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Dynamic response of a geotechnical rigid model container with absorbing boundaries

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ABSTRACT

One of the major challenges encountered in earthquake geotechnical physical modelling is to determine the effects induced by the artificial boundaries of the soil container on the dynamic response of the soil deposit. Over the past years, the use of absorbing material for minimising boundaries effects has become an increasing alternative solution, yet little systematic research has been carried out to quantify the dynamic performance of the absorbing material and the amount of energy dissipated by it. This paper aims to examine the effects induced by the absorbing material on the dynamic response of the soil, and estimate the amount of energy reduced by the absorbing boundaries. The absorbent material consisted of panels made of commercially available foams, which were placed on both inner sides of end-walls of the soil container. These walls are perpendicular to the shaking direction. Three types of foam with different mechanical properties were used in this study. The results were obtained from tests carried out using a shaking table and Redhill 110 sand for the soil deposit. It was found that a considerably amount of energy was dissipated, in particular within the frequency range close to the resonance of the soil deposit. This feature suggests that the presence of foams provides a significant influence to the dynamic response of the soil. The energy absorbed by the boundaries was also quantified from integrals of the Power Spectral Density of the accelerations. It was found that the absorbed energy ranged between a minimum of 41% to a maximum of 92% of the input levels, depending mainly on the foam used in the test. The effects provided by the acceleration levels and depth at which the energy was evaluated were practically negligible. Finally, practical guidelines for the selection of the absorbing material are provided.

1. Introduction

Geotechnical physical modelling is an established method to investigate seismic soil–structure interaction problems and seismic response of soil deposits. Whether the tests are carried out using shaking tables at normal gravity or geotechnical centrifuges, the soil stratum needs to be confined in a container with relatively small dimensions. A significant challenge encountered when performing geotechnical physical modelling consists of minimising the boundary effects created by the model confinement, therefore to simulate free-field seismic conditions.

Over the past decade, researchers have developed different types of model container to minimise the effects introduced by the artificial boundaries. One example is represented by flexible soil containers. Assuming that the soil layer and the adjacent end-walls behaves as an assembly of equivalent shear beams, the container is designed to mimic the shear beam response. This can be achieved by matching the shear stiffness between the model container and the soil it includes [13,39,34,35,15]. This type of container is commonly made by aluminium rings spaced by soft rubber layers which provide the desired lateral stiffness. However, due to the high non-linearity of the soil, particularly at large strains, the matching between the soil and container stiffness is possible only for a predefined range of strains, and it is generally not suitable for soil subjected to large deformations, such as those measured during soil liquefaction.

A new type of model container with flexible boundaries was first introduced by Whitman et al. [37] to study liquefaction phenomena. This new container concept has been subsequently used by many research teams [20,26]. The design principle of the flexible laminar box consists of minimising the lateral stiffness of the container to match the one of the liquefied soil column. This can be achieved by using a stack of aluminium rings supported

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individually with bearings, which permit a relative movement between the rings with minimal frictions. Several studies have confirmed that the laminar container is compatible with the large soil deformation expected during the simulation of earthquake-induced liquefaction. However, the laminar box may not replicate the actual boundary conditions when the soil column is not fully liquefied or is subjected to low strain levels.

The model container with rigid ends has been used by several research groups in both centrifuge [38,1,30] and 1-g shaking table tests [16,27]. Numerical studies conducted by Whitman and Lambe [38] and Fishman et al. [16] have demonstrated that the effects caused by the rigid boundaries are significant up to a distance of 1.5–2.0 times the depth of the soil stratum. To increase the volume of soil subjected to the free-field condition, soft material can be placed on the inner sides of the model container, which in turns diminish the reflection of body waves from the boundaries and also the P-wave generation.

Duxseal material (a putty-like, pipe sealant rubber mixture compound) has been extensively used in the past decade for centrifuge modelling [12,9,10,31,33] due to its high damping and relatively high stiffness required for high stress level attained during the spin-up process. Cilingir and Madabhushi [10] reported that Duxseal can absorb up to 65% of incident P-waves. In experimental modelling conducted on a shaking table at normal gravity, the relatively low stress at which the model is subjected, makes Duxseal material too stiff and therefore it is generally replaced by softer material such as conventional foam [18,4].

In the recent years, due to the relatively simple design and low cost of the material, the use of absorbing boundary for geotechnical containers has become an increasing alternative solution for minimising generation and reflection of body waves from the artificial boundaries. Despite this, limited systematic experimental studies have been carried out to investigate the effects induced by the absorbing material on the dynamic response of the soil deposit. This paper aims to examine the effects induced by the absorbing material on the dynamic response of the soil and also attempts to estimate the amount of energy reduced by the absorbing boundaries. The absorbent material consisted of panels made of commercially available foams, which were placed on both inner sides of the end-walls (i.e. walls perpendicular to the shaking) of the soil container. Specifically, three types of foam with different mechanical properties were used in the study. The results were obtained from high-quality tests carried out in a shaking table using Redhill 110 sand for the soil deposit. It was found that a considerably amount of energy was dissipated particularly in the frequency range close to the resonance frequency of the soil deposit, which suggest that the presence of foams significantly influenced the dynamic response of the soil. Finally, the energy absorbed by the boundaries was quantified by means of frequency integral of the Power Spectral Density of the acceleration time histories. It was found that the absorbed energy ranged from a minimum of 41% to a maximum of 92%, depending principally on the foam used in the test. Based on the analysis carried out in this study, it was concluded that the effects of the acceleration level applied to the container on the amount of energy dissipated by the boundaries was practically negligible.

2. Soil prototype and wave propagation model

The vast majority of research activities in earthquake engineering are based on the simulation of an idealised infinite lateral extent soil stratum that overlays the bedrock, which is shaken at its base (see Fig. 1). It is commonly assumed that the input motion is one-dimensional and its energy is transmitted in the form of pure shear waves propagating vertically within the soil medium [39]. The shaking causes shear stresses, τ_{xz}, in both horizontal and vertical planes, whereas the horizontal and vertical stresses, σ_x and σ_z, remain constant. The state of stress for a soil layer subjected to a horizontal shaking having acceleration $a_h = k_x \times g$ can be derived as follows [21]:

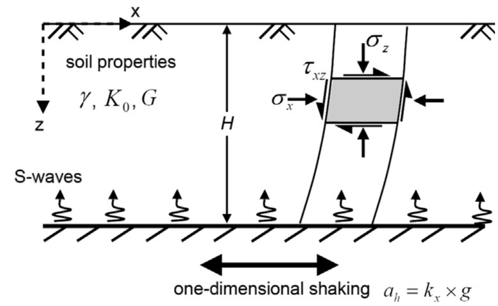

Fig. 1. Shear-beam idealisation of infinite lateral extent stratum overlying a bedrock subjected to one-dimensional shaking.

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} = k_x \times \gamma \tag{1}$$

where k_x is the coefficient of horizontal acceleration, g is the gravity acceleration, γ and K_0 denote the unit weight and coefficient of earth pressure at rest, respectively.

The solution in terms of dynamic free-field stresses can be expressed as [23]:

$$\begin{cases} \sigma_x(z) = K_0 \times \gamma \times z \\ \tau_{xz}(z) = k_x \times \gamma \times z \end{cases} \tag{2}$$

From Eq. (1), it may be observed that the dynamic state of stress is given by the static free-field horizontal stress, σ_x and the shear stress, τ_{xz}, introduced by the horizontal shaking. Assuming a linear stress–strain relationship, the mode shape of the soil column having a depth H is given by the parabolic equation expressed as follows:

$$u(z) = k_x \frac{\gamma \times (H^2 - z^2)}{2 \times G} \tag{3}$$

The mode shape function given in (3), corresponds to the so-called elastic shear beam idealisation. This assumes that the soil column undergoes a simple shear deformation with the rotation of the vertical planes while the horizontal planes remain horizontal.

However, in the model test, the deformation of the soil medium is restricted by the artificial boundaries. Therefore, the actual mode shape may be significantly different from the one related to the shear beam idealisation. Moreover, during the shaking, the soil near the boundaries may undergo compression and extension deformations causing the generation of P-waves.

In an infinite elastic medium two types of body waves may propagate, compression (P-waves) and shear waves (S-waves). Shear waves can be decomposed into two normal polarisation components, i.e. SV-wave, which are polarized in the vertical planes and SH-wave, which are polarized in the horizontal planes. The wave equation for the one-dimensional case that describes the propagation of body waves within an elastic isotropic medium is given by [22]:

$$\rho(x)\frac{\partial^2 u}{\partial t^2} = \frac{\partial}{\partial x}\left[(\lambda + 2G)\frac{\partial u}{\partial x}\right] \tag{4}$$

where $u = u(x,t)$ is the longitudinal displacement in the x-direction due to compression waves or transverse displacement perpendicular to the x-direction due to shear waves. $\lambda(x)$ and $G(x)$ are the Lamé's constants (G is commonly called shear modulus of the medium), which, for an isotropic material, may be related to the