DESIGN OF A LARGE-SCALE BIAXIAL SOIL-BOX FOR SEISMIC SOIL-STRUCTURE-INTERACTION STUDIES

A. Bitsani\textsuperscript{1}, D. Istrati\textsuperscript{1}, I. G. Buckle\textsuperscript{2}, R. Motamed\textsuperscript{3}, S. Elfass\textsuperscript{3}, P. Laplace\textsuperscript{4} and R. Siddharthan\textsuperscript{3}

ABSTRACT

This study presents results from dynamic analyses of a 1D soil-column and a 2D slice of the soil with the box walls that have been conducted in order to inform the design of a large-scale biaxial soil-box and understand its dynamic behavior. The numerical work demonstrated that (a) equivalent linear site response analyses give similar results with nonlinear analyses for levels of shaking with PGA up to 0.5g, but they over-predict the base shear forces and under-predict the shear strains for higher levels of shaking, (b) the soil nonlinearity limits the increase of the base shear, offsets the fundamental period of the soil, increases significantly the soil-strains, and results in de-amplification of the input motion towards the surface, and (c) large overturning moment is generated at the bottom of the soil-box during extreme ground shaking, and this moment can introduce significant uplift in the walls, meaning that the walls should be designed for both shear and tension. This work demonstrates that soil-boxes with flexible walls in every direction are witnessing vertical soil displacements in regions close to the walls that disturb the soil and lead to a significant boundary effect. In order to ensure that the soil-box behaves as realistically as possible, it is necessary to have walls with small lateral shear stiffness but very high axial and bending stiffness, together with a nearly perfect contact (high-coefficient of friction) at the soil-wall interface, which will transfer the complementary shear at the edges of the soil to the walls.

\textsuperscript{1}Graduate Research Assistant, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557, (email: abitsani@nevada.unr.edu)
\textsuperscript{2}Postdoctoral Researcher, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557, (email: distrati@unr.edu)
\textsuperscript{3}Professor, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557
\textsuperscript{4}Research Professor, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557

ABSTRACT

This study presents results from dynamic analyses of a 1D soil-column and a 2D slice of the soil with the box walls that have been conducted in order to inform the design of a large-scale biaxial soil-box and understand its dynamic behavior. The numerical work demonstrated that (a) equivalent linear site response analyses give similar results with nonlinear analyses for levels of shaking with PGA up to 0.5g, but they over-predict the base shear forces and under-predict the shear strains for higher levels of shaking, (b) the soil nonlinearity limits the increase of the base shear, offsets the fundamental period of the soil, increases significantly the soil-strains, and results in de-amplification of the input motion towards the surface, and (c) large overturning moment is generated at the bottom of the soil-box during extreme ground shaking, and this moment can introduce significant uplift in the walls, meaning that the walls should be designed for both shear and tension. This work demonstrates that soil-boxes with flexible walls in every direction are witnessing vertical soil displacements in regions close to the walls that disturb the soil and lead to a significant boundary effect. In order to ensure that the soil-box behaves as realistically as possible, it is necessary to have walls with small lateral shear stiffness but very high axial and bending stiffness, together with a nearly perfect contact (high-coefficient of friction) at the soil-wall interface, which will transfer the complementary shear at the edges of the soil to the walls.

Introduction

Nuclear facilities frequently have deep massive foundations, which are large enough to affect the response of neighboring soil and the nature of ground shaking these facilities have to withstand. Despite this well-recognized phenomenon, the ramifications of soil-structure interaction (SSI) are not completely understood due to the nonlinearity of the mechanics involved. As a consequence, only simplified elastic models are currently used to study SSI for these and other facilities. To address this situation, the U.S. Department of Energy (DOE) has funded a multi-institutional project to investigate SSI effects in nuclear facilities. To this end, the research team at University of Nevada Reno (UNR) is fabricating a 400-ton, laminar, biaxial soil box and corresponding shake table, which will be used to (a) explore SSI phenomena at a scale not currently possible in the U.S., and (b) validate the ESSI nonlinear computational framework, developed by UC Davis.

1Graduate Research Assistant, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557, (email: abitsani@nevada.unr.edu)
2Postdoctoral Researcher, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557, (email: distratii@unr.edu)
3Professor, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557
4Research Professor, Dept. of Civil & Environmental Engineering, University of Nevada, Reno, NV 89557

When the ground is subjected to seismic loading, the soil can move freely in the lateral direction as it is an infinite domain. All the vertical soil columns behave in pure shear and have the same response if they are in free-field and the waves propagate in the vertical direction (no oblique angle). Therefore, in order to study the seismic behavior of the soil in such cases, it is sufficient to study the behavior of one vertical soil column via site response analyses. Various methods and tools have been developed and are currently available for site response analyses, including both frequency domain and time-domain approaches. Linear and equivalent linear analyses are commonly used because they are simple and can be conducted in the frequency domain, eliminating the sensitivity to certain numerical parameters (e.g., time-step) that characterize the time-domain analyses. Nonlinear analyses can simulate more accurately the soil response, but they are not as commonly used as the equivalent linear analyses due to their complexity, lack of guidance, and validation with actual recorded data during strong shaking with large strains. Recent research studies have focused on various topics, such as the proper use of several numerical codes for nonlinear analyses, the application of Rayleigh Damping in SRAs, the matching of the soil behavior at small-strains and large-strains (e.g., [1]), the development of frequency independent damping formulations ([2]), and the comparison of nonlinear analyses with recorded data from vertical arrays ([3]-[4]).

Although site response analyses are a very useful tool, they can be used only for free-field motions and only for certain field conditions where the wave propagation is totally vertical. To study the dynamic soil behavior for areas where soil-structure-interaction is significant (e.g., massive or embedded structures), more advanced numerical and experimental methods are required. Numerically SSI is studied using 2D and 3D finite element models, while experimentally this is done via centrifuge or 1g-shake table testing. Several soil-boxes with different dimensions and wall configurations usually at small-to-moderate scale, with max in-plane dimension between 1m to 3m (e.g., [5]-[7]) have been developed in the last few decades. Dihoori et al. ([8]) investigated the dynamic behavior of two uniaxial laminar shear boxes with the larger one having a length of 5m, and demonstrated the existence of wall end effects for large magnitude shaking, which led to circulation of the soil close to the walls and deviation from 1D pure shear behavior, highlighting the significance of the soil-wall interaction. The above study concluded that it is important to understand the behavior of the box itself in order to properly interpret the experimental results. Other large-scale soil-box have also been developed and used in several studies such as the ones presented in [9] and [10].

Objectives

The objectives of this study are to present part of the advanced computational modeling and parametric numerical analyses that were conducted in order to understand (a) the dynamic behavior of a simplified soil column and a complex soil-box system, (b) the role of soil nonlinearity, (c) the interaction of the walls with the neighboring soil columns, (d) the effect of the wall properties on the dynamic response of the box, and (e) the role of sliding at the soil-wall interface. It is important to understand the significance of the above parameters for different levels of ground shaking, from frequent low-level events up to extreme events that will exceed the design basis level.
1D Site Response Analyses in DEEPSOIL

Description of Numerical Models

During the preliminary design phase the height of the soil-box was estimated to be 20ft, and a soil column model with the same height was developed in DEEPSOIL ([11]). The model was discretized using 1ft deep soil layers, meaning that there were 20 soil layers in total. For the analyses two soil types were initially considered, a dense one with $\gamma = 120$pcf and $Dr= 75\%$, and a loose one $\gamma = 90$pcf and $Dr= 30\%$. The fundamental periods were 0.13sec and 0.16sec for the two previous soil types respectively. Since the software has the capability of conducting different types of analyses, the authors conducted linear analyses as well as equivalent linear and nonlinear analyses. In the analyses the MKZ model was used with Non-Masing unloading-reloading rules in order to capture the hysteretic soil behavior. The Seed & Idriss backbone curves were used as a reference curves in the initial analyses, and then the sensitivity of the results to the backbone curve was examined via comparison with Darendeli’s curves. The numerical analyses were conducted for a suite of eight, two-component ground motions taken from the PEER database, for sites with similar seismogenic and geotechnic features as found at the sites of different nuclear facilities. The selected motions with the corresponding site conditions are shown in Table 1. These ground motions were initially scaled linearly to a PGA equal to 0.26g and then different scaling factors were used in order to achieve strong shaking of up to 1.04g (SF=4).

<table>
<thead>
<tr>
<th>No.</th>
<th>Earthquake</th>
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<th>M</th>
<th>Site Vs30 (m/s)</th>
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<td>213</td>
<td>D</td>
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<td>6</td>
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<tr>
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<td>Erzincan</td>
<td>6.7</td>
<td>352</td>
<td>D</td>
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</tbody>
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Linear, Equivalent Linear and Nonlinear SRAs

This section will present results from linear, equivalent and nonlinear analyses. Linear analyses were conducted to increase our understanding of the dynamic response of the soil-column and get an upper bound of the stresses and forces. Moreover, at very small shear strains the soil nonlinearity is small and linear analyses might realistically predict the response. For larger strains, a standard practice for the industry is to conduct equivalent linear analyses This type of analyses simplify the nonlinear problem by solving it as linear problem with consecutive iterations on the shear modulus and damping values. Two of the main parameters of interest for the design team was the base shear that the new system would have to withstand, and the maximum shear strains
that the soil will reach during shaking. This parameters directly obtained or calculated from 1D site response analyses of different magnitudes with scale factors between 0.5 (PGA=0.13g) and 4 (PGA=1.04g). These parameters are plotted in Fig. 2 for the three types of analyses and the El Centro 180 input motion. As expected the linear analyses give an upper bound for the base shear and a lower bound for the shear strains, and even at a PGA=0.13g the linear analyses over-predict the base shear by a factor of 2. At PGA=1.04g (SF=4) this over-prediction is by a factor of 5, demonstrating that linear analyses cannot capture properly the behavior of the soil column at such high levels of shaking. On the other hand, equivalent linear analyses seem to give identical results with nonlinear analyses up to a PGA of 0.26g, and relatively close results up to PGA of 0.5g (SF=2). In particular, at SF=2 the equivalent linear analyses over-predict the base shear by 18%, while at SF=4 this over-prediction is 30%. Regarding the shear strains the equivalent linear analyses are under-predicting them as expected, however the interesting thing is that the largest difference occurs at SF=2 (44% lower) instead of SF=4 (25% lower). The fact that the equivalent linear analyses give values relatively close to the nonlinear ones, gives an extra level of confidence in the nonlinear numerical solution. It must be noted that the base shear has been calculated for assumed 18ft x18ft in plane dimensions and 20ft height with a total weight of 780kips.

Figure 1. Diagrams with max shear strains (top) and max base shears (bottom) for different ground shaking levels of the El Centro 180 record

**Effect of Ground Shaking Intensity**

Since one of the main objectives of the new system is to conduct seismic experiments that will introduce both significant soil nonlinearity and significant SSI effects, it was deemed critical to understand the behavior of the soil-box at different levels of shaking and determine the response of the soil surface and the associated frequencies, which will prove useful for the optimal selection of the structural properties for future SSI experiments. To this end, Fig. 2 shows the acceleration response spectra at the surface of the soil column for two levels of shaking for several ground motions. As expected at the lowest level of shaking, the surface acceleration response spectra is maximized at a period close to 0.15-0.22 sec, which is relatively close to the fundamental period of the soil column (0.13sec), indicating small levels of soil-strains. On the other hand, at the higher level of shaking the peak PSA occurs at approximately 0.5-0.6sec, indicating significant shifting of the fundamental period of the soil column due to the softening that takes places after the soil yielding. This indication is strengthened via the examination of the PGAs at different soil depths. For SF2 the ground accelerations are amplified from the bottom to the surface, however for SF4 this is not happening but instead for some motions the accelerations are reduced at the top.
indicating significant soil nonlinearity. Examination of the maximum strains revealed that for SF1 strains are less than 0.2%, while for SF4 they are very large with most of the motions being in the range of 1-5%. These large strains were translated into significant horizontal relative displacements, which were seen to be in the range of 2 to 5.5 inches at the surface (for most motions). In summary, the soil nonlinearity limits the increase of the base shear, which is beneficial for the actuators of the shake table, however it increases significantly the shear strains meaning that the soil-box should be able to accommodate larger relative displacements.

Figure 2. Acceleration response spectra at surface (top), profile of peak ground accelerations (middle), and profile of maximum shear strains, for two levels of shaking, PGA=0.26g (left) and PGA=1.04g (right)

2D Nonlinear Dynamic Analyses in LS-DYNA

Description of 2D numerical models

In order to advance the understanding of the behavior of the actual soil-box and provide information for its design more advanced types of analyses are required in addition to the 1D SRAs. In particular more complex models, which simulate the soil and the walls of the box should be developed. To this end, the general purpose commercial finite element software LS-DYNA ([12]) was selected for the development of advanced finite element models. The soil was simulated using the MAT_HYSTERETIC_SOIL as in [13], which is a nested surface model that consists of
ten superimposed elastic-perfectly plastic layers. Strength-adjusted backbone curves were used as input following the same approach as in [4]. For simulating the seismic motion prescribed boundary conditions and particularly acceleration time histories were applied at the bottom nodes of the last soil layer. SPC constraints were used to constrain the out-of-plane displacements of all the nodes of the soil column, as well as the vertical displacements of the bottom nodes. Two construction stages were defined, with the first one applying the gravity loading to develop the correct vertical soil stresses, and the second one applying the lateral seismic motion. In addition to the hysteretic damping automatically calculated by the nonlinear material model, 2% frequency-independent damping was applied in order to capture the small-strain damping. The walls were simulated as interchangeable layers of a very stiff material –steel/aluminum- and a very soft material, namely rubber. These layers were simulated via 3D solid elements with two elastic materials, and these elements were assumed to be perfectly connected to the soil elements next to them. Since in reality it was expected that the elongation of a certain layer of the walls would be minimal/negligible, this was simulated in the 2D slice model by assigning horizontal constraints at the external nodes of the walls that had the same elevation.

**Selected Results – Model with Perfect Contact at Soil-Wall Interface**

This section will present numerical results for the aforementioned 2D model with flexible walls (in every direction). Fig. 3 shows the deformed shape and the shear stresses in the model at \( t=22.4 \) sec. From the deformed shape it can be observed that there are some vertical displacements close to the walls of the box, indicating that the box does not behave purely in shear. Moreover, for a certain soil layer the stresses are not uniform along the whole length of the layer, with the two-three soil columns closer to the walls witnessing different stresses than the ones close to the center of the box, demonstrating the existence of a boundary effect caused by the walls. To get a more quantitative insight, Fig. 4 shows the PGA profile recorded at the center of the box and the columns close to the left and right walls. As expected the acceleration histories at the bottom nodes are identical, which is reasonable since all these nodes were assigned the input motion. However, as the shaking propagates from the bottom to the surface of the soil, differences in the accelerations of the left and right column relatively to the center one start appearing. For most soil layers the PGAs in the middle column are larger than the ones in the other columns. It is interesting though that the two soil columns (left and right) close to the walls of the box witness very similar PGAs.

Despite the consistent trend in the PGAs, there is no consistency in the maximum shear strains with the soil layers of the left and right columns below the mid-depth witnessing smaller strains than the center column, and the ones above the mid-depth witnessing larger strains. Fig. 5 shows the vertical forces in all the boundary nodes at the bottom, at two different instants during the shaking at an instant close to the PGA. An interesting observation that can be made by examining this graph is that although pre-shaking all the boundary nodes have compressive forces due to the self-weight, when the shaking starts the vertical forces in the nodes below the walls become out-of-phase, indicating the significance of complementary shears at the soil-wall interface and the generation of overturning moment at the bottom of the soil-box. This overturning moment can be so significant that the uplift forces introduced in the wall can significantly exceed the counter-acting weight resulting in large tensile bearing forces. This means that the bearings of the walls should be designed to take both shear and tension. This moment seems to distort the soil areas close to the walls and alter the shear strains relative to the ones at the center of the box.
Figure 3. Snapshot of the deformations (left) and the shear stresses (right) of the 2D soil-box model at t=22.4sec

Figure 4. Peak ground accelerations (left) and peak shear strains (right), recorded at the left, middle and right soil column of the 2D soil-box model at t=22.4sec

Figure 5. Vertical reaction forces at the boundary nodes below the box at different locations along the length of the 2D model, recorded during the shaking

Effect of Wall Stiffness

The preliminary nonlinear analyses presented up to this point revealed the existence of a boundary effect that resulted in the creation of disturbed regions of soil close to the walls. In all these models the walls of the box consisted of steel and soft rubber with a small elastic modulus resulting in a very small shear stiffness of the box (desired feature), as well as a small axial and bending stiffness.
The small axial and bending stiffness coupled with the significant overturning moment and complementary shear lead to noticeable vertical wall displacements during the horizontal ground shaking, demonstrating the existence of a complex soil stress state next to the walls, different from the targeted pure shear. To deal with this issue and get an insight into the effect of wall stiffness different design alternatives were considered. In this paper, only the first modification will be presented, which was the addition of vertical constraints to all the nodes of the left and right wall respectively meaning that the walls were now allowed to deflect horizontally based on the low shear stiffness of the laminar walls, however they were not allowed to undergo any vertical displacements (practically zero axial and rotational deformation of each rubber layer), leading to elimination of flexural effects.

Figure 6 shows a snapshot of the contours of shear stresses for the 2D soil-box models with and without vertical constraints, obtained from LS-PrePost. It is very interesting that although the boundary effect and the non-uniform shear stresses in the case of the model without the constraints seem to extend to a distance from the wall equal approximately to 15% of the total length of the slice, the respective distance is minimized when vertical constraints are used, demonstrating that the soil is now in pure shear. This indicates that the significant boundary effect observed in the previous section was due to the flexural behavior of the walls (small axial and bending stiffness of the rubber) and the existence of a perfect contact between the soil and the walls, which transferred all the flexural effects to the soil. One of the most interesting conclusions that can be reached from Fig. 7 is that although the base shear increases slightly with the addition of vertical constraints, the axial forces in the walls increase by an outstanding factor of 3. This result becomes even more interesting since the same figure shows that the overturning moment in the model with the vertical constraints is smaller. This can be possible explained by the fact that in the case where there were no vertical constraints the larger overturning moment was taken partially by the walls of the box and a soil region close to the walls that is highly disturbed and in a complex stress state. On the other hand, when vertical constraints are present in the walls, the axial and flexural stiffness of the walls is very high (almost rigid), most of the soil is in pure shear, and the overturning moment is translated into axial forces in the walls. Results from additional parametric analyses can be found in [14].
Conclusions

This study presented part of the computational modeling and analyses that have been conducted in order to inform the design of a large-scale biaxial soil-box and to understand its behavior for different wall properties. The numerical results give an insight into the seismic behavior of the soil-box and are expected to be useful to other research teams designing their own soil-box. This study demonstrated that:

- Equivalent linear site response analyses give similar results with nonlinear analyses for small to moderate levels of shaking (PGA=0.5g), but they over-predict the base shear forces and under-predict the shear strains for higher levels of shaking.
- The soil nonlinearity limits the increase of the base shear, offsets the fundamental period of the soil, increases significantly the soil-strains, and results in de-amplification of the input motion towards the surface.
- Laminar walls that are flexible in every direction are witnessing vertical soil displacements in regions close to the walls, indicating that the soil is not in pure shear, demonstrating the existence of a significant boundary effect caused by the walls.
- Large overturning moment is generated at the bottom of the soil-box during extreme ground shaking, and this moment can introduce significant uplift in the walls via the
complementary shears, meaning that the walls should be designed for both shear & tension.

- To ensure that the soil-box will behave as realistically as possible, it is necessary to have walls with small lateral stiffness but very high axial and bending stiffness, together with a nearly perfect contact (high-coefficient of friction) at the soil-wall interface, which will transfer the complementary shear of the soils to the walls and minimize the boundary effect.

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