Shaking table tests on rigid soil container with absorbing boundaries

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SUMMARY:
An important consideration in laboratory scale dynamic soil structure interaction study is to replicate the semi-infinite boundary condition in the scaled soil container. This is usually done by using a rather expensive arrangement of the side walls of the box. In this paper, a simplified economic layout is proposed whereby soft absorbing energy materials are used at the end- walls of rigid soil container. The physical model is designed to replicate an idealised stratum of soil subjected to one-dimensional shaking applied to the bedrock. In order to minimize the reflection and generation of *P* waves from the artificial boundaries, absorbing materials were placed at the end-walls. Experimental results obtained from a series of tests conducted using the shaking table available at the *Bristol Laboratory for Advanced Dynamics Engineering* (BLADE) are presented and discussed.

Keywords: shaking table, model tests, absorbing boundary, waves propagation, conventional foam

1. INTRODUCTION

Physical modelling of scaled models is an established method for understanding failure mechanisms and verifying design hypothesis in earthquake geotechnical engineering practice. One of the requirements of physical modelling for these classes of problems is the replication of semi-infinite extent of the ground in a finite dimension model soil container. Soil strata within the ground or underneath a prototype structure have infinite lateral extent while a model test will have a finite size. The challenge is therefore to replicate the boundary conditions of a ground in a container with finite dimensions. Differently from the real scenario, the artificial boundary conditions introduced by the container may reflect and generate *P* waves, which results in a distortion of the free-field conditions. Therefore, the design of the soil container should be carried out in such a way to replicate as close as practicable the stress-strain condition of an infinite lateral extent and finite depth soil profile. Before presenting the main requirements that should be satisfied during the design of a soil container, the stress field that characterise a semi-infinite extent of soil layer is illustrated. Finally, typical experimental results, which were obtained from a series of tests carried out using a container with absorbing boundaries, are presented and discussed.

1.1 Stress field within the soil before and during 1-dimensional shaking

1.1.1 Before the shaking

In the geostatic condition the vertical and horizontal planes are principal stress planes and the normal stresses acting on them are principal stresses. The stress field at any point in a given plane in a mass of the soil can be represented by normal and shear stresses. The effective vertical σ'_v and horizontal σ'_h stresses are given by Eqn. 1.1 and Eqn. 1.2:

$$\sigma'_v = \gamma z \tag{1.1}$$

$$\sigma'_h = K_0 \sigma'_v \tag{1.2}$$

where γ and K_0 are the unit weight of the soil and the coefficient of lateral earth pressure at rest respectively.

1.1.2 During 1-dimensional shaking

As shown in Fig. 1.1, with the start of the horizontal shaking, shear waves (indicated by S-waves in Fig. 1.1) propagate vertically upward within the soil.

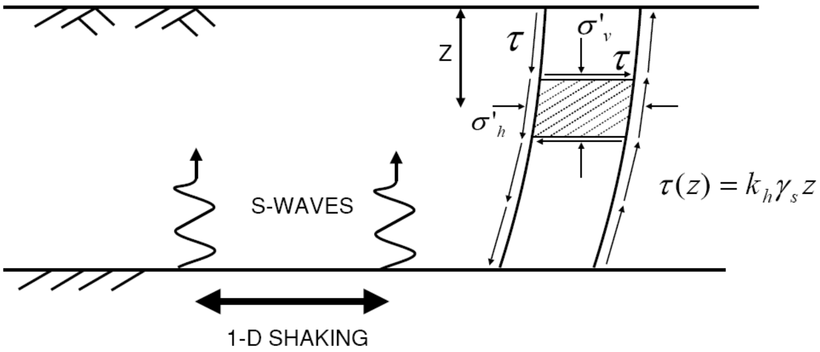


Figure 1.1 Soil layer of infinite lateral extent and finite depth subjected to a base shaking at its bedrock

Normal stresses remain constant while shear stresses in both vertical and horizontal planes increases. The shear stress, τ, induced by the horizontal shaking, at a depth z, may be estimated by Eqn. 1.3.

$$\tau(z) = k_h \gamma z \tag{1.3}$$

where k_h represents the coefficient of horizontal acceleration.

2. REQUIREMENTS OF SOIL MODEL CONTAINER

This section describes main requirements for designing a soil model container for one-dimensional shaking tests. A comprehensive review of the different types of soil model containers available is given by Bhattacharya et al (2011).

2.1. Stress similarity

As already mentioned in the previous section, one-dimensional horizontal shakings generate shear stresses in both vertical and horizontal planes. If the container end walls are frictionless, vertical stresses cannot develop and the stress field near the boundaries will be different from that of the prototype. However, if the model to be tested is placed in centre of the box and at a considerably large distance from the end-walls, such effects may be assumed to be minimal. The evaluation of the distance beyond which the stress field is not affected by the boundaries is complex and requires detailed experimental or numerical analysis. As shown in Fig. 2.1, during shaking, the mass of the soil, W, generates an inertia force, which can be represented as a horizontal load acting at the centre of inertia of the soil layer. This force is given by Eqn. 2.1.

$$F_{soil} = k_h W \tag{2.1}$$

From Fig. 2.1 it can be observed that, for the particular case considered here, the inertia force of the soil generates a clockwise overturning moment. For the stability of the system this overturning moment must be balanced by the shear stresses acting on the vertical plane. Therefore in absence of adequate friction between the end-walls and the adjacent soil, the shear stresses may not be capable of balancing the overturning moment.

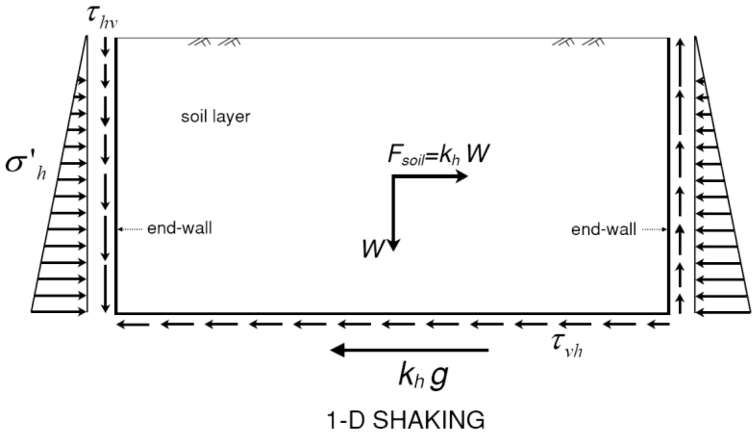


Figure 2.1 Schematic representations of shear and normal stresses generated within the soil layer due to the inertia of the soil, adapted from Zeng and Schofield (1996)

2.2. Propagation of input motion to the soil layer

An important feature of the soil container is represented by the fact that the shaking applied to the base of the container should be transferred to the upper layer of the soil. This condition may be accomplished by the use of a rough base, which enables the generation of shear stresses in the horizontal plane (i.e. at the interface between the soil and the base of the container).

2.3. Strain similarity

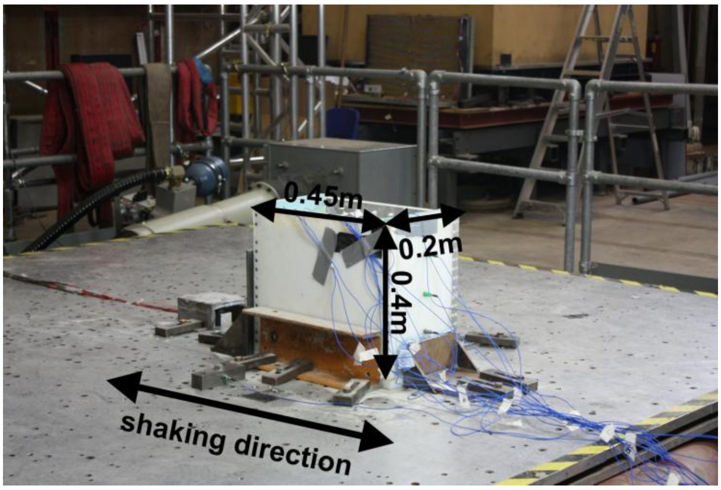
The displacement profile of the soil induced by the shaking has to satisfy the condition that at a particular depth the displacement is constant. In other words, the horizontal cross sections must remain horizontal. Moreover, the interaction between end-walls and soil has to be kept minimum in order to avoid generation of *P* waves from the boundaries. In the model container, the finite dimension of its width (the dimension orthogonal to the shaking) may cause an alteration of the plane-strain conditions. For one-dimensional shaking tests, this may be avoided by making the side walls smooth.

2.4. *P* waves generation and reflection problems

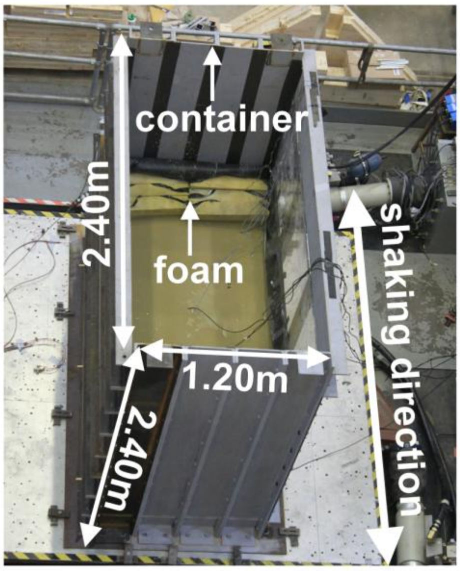
During the one-dimensional shaking, as the *S* waves will propagate through the soil layer, the soil next to the boundaries may undergo under compression and extension causing the generation of *P* waves. As a result, the actual response of the model will be affected by the interaction between *P* and *S* waves. Therefore the effects due to the reflection of the *P* waves from the artificial boundaries should be also taken into account during the analysis of the system response. In an infinitely extended soil layer this phenomenon is absent since there are no boundaries and the energy of the waves diminishes with distance. The attenuation of the energy may be explained considering two different mechanisms: The first mechanism is the friction generated by the sliding of the grain particles which converts part of the elastic energy to heat. This dissipation may be considered as function of the hysteretic damping of the soil. The second mechanism is due to the radiation damping which is related to the geometry of the propagation of the waves. As waves propagate, the energy will spread to a greater volume of soil and this is also known as geometric attenuation which can occur even in absence of damping. Further details can be found in Kramer (1996).

3. MODEL TESTS

A series of tests were carried out using the shaking table facility of the *Bristol Laboratory for Advanced Dynamics Engineering* (BLADE) at the University of Bristol. The shaking table consist of a 3 m x 3 m cast aluminium platform that is controlled by 8 hydraulic actuators (4 in the horizontal and 4 in vertical direction), which allow six-degrees of freedom motion. Each actuator has a dynamic capacity of 70 kN and has a maximum stroke of 300 mm, permitting to apply a maximum acceleration of 1.6g and 1.2g in the horizontal and vertical direction respectively. In this study, all tests were carried out shaking the table in one direction only. The physical models considered in this study is shown in Fig. 3.1a, and it consisted in a rigid soil container with dimensions of 0.450m length, 0.4m height and 0.2m width. Although not considered in this paper, the results obtained from these tests were then validated through a series of tests using a larger soil container with external dimensions of 2.4m length, 2.4m height and 1.2 width (see Fig. 3.1b).



(a)



(b)

Figure 3.1 (a) Small soil container considered in this study (b) larger soil container used for the validation of the results

These tests aim to investigate the behaviour of the absorbing material having different thicknesses and under different types of input motions (i.e. white noise, sine wave etc.). A schematic layout of the soil container and the instrumentation used in the tests is illustrated in Fig. 3.2. Red Hill 110 sand was used for this study. The main indexed properties are listed in Table 3.1.

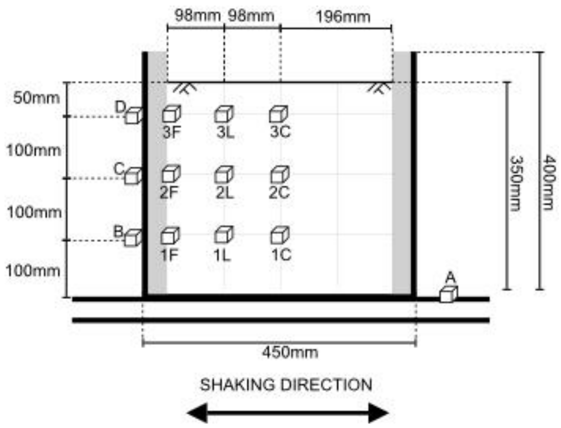


Figure 3.2 Schematic of soil container and instrumentation layout of the small soil container used for the parametric experimental investigation

Table 3.1. Indexed properties of Red Hill 110 sand.

Specific gravity, Gs	Minimum void ratio, e_{min}	Maximum void ratio,e_{max}
2.65	0.608	1.035

The soil layers were dry pluviated at a constant height in order to achieve a homogenous density within the soil layer.

3.1 Absorbing material

In order to reduce the reflection of waves from the rigid boundaries, soft material consisted of conventional foam, were placed at both internal sides of the end-walls. Similar soft material has been already used by colleagues studying liquefaction phenomena (Dash 2010 and Ha et al., 2011). A different material, so called duxseal, has been considered in the past (Coe et al., 1985), with the aim to reduce the energy and waves reflection from the end-walls. The foam was cut using a hot wire in sheet of different thicknesses. Then each sheet was glued on the inner side of the end-walls. In order to measure the dynamic behaviour of the foam itself, a series of accelerometers were glued on the foam's surface at different locations as shown in Fig. 3.3. The mechanical properties of the foam used in this study are listed in Table 3.2

Table 3.2. Mechanical properties of the conventional foam used in the tests.

Density, ρ	Young's Modulus, E	Poisson's ration, ν
270 kg/m^3	250 kPa	0.3

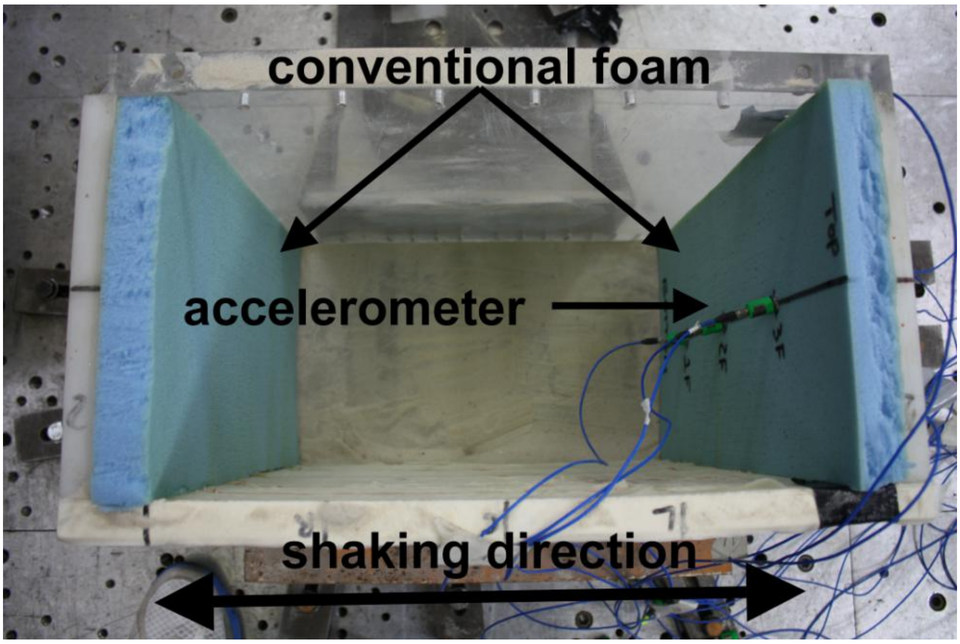


Figure 3.3 Soft material, namely conventional foam applied at both end-walls of small soil container

4. TYPICAL RESULS

This section describes typical results obtained from the experimental investigation carried out on the small model container. The results are expressed in terms of coherence versus frequency. The coherence is a measure of the correlation between two time series functions, at a given frequency. Mathematically, coherence (C_{SA}) at a given frequency f is defined by Eqn. 4.1, where P_{SS} is the Power Spectral Density of input signal, P_{AA} is the Power Spectral Density of output signal and P_{SA} is the Cross Power Spectral Density of two signals.

$$C_{SA}(f) = \frac{|P_{SA}(f)|^2}{P_{SS}(f)P_{AA}(f)} \tag{4.1}$$

In this study the coherence function was calculated in order to evaluate the amount of energy absorbed by the soft boundaries. Clearly, a lower value of coherence suggests that the two signals are not well correlated because a certain amount of energy has been taken by the absorbing boundaries. Fig. 4.1 shows the coherence function estimated considering as input signal the data recorded by the accelerometer placed on the outside wall of the container and, as output, the data recorded by the accelerometer placed on the inner side of the foam (or inner side of the wall for the case in which the foam was not used). For these results, the coherence was estimated when the soil container was subjected to a random broadband white noise with frequency ranging from 1Hz to 100Hz. As it may be observed from Fig. 4.1, the foam induced a considerably reduction of the coherence values, which may be caused by a higher dissipation of energy. Better results, in terms of energy absorption, are achieved using a thicker layer of foam (in this study two different thickness were considered, namely 1.5cm and 3cm) as demonstrated by the results plotted in Fig.4.1

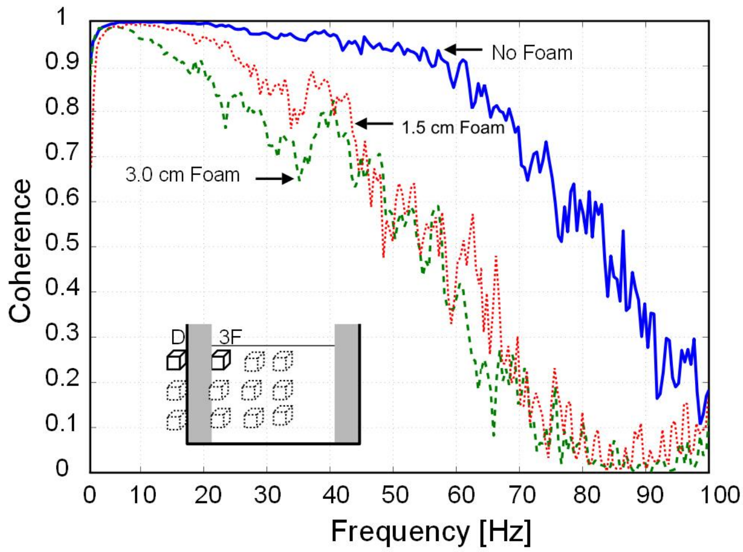


Figure 4.1 Coherence between external accelerometer D and 3F estimated considering white noise as input motion

The performance of the foam at different depths is illustrated by the coherence values plotted in Fig.4.2. The plot clearly shows that the amount of energy dissipated (which is indicated by a reduction in coherence) is much higher at a shallow depth than at deeper depths. This result may be explained by considering that at higher depths the soft material is compressed more and therefore its absorbing properties are consequently reduced.

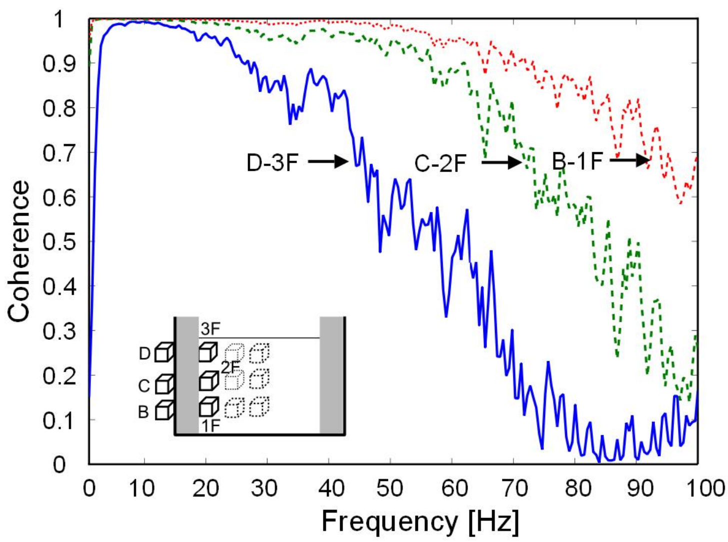


Figure 4.2 Coherence between external accelerometers and internal accelerometers placed on the foam (or inner end-wall when no foam was considered) for different depths, considering white noise as input motion

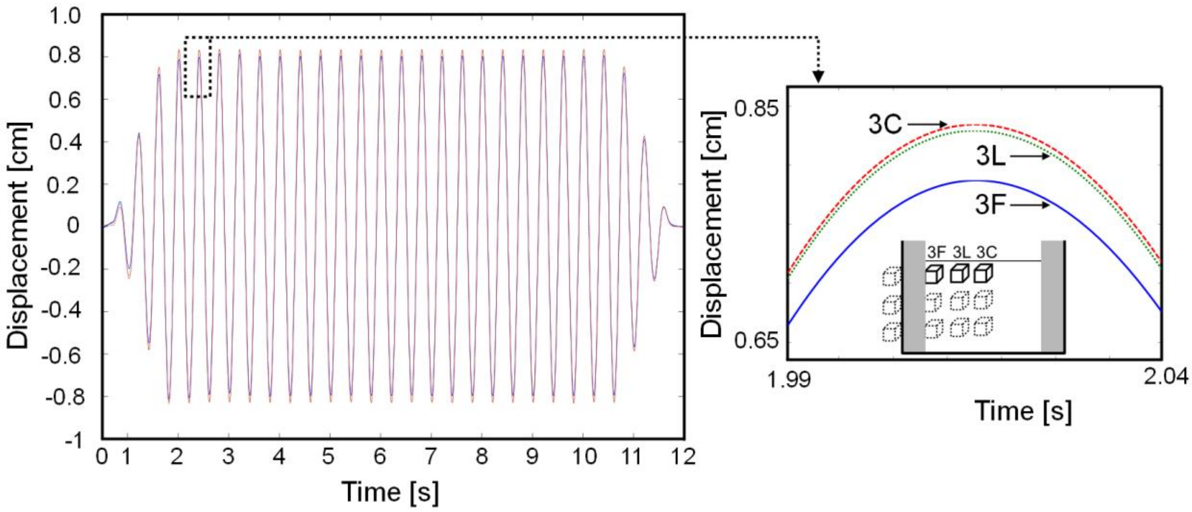


Figure 4.3 Displacement profiles measured at a particular depth in three different locations

Other tests were carried considering sine wave as input motion. Fig. 4.3 shows typical results obtained when the container was subjected to a sine wave at a frequency of 2.5Hz. The figure plots the displacement profiles measured at a particular depth in three different locations from the end-wall (as shown in Fig.3.2). As already mentioned before, considering a particular depth and an ideal semi-infinite extended layer subjected to a one dimensional shaking, the soil displacements should have same values. This condition translates in the fact that horizontal cross sections remain horizontal (which was of the requirement for designing a soil container). As shown by the data plotted in Fig. 4.3, the presence of the soft boundaries is advantageous since the displacement amplitudes are almost similar at the three locations. However, as illustrated by the close-up on the right of Fig. 4.3, higher displacements are recorded at locations far from the boundary as would be expected.

5. DISCUSSION AND CONCLUSION

One of the important considerations is laboratory scale dynamic soil-structure interaction studies is to replicate the infinite boundary condition in the scaled soil container. In an infinitely extended soil layer the energy associate with the wave propagations diminishes gradually due to the combined effect of hysteretic and radiation damping and also because the energy will spread to a greater volume of soil. In a soil container used for experimental studies, the finite dimension of the soil layer does not allow the complete dissipation of the energy induced by the wave propagation. Moreover the presence of the artificial boundaries induces the generation of *P* waves which may add inaccuracies on the expected response. In this study the performance of a rigid container with absorbing boundaries placed at both ends is investigated. Typical results have demonstrated that the presence of foam enables the dissipation of a certain amount of energy, which was assessed evaluating the coherence function between accelerometers placed on the outside and inner side of the artificial boundaries. The experimental results also demonstrated that higher absorption may be achieved using thicker sheet of foam. Finally in order to verify that the strain field in the soil was similar to that of the prototype, the displacement profiles at a particular depth was estimated from the acceleration records. Typical results showed that the displacement amplitudes were very similar between the accelerometers placed at different distances from the artificial boundaries, proving that the horizontal section remains horizontal also during the shaking.

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