.006	37.802	37.014
B2A3 G_s=35	17.961	20.236	19.555	176.646	247.890	227.100
B3A3 G_s=35	20.498	19.629	20.305	274.625	325.482	301.672

reductions of the efforts will be found.

- In connection with the layered media, analyzing Table 5 it can be concluded that, in case of taking into account the soil-structure interaction in the analysis, the effect of the layered soil can be neglected. This is due to the fact that the average differences, in relation to a halfspace model, are lower than 10 %. This conclusion is coincident with the experimental and theoretical results of Chandrashekhara et al. (1993). On the other hand, the right determination of physical properties of the first layer is very important.

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