16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING
THESSALONIKI
18 - 21 JUNE 2018

EXPERIMENTAL & NUMERICAL SIMULATION OF SOIL BOUNDARY CONDITIONS UNDER DYNAMIC EFFECTS

Omar S. QAFTAN[1], Laurence WEEKES[2], Tahsin TOMA-SABBAGH[3],
Levingshan AUGUSTHUS-NELSON[4]

ABSTRACT

When conducting earthquake simulation tests, one of the main concerns is the modelling of boundary effects created by artificial boundaries of a soil model container. The function of this soil container is to hold the soil in place during the excitation and to provide confinement. In reality, the soil is unbounded. However, the ideal soil container should simulate the free field soil behaviour as it exists in the prototype, by minimising the boundary effects. The key parameter in the design of the container is to satisfy the dynamic response of the adjacent soil. In this paper, the results of physical tests are compared with numerical simulation results. A cylindrical container (1 m in diameter and with 0.6 m in height of soil) with a flexible curved membrane was built and tested on shaker table. The harmonic loadings and artificial earthquake time history excitations were applied at the base of soil container. The responses of soil at different elevations were measured during the tests using accelerometers and displacement transducers.

To obtain more realistic results and understand the underlying mechanism, soil boundaries with flexible members (thin wall shell elements) was used to represent the membrane part of the soil container in FE implicit analysis. In all cases, the numerical output results were compared with measured values for different physical parameters. It was found that the soil container with specific design and dimensions has an insignificant effect on the soil response during the shaking events.

Keywords: Soil-structure interaction; Dynamic; Experiment; Finite element modelling.

1. INTRODUCTION

The correct representation of soil boundary conditions of a soil or soil-structure model, will directly affect the accuracy of the experimental test output. In reality, the soil is unbounded. However scaled physical or numerical models by their nature must be bounded, hence the effect of the soil boundaries employed is required to be studied due to their influence on the behaviour of soil or soil-structure model during experimental tests. For shaking table experiments, the container influences the soil behaviour of the soil foundation structure interaction (SFSI) system due to wave reflection on the container boundary and variation of system vibrational modes. A suitable simulation of the soil boundary is necessary to enable the soil in the container to represent the appropriate deformation response as the soil prototype and therefore minimise the impact of the boundary conditions. Many researchers have proposed different kinds of soil container to simulate the soil boundary conditions in physical dynamic tests. The most widely used containers are laminar box, winged wall box, rigid wall box with inner lining and the flexible container (Rayhani and El Naggar, 2008; Turan et al., 2009). The

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[1] Mr., PhD Student, School of Computing, Science and Engineering, the University of Salford, Manchester, United Kingdom, o.s.s.sadq@edu.salford.ac.uk

[2] Dr., Senior Lecturer, School of Computing, Science and Engineering, the University of Salford, Manchester, United Kingdom, l.weekes@salford.ac.uk

[3] Dr., Lecturer, School of Computing, Science and Engineering, the University of Salford, Manchester, United Kingdom, t.toma@salford.ac.uk

[4] Dr., Lecturer, School of Computing, Science and Engineering, the University of Salford, Manchester, United Kingdom, l.augusthusnelson@salford.ac.uk

region adjacent to the container wall is significantly affected by the boundary conditions in comparison to the soil further from the wall (Moss et al. 2010). It has been concluded that the ratio D/d should be taken as five by controlling the size of the structure plan, where D and d are the diameter of the soil container and the structure base diameter respectively (Moss et al., 2010).
Moss et al. (2010) and Tabatabaiefar and Massumi (2010) summarised different analysis outputs on many soil container types. The numerical analysis of the 40 ft deep deposit of San Francisco Bay mud was used as a case study. This test was carried on three different kinds of the container (Rigid wall box, wing wall box and flexible wall box). This numerical analysis demonstrated the advantage of a flexible container over rigid-wall designs in replicating the prototype response. Moss et al. (2010) drew two conclusions. Firstly, the flexible boundary container and the relevant constructional details should be conducted properly to minimise the box effect. Secondly, the container diameter should be five-times of the structure base width. Turan et al. (2009) showed validation and demonstration of the dynamic performance of the flexible barrel versus other the types of testing containers. It was concluded that the flexible wall barrel provides the most accurate representation of seismic soil response in comparison with the prototype soil. To simulate the soil boundary condition precisely, the flexible container was adopted to consider the response of soil foundation structure interaction under seismic effects. The scaled structural model width was 200 mm. According to Moss et al. (2010) conclusions, the proposed container dimensions are 1m diameter width and a 1 m depth. the soil sample depth was 600 mm. The main part of the soil container was a 5 mm flexible membrane wall which represents the soil boundary when the model is subjected to excitation of the shake table.

2- EXPERIMENTAL SIMULATION AND TESTING PROCEDURE

Chunxia et al. (2008) described single-axis flexible containers for 1 g seismic tests on shaking tables. Single-axis flexible containers permit movement in a single axis only and typically comprise either rigid guide walls that support laminae on bearings or laminae that are stacked on each other separated by bearings in addition to single-axis containers. Turan et al. (2009) and Moss et al. (2010) provide details of double-axis flexible containers for 1 g tests. Double-axis containers permit horizontal movement of the laminate in two principal directions. Turan et al. (2009)'s container comprises a ribbed membrane hanging from a top ring and supported by a frame using universal joints. An improved fixable container was adopted in this study and the container detail, soil and testing procedure are clarified as follows.

2.1 Experimental Set-up

A flexible container was designed and manufactured at the University of Salford as shown Figure 1. The flexible container consists of a 5 mm membrane cylinder wall with 1 m in height and 1 m in diameter supported individually by stiffener strips. The top ring is supported by lifting hooks which are supported by the overhead crane. The bottom base is fixed on the shaking table.

2.2 Soil Properties and Placement

The dynamic behaviour of soil is a complex task. To reduce the effect of density variation during the seismic excitation, dry sand with certain properties was used as the backfill material as shown in Table 1. This poorly graded sub-rounded particle has very limited volume change and the difference between the maximum and minimum dry densities is very little. These soil criteria help to eliminate the effect of soil volume change during the seismic excitation. Figure 2 and Table 1 show the grain size distribution and the properties of the sand respectively. The specific gravity of the sand is 2.68, and the other relevant soil properties are also shown in Table 1. The friction angle was measured as 34° in direct shear tests. The sand was placed in the container using the eluviation (raining) technique to achieve a uniform density. The actual relative density was achieved and measured by collecting samples in small cups with known volume extracted at different locations within the main container.

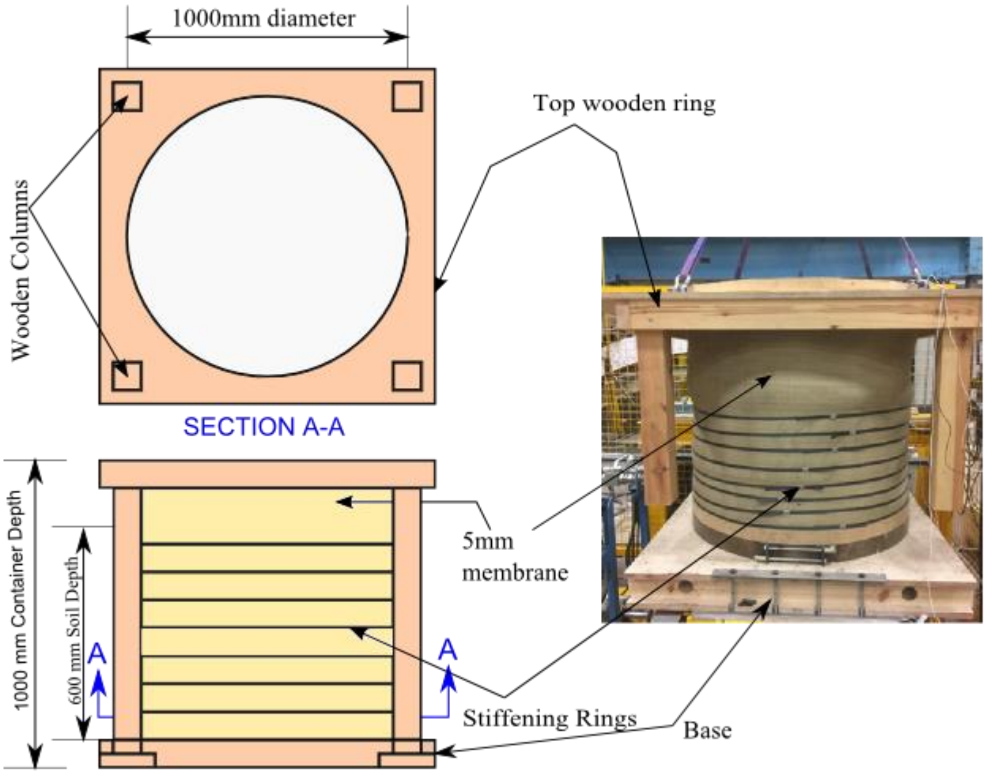

Figure 1. Soil container mounted on the shaking table

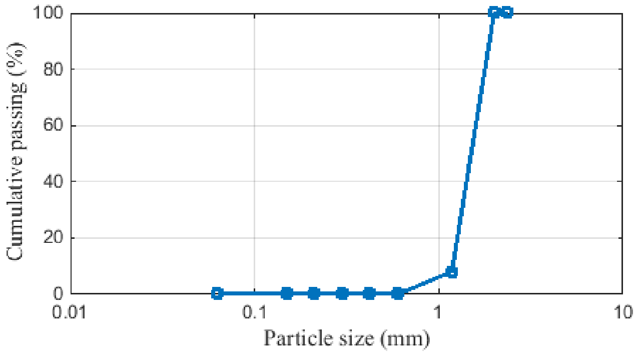

Figure 2. Grain size distribution of the tested sand

Table 1. Properties of the tested sand

Symbol	Details	Value
D10mm	Grain size	1.3 mm
D30mm	Grain size	1.5 mm
D50 mm	Grain size	1.7 mm
D60 mm	Grain size	1.8 mm
D mm	Particle size range mm	0.6 – 1.18
Cu	Coefficient of uniformity	1.38
Cc	Coefficient of curvature	0.96
	Soil classification	SP
	Soil description	Poorly graded sand
γ	Max. dry unit weight	15.5 kN/m^3
γ	Min. dry unit weight	14.5kN/m^3
e_{max}	Maximum void ratio	0.48
e_{min}	Minimum void ratio	0.6

2.3 Tests Performed and Instrumentation Details

Figure 3 shows the instrumentation layout across section along the diameter of the flexible container. The locating of accelerometers on the top of the soil surface would prove problematic when mobilising the mass of the accelerometer and it would be difficult to ensure full interaction between the soil particles and accelerometer. Therefore, three accelerometers were mounted 100 mm below the surface of the soil, which was ACC3, ACC4 and ACC5. ACC2 was situated almost at the centre of the soil mass. ACC5 and ACC6 were attached to the soil container boundary. ACC1 was connected to the shaking table. To investigate the effects of the soil container boundaries, a small amplitude (0.1 g) harmonic excitation was applied to the flexible container via the shaking table to ensure linear soil behaviour. Since all the accelerometers are accurate at frequencies more than 4 Hz, sinusoidal input motion was applied at 4 Hz with an amplitude of 0.1 g as shown in Figure 4.

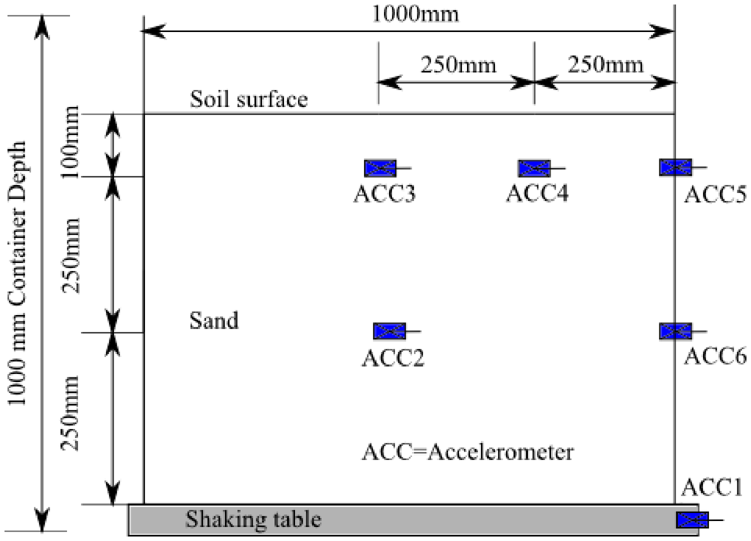

Figure 3. Accelerometer layout

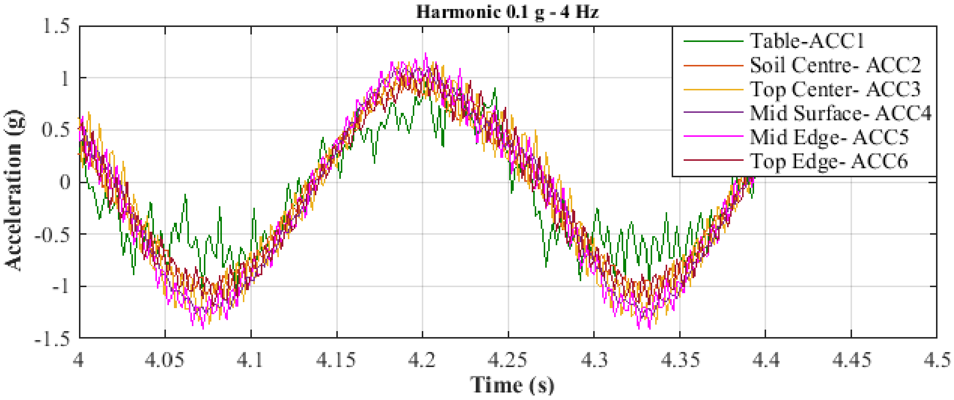

Figure 4. The effect of the container boundary of the soil response

2.4 Evaluation of Soil Container Boundary Effects

Figure 4 shows the acceleration time histories at accelerometers ACC1-ACC6. The results show that the differences among the responses at ACC1-ACC6 were insignificant. The response of ACC5 and ACC6 (situated on the container outer boundary), showed a more scattered shape. However, the peak amplitude remained almost same, which was very close to peak amplitudes measured by other six accelerometers. These results demonstrate that the flexible boundaries of the soil container functioned appropriately. The scattered shape at ACC5 and ACC6 can be considered with limited local effect on an area close to the wall container only.

2.5 Accelerogram Generation

By using the software Seismo Artif, four artificial time-history accelerograms were generated with different peak ground acceleration of (0.05 g, 0.1 g, 0.15 g, 0.2 g) as shown Figure 5. These events were generated from EC8 elastic spectra Soil Type C, Spectrum Type 2, and the derived response spectra are as close a match as possible with the target response spectra (also shown in Figure 5). These accelerograms were adopted as dynamic load inputs for the experimental and numerical models.

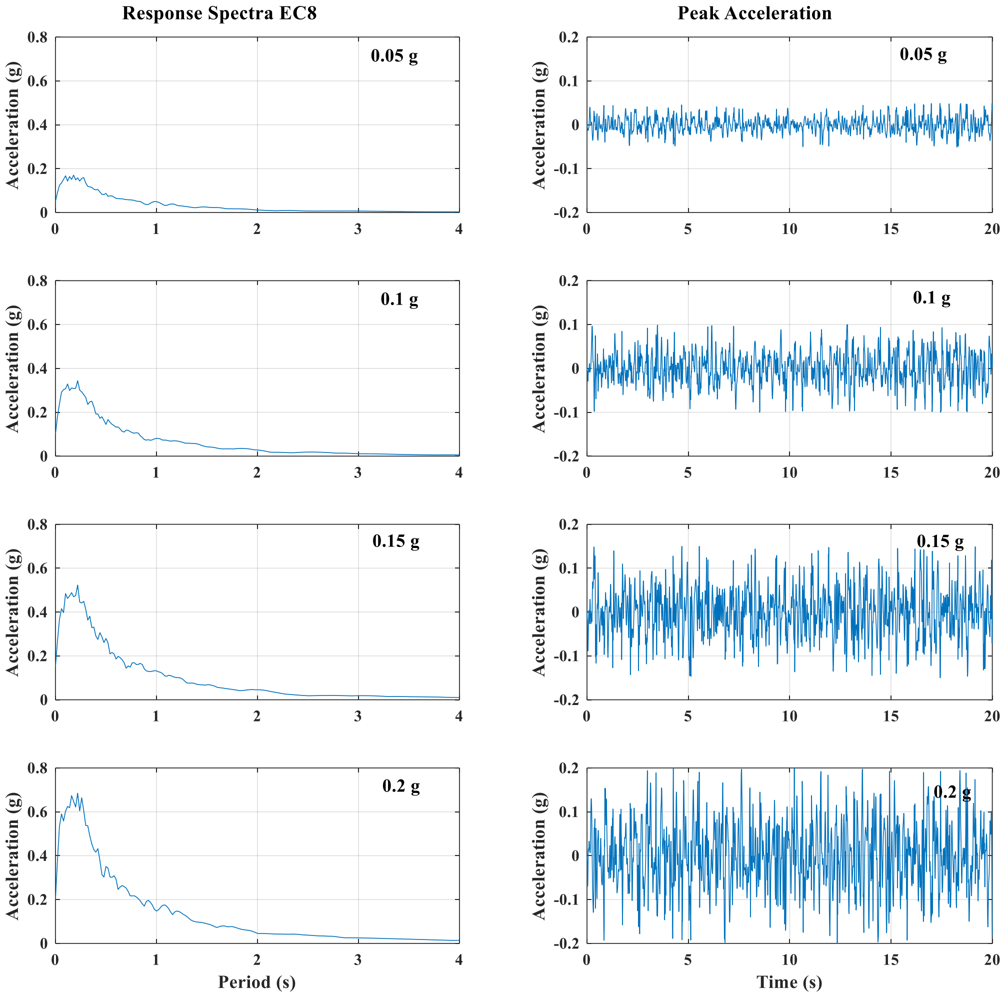

Figure 5. Acceleration input data and corresponding Response Spectra

3. NUMERICAL SIMULATION AND MODEL OUTPUTS

In the numerical modelling process, the soil medium is represented by solid elements, and each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints. Accordingly, a proper constitutive model representing the geomechanical behaviour of soil elements was implemented in ABAQUS to conduct an accurate SFSI analysis. A nonlinear Mohr-Coulomb model was adopted in this study to simulate the nonlinear soil behaviour and possible shear failure in the soil elements during the excitation (Conniff and Kiousis, 2007; Rayhani and El Naggar, 2008).

Table 2. Soil properties adopted in the numerical models

Parameter	Symbol	Unit	Value
Mass Density	p	kg/m^3	1500
Angle of friction	$\emptyset$	°	34
Poisson's ratio	v		0.22
Young's modulus	E	N/m^2	80x 10^6

Symmetrical boundary conditions (symmetry in the z-direction) were applied to simulate the soil boundaries. There is no deformation in the z-direction and no rotation about the x-and y-axes (circumferential boundaries of the soil constrained in all degrees of freedom), see Figure 6.

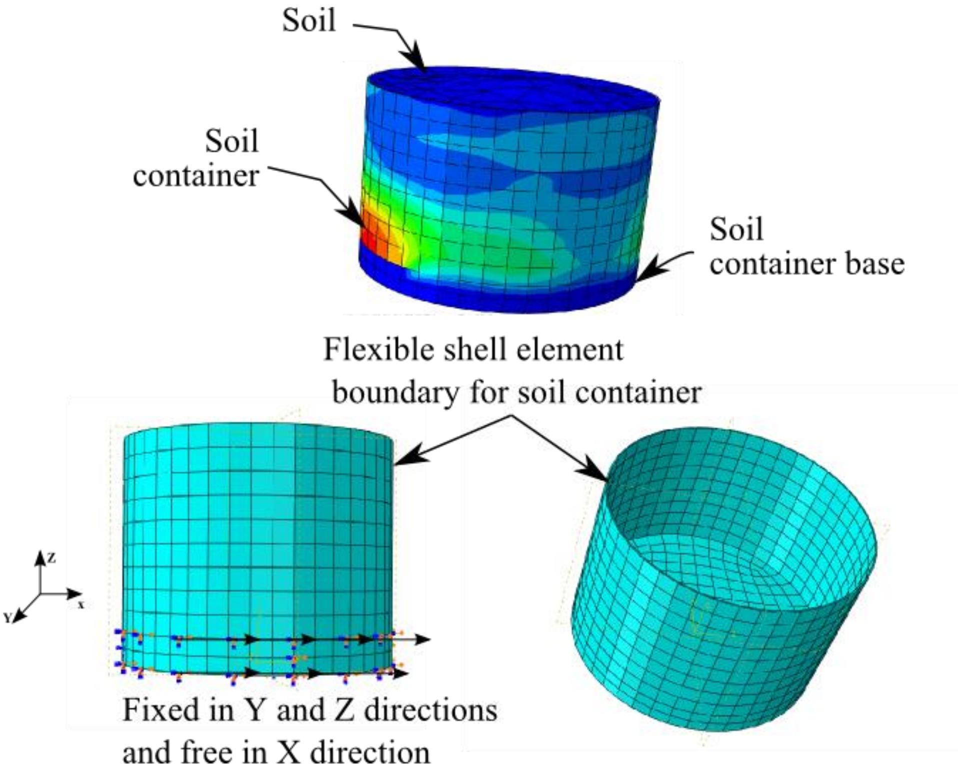

Figure 6. Soil element boundary model by ABAQUS software

3.1 Dynamic Analysis

Finite element method is a common tool for various fields of engineering. It is used for advanced numerical calculations, and it is developed from the theories of continuum mechanics, which studies equilibrium, motion and deformation of physical solids. ABAQUS is a powerful FEM tool to analyse 3D problems in various fields. It is also capable of running complex harmonic analyses and transient dynamic analyses.

The seismic ground motion was applied using a dynamic implicit time stepping approach. At the beginning of this step, the boundary condition that has been implemented to the sides of the soil is deactivated, and replaced with an alternative displacement/rotation boundary condition allowing for horizontal movement to be introduced into the whole system. This movement is controlled by applying an amplitude curve representing the dynamic ground displacements for a given earthquake time history.

4. DISCUSSION

The aim of this study was to validate the dynamic output of the experimental soil container test. The idea of this validation was to select a single point in both of experimental and numerical model and compare the output. The selected points were the soil centre in both of soil models. The dynamic behaviour of the soil is presented in terms of soil frequency and soil acceleration response to a fully nonlinear time-history dynamic finite element analysis performed to simulate the realistic dynamic behaviour of the soil and the container under seismic excitations. Solid elements were employed to model the soil deposit, and flexible boundary conditions were applied. Nonlinearity of the soil medium plays a very important role in the seismic behaviour of the soil-foundation-structure system (Kim and Roseset, 2004; Maheshwari and Sarkar, 2011).The results of experimental and numerical acceleration outputs of the 0.05 g and 0.1 g peak acceleration time history events have good agreement while the events of 0.15 g and 0.2 g are slightly are overpredicted. From plots of the power spectra, the experimental frequencies of all events have values around 7 Hz (and lower) while the numerical frequency outputs are around 5 Hz or lower. These discrepancies of both acceleration and frequency are due to experimental measurement methods. The experimental output was measured by the accelerometer, and this accelerometer has a mass of 50 grams. During the excitation, it is likely the accelerometer itself has a local effect on the experimental result in comparison with the numerical model output which is recorded from a selected node located at the centre of the soil mass. This is more noticeable for the events of 0.15 g and above. The measurement of acceleration and frequency spectra are shown in Figures 7 and 8.

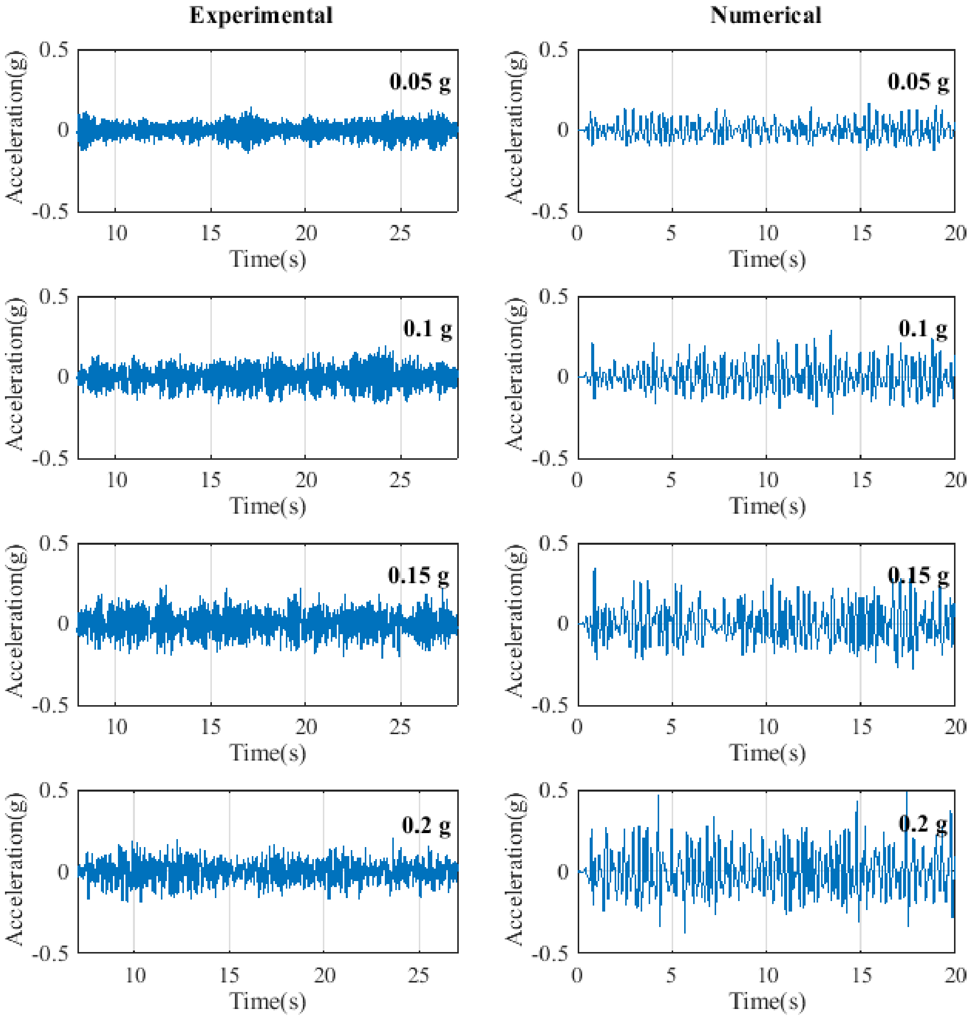

Figure 7. Experimental and numerical time-acceleration outputs at the centre of soil

It can also be seen that when examining the spectra, there is more ‘power’ evident at lower frequencies for the numerical model output. This is currently being investigated but it is likely that it may well be due to how damping is currently being addressed in the ABAQUS model.

It is well known that sand can have volumetric change when it sheared. For the medium-dense soil, seismic excitation makes a net contraction of the deposit evidenced as settlement of the sample surface. The test soil void ratio of soil decreased when the soil density increased. These variations should be reflected in the calculations for stiffness and shear stress. For the adopted soil in question, measured contractions had a negligible effect on other parameters and the volumetric change was insignificant.

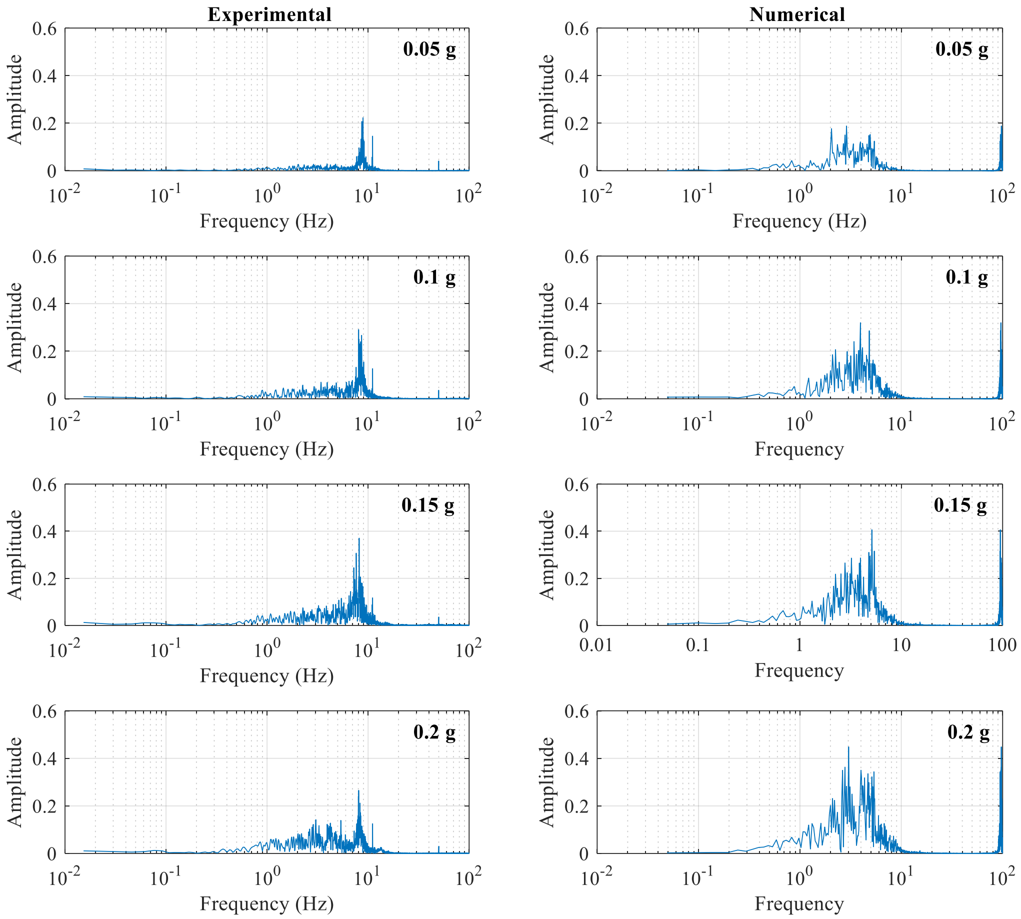

Figure 8. Experimental and numerical frequency outputs

5. CONCLUSION

Physical model testing is highly recommended for the research of seismic geotechnical problems because of the inadequacy of in situ information. This model is vital to simulate semi-infinite free-field soil deposits. This paper describes the design and performance of a flexible container, which is based on the base shear limitations of a 1 g shaking table. The performance of the flexible container is evaluated using a series of model tests. The output results show the effect of the boundary on measured accelerations and the frequencies recorded at the soil centre. However, more validation and study is required with different experimental measurement methodology, for example using alternative accelerometers.

In the past years, many numerical models for modelling the dynamic behaviour of geotechnical problems have been produced. Furthermore, sophisticated techniques are now available to tackle the analysis of complex soil-structure interaction. However, there is little experimental or prototype information to compare with the results of the numerical models. These experimental results have provided confidence in the numerical model developed in this study. The flexible container model developed in this paper can offer valuable insight into the seismic behaviour of large soil specimens.

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