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DESIGN VERIFICATION OF A LARGE SCALE LAMINAR SOIL BOX

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Abstract

Through a collaborative United States Department of Energy (US DOE) project, a large-scale laminar soil box is currently under construction at the University of Nevada, Reno. This box will form the core of a new experimental capability for studying the phenomenon of soil-structure-interaction (SSI) and provide new data for the testing and validation of SSI numerical models. Along with Lawrence Berkeley National Laboratory, San Francisco State University, and the University of California, Davis (UC Davis), extensive work on design verification of the soil box was conducted. Once completed, the octagonal shaped experimental system will measure 4.6m tall with an inner radius of 6.6m. Steel HSS beams and elastomeric bearings comprise the main structural system of the box itself. The ultimate goal of this large-scale soil box is to conduct shake table experiments and explore the potential SSI effects for representative nuclear facilities found in the United States. With the desire to investigate the influence of nonlinear soil behavior on the structural response, the computational simulations associated with the design verification of this system are quite complex. As a result, this paper covers the phased, systematic approach used in evolving the models for the soil box system from single brick elements to full-scale finite element models. This work was conducted with the RealESSI code, a finite element program developed at UC Davis. As part of this project, new structural elements were implemented into the program. As a result, the box verification studies started with simple single degree of freedom models verifying the capabilities of the new isolator element. From there, a single layer was modeled and finally a full box system. Using static analyses, the response of the box was initially understood prior to any introduction of the soil and confirmed the elastic behavior of the box. Next, the soil work was quite extensive with modeling taking place at the single brick, column, core, and then full-scale system. Using both linear and nonlinear soils for static and dynamic analyses, the constitutive models were calibrated and analyzed. This work presents one approach to addressing the need for verification studies to build confidence in large scale computational models, understand the complex dynamics of soil-structure systems, and prepare computational models for simulating future experimental configurations.

Keywords: laminar soil box, soil structure interaction, computational simulations, design verification

1. Introduction

A large-scale laminar soil box is currently under construction at the University of Nevada, Reno's Earthquake Engineering Laboratory as part of a United States Department of Energy (US DOE) project. This collaborative effort is bringing together the structural and geotechnical expertise of a number of institutions including Lawrence Berkeley National Laboratory (LBNL), University of Nevada, Reno (UNR), University of California, Davis (UC Davis), and San Francisco State University (SFSU). The goal of this new experimental testbed is to study the phenomenon of soil-structure-interaction (SSI) and provide new data for the testing and validation of SSI numerical models especially for representative nuclear facilities. To substantially extend the knowledge of SSI, a major objective of this experimental system is to enable soils to exhibit nonlinear behavior. This complex behavior will allow investigators to better understand the impact on structural systems as well as evaluate the ability of computational models to accurately predict the associated seismic risk.

The soil box as shown in Figure 1 is an octagonal cylindrical box measuring 4.6m in height with an outer diameter of 6.9m. The box consists of layers of steel HSS beams and elastomeric bearings as shown in Figure 2 to provide sufficient flexibility to the system. The interior side of the box has steel face plates welded onto the HSS beams to enclose the box from the soil material. This design was created by UNR based on the past performance of similar laminar soil boxes tested worldwide. Additional literature related to this box design can be found in Bitsani et al [1] and Wong et al [2].

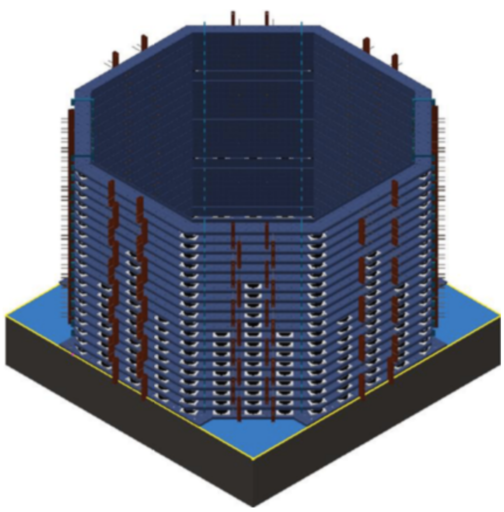

Fig. 1 – Large-Scale Laminar Soil Box Rendering

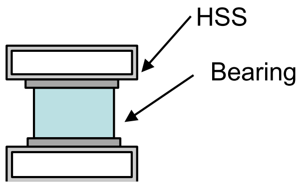

Fig. 2 – Side View of a Box Layer

To complement the design and construction of the soil box at UNR, the work at SFSU is focused on developing a computational model to verify the design and prepare for future validation against the experimental results. The coupled relationship of the flexible box and nonlinear soil presents intricate and

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complex behaviors that must be verified before being implemented in the full computational model. For this reason, the model was systematically developed in stages. This paper herein covers the approach to verifying the box and soil systems using the nonlinear finite element code Real ESSI [3]. This work aims to provide the larger engineering community insight into the verification process of a highly complex system and highlight the challenges, advantages, and continued efforts for this approach.

2. Approach

The modeling approach for this laminar soil box was taken in three main stages: box only, soil only, and box-soil system. The box and soil were modeled separately due to the detailed nature of each of these components as discussed below.

2.1 Box Only

For the box, there is a mixture of materials (i.e. elastomerics, steel) with a unique geometry introducing inherent complexities to the system dynamics. This box is an innovative application of bearings with 20 rings of steel supporting 19 layers of bearings with four different sets of properties and varying distribution of bearings through the height. This design is on the next frontier of bearing usage as the traditional systems are single layered. In this case, multiple layers of bearings are used to increase the flexibility of the box structure providing containment to the soil without hindering its movement.

As part of this project, various new structural elements were introduced into the Real ESSI system to aide in the development of the soil-box computational model. These additions included a new bearing element. Although a traditional elastic beam could suffice, the new bearing element [4] allows for the inclusion of any potential P-Delta effects. In this model, ideally the bearing will remain fully linear with no P-Delta behavior. However, it is important to ensure the model is capable of capturing this behavior in the case that the system reaches a level of excitation capable of initiating this behavior. The damping of each model stage was defined using 5% Rayleigh damping anchored to the first and third modes. In the case of the single bearing, stiffness proportional damping was applied.

Given that the system consisted of layers of similar HSS-bearing-HSS composition, the box itself was evaluated at the single bearing, single layer, and full system level (Figure 3). For each model, eigen and pushover analyses were conducted to ensure the appropriate mass and stiffness was being captured. At the single bearing level, the model also underwent a P-Delta Equilibrium Check which allowed for a base overturning moment to be calculated by hand and compared against the Real ESSI reaction moment at the base of the bearing.

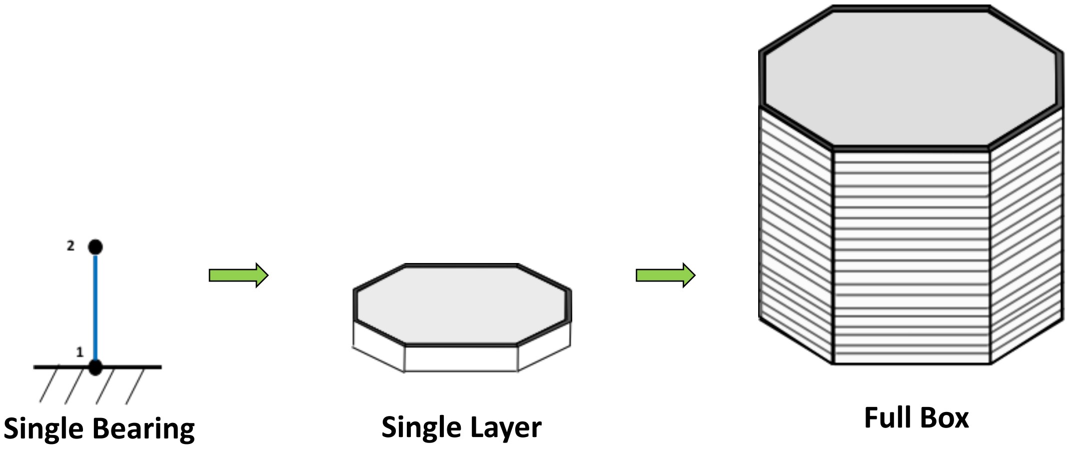

Fig. 3 – Box Modeling Approach (Note: Not drawn to scale)

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Next, a single layer of the box was modeled with the bottom section being of interest. This layer is comprised of a rectangular steel bottom plate, 32 bearings, and a HSS beam. The system was discretized such that there were 64 beam elements for the bottom plate and HSS beam rings in addition to 32 vertical bearing elements. In total, this single layer consisted of 128 nodes and 160 elements. In this system, a similar set of calculations were done via hand. The mass of all the elements were applied to the system as distributed mass rather than nodal mass. For these systematic checks, the degrees of freedom (DOFs) out-of-plane were restricted to simplify the mathematical scenario. Firstly, knowing the lateral stiffness of each bearing (30.3kN/cm) and the supporting weight of the system, the period of the single layer was calculated as 0.0386s. This is a rather stiff layer as it is at the base of the box's structural system and requires more stability than the layers above. This was then compared against an eigenanalysis in Real ESSI which resulted in a 0% absolute difference. The pushover analysis reinforced the linear response of the bearings while verifying the idealized behavior of the layer.

From here, the final step was the full box. In total, the full box consisted of 1,280 nodes and 1,656 elements (including beam and bearing). In this last step of the box only analysis, the same studies were conducted using the simplified DOF approach which allowed the entire system to be reduced to a simple shear structure with 19 lumped masses with the layer equivalent stiffnesses defined by the total lateral stiffness provided by the bearings at each layer.

This three stage approach incrementally added complexity to the model. This allowed the authors to better understand and identify potential issues with the material and geometry definitions before fully testing the 1,280 node model. This approach is extremely time efficient as the time needed for these analyses increased with model complexity. The single bearing and single layer analyses could be conducted in less than a minute. The full box took significantly more time anywhere between 10 to 20 minutes depending on the analysis. In considering time efficiency, testing the model at the bearing and layer levels provided significant opportunity to quickly check the models and perform any sensitivity analyses necessary. With the box verified, the next step was to build the soil model.

2.2 Soil Only

The modeling of soil is not a straightforward process due to the various material models available for use (i.e. Drucker Prager, Von Mises). The ultimate goal of the selected soil material model is to exhibit nonlinear response within the confines of the box structure. However, before implementing a fully nonlinear material, a linear material model was also used to verify that the soil system was defined appropriately. This also allowed for an inter-code comparison to be conducted with a LS-DYNA model. The soil modeling was broken down into stages similar to the box. In this case, the soil was evaluated as a single brick, column, core, and full soil-box as shown in Figure 4. As the specific soil to be used in the experimental testing has yet to be determined, a representative medium dense sand material was used in these models.

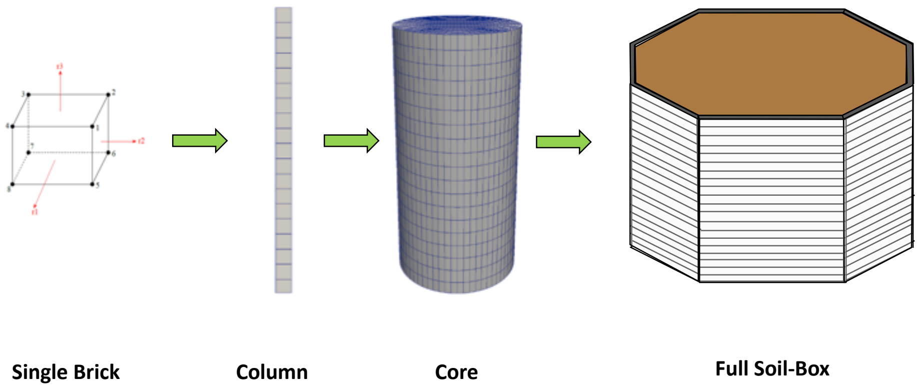

Fig. 4 – Soil Modeling Approach (Note: Not drawn to scale)

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Within the Real ESSI platform, a material driver was used that imposes two loads onto the system. The first is a confining pressure simulating the elevation or depth of a single brick. The second loading is a shear force to reach a defined maximum shear strain. In this case, our goal is to achieve as closely as possible a 1% shear strain. Using this driver, a variety of soil material models were implemented to understand their behavior throughout the depth of the soil box with relatively minimal computational demand. These material models included a linear, von mises, and multi yield material [5] available in Real ESSI. Using these models, the behavior at various depths could be explored. The linear material was used to calibrate the single brick element which consists of 8 nodes and 8 Gauss points. As expected, with increasing depth, the slope of the stress-strain curves increased corresponding to increasing shear moduli as shown in Figure 5. From here, two nonlinear material models were evaluated. The goal in this case was to match a G/Gmax curve as closely as possible to a curve provided by UNR that was fitted to Seed and Idriss [6] shown in Figure 6. As in the case of this scenario, there was no access to test results to aide in the calibration of the soil material model. As a result, the calibration was based on matching the G/Gmax curve along with meeting the yield strength values provided for each layer. Based on this, the soil material was calibrated through the soil depth.

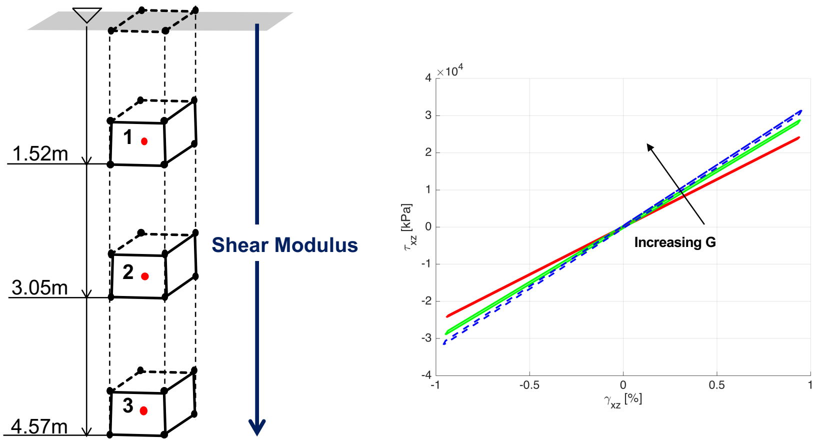

Fig. 5 – Material Driver Brick Analysis through Depth of Soil with Linear Results (Right)

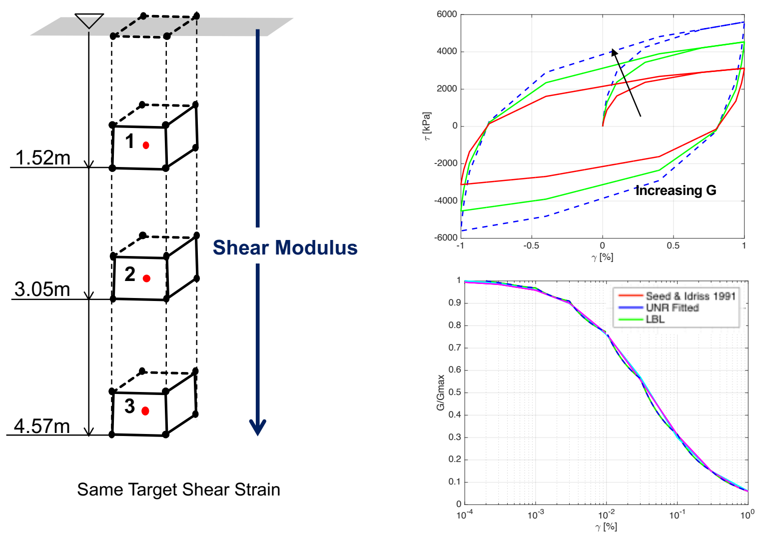

Fig. 6 – Material Driver Brick Analysis with Nonlinear Soil Material – Hysteresis & G/Gmax Curve (Right)

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The next steps in the process consisted of the single column, core and full soil-box. In the case of this project, this process actually took place in reverse. Significant effort was placed at calibrating the soil material and then implemented into the full soil-box based on the assumption that only the full soil mass could produce the most accurate response to any type of analysis (which was later disproved). In doing so, this model was large with 2,900 nodes and 2,508 elements encompassing both the box structure and the soil. Two different full soil-box models were used: 1) tied nodes and 2) contact elements between the box and soil. Running this large scale system resulted in computational studies taking 6 to 24 hours running sequentially for simple analyses. With the inclusion of a nonlinear soil, the use of parallel computing reduced the analysis to several days versus several weeks which is still a very time intensive process for simple checks. Although the soil was calibrated at the single brick level, calibrating a full complex system such as this is quite difficult given the geometry and the complex dynamics between the soil and box surface. Results from a comparable LS-DYNA model were available for comparison aiding in the efforts to build confidence in the ability to model this soil-box system in various finite element software.

In addressing this extensive computational time, efforts changed to find a means of reducing the system to a more computationally efficient means of conducting exploratory studies on the material models. This led to the creation of a single column and core model whose results could be compared against the full soil-box system.

The single soil column is comprised of 19 brick elements; each brick representing a single layer of soil in the box. The column had a two-stage loading scenario similar to the single brick. In this case, master-slaving the nodes of the brick allowed the system to be loaded with gravity without dilation of the material. (Master-slaving is a process for which a single node in a layer controls the movement of the other nodes in specified degrees of freedom.) The column then was tested using pushover and dynamic excitations to generate a response for the system. Before discussing the results of the column, it is important to discuss the core and full soil box system. The core is a 2.7m diameter cylinder section of soil with the same layering as the column and full soil system. The core has the same set of constraints applied to ensure that the core does not dilate during gravity loading and is only allowed to shear for sub sequential excitations. This conditioning imposes similar constraints as those the box would create in the full soil-box system. Considering that the column and core are both a sub-set of the full-soil box system, let us review the results. As shown in Figure 7, the results for the column and core systems match with extreme confidence with the full soil-box for the elastic soil material. These results were recorded at the top of the surface as these responses will inform the potential behavior of the superstructure placed on top of the soil substrate.

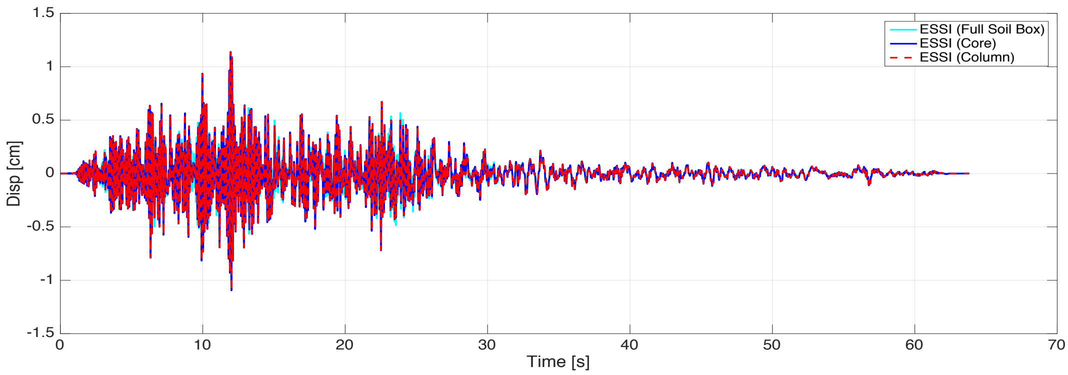

Fig. 7 – Elastic Soil Material Displacements at Top of Soil For Column, Core, and Full Soil-Box

In looking at these same models with nonlinear material, the level of confidence was not as strong but reasonable. As shown in Figure 8, the three models are plotted in the same graph for the von mises material. Here there core and column appear to have higher displacements than the full system. However, in looking at the permanent offset of the models, there is an interesting response between the column and core. Considering that the core is closest in size to the column, one would expect the core to have the most similar

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response to the full system. However, in this case, the column actually provided the closest response. As the core is being sought as the means of testing not only soil models but also potential experimental systems, this anomaly is subject to current studies. Understanding the variation in the response will be key to refining this model a bit further to ensure that the behavior can be accurately captured at any of these levels. Notably, however, the column and core show very similar responses. The full system has some additional high frequency responses especially in the 10 to 20 second segment that were not captured as well with the simplified models.

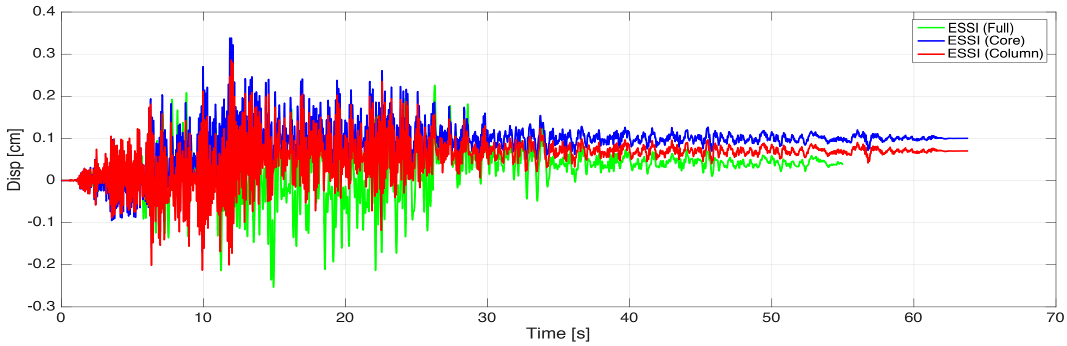

Fig. 8 – Nonlinear Von Mises Soil Material Displacements at Top of Soil For Column, Core, and Full Soil-Box

3. Conclusion

The goal of model verification is simple: ensure that the physical situation is captured accurately in the computational representation. Although this idea is very logical and a seemingly simple task, this process can actually be one of the lengthiest and difficult tasks in a project. For this soil-box, the geometry, materials, and interfaces of box and soil present a very unique situation with numerous dynamic components coming together with a single objective: provide a reasonably flexible structure to allow soil movement to initiate nonlinear response. With each component of the full system having a major role in this objective, it was important to understand the behavior and performance at the component and system level.

For the box structure, this could easily be broken down into the bearing element then layers of the box. With each stage of the process, new intricacies were introduced into the model presenting an opportunity to observe how the component response scaled up. By doing this, the box structure was fully understood and modeled with precision and accuracy measured against hand calculations, inter-code comparisons, and use of basic mechanics equations.

For the soil system, although it is comprised of only soil, there were fifteen different sets of soil properties giving each layer a unique strength and stiffness. Due to this stratification of material and the nature of soil material models, the parameter definitions had to be calibrated for every layer. This was initially done using a single brick element. Based on the experience of this model, it was determined that an efficient approach to developing the full soil mass is very similar to the box structure. A single column and core can be developed to alleviate the immense time commitment required especially for nonlinear materials. The linear material comparison between the single column, core and full system showed excellent confidence of the response at the top of the soil mass for all three models. However, for the nonlinear system, the column compared the best to the full system. This was an interesting result given that the expectation was for the core model to be the most representative simplified system. Although there is this slight discrepancy between the three models, the fact that the column and core can provide preliminary results at a significantly reduced length of time. Given the necessity to run various soil model scenarios, the use of this multi-stage process will continue to be applied for this project. Research will continue to understand the variance in the column and core models to find a means of improving this verification step.

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Overall, the use of multi-stage verification is an immense asset to any model. Having results to build upon at every stage of the model construction, enhances the ability for researchers to be confident in their simulations and provide a quality product. The model and approach discussed here is an example of one path to verification. Given the components involved in the soil box system, this approach worked the best. In general, the verification process needs to be evaluated in terms of the elements, materials, and other model details that could add complications to the overall system as well as provide information contributing to progressive model development.

4. Acknowledgements

This research was supported by the U.S. Department of Energy.

5. References

References must be cited in the text in square brackets [1, 2], numbered according to the order in which they appear in the text, and listed at the end of the manuscript in a section called References, in the following format:

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