DYNAMIC BEHAVIOUR OF SOIL-STEEL FRAME SYSTEMS: A SHAKING TABLE EXPERIMENT

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This paper presents an experimental investigation of soil-structure interaction. The study tests a small-scale steel frame model using shaking table. The model features two columns, connected by a foundation beam and a girder at the top with the superstructure's mass. The testing encompassed two distinct configurations: first where the model was fixed to the shaking platform and second where the model was placed on a sand bed. Throughout the experiments, displacements were meticulously recorded over time, by a system for optical measurement. A local Drava sand was chosen for the experiment. Notably, the experiments were conducted under both dry and saturated conditions. Analyzing the results one can conclude that fixed base models have different behaviour compared to models founded on soil. Stiffness of the soil has a big impact on the behaviour of the soil-structure system where stiffer foundation soil results with behaviour closer to fixed base case while the flexible soil changes behaviour of the models considering the displacements which are the result of dynamic excitation.

Keywords: experiment, soil-structure interaction, shaking table, small-scale model, optical measurement

1. INTRODUCTION

Soil-structure interaction remains attractive research topic for numerous researchers [1-3]. Many of researchers base their studies on data acquired through either field-based or laboratory-based experimental measurements. After a brief literature review, it becomes evident that three types of experiments are most frequently employed in the examination of soil-structure interaction: (i) centrifuge tests, (ii) shaking table tests, and (iii) in-situ tests.

Centrifuge tests are particularly informative in the realm of geotechnical research, although their smaller scale looks for a comparison with experiments conducted in a larger scale. Larger-scale models facilitate the incorporation of larger measuring instruments and more closely emulate the behavior of real-world systems.

Although large-scale experiments are encouraged, due to their high costs and laboratory limitations, they are not always possible. Considering all limitations, original experimental research of soil-structure interaction is planned and carried out by the authors. The main goal of the research was to investigate the impact of foundation soil flexibility on the seismic behaviour of the structures with shallow foundations through original experimental research on small-scale models and parametric analysis.

Furthermore, in order to investigate soil structure interaction, experimental research studied by other authors are briefly presented Prevost and Scanlan's study in 1983 [4] delved into the dynamic effects of soil-structure interaction. Their research involved subjecting individual piles, groups of piles, and a shallow circular foundation to testing in a geotechnical centrifuge. The Knappett et al [5] studied the mechanisms underlying the failure of foundation load-bearing capacity under seismic loads where foundation strips were tested using a shaking platform. Research from 2010 by Anastasopoulos [1] conducted experiments with an inverted pendulum clamped to a square base foot, tested in a shear box on a shaking platform. Pender et al [6] explored the behavior of tilting and rocking of shallow foundations subjected to cycling loading in situ. Abate and Massimino [7] focused on the effects of dynamic interaction among soil, foundation, and structure. Their experimental setup involved testing of a steel 3D frame on a foundation plate using shaking platform, unveiling the dynamic behaviors and responses within such systems. Further research by Pender et al[8] studied soil-structure interaction through centrifuge experiment using simple two-dimensional models with square foundations in geotechnical centrifuges. Dynamic 3D tests were conducted by Hirave and Kalyanshetti [9] testing a foundation plate on a shaking platform. Finally, in 2019, Kumar and Mishra [3] explored the influence of structure characteristics on soil-structure interaction. Their research involved employing 3D models of structure on foundation slabs, single foundations, and foundation strips on a shaking platform, offering valuable insights into how diverse structural attributes, such as foundation slabs, single foundations or foundation strips, impact the interaction with the underlying soil.

Collectively, all of these studies contribute to a comprehensive understanding of soil-structure interaction and were used as a guideline in designing of experimental research conducted by the authors.

2. EXPERIMENTAL SETUP

Dynamic effects of soil-structure interaction were observed on a scaled model Comparable experimental investigations of the same nature and scale can also be found in [5, 10, 11]. As part of the project, dynamic tests were carried out on a scaled frame model with varying foundation conditions. Initially, the model was fixed at the foundation level (designated as soil category A according Eurocode 8 [12]), and subsequently, the same model underwent testing when situated on compacted sand (representing the soil category E found in norm [12]) as it is shown by Figure 1. The structural model was tested under both dry and saturated sand foundation conditions. These experiments took place at the Laboratory for Structures at the Faculty of Civil Engineering, University of Rijeka.

2.1. STRUCTURAL MODEL

The experimental model is constructed of steel frame, consisting of two columns connected by a sturdy foundation and a rigid beam. The columns are welded at their bases to rectangular pipe, which represents the foundation, and at the top, steel plates are combined to form a rigid beam. To simulate the superstructure mass, a rigid beam was employed.

The foundation itself was fashioned from rectangular pipes, characterized by a cross-sectional dimension of 60 x 40 mm and a solid 5 mm wall. The columns were made from steel sheets, measuring 20 mm in width, 2 mm in thickness, and standing at height of 162 mm all shown in Figure 2. The beam was assembled

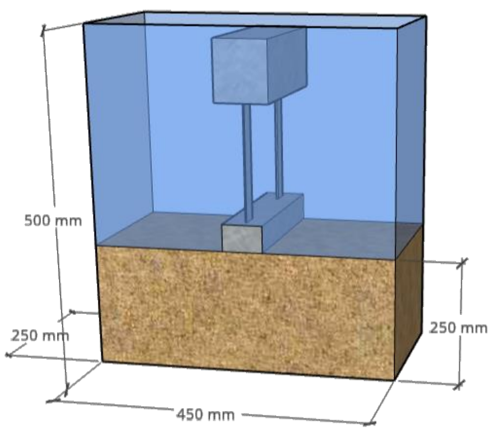


Figure 1. Experimental setup

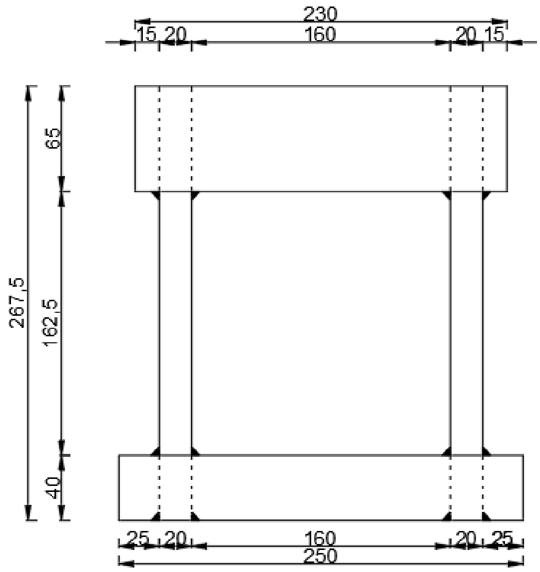


Figure 2. Structural model [dimensions are in mm]

from 10 steel plates, each 65 mm wide and 6 mm thick. Notably, the steel grade utilized in this model was S275. The model as a whole weighted a total of 8.68 kg, with the mass ratio of the upper beam to the foundation beam estimated at roughly 3.5:1. The calculated pressure imposed on the foundation soil by the model was approximately 580 Pa.

2.2. MEASURING INSTRUMENTS

To monitor displacement and acceleration during the experiment, accelerometers were positioned at various key points. These accelerometers were placed on top of the structural model, on the foundation (Figure 4), and on the shaking table platform. Additionally, two optical measuring systems were used to register the displacements accurately.

The GOM Aramis 4M contactless optical 3D system, denoted as "4" in Figure 3, was used to capture the structural model's movements. Simultaneously, the GOM Aramis 12M contactless optical 3D measurement system, identified as "3" in Figure 3, was tasked with tracking soil deformations. This comprehensive approach allowed us to collect data on both the structural response and the changes in the soil during the experiments.

Dynamic response of the structural model was recored at a high frame rate of 160 frames per second, capturing it in full resolution. Dynamic tests were performed by applying dynamic excitation using the Quanser ST-III earthquake platform (marked with number “2” in Figure 3), with ground plan dimensions 70 cm x 70 cm and the possibility of maximum acceleration of

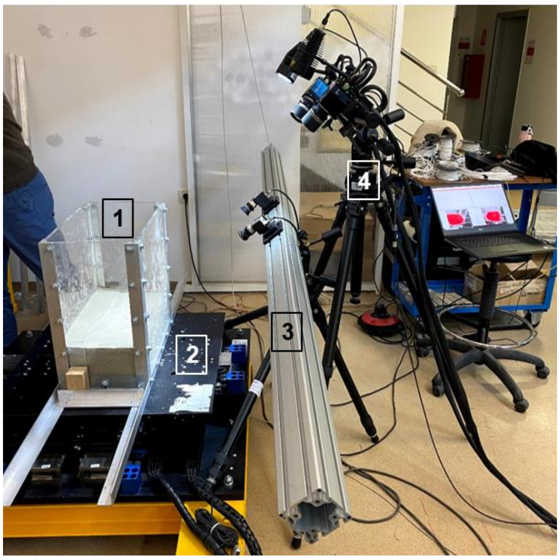


Figure 3. Experimental setup

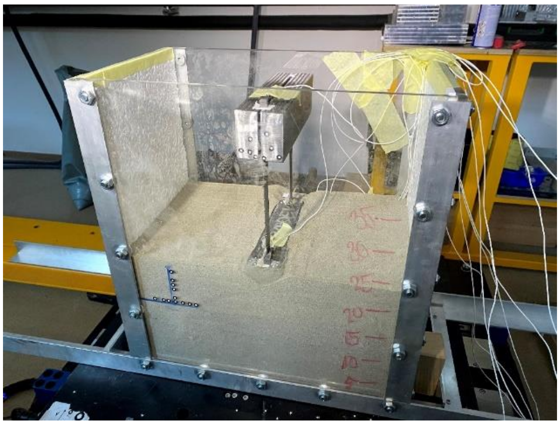


Figure 4. Experimental model with measuring instruments

1 g in both directions at a maximum load of 120 kg.

2.3. FOUNDATION SOIL

For the preparation of the soil model, local Drava sand was used. The properties of sand can be found in study published by Jagodnik et al [13]. Sand was embeded in the rigid container (marked as 1 in Figure 3) which was made of aluminum profiles that formed the frame for plexiglas. Plexiglas was chosen for the container since it is resonubly light and allowes observation and optical measurement of sand behavior before, during, and after testing. The container was reigidly attached to the shaking table. The total mass of the container was 34,8 kg. Due to the limited load capacity of the shaking table (120 kg), the entire model, together with the container and sand, was prepared in accordance with the scaling recommendations given in [14].

Dry sand was methodically placed in approximately 5 cm thick layers. Following the placement of each layer, the shaking table platform was activated, subjecting it to high-frequency vibrations for a duration of roughly 2 minutes. Prior to embedding each layer into the container, all the sand was carefully weighed to determine its mass. After the compaction process was completed, the volume of the sand was measured. These measurements allowed calculation of the density of the compacted sand. The analysis indicated that the mean density of the sand in the layers was close to 1550 kg/m³.

2.4. EXCITATION

Sinesweep function had been chosen as an excitation to ascertain the fundamental frequencies of the tested cases. Additionally, the Kobe 1995 earthquake record was utilised to excite the models, varying the maximum amplitude (A) from 0.2 mm to 0.4 mm.

Testing sequence began with the models initially attached directly to the shaking table platform. Subsequently, they were placed on a layer of sand embedded within the container. Finally, the tests were repeated using saturated sand. This comprehensive approach allowed exploration of the dynamic response of the model under different conditions.

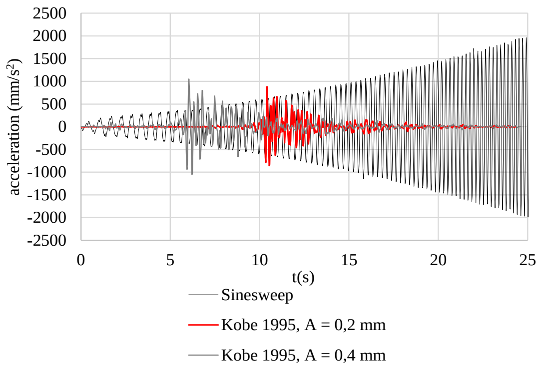


Figure 5. System excitations

3. RESULTS

This chapter presents displacements measured at the top and foundation beam for excitations: Sinesweep function (Figure 6), Kobe earthquake A= 0,2 mm (Figure 7) and lastly, Kobe with an amplitude of A= 0,4 mm (Figure 8). It can be noticed that the displacement of the top beam is smaller for the systems with foundations placed on the sand (Figure 6 (a), Figure 7 (a), Figure 8 (a)). Smaller vibration amplitudes of top beam go in hand with the

Table 1. Top beam displacement ratios for sinesweep function

t(s)	$A/A_{fixed\ base}$	
	Dry sand	Saturated sand
2	99.82%	99.82%
4	74.28%	99.78%
6	13.24%	14.29%
8	12.28%	5.85%
10	9.39%	6.87%
12	7.83%	6.96%
Average	36.14%	38.93%

Table 2. Top beam displacement ratios for Kobe 1995 A=0,2 mm

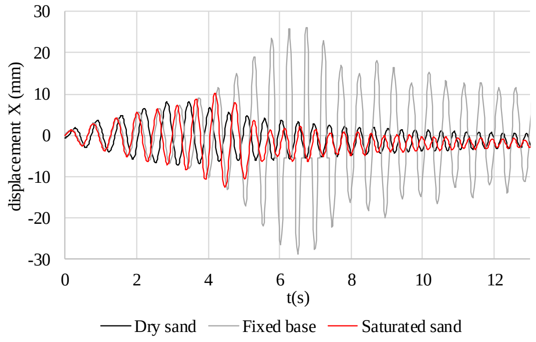
t(s)	$A/A_{fixed\ base}$	
	Dry sand	Saturated sand
11	112.50%	120.83%
13	62.35%	71.88%
15	68.33%	85.00%
17	76.92%	95.02%
19	47.06%	76.47%
Average	73.43%	89.84%

Table 3. Top beam displacement ratios for Kobe 1995 A=0,4 mm

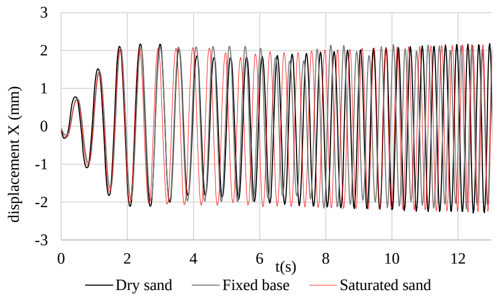
t(s)	$A/A_{fixed\ base}$	
	Dry sand	Saturated sand
7	17.76%	47.96%
9	21.30%	33.33%
11	5.98%	12.03%
13	4.93%	3.15%
15	9.62%	34.62%
Average	11.91%	26.22%

hypothesis that soil can be observed as isolator/damper in soil-structure systems. Tables 1., 2. and 3. serve as a comparison of experimental research conducted on different foundation conditions. Overall results show higher damping properties when the model is founded on dry sand compared to saturated sand. Exact percentage should be taken conservatively and should be used only as a guideline not a rule.

Results of experimental research conducted on saturated sand are compared to results on dry

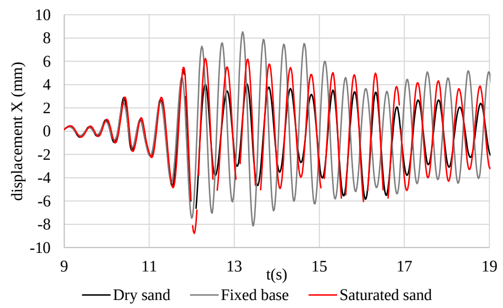


(a) Top beam

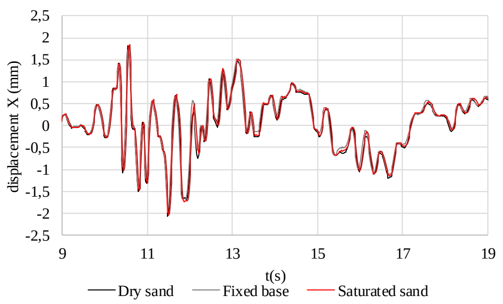


(b) Foundation strip

Figure 6. Structural response for sinesweep function



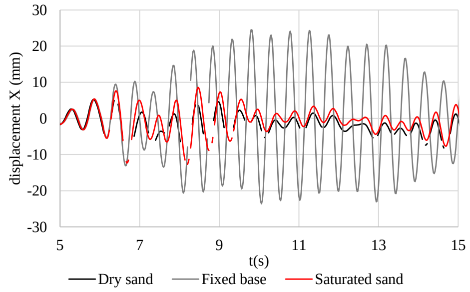
(a) Top beam



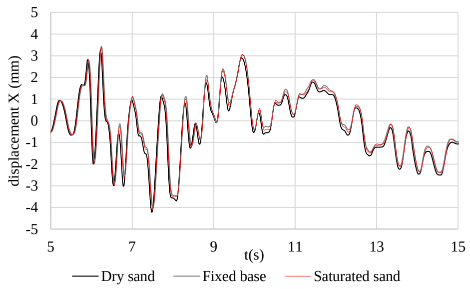
(b) Foundation strip

Figure 7. Model vibration excited by Kobe 1995 A=0,2 mm

sand. It is observed that the soil effects are less noticeable in the case where the sand was saturated. Saturated sand is stiffer compared to dry sand which means that the saturated sand case behaves similar to fixed base condition.



(a) Top beam



(b) Foundation strip

Figure 8. Model vibration excited by Kobe 1995 A=0,4 mm

Vibrations of the foundation strip are presented in Figure 6 (b), Figure 7 (b) and Figure 8 (b).

When comparing the fixed base condition to the dry and saturated sand case it is noticeable that no major slippage occurred at foundation level. This was concluded since the foundation vibrations measured on sand are almost identical to displacements measured for the fixed base case.

4. CONCLUSION

Dynamic soil-structure interaction experiments are very useful because they bring valuable insights into the behaviour of structures and the soil. The soil-structure interaction effects are still investigated by many to determine the contribution of the soil in the seismic behaviour of soil-structure systems. Small-scale experimental research was conducted using earthquake platform to simulate real excitation. Steel frame model was tested with fixed base and but also founded on sand. A local river sand in dry and saturated conditions was used to simulate the soil. The model vibrations were measured at the top of the model and at the foundation level for three different excitations. It is noticeable that horizontal vibrations for models tested on sand are lower when compared to the fixed base case which could lead to conclusion that compliant soil can be observed as an isolator. Further, horizontal vibrations measured at the foundation level showed no significant slippage happening at the foundation level.

The main goal of the research was to investigate the impact of foundation soil flexibility on seismic behaviour of structures with shallow foundations through original experimental research on small-scale model. Analyzing the results one can conclude that fixed base models have different behaviour compared to models founded on soil. Further, stiffness of the soil has a big impact on the behaviour of the soil-structure system where stiffer foundation soil results with behaviour closer to fixed base case while the flexible soil changes behaviour of the models considering the displacements which are the result of dynamic excitation. Precisely, when sinesweep excitement was observed, dry sand resulted with average of 36% and saturated sand with 39% of top beam displacements of the fixed base case. Kobe 1995 A=0,2 cm excitement showed 73% and 89% of top beam displacements for dry and saturated sand while Kobe 1995 A=0,4cm showed much higher damping properties where dry sand had 12% and saturated sand 26% od fixed base case top beam displacements. One can conclude that damping properties have higher impact when stronger excitement was used, yet it needs to be taken into account that tests where done in following order: sinesweep, Kobe 1995 A=0,2 cm and Kobe 1995 A=0,4 cm which results in changes in the soil properties as the tests went on.

Although certain conclusions can be drawn, extended experimental research and thorough numerical modeling could provide better understanding of the effects in the soil and confirm results presented within this paper.

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