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Effect of soil-structure interaction on sand deposits supported by a sheet-pile wall under liquefied conditions

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ABSTRACT: Retaining structures in waterfront areas are sensitive to seismically triggered liquefaction, leading to large deformations of the backfill and the retaining structure. The response of such systems depends heavily on the soil parameters, one of the most important being its relative density. This paper summarizes the key aspects of three centrifuge experiments performed at the Center for Earthquake Engineering Simulation (CEES) at Rensselaer Polytechnic Institute in 2020 as part of the experimental campaign for the Liquefaction Experiments and Analysis Project (LEAP-2020). The three models reflected the same prototype problem of a rigid floating sheet-pile quay wall supporting a 3-m-deep liquefiable soil deposit, of loose, medium dense and dense soil relative densities. The three models observed the same building technique and were subjected to the same target dynamic input motion.

Keywords: Centrifuge modeling, liquefaction, sheet-pile wall, dilation, lateral spreading.

1 INTRODUCTION

Waterfront areas are susceptible to earthquake induced liquefaction as a combined result of the high water table and the deposits of granular materials, which are commonly found in such locations. Consequently when the soil liquefies, the retaining structures in those areas sustain large seaward displacements accompanied by soil settlement and lateral spreading in the backfill (e.g., Yamaguchi et al., 2012).

The extent of the system's developing deformations depends largely on the susceptibility of the soil to liquefy when subjected to dynamic loading. It has been found that soil relative density plays a decisive role in that aspect of the system's response (De Alba et al., 1976). Evidently, increasing the soil's relative density (compaction) is one of the most common amelioration measures against soil liquefaction (Sumer et al., 2007, Zekri et al., 2015)

The Liquefaction Experiment and Analysis Project (LEAP) is a continuing international collaboration, which aims at creating a databank of reliable experimental data for liquefaction hazards. The experimental data produced by different centrifuge facilities, will be utilized for the validation and verification of advanced numerical tools and new protocols for these procedures will be established.

The experimental campaign of the Liquefaction Experiment and Analysis Project in 2020 (LEAP-2020), investigated the response of a rigid floating sheet-pile quay wall, which supported a 3-m- deep liquefiable sand deposit. This paper summarizes the results from three centrifuge models developed and tested at the geotechnical centrifuge facility of the Centre for Earthquake Engineering Simulation (CEES) in Rensselaer Polytechnic Institute (RPI). All models reflected the same prototype problem, varied however in terms of soil relative density, corresponding to loose, medium dense and dense deposits respectively. All models were subjected to the same target input dynamic loading.

2 EXPERIMENTAL METHODOLOGY

The prototype problem consisted a 3-m excavation on a saturated sand deposit, which was supported by a rigid floating sheet-pile quay wall. The wall was embedded in a very dense stratum with thickness of $1\ m$. The soil relative density of the upper layers in the sand deposit varied depending on the model.

The soil deposit was air-pluviated dry using clean Ottawa F-65 sand, by maintaining consistent velocity, drop-height and flow rate during sand raining. The achieved soil relative density for the very dense stratum was $D_r \approx 90\%$ consistently for all models. The loose, medium dense and dense deposits had relative densities of $D_r \approx 55\%$, $D_r \approx 65\%$ and $D_r \approx 75\%$ respectively. The models were constructed in a rigid aluminum container with a PMMA window (Figure 1a) and the adopted scaling factor was $N = 23$. All

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dimensions henceforth are provided in prototype scale. The miniature sheet-pile wall was designed to respond as a rigid body, was made of aluminum and had thickness of $0.109\ m$.

Before construction of the model, high-friction interface between the soil and the base of the container was facilitated by means of a water-resistant sanding sheet made of Aluminum Oxide, which was attached on the container base (Figure 1b). In this way, sliding of the soil deposit relative to the container during the dynamic motion was minimized. Moreover, at the location of the sheet-pile wall, strips of teflon tape served a dual purpose: (a) they created consistent boundary conditions for the sheet-pile wall on the PMMA and aluminum sides of the rigid container; and (b) they minimized the friction between the sheet-pile wall and the container walls. A thin layer of high viscosity silicone grease spread on the Teflon tape ensured effortless sliding of the sheet-pile wall (mimicking practically roller conditions), and minimized also the migration of soil grains from the backfill to the excavated side. During sand pluviation, the sheet-pile wall was fixed with clamps preventing its rotation during model building (Figure 1c), while teflon tape prevented its vertical sliding (Figure 1d).

As shown in Figure 2, the employed instrumentation included embedded accelerometers and pore pressure transducers (PPTs) in designated locations in the deposit. The achieved coordinates of all instrumented locations were repeated with high fidelity in the three models. The backfill settlements as well as the sheet-pile lateral displacements were monitored by means of Linear Variable Displacements Transducers (LVDTs). The contact pressures exerted on the wall by the backfill were measured with a tactile pressure sensor (manufactured by Tekscan Inc.). The sensor was attached to the sheet-pile wall as shown in Figure 1c.

The centrifuge models were prepared for saturation on the centrifuge swing as described in (Korre et al., 2020). In accordance with the centrifuge similitude laws (Garnier et al., 2007) viscosity of $23\ cP$ was introduced to the methylcellulose solution, which was utilized as viscous fluid.

The testing protocol was executed under a $23g$ gravitational field. The testing sequence included in-flight Cone Penetration Test (CPT), for soil characterization and as a means of quality control for the models. The CPT was followed by a destructive synthetic tapered sinusoidal acceleration input motion with five strong cycles of maximum acceleration at $0.15g$ and a predominant frequency at $1\ Hz$.

Fig. 1. Photos during model construction.

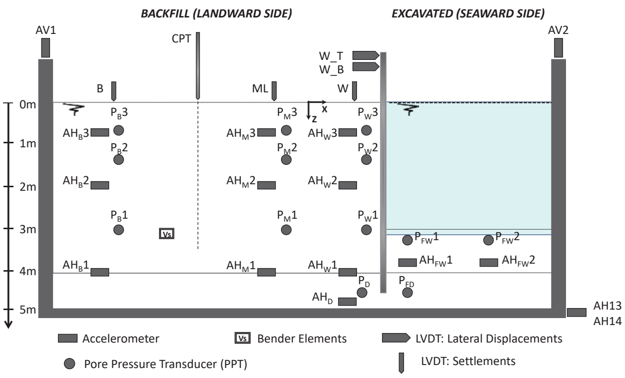

Fig. 2. Experimental layout of the centrifuge models.

3 SOIL CHARACTERIZATION

In all models the CPT trials were performed in multiple locations (approximately at $2.5\ m$, $6\ m$ and $7.5\ m$ from the container boundary) in order to verify the consistency of the achieved relative density along the backfill (Figure 3). The ultimate measured tip resistance in each location of the backfill reveals high consistency in the achieved relative density of all models. Slightly higher tip resistance is recorded for the medium dense and dense models, in the location closer to the container boundary. This discrepancy may be attributed to boundary effects introduced during pluviation, since collision of the grains with the container boundaries may have affected their velocity and by extension the locally achieved soil relative density.

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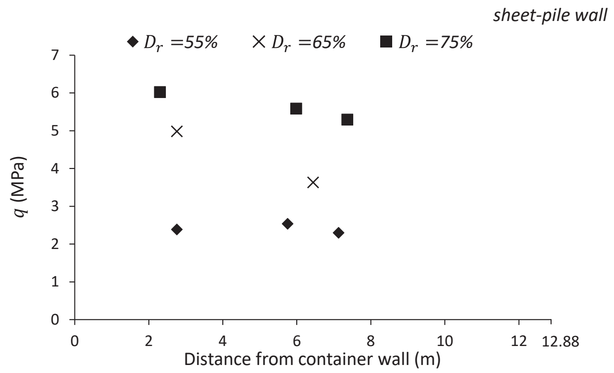

Fig. 3. Ultimate tip resistance measured during CPT trials in different locations of the backfill.

4 DYNAMIC RESPONSE

The acceleration input motion was recorded by two accelerometers (AH13 and AH14) as a contingency, which were mounted at either side of rigid container base (Figure 2). Their average response is illustrated in Figure 4(c) and reveals high fidelity in the reproduction of the input motion in all performed experiments. The average vertical acceleration response of the model from accelerometers AV1 and AV2 (Figure 4f) reveals minor rocking of the model, which is not expected to have significantly affected the system's response.

For the soil acceleration response negative acceleration values indicate dilative behavior, due to the seaward rotation of the sheet-pile wall. Due to its proximity to the sheet-pile wall, location W3 is chosen as a representative case for the soil dynamic response in all models. The effect of low relative density becomes evident in the acceleration response, since for the loose model after $t \approx 9.5\ s$ strong de-amplification of the acceleration values is observed, indicating conditions of increased excess pore water pressure (EPWP) (Figure 4a). Such an effect becomes apparent in the acceleration response of the medium dense model after $\sim 4\ s$. Observe that in the loose model the dilation peaks (negative acceleration values) are also significantly decreased compared to the ones in the medium dense model. Consistently with the acceleration response, the excess pore water pressure ratio in the loose model reveals conditions of soil liquefaction ($R_u = 1$) at $t \approx 9.5\ s$ or approximately after 10 cycles, whereas in the medium dense model this occurs $\sim 4\ s$ later (Figure 4b), or approximately after 13 cycles. Overall, the comparison of the two time histories reveals significantly milder dilative behavior for the loose model compared to the medium dense one.

Moving on to the comparison between the dense and medium dense models, the acceleration response in location W3 reveals good agreement between the two experiments, with the dense model developing significantly stronger negative acceleration peaks associated with dilative behavior (Figure 4d). Significantly stronger dilative response is observed also in the EPWP ratio response for the dense model, compared to the medium dense one. The dense model exhibited also conditions of $R_u = 1$ after about 16 cycles of the input motion. Nevertheless, the rate of accumulation and amplitude of EPWP for the two experiments are in good agreement 4(e).

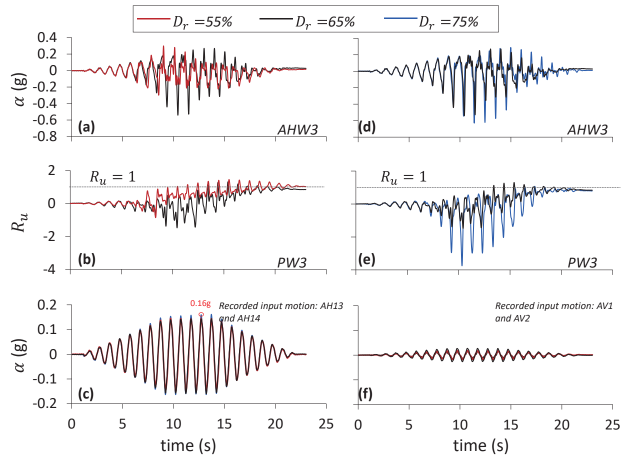

Fig. 4. Comparison of the recorded input motion and dynamic response for the centrifuge models.

Figure 5a illustrates the time history of lateral displacements, as they were recorded at the crest of the sheet-pile wall in the performed experiments. In the medium dense and dense models the permanent lateral displacements accumulated in a comparable rate and at a similar ultimate value. On the other hand, the wall in the loose model became mobilized $\sim 3\ s$ earlier and accumulated rapidly $\sim 75\%$ higher residual displacements.

This outcome is partially expected, since the soil in the loose model revealed significantly milder dilative behaviour and remained under liquefied conditions longer, which promoted the more rapid accumulation of displacements. To better understand the effect of soil dilation on the response of the sheet-pile wall, Figure 5(b-c) provides also the Average Contact Pressure (ACP), as it was measured with the tactile sensor. Due to the differences in the response along the depth of the backfill, the ACP time histories are provided by dividing the backfill in two layers (Figure 5b-c). The tactile sensor did not function properly for the dense model, therefore the comparison is provided for the loose and medium dense models. Figure 5(b) presents the comparison of the ACP time history for the top layer of the backfill, revealing opposite trends in the response between the medium dense and the loose model. The former develops strong unloading peaks on the wall while the latter exerts consistently increasing lateral pressure on the retaining structure. This is attributed to the significantly stronger dilation in the soil behaviour for the medium dense model, leading to recurring re-stiffening of the soil. In the deeper layers the dilative behaviour is less pronounced, therefore the response of lateral pressure on the sheet-pile is more comparable between the loose and medium dense models.

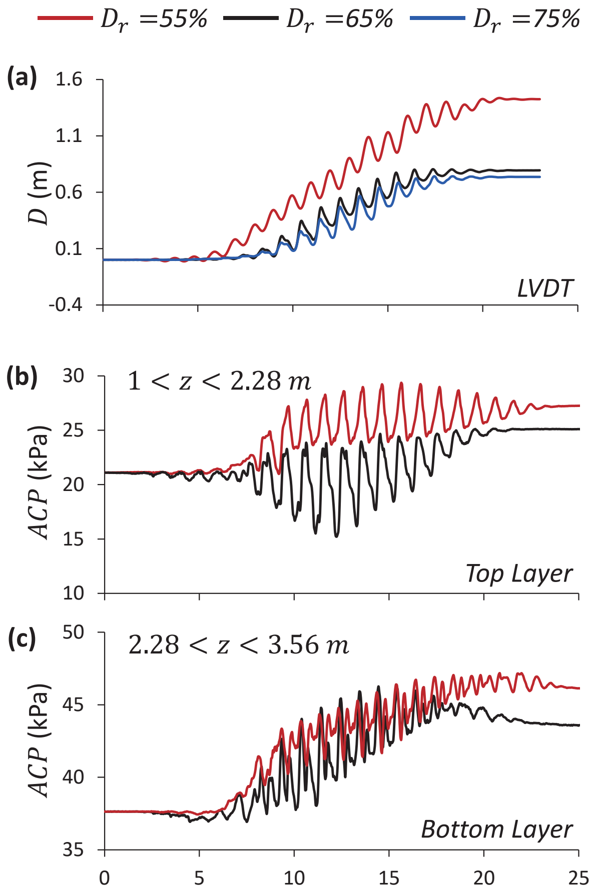

Fig. 5. Comparison of the sheet-pile wall lateral displacements and average contact pressure exerted on the wall by the backfill.

5 CONCLUSIONS

Overall, the conducted experiments shed light on the critical role of soil relative density in the response of the system under liquefied conditions. The three models were built following a consistent methodology and had consistent relative density. The loose model exhibited overall less dilative behavior and liquefied ($R_u \approx 1$) earlier which led to earlier mobilization of the sheet-pile quay wall and rapid accumulation of lateral displacements. On the other hand, the response of the dense and medium dense models showed that increase of the soil relative density led to stronger dilative response and soil liquefaction occurring later compared to the loose model. The significant re-stiffening of the soil, especially in the proximity to the sheet-pile wall, led to unloading of the retaining structure. As a result, the sheet-pile wall accumulated lateral displacements at a milder pace, with an overall smaller residual value.

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