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Identification of dynamic soil properties through shaking table tests on a large saturated sand specimen in a laminar shear box

Chi-Chin Tsai [a,*], Wei-Chun Lin [a], Jiunn-Shyang Chiou [b]

[a] Department of Civil Engineering, National Chung Hsing University, Taiwan
[b] Department of Civil Engineering, National Taiwan University, Taiwan

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ABSTRACT

Many laminar shear boxes have recently been developed into sliding-frame containers that can reproduce 1D ground-response boundary conditions. The measured responses of such large specimens can be utilized to back-calculate soil properties. This study investigates how the boundary effect in large specimens affects the identified soil properties through shaking table tests on a soil-filled large laminar box conducted at the National Center for Research on Earthquake Engineering in Taiwan. The tested soil-box system is unique because only 80% of the container is filled with soil. This system can be regarded as a two-layer system: an empty top and soil-filled bottom. The dynamic properties of this two-layer system are identified through various approaches, including theoretical solutions of wave propagation, free vibration, and nonparametric stress–strain analyzes. Therefore, the coupling effect of the box and soil can be evaluated. Results show that, compared with the two-layer system considering the influence of the box, the conventional approach with a single-layer system slightly underestimates shear wave velocity but obtains the same damping ratio of the soil layer. In addition, the identified modulus reduction and damping curves in the two-layer system are consistent with those obtained in a laboratory test on a small specimen. Furthermore, based on detailed acceleration measurements along different depths of soil, a piecewise profile of shear wave velocity is built. The identified shear wave velocity increases with depth, which is not uniform and differs from the constant velocity typically assumed for the specimen.
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1. Introduction

Soil in a level ground of infinite extent under earthquake shaking is usually modeled as a soil element undergoing a simple shear loading condition. Small soil specimens are generally tested in laboratories (e.g., using triaxial compression apparatuses and simple shear devices) under regular or irregular dynamic loads to study soil behavior, such as stress–strain relationship and liquefaction. Stress conditions and deformations in soil elements in these test types are significantly affected by boundary conditions because of the size of the specimens. Moreover, loading conditions generally do not reflect real-field situations because of the limitations of loading devices.

An increasing number of downhole arrays are currently available for measuring motions on ground surface and within a soil profile. These arrays provide valuable data in understanding in situ soil behavior under earthquake shaking. Different approaches, including nonparametric stress–strain analysis [1,2] and parametric [3,4] inverse analysis schemes, have been developed to identify dynamic soil behavior through downhole measurement. However, learning soil behavior from field measurements is an inherently inverse problem that can be challenging to solve. The extraction of soil properties also depends largely on the availability and spacing of measurements in a downhole array. Furthermore, the uncertainty of in situ conditions is uncontrollable.

As an intermediate condition between small-specimen laboratory tests and less controllable downhole measurements, large soil specimens are placed on shaking tables [5,6] or centrifuges [7]; thus, soil behavior under realistic seismic loading conditions can be observed and analyzed. Several laminar shear boxes (e.g., [6,13]) have recently been developed into sliding-frame containers to reproduce 1D ground-response boundary conditions. Dietz and Wood [6] evaluated dynamic soil properties by shaking table test on a large soil-filled laminar box. Three different excitation motions: random [9], pulse [10] and sinusoidal [11] were employed to evaluate the strain-dependent shear stiffness and damping. Afacan et al. [7] constructed centrifuge models in a laminar container to study the site response of soft-clay deposits over a wide strain range. Dense sensor arrays were used

* Corresponding author. Tel.: +886 422872221x323; fax: +886 422862857.
E-mail address: tsaicc@nchu.edu.tw (C.-C. Tsai).

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for the back-calculation of modulus-reduction and damping values. Mercado et al. [4] identified shear wave velocities and their reduction against strain through an optimization analysis of the centrifuge test of a laminar container. Experimental data from large specimens complemented the laboratory geotechnical investigation technique. However, the boundary effect can also be an issue that affects how soil properties are identified, as in the case of small specimens. Lee et al. [12] investigated the boundary effects of a laminar container on the seismic response acquired from accelerometers and pore pressure transducers at various depths and distances from the end walls. The results of the analysis revealed minimal boundary effects on the seismic responses, which confirmed the finding of the previous study [7,13] that measurements on the container agree with that within the specimen. Therefore, a laminar container may be used effectively to simulate 1D shear wave propagation in shaking table tests and the measurements on the container are commonly adopted for analysis. Nevertheless, although boundaries do not affect responses and measurements, they can still influence the identified properties. Such an issue has not yet been discussed.

In this study, the boundary effect on how dynamic properties are identified is investigated through a series of shaking table tests on a large soil-filled laminar box. The tests are conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan [8]. Unlike the common test condition that the container is fully filled with soil, only 80% of the container is filled with soil in these tests. Therefore, not only the shear wave propagation characteristics of sand can be identified, but also the coupling effect of the box and soil can at the same time be evaluated. The coupling effect of the box and soil is assessed by regarding the box and soil as a two-layer system with an empty top and soil-filled bottom. The shear wave velocity (*Vs*), damping ratio (*D*), and their variation against strain are identified through various approaches, including theoretical solutions of wave propagation, free vibrations, and nonparametric stress–strain method. The boundary effect (i.e., the laminar box) on the identified value is discussed.

2. Laminar shear box test

The laminar shear box developed at NCREE is composed of 15 layers of sliding frames, as shown schematically in Fig. 1 [13]. The size of the soil specimen in the box is 1880 mm × 1880 mm × 1300 mm. These 15 layers of frames (80 mm each) are separately supported on the surrounding rigid steel walls, one above the other, with a vertical gap of 20 mm between adjacent layers. Therefore, each layer of frames can move independently at different depths and directions, thereby mimicking 1D ground-response boundary conditions. The mass of each frame layer is approximately 8% of the mass of a 100 mm layer of soil enclosed by an inner frame.

2.1. Instrumentation

Transducers for acceleration measurements (i.e., Ay1 to Ay15 on each frame layer) were placed at various depths on the outside rigid walls (Fig. 2); piezoresistive accelerometers (e.g. PCB4Y) for acceleration measurements were also placed at different locations within the soil. Several comparisons were conducted to show that the accelerations on the frames are consistent with those within soils prior to liquefaction [13]. Afacan et al. [7] also pointed out that the measurement on the outer frames can represent the response within soils. Thus, the accelerations on the laminar box frame were directly utilized to analyze the induced motion under shaking.

2.2. Sample preparation

Fine silica sand from Vietnam was used in the experiments. The basic properties of this sand are given in Table 1. In this test, the wet sedimentation method was used for specimen preparation. Only 80% of the container was filled with soil. Fig. 2(a) shows that Ay3 is located on top of the soil. The P-wave velocity of the specimen was measured horizontally across the specimen at different depths to confirm the saturation of the soil specimen. The measured P-wave velocities were between 1500 and 1700 m/s at various depths, except on the sand surface probably because of the minor unevenness of the surface and trapping of air bubbles. The range of the measured P-wave velocities showed that the soil specimen prepared through the wet sedimentation method was fully saturated [8].

2.3. Selected test cases for analysis

A series of shaking table tests was conducted on the sand specimen in a biaxial laminar shear box starting from August 2002 [8]. The purpose of test was to investigate the liquefaction behavior of sand. In this study, we selected 15 cases in the test sequence conducted in October 2004 for analysis. These cases were selected because no liquefaction was observed. The excess pore water pressure during shaking was very small. The input motions of Cases 19, 35, and 54 were scaled acceleration recorded at She-tou seismograph stations during the Chi-chi earthquake, and the input motions of the others were sinusoidal acceleration with different amplitudes and frequencies (Table 2). The relative density, *Dr* (%), of each test was estimated based on the accumulated settlement of the previous tests and initial relative density,

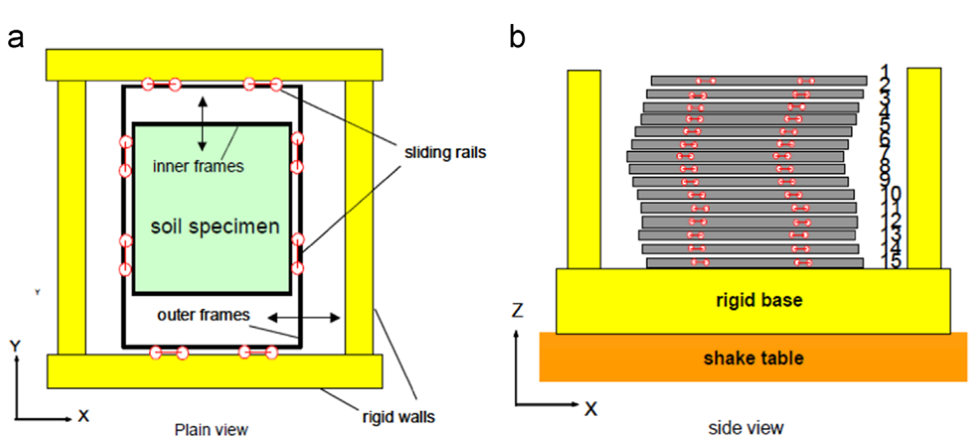

Fig. 1. Schematics of the biaxial laminar shear box [13].

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