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Duct seal design considerations in a rigid container for dynamic centrifuge modeling of liquefiable deposits

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ABSTRACT: Centrifuge modeling represents, with finite size, soil layering effects that in prototype may have infinite lateral extent. Different container types each have advantages and disadvantages in their ability to represent the prototype behavior of a soil deposit and its infinite boundaries. The appropriate choice and design of the centrifuge container, therefore, depend on the research questions of interest and modeling priorities. Rigid containers can easily be made of three aluminum sides and one transparent side, allowing for particle image velocimetry (PIV) with high-speed photography. A transparent Perspex wall enables visualization of various deformation mechanisms in a stratigraphically variable and layered liquefiable soil profile, which was a priority for the presented study. The rigid boundaries, however, inherently amplify wave reflections compared to softer boundaries like a laminar box, which can adversely impact the reliability of observations in a dynamic test, particularly accelerations. These adverse effects can be reduced by applying Duct Seal on the end walls to absorb a portion of the incident wave energy. In this paper, we summarize the design objectives and construction of a new rigid container at the University of Colorado (CU) Boulder's 400g-ton, 5.5 m radius centrifuge facility. Fully-coupled, 3-D, nonlinear numerical simulations of the intended centrifuge experiments help evaluate the boundary effects associated with a rigid container and the influence of duct seal (DS) with varying thicknesses and properties on spectral accelerations within the model specimen with and without a building model. The results point to the importance of adding DS in rigid containers to improve the accuracy of predicted accelerations closer to the container boundaries (L/B<4) when compared to an idealized laminar condition.

Keywords: Centrifuge modeling, particle image velocimetry, boundary effects, deformation mechanisms, liquefaction.

1 INTRODUCTION

Recent developments in geotechnical engineering research include the implementation of Particle Image Velocimetry (PIV) to visualize deformation mechanisms within a visible soil section in dynamic centrifuge testing. High frame rate cameras are used to capture digital images of an exposed plane of the soil model through a transparent window on one side of the container, often requiring the design of a container with rigid boundaries. Rigid containers can, however, introduce large boundary effects as opposed to other container types commonly used in dynamic testing, such as laminar or flexible-shear-beam containers. Previous centrifuge studies have highlighted the need to include duct seal inclusions to the sidewalls of a rigid container to reduce boundary effects. Some benefits include the partial reduction of wave reflection, allowing the absorption of 65% of the incident wave energy as quantified by Steedman and Madabhushi (1991), and the reduction of sidewall lateral stiffness (Cheney et al. 1998).

A series of centrifuge tests is planned at CU's 400 g-ton centrifuge facility to measure and visualize the deformation mechanisms in interlayered liquefiable soil deposits, in the far-field and near a structure, using PIV techniques. This paper first describes the design considerations and construction challenges of a new, transparent, rigid container used for the planned experiments. Fully-coupled nonlinear finite element analyses of the anticipated centrifuge experiments are then used to quantify the boundary effects introduced by a rigid container compared to other container types. The seismic response is evaluated in terms of spectral accelerations, excess pore pressures, and settlement. A limited sensitivity study is then performed to investigate the influence of duct seal thickness, uncertainties in its properties, and distance to lateral boundaries on the response in the container.

2 DESIGN AND CONSTRUCTION

The inside dimensions of the new rigid container without a Duct Seal interface were selected as 967 (Length) x 375 (Width) x 350 (Height) mm in model scale (Fig. 1), for an anticipated centrifugal acceleration of 70g. This size was determined based on the limitations of the centrifuge platform in both plan view and headroom space and to minimize boundary effects on the response of soil and structure under investigation. Whitman & Lambe (1986) quantified the zones close to the end walls as 1.5-2 times the depth of the soil affected by the artificial boundary, leading to a target length to height ratio (L/H) above 3. The designed container represents a ratio (L/H) of 3.8 for a characteristic soil profile with H=18 m (note: all dimensions are in prototype scale unless specified).

The Duct Seal (manufactured by Gardner Bender) inclusions, the thickness of which is designed in this paper, to be placed at the elevations corresponding to the soil profile is shown in Fig. 1b. Rigid containers can easily be made of three aluminum sides and one transparent Perspex wall, allowing for visualization on one side. The Perspex was designed as a 76 mm-thick concentric rectangle with extruded portions on both sides. Two extra metal framing sides with cavity sections enclosed the Perspex wall to ensure better sealing and support. For design purposes, a limit of $\delta/H=0.003$ was desired to prevent reaching an active condition in loose sand (Das, 2016), where δ is the sum of the maximum lateral deflection from the front and back plates, and H is the total depth (400 mm in model scale, from the top of the angle to the base plate). Therefore, the maximum static lateral deflection was limited to 1.2 mm in model scale when filled with saturated sand during spin up to 70g, assuming a $K_O=1$, which may be approached momentarily in a liquefied state.

Finite element analyses were performed initially to study the sensitivity of the container's lateral deflection profile along the container's long span to the properties of aluminum and acrylic when filled with saturated sand (Fig. 1a). At the design stage, the aluminum and acrylic materials were assumed simplistically to remain linear-elastic. The static lateral earth pressures were theoretically evaluated based on a uniform sand layer with a saturated mass density of $\rho_{SatSoil}=2{,}000$ kg/m^3, centrifugal acceleration N=70, and a conservative coefficient of at-rest earth pressure of $K_O=1$ at the time of liquefaction. The back and front plates had a maximum deflection of 0.6 and 0.4 mm, respectively, totaling 1 mm in model scale (70 mm prototype). The container's geometry and properties were selected to obtain a maximum deflection of about 1.2 mm (threshold). This represents a conservative estimate because the anticipated series of centrifuge tests cover a soil height of 18 m as opposed to the entire container height (24.5 m). Further, the four steel instrumentation racks that span the container width and would thus brace the container were not considered during the analysis.

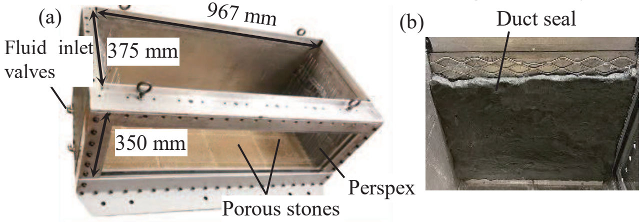

Figure 1. The new transparent rigid container designed for dynamic experiments at the CU 400 g-ton centrifuge facility: (a) photograph of the fabricated container with its various dimensions, and (b) view of Duct Seal and shear rods at the end of the container edge

Due to plane-strain (2D) requirements when introducing PIV, a single-degree-of-freedom (SDOF) structure representing the key dynamic properties of a typical 4-story moment-resisting frame structure, founded on a stiff strip foundation was designed for an upcoming series of centrifuge tests. The structure was made of aluminum representing a foundation width (B) of 10 m and a height to width ratio (H/B) of 1.4, with a bearing pressure of approximatively 90 kPa. The fixed-base natural period, measured from impact hammer tests, was 0.87 sec. The distance between the foundation edge and container lateral boundaries (L) was 27 m, representing an L/B ratio of 2.7.

3 NUMERICAL MODELING

To investigate the boundary effects for the planned centrifuge tests and design the duct seal geometry in the box, fully-coupled, 3-D, nonlinear finite element analyses were performed using the OpenSees platform (Mazzoni et al. 2006) and the multi-yield surface soil constitutive model PDMY02 (Yang et al. 2008). The numerical analyses, calibration of soil, and damping parameters follow Ramirez (2019) and Hwang et al. (2021), which were obtained based on a range of monotonic and cyclic triaxial tests on the same soil types planned for the centrifuge experiments. As the centrifuge tests will focus on investigating the response of layered deposits most representative of in-situ conditions, the modeled soil profile shown in Fig. 2a consisted of 3 layers of saturated Ottawa sand, with a 6 m-thick looser and liquefiable layer in the center at a relative density (D_r) of 40%. The bottom and top layers had D_r=90% with thicknesses of 10 and 2 m, respectively. The SDOF structure is modeled using a beam-column element assembly to match the design bearing pressure. The duct seal material (DS) is modeled as impervious and linear-elastic with E_{DS}=800 kPa, ν=0.46, and ρ=1.65 Mg/m^3 based on Popescu & Prevost (1993). A baseline DS thickness (t_{DS}) of 24 mm (model scale or 1.68 m in prototype scale) was selected, similar to other dynamic centrifuge studies (e.g. Adamidis 2017). The dimensions of the soil profile corresponded to the inside dimensions of the designed container, now considering t_{DS}. A Rayleigh damping value of 3% was assigned to the soil and DS based on the modal frequencies of the soil deposit (Ramirez 2019). The 1995 Kobe-L earthquake motion (PGA=0.37g) used in prior centrifuge studies at CU was applied to the numerical models at both the base and side nodes of the model.

Fig. 2 presents the 5%-damped acceleration response spectrum (S_a) within soil inside the rigid container with and without duct seal in the middle of the liquefiable layer at L/2 from the container side boundaries and the foundation edge and in the middle of the container, both with and without a building. An Idealized Laminar Container (ILC) with an L/B=4 without a structure is used as benchmark that we strive for or compare other results with. The ILC with L/B=4 was first proposed by Kassas et al. (2021), to best represent free-field conditions by minimizing boundary effects. In addition, Fig. 2b-c also presents the total shear strain contours accumulated at the end of shaking within the rigid container with/without DS. All cases are examined with and without the presence of the structure at the center of the container. For all cases presented, liquefaction was predicted in the liquefiable layer.

The comparison of shear strain contours in Fig. 2b-c revealed that the DS allows more deformation in the liquefiable layer and at the L/2 location both with and without a structure compared to the container without DS, where the shear band is interrupted by the rigid lateral model boundaries. For the case without a structure, where the L/2 readings in the middle of the liquefiable layer were located in a zone with moderate shear strain accumulations (Fig. 2b), the use of duct seal in a rigid container showed some improvement in S_a when compared to ILC in periods (T) of 0.4 to 1.3 s (Fig. 2e). The response in the center of the container (Fig. 2f), where low shear strain levels were observed, showed a smaller difference in S_a between the two cases over most of the spectrum compared to the other locations. At this location, for short periods and $T \cong 0.3$ s, both cases were found to slightly overestimate the response compared to ILC, while w/o DS better approximated the ILC response from 0.3-0.4 s. The L/2 location with a structure coincided with the edge of the building's zone of influence (Fig. 2b). In this case, the difference between ILC and the rigid container (with/without DS) (Fig. 2d) was slightly larger than the case without a structure (Fig. 2e-f), as larger shear strains were observed due to the response of the building. In general, the predicted S_a's in a rigid container with and without DS compared relatively well with ILC over the spectrum. The presence of DS did not notably affect the accelerations at the center of the container for the conditions and container dimensions investigated here. The influence of DS was more noticeable at locations closer to container boundaries, such as at a distance of L/2, which are important for evaluating far-field conditions in the centrifuge.

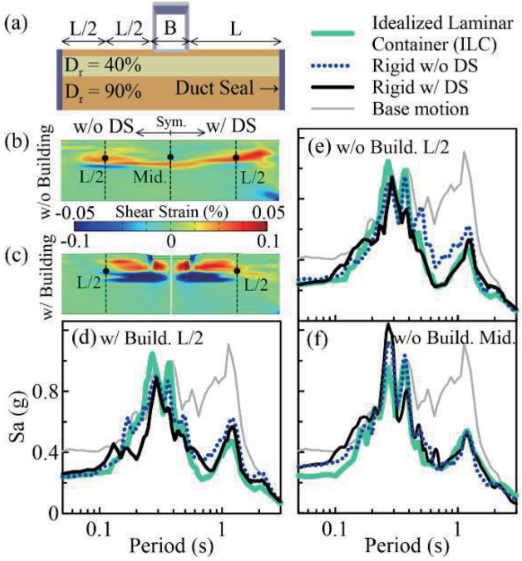

Fig. 2. a) Centrifuge model profile. (b-c) Contours of accumulated total shear strain at the end of shaking with/without duct seal (DS): b) without a building, c) with a building. (d through f) Comparison of acceleration response spectra (5%-damped) in the middle of the liquefiable layer (represented by black dots in panel b) for a rigid container with/without DS boundaries: d) with a building, at a distance of L/2 from the foundation edge, e) without a building at L/2, and f) without a building in the center of the container.

Fig. 3 summarizes the results of a sensitivity analysis on the acceleration response spectra computed in the middle of the liquefiable layer at the L/2 location (which was most sensitive to DS choice) compared to ILC. First, to validate the impact of t_{DS} and explore its influence on seismic site response, t_{DS} was varied in Fig. 3a from 18 to 35 mm (in model scale or 1.26 to 2.45 m in prototype scale). These values were chosen based on the characteristics of the container. A t_{DS}=18 and 35 mm led to a better match in Sa with ILC around the motion's predominant period (T_p) from T=0.2-0.4 s. However, the short period response was better approximated by t_{DS}=24 mm, while no clear improvement was observed in accelerations at other periods for the other thicknesses investigated. Given these results and considering that DS is typically commercially available in 1-inch thickness, a thickness of 24 mm was selected to facilitate constructability, which was found to be consistent with other previous centrifuge PIV studies (e.g., Adamidis 2017).

To evaluate the influence of the uncertainty in the duct seal properties, E_{DS} is then varied in Fig. 3b from 400 to 1600 kPa, while keeping t_{DS}=24 mm constant, as proposed by Kassas et al. (2021). The lower bound estimate of E_{DS}=400 kPa offered a better match to ILC at both short and long periods and around T_p. Overall, for the conditions investigated, the spectral accelerations at the L/2 location were highly sensitive to the assumed value of E_{DS}. In addition, the small-strain damping ratio was subsequently varied from 3 to 30% (although not shown here for brevity) while keeping t_{DS} and E constant, which caused a negligible effect on S_a.

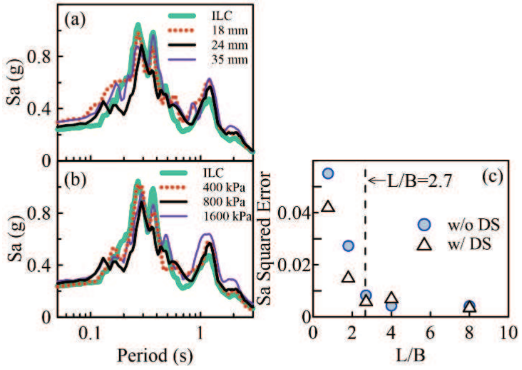

Fig. 3. (a-b) Comparison of the influence of a) duct seal thickness (t_{DS}=18, 24, 35 mm) and b) duct seal stiffness (E_{DS}=400-1600 kPa) on acceleration response spectra (5%-damped) in the middle of the liquefiable layer in the far-field (L/2 location) in the presence of a building. c) Comparison of the influence of container type and distance to lateral boundaries (L/B) on the mean squared error of acceleration response spectra residuals from T=0-3 s.

Finally, the influence of the domain size on boundary effects is evaluated by varying the distance to container sides expressed with the L/B ratio in Fig. 3c. The response in the rigid container (with/without DS) was compared to ILC by computing the mean-squared error of the response spectrum residuals ($S_{a\text{-Res}}=\ln[S_{a\text{-ILC}}(T)]-\ln[S_{a\text{-Rigid/DS}}(T)]$) from T=0-3s in the middle of the liquefiable layer. In Fig. 3c, we present the mean-squared error of S_a residuals against L/B for a container with rigid boundaries with and without DS. In general, the accuracy improved in predicting ILC S_a with increasing L/B both with and without DS, suggesting a decrease of boundary effects with increasing domain size. At low L/B ratios, larger mean squared errors were observed with rigid boundaries with no DS. For L/B=2.7 (designed container dimensions), the DS model resulted in a lower mean squared error compared to the rigid case.

4 CONCLUSIONS

This paper outlines the design and characteristics of a rigid centrifuge container to investigate and visualize the deformation mechanisms in layered liquefiable deposits under shallow foundations. Fully-coupled, 3-D, nonlinear finite element analyses are performed to evaluate the influence of container type (rigid versus laminar) as well as the presence and properties of duct seal (DS) in a rigid container on boundary effects, primarily in terms of spectral accelerations. In addition, the influence of DS thickness, uncertainties in its properties, and container size is investigated on spectral accelerations within a layered, liquefiable soil profile with and without a structure. In general, this study underlines improvements in predicted accelerations closer to the container boundaries (L/B<4) in a rigid container in terms of accuracy when including DS to reduce the reflection of incident waves. These findings also highlight the important influence of proximity to the lateral boundaries on accelerations within the container, even in highly nonlinear soil profiles such as those that are liquefiable. These observations have implications for the design of future dynamic centrifuge experiments involving soil-structure interaction on liquefiable deposits.

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