The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

Physical Modelling in Geotechnics

A micro laminar box coupled with a piezoelectric shaking table for centrifuge testing

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ABSTRACT: Cyclic and dynamic loading produces an accumulation of residual strains and changes in the soil strength. Small scale models provide a useful tool for studying boundary-value problems, such as the cyclic and dynamic soil response. In this work, we present a micro laminar box coupled with a piezoelectric shaking table designed for centrifuge testing, allowing the dynamic instrumentation of the soil model boundaries, while remaining as light as possible. The innovative points of the current experimental setup are the dynamic actuator and the size of the laminar box allowing the parametric study of the dynamic soil behavior with ease. The laminar box consists of a series of rectangular hollow frames made of PMMA and joined together with micro linear bearings. The model instrumentation provides information on the model boundary accelerations and pore pressure. In this work, we present tests on sand under an acceleration of 1g, 30g, and 60g, exploring a range of frequencies between 100 Hz to 1000 Hz. The results provide evidence of the model's ability to represent the site effects on a sand layer. Moreover, the system provides a simple model for parametric studies which could have potential use in soil dynamics student course projects.

Keywords: dynamic response, wave amplitude, basal vibration, cyclic loading, soil layer.

1 INTRODUCTION

Earthquakes represent a significant hazard for society and infrastructure. Between the years 2000 to 2021, earthquakes were responsible globally for more than 730,000 deaths and damages for an estimated cost of USD 652'957,244 (US dollars), compromising mostly communities near mountains and coastal areas (EM-DAT, 2021). Therefore, there is a need for studying the effect of dynamic and cyclic loading through a soil layer. Seismic effects in a soil layer must deal with the challenge of applying a shaking signal that reproduces the seismic movement and allows the upscaling of field conditions. Centrifuge testing is a valuable tool in geotechnical engineering, due to its ability to combine conventional physical modeling with the replication of in situ seismic loads, and in situ stress conditions (Jung Lee, Chen Wei, & Chieh Kuo, 2012). The use of the centrifuge is an alternative for avoiding large-scale setups. The up-scaled stress field is achieved by increasing the effective acceleration within a rotating model by a factor of N, proportional to the centrifugal acceleration's increase relative to Earth's gravity g (Madabhushi G. , 2014).

A centrifuge test needs a container for the soil model, maintaining a constant horizontal cross-section during shaking (Whitman R. V., 1981). Laminar containers or laminar boxes coupled to a shaking table have been used for dynamic tests since the '70s. Morris (1979) used a shaking mechanism composed of springs and masses which were jacked away and released in a rigid container with a cross-section of 500 mm by 565 mm. Whitman (1981) carried out tests in a stack of rings of 30.5 cm in diameter, measuring the soil dynamic behavior with a series of load cells, accelerometers, displacement transducers, and, for saturated tests, pressure transducers. Moreover, Lee *et al.* (2012) developed a laminar container for centrifuge testing, consisting of 38 lightweight rectangular aluminum frames. Each frame was separated from the adjacent frames by roller bearings specially designed for minimal friction resistance during translation. More recently, Soriano (2021) developed a laminar model container built by a series of rectangular frames separated by cylindrical bearings, minimizing the friction between the frames. The resultant laminar box was designed to have "zero" lateral stiffness, then the model lateral deformations were driven by the soil mass. The laminar box had a plan area of 500 mm by 250 mm, and 300 mm depth and the weight of an individual frame with the cylindrical bearings was 2.1 kg (Soriano, 2021).

The systems described above recorded accelerations at different heights along with the model box, varying as a soil model response.

Most laminar boxes are designed for centrifuges with a working radius of approximately 4 m (Soriano, 2021). This working radius bounds the model dimension's container inside the centrifuge. For centrifuges with a working radius smaller than 1m, the laminar box dimensions are limited to a few tens of centimeters. Therefore, the current paper presents the development of a novel micro laminar box coupled with a piezoelectric shaking table for small centrifuges, allowing a full model instrumentation and simplifying the preparation protocol. The shaking table system allows the dynamic instrumentation of the boundaries of a soil model undergoing shaking while remaining as light as possible. This work's main objective is to determine the performance of both the shaking table and the laminar box under a centrifugal acceleration field and variable input frequencies. The shaking table and laminar box performance will confirm its suitability for testing cyclic and dynamic processes in short beam centrifuges. The following section presents the main characteristics of the experimental setup (Sec. 2), and Sec. 3 presents the shacking table and laminar box performance at accelerations of 1*g*, 30*g*, and 60*g*. Finally, the main conclusions and the scope for future works are discussed.

2 METHODS

The experimental setup is divided in two elements, a shaking table, and a laminar box (see Fig. 1(a)). The shaking table consists of an aluminum base-plate laying over two mini-rail bearings and connected to a fixed piezoelectric actuator (APA 120 ML, Cedrat technologies). The shaking table is connected to a function generator 3 MHz DDS and an amplifier Made by Cedrat Technologies. The laminar box consists of six rectangular hollow PMMA frames joined together with two micro linear bearings (LLMHS 7 TA). The rectangular frames have external dimensions of 9 mm thick, 90 mm wide, and 95 mm long, with a 3 mm depression on its long side, and internal dimensions of 52 mm wide and 85 mm long. The current setup consists of seven frames with a total height of 69 mm, and an internal height of 67 mm, resulting in an internal total volume up to 283 cm^3. The model instrumentation consists of three external side accelerometers, measuring the model boundary accelerations at heights $z = [0, 35.5, 66]$ mm. Also, a 15 psi miniature pressure sensor (Honeywell, 26PC) is installed on the base-plate and measures the basal pore water pressure.

The calibration tests, under a laboratory acceleration of 1*g* are performed by fixing the shaking table to a perforated aluminum plate and adding 22.8 kg iron-plates, restricting the external movement. For the centrifuge tests, an aluminum box encased the experimental setup, protecting it from potential air drag during flight and securing the model and instrumentation (see Fig. 1 (b)).

The soil layer is made of poorly-graded sand, with a mean grain diameter of 0.8 mm. Tests are performed in dry and saturated conditions. Each test started by placing a hand-made latex membrane inside the laminar box. Next, the laminar box was filled with dry sand into the latex membrane with a density of 1.48 gr/cm^3, equivalent to a relative density $Dr = 0.43$. For the saturated tests, the sand layer was flooded by the water column method. The soil is shacked at its base and the soil vibration is evaluated by measuring the frames side-accelerations at the heights *z*. A sinusoidal signal is employed in all tests as an input motion, covering a frequency range between 100 Hz and 1000 Hz, with an input voltage of 0.5 V. The accelerometers signal is recorded at a sampling rate of 25.6 kHz, with an external dynamic signal acquisition module.

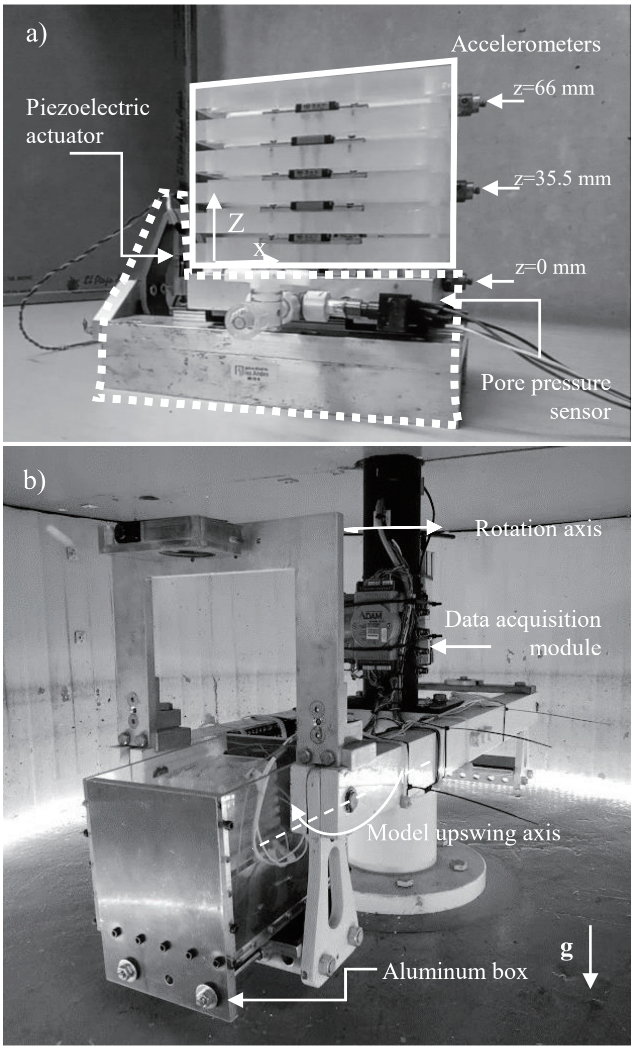

Fig. 1. Photograph of the micro laminar box (continuous line) coupled with the piezoelectric and the shaking table (dotted line) (a). Setup for the data acquisition inside the 0.8 m radius centrifuge at Universidad de Los Andes (b)

3 RESULTS AND DISCUSSION

Three experimental campaigns are presented in this work, testing the experimental setup and the sand layer under effective accelerations of 1*g*, 30*g*, and 60*g*. The input frequency and voltage are programmed by the function generator connected to the amplifier. Figure 2 shows the recorded signals in height for dry and saturated tests, both in the time and frequency domain. The sand is subjected to a ground motion at 250 Hz under a macro-gravity of 30*g*, while the accelerations were recorded at the laminar box base, mid-height, and top frame. For the saturated condition, the ground acceleration is presented on the left axis and the basal pore pressure on the right axis. In both cases the signal sinuosity is clear, proving its propagation through the soil layer.

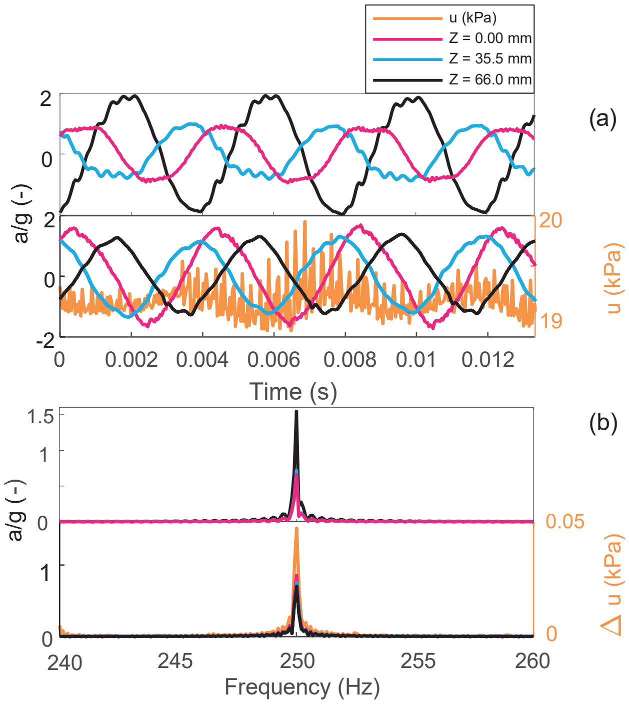

Fig. 2. Recorded acceleration at the laminar box base (z = 0 mm), mid-height (z = 35.5 mm), and top (z = 66 mm), for a ground motion at 250 Hz and under a macro-gravity of 30*g* in the time domain (a) and in the frequency domain (b) for sand in dry and saturated conditions.

In Figure 2(a), the dry test presents an increment of the wave amplitude within the soil layer. In contrast, for the saturated test, the wave amplitudes show similar values in the base, the middle, and at the top, with higher ground accelerations. Figure 2(b) shows the Fourier spectra for dry and saturate tests. The system's harmonic response is clearly preserved in height and by the input frequency (*i.e.,* 250 Hz). In the dry test, the acceleration recorded at the top was the highest reaching a value of 1.54 *g*, while in the saturated test, the acceleration recorded at the base was the highest. Also, the pore pressure Fourier spectra reflects a coherent evolution of pore-pressures and preserve the input frequency, proving the functionality of the pore pressure sensor for dynamic tests.

Figure 3 shows the peak amplitude response at the base at 1*g*, 30*g*, and 60*g*, as a function of input frequencies for dry tests (see Fig. 3(a)) and for saturated tests (see Fig. 3(b)). Moreover, the inset in Fig. 3(a) shows the amplitude ratio between the accelerations recorded at the laminar box base and top, for both dry and saturated tests.

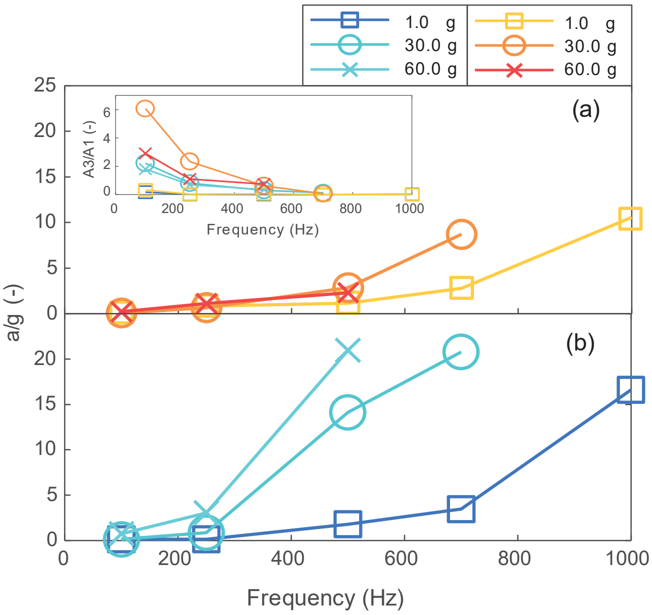

Fig. 3. Micro laminar box peak amplitude response at the base and as a function of input frequencies for an input voltage of 0.5 V in dry condition (a) and saturated condition (b) and the amplitude ratio between the recorded acceleration in A3 (z=66mm) and in A1(z=0) in dry condition inset in Fig. 3(a).

The evolution of peak amplitudes increases with the test macro-gravity (see Fig. 3). Moreover, the amplitude ratio between base and top vanishes for input frequencies higher than 500 Hz, marking a clear dissipation within the soil layer (see inset in Fig. 3(a)). The results demonstrate that the amplitude reached values of 20g, proving the capability of the shaking table and the piezoelectric actuator for simulating strong seismic events and clean cyclic loading.

Figure 4 shows the liquefaction ratio L_r for the saturated tests. This liquefaction ratio is defined by Eq. 1, where u is the basal pore pressure, σ_v is the effective basal stress, and N is the scaling factor.

$$L_r = \left(\frac{u}{\sigma_v \ N \ g}\right) \quad (1)$$

The results are similar for both macro-gravities of 30*g* and 60*g* since u and σ_v are scaled proportionally by N. Nevertheless, these results show the measurement capability of the pore pressure sensor for evaluating liquefaction under cyclic and dynamic loads.

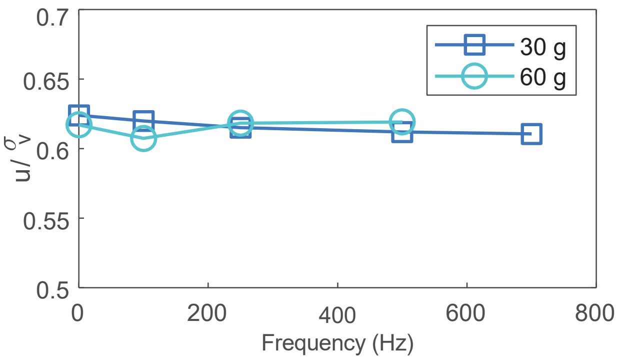

Fig. 4. Liquefaction ratio as a function of input frequencies, for an input voltage of 0.5 V in a saturated condition.

4 CONCLUSIONS.

This paper presents the development and testing of a novel micro laminar box coupled with a piezoelectric shaking table. The innovative points of the current experimental setup are the dynamic actuator and the size of the laminar box allowing the parametric study of the dynamic soil behavior with ease. The performance of the shaking table and the laminar box was addressed for a sand layer under effective accelerations of 1*g*, 30*g*, and 60*g*. The shaking table performance was tested for a range of input frequencies from 100 Hz to 1000Hz. The results show that the acceleration through the soil layer clearly reproduces the sinusoidal nature applied at the base. Also, the acceleration peak values proved the capability of the shaking table and the piezoelectric actuator for simulating cyclic and dynamic loading covering a wide range of input accelerations. Finally, the results show the measurement capability of the pore pressure sensor and its potential use for evaluating liquefaction in saturated and partially saturated soils.

The experiments presented in this paper prove the usefulness of the micro laminar box for centrifuge testing and its possibility for studying the dynamic response of more complex systems.

ACKNOWLEDGEMENTS

The authors would like to thank Julieth Monroy from Universidad de Los Andes for her technical support in the design and elaboration of experiments. Also, the authors would like to thank Universidad de Los Andes for the financial support.

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