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A criterion to assess the relevance of structural flexibility on the seismic response of large buried structures

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ABSTRACT

This paper analyzes the requirements of the models needed to estimate the seismic motions observed along large cylindrical buried structures by performing a parametric analysis of the problem using two different models: one in which the buried structure is considered as perfectly rigid, and another one in which its actual structural flexibility is taken into account. The study is performed using a Beam-on-Dynamic-Winkler-Foundation approach, and the models are previously verified by comparison against results obtained for the problem at hand using a more rigorous 3D multidomain boundary element model. The results obtained by comparison of the seismic responses estimated by both models are used to build and propose a specific criterion that can be used to elucidate under which circumstances is it possible to neglect the structural flexibility. It is found that, contrary to what is commonly assumed, the structural slenderness ratio alone cannot be used, in general, to predict the validity of the rigid structure approach: embedment lengths, soil stiffness, depth of interest and natural period of study are, also, key parameters that need to be taken into account. A close-form criterion, is proposed in table form taking all such parameters into account.

1. Introduction

Assessing the motions arising at different points within buried structures due to the action of incoming seismic waves may be needed when such structures are due to house sensitive equipment such as instruments, turbines, pumps, etc. In many occasions, the systems under study are big massive structures. Therefore, when setting up a model for studying these motions of seismic origin within the structure, one aspect to consider is whether it is really needed to take into account its actual structural flexibility or, on the contrary, a perfectly rigid representation of it is enough, mainly in cases of stout, non-slender configurations. It might be tempting to consider those large non-slender structures as perfectly rigid in relationship with the surrounding soil. The kinematic response of an actual structure of that kind is studied for instance in Vega et al. [1], where differences between rigid and flexible approaches are quantified and, even though the structure was non-slender and, apparently, very rigid, the rigid and flexible models provided results with important discrepancies, observation which provided motivation for the present piece of research.

With a few exceptions related to the impedance problem (see e.g. Saitoh and Watanabe [2]), the available literature on the topic does not include proposals of well-founded general criteria for making this kind of decision. For this reason, this paper contributes to this issue by presenting a criterion that can be used for practical purposes by structural and geotechnical engineers to establish if a structure under seismic excitation can be considered as a rigid body or, on the contrary, its real flexibility can not be neglected. The criterion is based on a parametric analysis that studies the errors between the motions of seismic origin provided by two models in which the buried structure is considered from both points of view (perfectly rigid or with its actual flexibility).

In this respect, this parametric analysis is performed using Beam-on-Dynamic-Winkler-Foundation (BDWF) approaches, previously verified by comparison against results obtained for the problem at hand using a more rigorous 3D multidomain boundary element model [3,4]. These BDWF approaches follow the line of previous works related to the dynamic analysis of piles (Flores-Berrones and Whitman [5]; Gazetas and Dobry [6]; Kavvadas and Gazetas [7] or Mylonakis [8]) or rigid foundations (Gerolymos and Gazetas [9] and Varun et al. [10]). These are very well known models in which the structure is modeled as a beam, and the surrounding soil is represented through unconnected springs and dashpots distributed along its buried length. One of the main differences between such models lies in the way to establish the properties of those springs and dashpots. In this sense, most BDWF models found in the literature could be classified in the following two groups: a) models that adjust those properties based on numerical models that

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take into account the actual nature of the problem (see e.g. Makris and Gazetas [11]; Makris [12] or Kavvadas and Gazetas [7]) and b) models that propose those values based on theoretical wave propagation approaches as closed-form functions in the frequency domain, as in the work of Baranov-Novak [13] who develop an elastodynamic plain-–strain approach, assuming that the soil is divided in an infinite number of independent thin horizontal slices, and provide a simplified formulation of stress field in soil. The classic expression provided by Novak et al. [14], that are also part of this second group, will be the one used in the models presented herein. Finally, we can not fail to mention the existence of other more evolved analytic models formulated as solutions of the three–dimensional problem (Tajimi [15]). In this sense, the works of Mylonakis [16], Anoyatis and Lemnitzer [17] or Bahrami and Nikraz [18] are very interesting.

The specific problem addressed in this work is one corresponding to a cylindrical structure (hollow or solid) embedded in a half–space. The study has been carried out using a wide range of properties for both, structure and soil. Taking into account the embedded length of the structures included in this analysis, the hypothesis of a homogeneous half–space to model the ground may be unrealistic in some practical problems. Thus, this work should be understood as a first approach to the problem that has the purpose of provide a simple engineering criterion in order to be able to discern under which circumstances it is realistic to assume a rigid seismic behaviour of the structure. In that case, it will be possible the use of, e.g., calibrated Winkler models in the line of the mentioned Gerolymos and Gazetas [9] or Varun et al. [10], or well established response functions for perfectly rigid structures (such as, for instance, those provided by the classic works of Elsabee et al. [19] or Kausel et al. [20] and more recently Conti et al. [21]), without the need of using more rigorous and sophisticated models, in the line of continuum–base approaches as the ones used, for example, for the analysis of the seismic response of tunnels [22–26], or for the seismic analysis of real pumping structures, as the aforementioned Vega et al. [1].

This paper is structured as follows. After the introduction, the problem at hand is presented in Section 2, as well as the key aspects and parameters that affect the seismic response of the system. The methodology and the BDWF models formulation, are explained in Section 3. Section 4 includes validation results of the BDWF models against a more rigorous 3D multidomain boundary element model. Finally, results and the criterion proposed are included in Section 5, followed by conclusions in Section 6.

2. Problem description

In order to look into the influence of the structural flexibility on the seismic response of large buried structures, the results of two different models, that consider the structure either as a flexible solid or as an infinitely rigid body, are compared and analyzed (see Fig. 1).

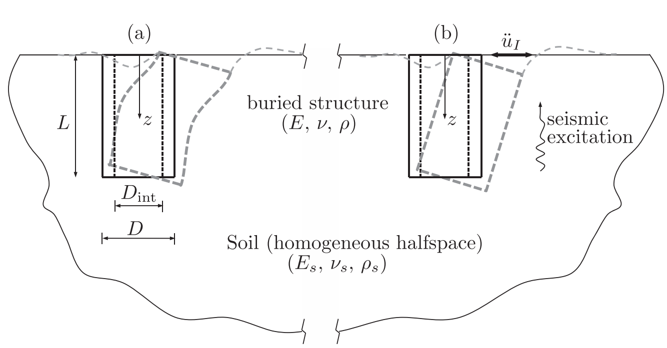

Fig. 1. Problem description. Influence of the structural flexibility on the seismic response of large structures buried in homogeneous soil. (a) Deformable solid approach, (b) Rigid body approach.

The structure is idealized geometrically as a completely buried solid cylinder of diameter D or a cylindrical shell with constant outer and inner diameters D and $D_{\rm int}$, and length L. The type of section will be specified by a parameter $\delta = D_{\rm int}/D$ defining a hollow $(0 < \delta < 1)$ or solid $(\delta = 0)$ cross section. Welded contact conditions are assumed at the interface between the structure and the surrounding soil, which is assumed to be a isotropic and homogenous half–space with Poisson's ratio ν_s, density ρ_s and shear wave velocity V_s. The system, for which a linear–elastic behaviour is assumed, is subjected to vertically–incident shear waves.

The properties of the soil, the flexibility of the structure and the variability of the seismic incident field along the buried length of the structure are three key aspects that affect the seismic response of the system. In this study, the flexibility of the structure depends on the type of cross section (solid or hollow), the material properties, and the slenderness ratio. The variability of the incident field, on the other hand, is related to the soil wave velocity (or soil stiffness) and the characteristics of the seismic waves. Thus, the study will be performed varying the following four parameters of the problem: a) Type of structural cross section: hollow $(\delta = 0.85)$ or solid $(\delta = 0.00)$; b) Slenderness ratio of the structure $(L/D = 2 - 10)$; c) Soil shear wave velocity $(V_s = 200 - 1000\ \mathrm{m/s^2})$ and; d) Embedment lengths of the structure $(L = 20,\ 40,\ 60\ \text{and}\ 80\ \mathrm{m})$.

The rest of properties, considered as non–relevant for the aim of this study, are kept constant. The structure is assumed to be made in concrete, characterized by its Young's modulus $E = 2.76 \cdot 10^{10}\ \mathrm{N/m^2}$, Poisson's ratio $\nu = 0.2$ and density $\rho = 2500\ \mathrm{kg/m^3}$. On the other hand, Poisson's ratio $\nu_s = 0.3$ and density $\rho_s = 1570\ \mathrm{kg/m^3}$ are kept constant for the soil. With all this, the resultant relationships between structural concrete and soil stiffnesses at the limits of the scopes defining each ground type are also presented in Table 1. A wide range of values for the ratio E/E_s is covered, going from below 3 for ground type A to over 200 for ground type D.

The range of soil properties given above covers Eurocode–8 [27] ground types A, B, C and D. The vertically–incident SH wavefield that impinges the system generates free–field ground surface accelerations compatible with the type 1 design elastic horizontal ground motion acceleration response spectra also provided by Eurocode–8 [27] for each ground type. Therefore, different synthetic accelerograms, one for each ground type, are used as excitation motion according to the shear wave velocity defining the soil in each configuration.

The response will be studied in terms of accelerations measured at five points with different depths along the structure, $z/L = 0.00$ (top of the structure), 0.25, 0.50, 0.75 and 1.00 (bottom of the structure). The main objective is presenting a criterion to decide when is the hypothesis of infinite rigidity valid for a large buried structure. Therefore, the results need to be synthesized and presented in terms of the deviation of the response obtained from the rigid body assumption with respect to a flexible structure model. This deviation is defined as differences between the horizontal acceleration elastic response spectra characterizing the horizontal motions at different depths. These differences will be quantified in terms of average

Table 1
Relationships between structural concrete and soil stiffnesses at the limits of the scopes defining each ground type.

Ground type	V_s (m/s)	E_s (N/m ^{2})	E/E_s
A	1500	$1.024 \cdot 10^{10}$	~ 3
	800	$2.912 \cdot 10^{9}$	~ 10
B	800	$2.912 \cdot 10^{9}$	~ 10
	360	$5.897 \cdot 10^{8}$	~ 50
C	360	$5.897 \cdot 10^{8}$	~ 50
	180	$1.474 \cdot 10^{8}$	~ 200
D	<180	$<1.474 \cdot 10^{8}$	>200