Stability of Rigid Blocky Structures on Uniform Sand Subjected to Harmonic Horizontal Base Excitation

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ABSTRACT: Numerous researchers previously investigated the behaviour of stiff constructions on rigid bases or deformable media, such as soil. For both structural and geotechnical engineers, the behaviour of a rigid structure on the soil under static or cyclic actions, such as self-weight, wind, or earthquake, is of major significance. The consequences of such forces on the structure itself as well as the soil must be taken into consideration. The interaction between the soil and the structure constructed on it is extremely important. The paper presents the response of a stiff block subjected to cyclic horizontal load such as earthquake. The solid aluminium block 6 cm wide and height to width ratio (H/B) of 4.5 has been subjected to horizontal excitation using a shaking table. The block was placed on the sand (D = 0 cm) or embedded in the sand (D = 2 cm). A sinusoidal displacement function with varying amplitude and frequency was used for the horizontal excitation. The amplitude ranged from 0.5 to 5 cm, while the frequency ranged from 0.5 to 3 Hz. The critical amplitude and frequency combination for a certain height to weight ratio was found using combinations of different frequencies and amplitudes. This information was later used for further investigation and numerical verification. A stiff block's displacement as well as the displacement of the sand beneath it were monitored using the ARAMIS contactless measuring system. The results obtained from this DIC approach were later used to compare the results of numerical analysis.

1 INTRODUCTION

Inertial forces occur both horizontally and vertically as the ground and foundations vibrate during an earthquake. Over many years, researchers have investigated how rigid blocks react to seismically induced loads and how they respond to movements in the ground. Physical and numerical models of rigid structures have been used. Neves et al. (2012) investigated the seismic response of an urban building block. They considered elements such as nearby structures, in-plane stiffness of floors and roofs, and localised strengthening actions as they focused on understanding the overall behaviour of the block and the local response of individual buildings. The dynamic response of stiff buildings to simultaneous horizontal and vertical ground shaking was investigated by Hao and Zhou (2012). They found that the stability of a rigid structure depends on its slenderness as well as the amplitude, frequency, duration, and ground motion. They also emphasized the difference between ground shaking triggered by explosions and seismic ground motion. The behaviour of stiff blocks with geometric imperfections in seismic motions was studied by Mathey et al. (2016). Their numerical and experimental analysis showed that non-negligible out-of-plane movements can occur due to initial conditions or apparent horizontal excitations. Within a certain range of peak ground acceleration, they also discovered that geometric errors slightly increase the probability of rocking and overturning in earthquake signals. In their 2014 study, Vassiliou et al. investigated the dynamic response of individual flexible rocking bodies. They proposed a nonlinear elastic viscous damped zero-length spring rocking model for flexible structures and validated it by using overturning analysis of rocking blocks subjected to recorded ground motion stimuli and analytical solutions. Their research has shown the importance of considering the flexibility of structural elements in areas where rocking is expected.

The aim of this work is to investigate the dynamic behaviour of rigid blocks and to present an experimentally constructed model of a rigid foundation on deformable soil media.

This work aims to investigate the behaviour of a rigid block in deformable soil. The focus is on validating the behaviour of the block using an optical measuring device and basic numerical models.

2 EXPERIMENTAL SETUP AND EQUIPMENT

2.1 Experimental setup

The laboratory experiments were carried out in the Structural laboratory within the Faculty of Civil Engineering at the University of Rijeka, Croatia. A small shaking table was used for the tests to simulate dynamic loads. Figure 1 illustrates the dimensions of the test model. A custom-made box with a height of 50 cm and a length of 100 cm was made to carry out the small-scale physical tests. As shown in Figure 2, the box was filled with uniformly graded sand. The width of the box can be varied between 6 and 18 centimetres, depending on the width of the foundation, and a sufficient distance was ensured between the block and the sides of the box so that they do not touch each other. The laboratory experiments are carried out with a block that has a cross section of 6 x 6 cm. The block used had a height- to- width ratio of 4.5, indicating its height was 27 cm. Due to the weight capacity of the seismic platforms, an aluminium "L"-profile with a thickness of 2 mm and a width of 25 mm was used for the construction of the box frame. This design decision guarantees adequate rigidity and minimises the weight of the box.

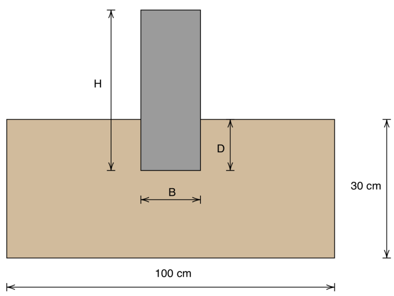

Figure 1. Schematic depiction of a physical and numerical model

Transparent acrylic plastic, also known as plexiglass, has been placed on the front of the container to make it easier to detect displacements using non-contact optical technology. Specific gravity of the sand used is 2.66, mean grain size (D50) is 0.28 mm, and the effective grain size (D10) is 0.18 mm. The uniformity and curvature coefficients are 1.67 and 1.07 respectively. The soil type used in these experiments is known as DrOS018 and was investigated and documented by Jagodnik et al. (2020). The prepared sand had a target relative density of 33%, which corresponds to an initial void ratio, e0, of 0.844. Using the undercompaction method, the sand was placed in the container in layers to achieve a homogeneous density of the material (Ladd, 1978). An undercompaction of 5% was used to compact the sand. The dynamic loading parameters, including the amplitude (A), the frequency of the harmonic function (f) and the embedment of the block (D) for each experiment, are shown in Table 1.

Table 1. Physical and numerical tests

Test ID	Embedment depth (cm)	Frequency (Hz)	Amplitude (cm)
EXP 14	2	3	0.5
EXP 17	0	3	0.25

Figure 2 presents a box that has been appropriately filled with sand, along with rigid block, markers, shaking table and cameras. The markers required to monitor displacement have been randomly placed on both the block and in the soil medium.

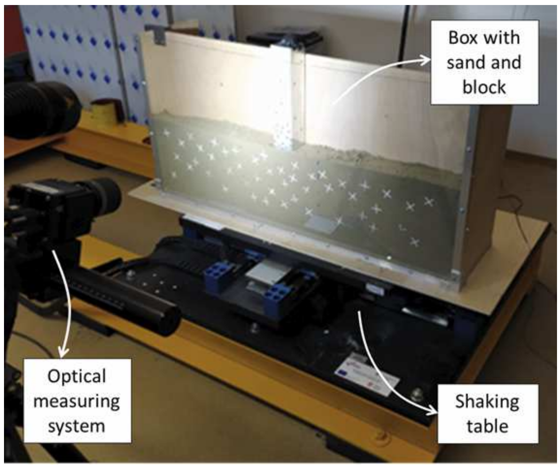

Figure 2. Photo of a rigid block on deformable media physical model

2.2 Optical measuring system and excitation system

A LabView-based programme controls an electromagnetic motor that drives the Quanser STI-III seismic platform, which simulates dynamic loads. A dynamic load in the form of a sinusoidal displacement function is defined within the programme interface. The platform top plan dimensions are 625 x 625 mm, its motion in each direction is 15 cm and its operating frequency range is 0 - 20 Hz, while the actual frequency range for the permanent sinusoidal frequency, within which the actual monitored function is close enough to the input function, is 0 - 10 Hz. An acceleration of 1g can be generated in both directions in the horizontal plane with a maximum mass of 130 kg on the platform.

The GOM Aramis 4M optical system, which can measure displacements and strains on the model's surface, was used to track the block's behaviour. The system is made up of two high-speed cameras with a 2400x1728 pixel resolution able to take pictures with 168 fps. Every experiment was recorded at 50 frames per second, and the horizontal displacement corresponding to the midpoint of the block's base was determined using post-processing.

3 NUMERICAL SIMULATIONS

The reaction of the block under dynamic loading was numerically simulated using the computer program Rocscience 2 (hereafter RS2). RS2 uses the finite element method to solve the system of equations. The numerical simulations were performed for two selected models, listed in Table 1, based on laboratory studies. These models differed in the frequency (F) and amplitude (A) of the dynamic load and the embedment depth of the block (foundation depth (D)). The behaviour of sandy material was modelled using the Mohr-Coulomb soil model, which was extended by Finn’s formulation (Martin et al., 1975, Pietruszczak, 2010; Potts & Zdravković, 1999). Finn's model adopted the independence of cyclic shear strain and volumetric strain as defined by Martin et al. (1975) or Bryne (1991). A linear elastic material model was used for aluminium blocks.

The phases of the numerical analysis procedure were divided into a total of sixteen time intervals. Each phase ended with the recording of displacement data. The initial state, denoted by the time t = 0 s, is defined by the static conditions that exist before the dynamic load is applied.

Isoparametric four-noded quadrilateral finite elements were used in a numerical model created with the RS2 computer program (e.g. Bathe, 2008; Carter et al., 2002; Desai & Kundu, 2001; Lees, 2016; Puzrin, 2012). The minimum length of the element given by the wave velocity was considered according to the recommendations of Kuhlemeyer and Lysmer (Kuhlemeyer & Lysmer, 1973). In the first phase of the simulation, standard boundary conditions were defined that limited the horizontal displacements along the sides of the model and the vertical and horizontal displacements at the bottom.

During the simulation, dynamic boundary conditions were applied to the bottom of the model to absorb dynamic loading waves and to the sides to allow uniform movement of the points of the model on both sides (a constrained boundary condition). The dynamic excitation is applied to the bottom of the model and the load is applied as a temporal displacement. The measured data from the optical measurement devices are used as the dynamic excitation.

The "joint" function was used to represent the interaction between the rigid block and the sand (Bathe, 2008). A tangential stiffness of 5 kPa per meter and a normal stiffness of 1000 kPa per meter were used to define the "joint" element. The mechanical properties of the material used are listed in Table 2.

Two types of numerical simulations were performed, one with a friction angle of 30° and one with a friction angle of 33°, as defined in Table 2.

Table 2. Mechanical characteristics of simulated materials

Element	Material name	Young’s modulus (GPa)	Poisson ratio (-)	Material model	Friction angle (º)	Cohesion (kPa)	Finn’s extension
Soil	DrOs018 Sand	0.016	0.3	Mohr – Coulomb	30&33	0	Bryne
Block	Aluminium	70 GPa	0.34	Linear Elastic	-	-	-

4 RESULTS AND DISCUSSION

4.1 Results of block’s stability tests

To determine the global overturning stability of a rigid block embedded 2 cm deep in sand and placed on the sand, a series of shake table laboratory tests were performed. The rigid block was subjected to various combinations of loading frequencies and amplitudes. The aim was to determine the global overturning stability of a rigid block and to define the stability diagram. The global stability of the rigid block is defined as the point at which the block overturns. The stability diagrams obtained are shown in Figure 3, for the block on the sand (Figure 3(a)) and for the block embedded in sand (Figure 3(b)). The most critical scenario is when the block is resting on the sand material (D = 0 m). The figure shows that the rigid block is very unstable for displacements of less than 1 cm and loading frequencies of more than 2 Hz. The critical combination for 2 cm embedment is around 3 Hz. The system can withstand displacements with larger amplitudes if it is loaded more frequently. A higher embedment requires additional investigations and laboratory tests in order to be able to make a better statement.

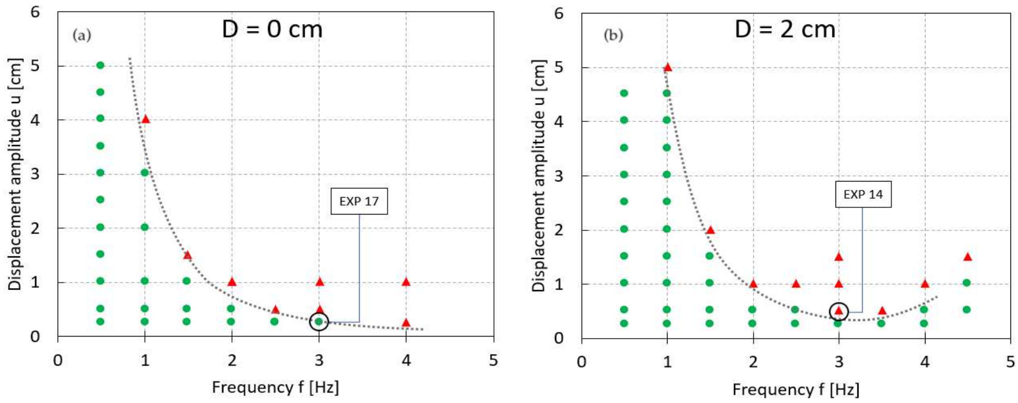

Figure 3. Results of a stability test on two types of models: (a) rigid block on a soil surface and (b) rigid block embedded in soil

4.2 Behaviour of block in time

To better understand the behaviour of the rigid blocks, the experiments labelled “EXP 14” and “EXP 17” are examined in more detail. All shaking table experiments lasted 10 seconds. The results are presented based on the point at the bottom of the rigid block labelled “T3”. The behaviour of the rigid block during these tests was monitored using the GOM Aramis 4M optical system.

The experiment labelled “EXP14” was selected because it is located near the global minimum in the amplitude-frequency domain. For a more precise analysis, a frequency of 3 Hz with an amplitude of ±5 mm was chosen. The results of the block behaviour are shown in Figure 4. Figure 4(a) shows the vertical displacements, while Figure 4(b) shows the relative horizontal displacements. The results of the displacements are shown in relation to the point “T3”. The black line represents the measured displacements, while the red and blue lines show the displacements obtained by the numerical simulations. The green line represents the horizontal excitation of the shaking table. The start of the shaking is at t=1.17 s, as shown in Figure 4. In a period of 1-3 seconds (Figure 4(a)) after the start of the loading sequence, the block initially begins to settle, but then loses its stability and overturns (t = 4.5 s). The horizontal displacements are derived as relative displacements with respect to the shaking table. Figure 4(b) shows that the block follows the shaking until t = 3.3 s, when it gradually begins to tilt to one side. Complete overturning is reached at t = 4.5 s.

The numerical simulations show good agreement with the horizontal displacement up to t = 2 s, especially for the model with a friction angle of 33°. The vertical behaviour of the numerical simulation of the rigid block agrees well with the measured results up to 2.8 seconds after the test started. The direction of the vertical displacements has the same tendency as in the physical model. Although the settlement rate of the numerical model is slightly higher than that of the physical model, the numerical simulation has captured the trend of vertical displacement very well up to 4s. After that, the block either begins to either tilt ($\phi = 33°$) or shows additional settlement ($\phi = 30°$). The horizontal behaviour follows the trend of the laboratory experiment with a decrease in the amplitude of the vibrations, which is interpreted as a loss of stability of the block. Numerical simulations with a friction angle of 30° did not capture the full values of the amplitude of the block rocking but showed the trend of the horizontal displacement with good agreement.

A photo of the recorded behaviour of the rigid block in the “EXP14” test can be found in Figure 5. The overturning instability captured in time t = 4.68s shows a clear heave on the right-hand side of the rigid block.

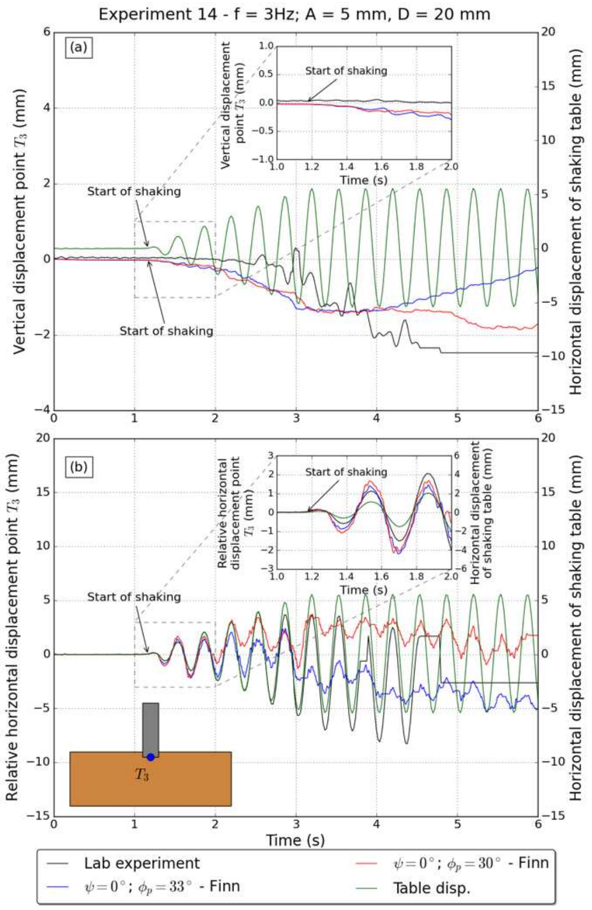

Figure 4. Detailed results of a stability test of "EXP14": (a) horizontal displacement of point" T_3" and (b) vertical displacement of point" T_3

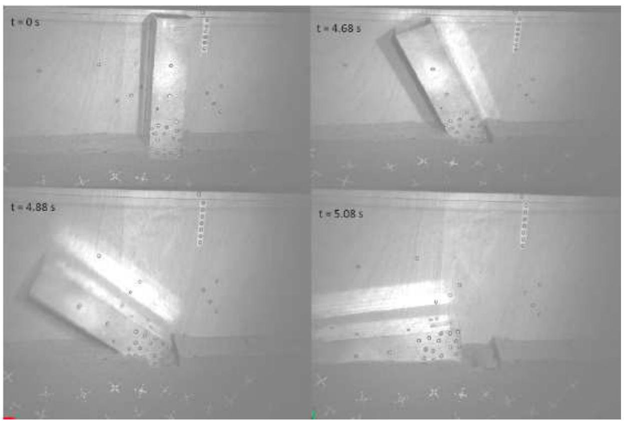

Figure 5. Behaviour of rigid block in the test labelled "EXP14"

When the rigid block is placed on the sand and shaken with an amplitude of 2.5 mm at a frequency of 3 Hz, the stability tests (shown as stable in Figure 3) show that the block can be both stable and unstable. This means that a small irregularity in the test preparation can lead to instability of the block. The test labelled "EXP17" was therefore selected for closer monitoring and analysis. The results of the monitored displacement at point "T3" are shown in Figure 6. Figure 6(a) shows the vertical displacements and Figure 6(b) shows the relative horizontal displacements. As in Figure 4, the black line represents the displacements measured by the high-speed camera, while the displacements obtained by numerical simulations are shown in red and blue. The horizontal excitation of the shaking table is shown with a green line. The shaking starts at t = 0.17s. The block begins to settle at t = 1.75 s (Figure 6(a)), approximately 1.6 s after the start of the test. It is clear from the results shown that the block does not exhibit any unstable behaviour. It gradually settles to a value of less than 0.5 mm (Figure 6(a)) while following the movement of the shaking table in the horizontal direction (Figure 6(b)).

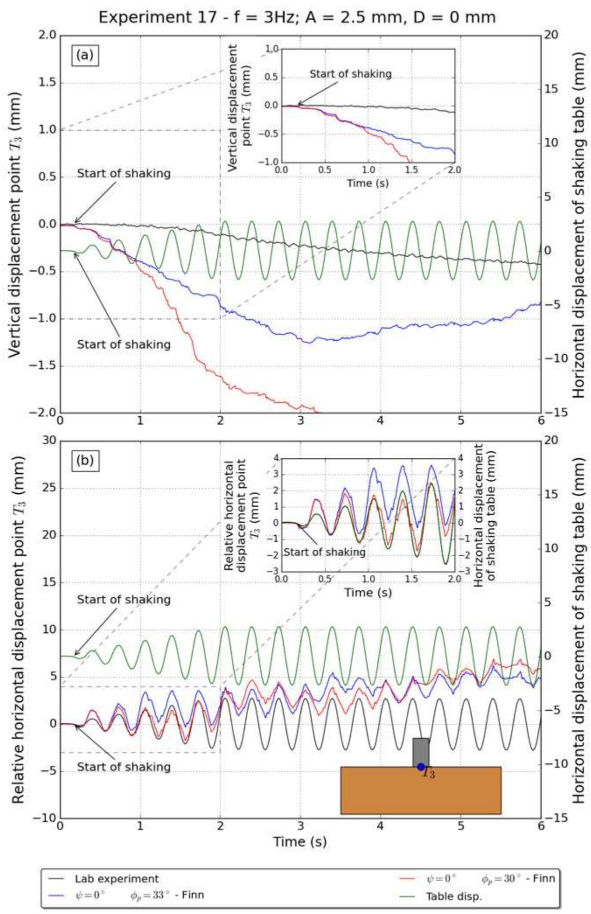

Figure 6. Detailed results of a stability test of "EXP17": (a) horizontal displacement of point" T_3" and (b) vertical displacement of point" T_3

However, the numerical simulations show a different behaviour. For sand modelled with a lower strength (ϕ = 30°), the block begins to settle immediately after the start of the test and settles to 1.5 mm at time t = 1.75 s (Figure 6(a)). The time t = 1.75 s can be considered as the inflexion point, i.e. the point at which the material under the block has compacted and the settlement rate has been reduced, but the block continues to settle. The sand modelled with the higher strength (ϕ = 33°) exhibited a lower settlement rate and reached about 0.8 mm at time t = 1.75 s. The block settled at the same rate until t = 3.1 s and then began to tilt (Figure 6(a); approximately 3 seconds after the start of the test).

The horizontal behaviour of the numerically simulated rigid block shows that the block modelled on sand with lower strength (ϕ = 30°) follows the trend of the laboratory experiment very well up to t = 2s. After t = 2s, the blocks begin to move relative to the shaken base on which the load was applied.

The block modelled on a higher strength sand (ϕ = 33°) shows a good trend until t = 1s. After that, the block begins to move relatively differently from the soil model. The amplitude of the displacement decreases, and the block moves on average 5 mm in the right direction compared to the beginning of the test. This movement in the right direction starts at t=2s, as in the model simulated with weaker soil strength (ϕ = 30°). The difference between the physical test and the numerical simulations could be due to the initial imperfections in the preparation of the test, as described earlier in the text. Further tests and simulations should be carried out to confirm this behaviour.

5 CONCLUDING REMARKS

Physical and numerical models of small-scale rigid block tests are presented in this paper. Both global overturning stability and detailed analysis of rigid block behaviour were analysed. Critical combinations of frequency and amplitude for rigid block on top of sand and rigid block embedded in sand were measured in detail and the results were used to validate the numerical model. The stability of a rigid block is greatly dependent on the amplitude and frequency of dynamic stresses.

For a block lying on sand, instability arises for displacements less than 1 cm and loading frequencies more than 2 Hz. When the block is placed 2 cm in the sand, its critical frequency rises to roughly 3 Hz, demonstrating that embedment improves stability by allowing the block to resist larger displacements and higher loading frequencies. In the EXP14 test, the block first settled before overturning at around 4.5 seconds. For horizontal displacements up to two seconds, the numerical simulations for this test exhibited a strong agreement with the experimental results, with improved accuracy at a friction angle of 33°. The vertical displacements determined with numerical simulations show a good trend up to 2.8 seconds after the start of the test. From then on, the trend of the vertical displacements begins to differ.

Numerical models for the EXP17 test showed that sand with a friction angle of 30° led to greater and immediate settlement, while sand with a friction angle of 33° resulted in less tilting and a slower rate of settlement. However, after two seconds, the horizontal displacements in the simulations were not the same as the experimental results, suggesting that further research is needed to understand soil-block interactions.

Overall, numerical models corresponded to the displacement trends seen in experiments, especially in the early loading phases. Differences between the numerical and physical results were related to imperfections in the initial test setup as well as soil model parameters. The expected behaviour was significantly influenced by the friction angle, where larger angles produced displacement models that were more accurate.

Displacement monitoring with optical measurement equipment proved acceptable providing essential information for model validation. To fully understand stability dynamics, future research should include testing with various embedment depths and soil characteristics. Furthermore, identifying issues earlier in test preparation would increase the accuracy of physical models. The findings emphasize the need of detailed analysis methodologies in predicting rigid block stability under seismic loads, providing the way for more earthquake-resistant design approaches.

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