Repeatability potential and challenges in centrifuge physical modeling in the presence of soil-structure interaction for LEAP-2020

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Abstract. The LEAP (Liquefaction Experiment and Analysis Project) is a continuing international collaboration to create a reliable databank of high-quality experimental results for the validation of numerical tools. This paper investigates the response of a floating rigid sheet-pile quay wall under conditions of seismically induced liquefaction, embedded in dense sand and supporting a saturated liquefiable soil deposit. The experimental challenges related to repeatability in physical modeling in such a soil-structure-interaction regime are also discussed. To this end, three experiments performed at Rensselaer Polytechnic Institute (RPI) as part of the experimental campaign for the LEAP-2020 are discussed herein. Models RPI_REP-2020 and RPI10-2020 investigate the repeatability potential in centrifuge modeling in the presence of soil-structure-interaction. Model RPI_P-2020 is the pilot test of the LEAP-2020 experimental campaign at RPI and investigates the effect of the wall's initial orientation on the system's dynamic response and soil liquefaction, as a possible "defect" in the model construction procedure. The three models were built in a consistent way, employed comparable instrumentation layout while simulating the same prototype and comparable soil conditions. The three models were subjected to the same acceleration target input motion, which was repeated across all three models with high consistency.

Keywords: *Centrifuge modeling, liquefaction, sheet-pile wall.*

1 Introduction

Several case histories in past earthquakes have underscored the severity of infrastructure damage in coastal areas due to seismically triggered liquefaction [1], [2]. Sheet-pile quay walls have shown to be particularly vulnerable to this phenomenon developing excessive lateral displacements towards the waterfront, as a combined result of the seismic excitation and the interaction with the backfill [3], [4].

Several experimental studies have been conducted by means of shake table tests as well as geotechnical centrifuge testing, mainly to investigate the effect of the sheet-pile wall response on the structures and their foundations resting on the backfill, under seismically induced liquefaction [5], [6]. Several experimental investigations utilizing a geotechnical centrifuge have also been conducted to shed light on the sheet-pile wall response as a mitigation measure against earthquake-induced liquefaction [7], [8], [9].

This paper presents a summary of the results from three centrifuge tests performed at Rensselaer Polytechnic Institute (RPI) as part of the experimental campaign for the Liquefaction Experiments and Analysis Project (LEAP). The LEAP is an ongoing international collaboration aiming at generating a databank of reliable experimental data for seismically induced soil liquefaction, which can be utilized for the validation of numerical tools.

One of the experiments presented herein was the pilot test of the experimental campaign (RPI_P-2020). It aimed at shedding light on the mechanisms of the system's response and contributed to the design improvement for the subsequent experiments. The pilot test was followed by the benchmark test of the LEAP-2020 experimental campaign at RPI, RPI10-2020, which was later repeated in model test RPI_REP-2020. The overview of the experiments discussed herein is presented in Table 1. The main aspects of the response as well as the challenges and lessons learned from these experiments are discussed in the following sections.

Table 1. Overview of the centrifuge experiments.

Experiment	Dr (%)	a_{max} (g)	Details
RPI_P-2020	65 / 90	0.17	Wall initial rotation ≈ 2°
RPI_REP-2020	65 / 90	0.16	-
RPI10-2020	65 / 90	0.17	-

2 Experimental Methodology

The experimental layout for the benchmark test RPI10-2020 presented in Fig. 1, illustrates the soil model consisting of two layers, a dense one with soil relative density D_r ≈ 90% and a medium dense one with D_r ≈ 65% . The dense layer provided the embedment of the floating rigid sheet-pile, which supported the 3m-deep excavated backfill. Practically the same layout was adopted also for the pilot test, with small variations in the elevations of some sensors.

A consistent experimental methodology was adopted for the construction of the model tests presented herein. The experimental methodology entailed preparation of the rigid aluminum container, construction and saturation of the model and application of the testing sequence. All models observed the scaling laws for centrifuge testing [10] and were conducted at $23g$ gravitational field. All dimensions henceforth are presented in prototype scale.

2.1 Container Preparation

The utilized aluminum container for the centrifuge experiments was practically rigid, and had a PMMA window along its longitudinal side (Fig. 2). Preparation of the container prior to model construction, established highly consistent boundary conditions for all model tests performed.

The boundary conditions entailed a rough surface at the base of the model and consistently smooth interface between the sheet-pile wall and the container sides. The former was facilitated by means of a water and tear resistant sanding sheet with cloth backing which was attached with glue on the bottom of the container, and minimized the sliding of the soil model relative to the container during shaking (Fig. 2a). The latter was achieved (a) by means of teflon tape, attached to the container sides at the installation location of the sheet-pile wall (Fig. 2a-b); and (b) by means of high viscosity silicone grease, which was applied along the sides of the wall. The tape layers contributed to effortless sliding of the sheet-pile wall inside the container, creating consistent boundary conditions on either side of the wall while at the same time minimizing the gap between the wall and the container boundaries. The role of the silicone grease was also instrumental in the prevention of grain migration from the backfill to the excavated side. Upon installation of the wall, clamps and tape were installed to prevent any verti-cal sliding or lateral rotation of the structure during model construction (Fig. 2b-c).

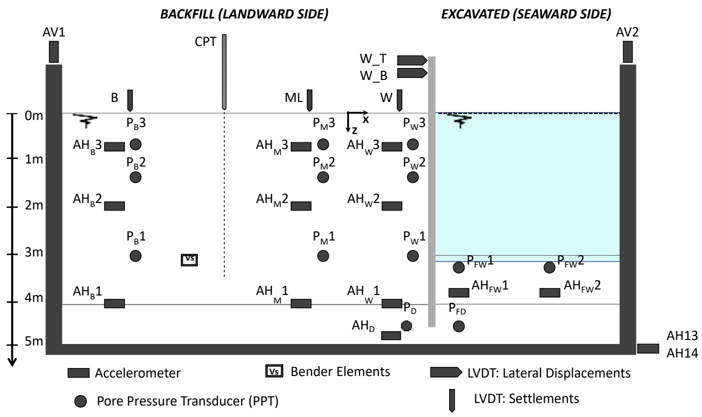

Fig. 1 Experimental layout of benchmark model test RPI10-2020.

2.2 Model Construction

The soil models were pluviated with dry Ottawa F-65 sand by means of air pluviation in horizontal layers, maintaining consistent drop-height and velocity to ensure consistent relative density along the depth. Compaction through tapping took place after pluviation of the bottom layers, to achieve the mass density of approximately $1.73\ kg/m^3$ ($D_r \approx 90\%$). The corresponding achieved mass density for the medium dense layers was approximately $1.66\ kg/m^3$, corresponding to $D_r \approx 65\%$.

Between the soil layers, the accelerometers and pore pressure transducers (PPTs) were embedded, observing the prescribed locations. After construction, the model was transferred to the centrifuge basket and was prepared for saturation as described in [11]. The clamps supporting the wall were removed, thus allowing the model container to be sealed. Saturation took place at a slow supply rate of viscous fluid at $23cP$ viscosity, to prevent hydraulic piping failure and avoid leaving dry pockets of soil inside the model. Due to technical limitations the free standing water in the excavated side could not be instrumented. Nevertheless, the influence of the water on the overall system's response is not expected to have influenced the results significantly.

Before spinning the centrifuge, the verticality of the sheet-pile was visually inspected with a spirit level in all model tests. For RPI_P-2020, it was found that the wall had tilted about $1°$ towards the excavated side, corresponding approximately to $0.03\ m$ in prototype scale displacement at the soil surface. Since this was observed only during the pilot test, this "defect" was attributed to the installation technique of the wall in the pilot model. This was one of the main challenges during model construction. Further improvement of the installation technique in the subsequent tests included improving the attachment of the securing clamps and tape, and taking additional measurements during the wall installation.

During spin-up of the centrifuge, the rotated sheet-pile in the pilot model test, sustained further rotation of about $0.7°$, as a result of the de-stabilizing component from the centrifugal acceleration field. Therefore, the total initial rotation of the sheet-pile wall in the pilot test prior to shaking was assumed to be approximately $1.7°$, corresponding to displacement of about $0.06\ m$ in prototype scale at the soil surface.

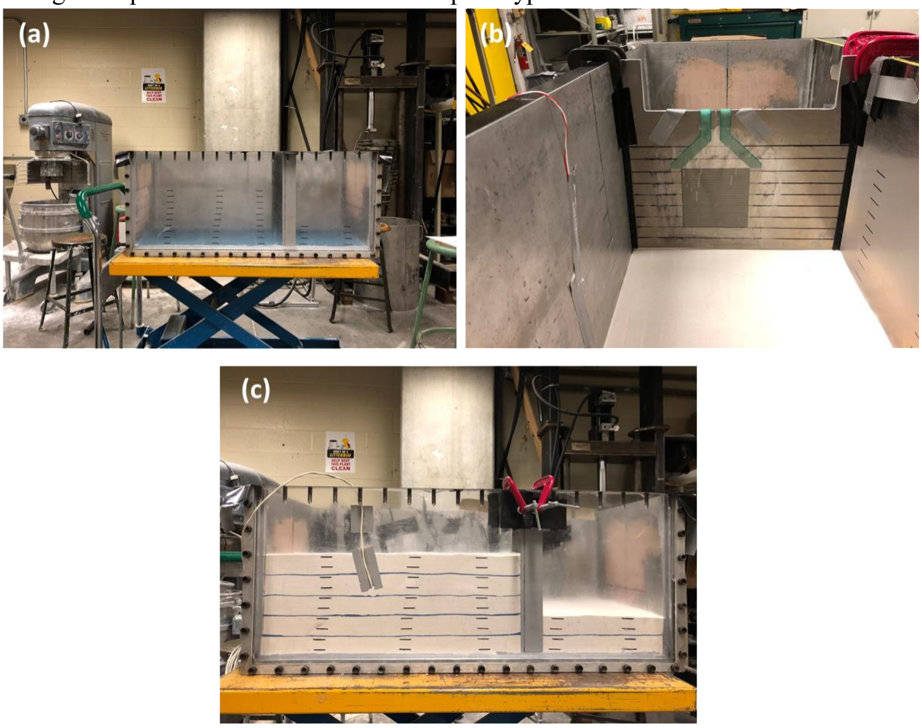

Fig. 2 Photos during model construction of the RPI10-2020 model.

2.3 Testing Sequence

All models discussed herein were subjected to a bender element trial before and after the destructive shaking, revealing consistent shear wave velocity measurements for all models. This further corroborated the consistency in the achieved relative density for all model tests presented herein.

The models were subjected to a tapered sinusoidal acceleration input motion along their longitudinal direction, with 5 cycles at the maximum target acceleration of $0.15g$. The achieved horizontal input motion was recorded by accelerometers AH13 and AH14, attached to the base of the rigid container (Fig. 1). Their average response is illustrated in Fig. 3a, while the vertical response (average of AV1 and AV2) is shown in Fig. 3b. Observe that the amplitude of the vertical acceleration response of the rigid container was minimal and is not expected to have had any major impact on the model response. Fig. 3 also confirms the high degree of repeatability of the input motion for RPI_P-2020, RPI10-2020 and RPI_REP-2020.

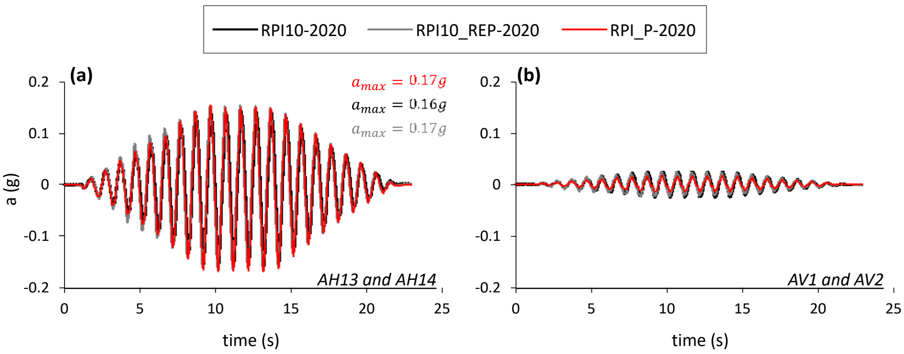

Fig. 3 Recorded (a) horizontal and (b) vertical acceleration response of the rigid container.

3 Experimental Results

The observed acceleration response in the dense stratum was practically identical to the input motion and the corresponding excess pore pressure ratio $R_u \leq 0.60$ in all performed experiments. Due to space limitations, Fig. 4 illustrates the comparison of the response in terms of accelerations only for location AHW3 and excess pore pressure ratio $R_u = \frac{\Delta u}{\sigma_v'}$, for location PW2 (PW3 malfunctioned for PRI_P-2020). A more detailed description of the experimental results will become available in an upcoming journal publication.

High consistency is observed among all model tests in the recorded acceleration of the AHW3 location (Fig. 4). Strong dilation spikes (negative acceleration peaks) reveal the re-stiffening of the soil as the sheet-pile rotated towards the excavated side (seawards). Slightly higher dilation peaks are observed in RPI_REP-2020 compared to RPI10-2020.

In terms of excess pore water pressure (EPWP), the comparison is satisfactory revealing good agreement in terms of the amplitude and accumulation rate of EPWP. As illustrated in Fig. 4, the soil in models in RPI10-2020 and RPI_REP-2020 liquefied ($R_u \approx 1$) approximately at $t \approx 13.5\ s$, whereas in the pilot test soil liquefaction occurred approximately 3 s later. Moreover, discrepancies in the negative pore pressure peaks are observed, with RPI10-2020 exhibiting significantly stronger dilative response compared to RPI_P-2020. This may be partly attributed to the deeper embedment depth (approximately 0.5 m) of the PW2 sensor in the pilot test. An additional factor accounting for this difference may also be the initial seaward sheet-pile rotation in the pilot model, as will be discussed in the following sections.

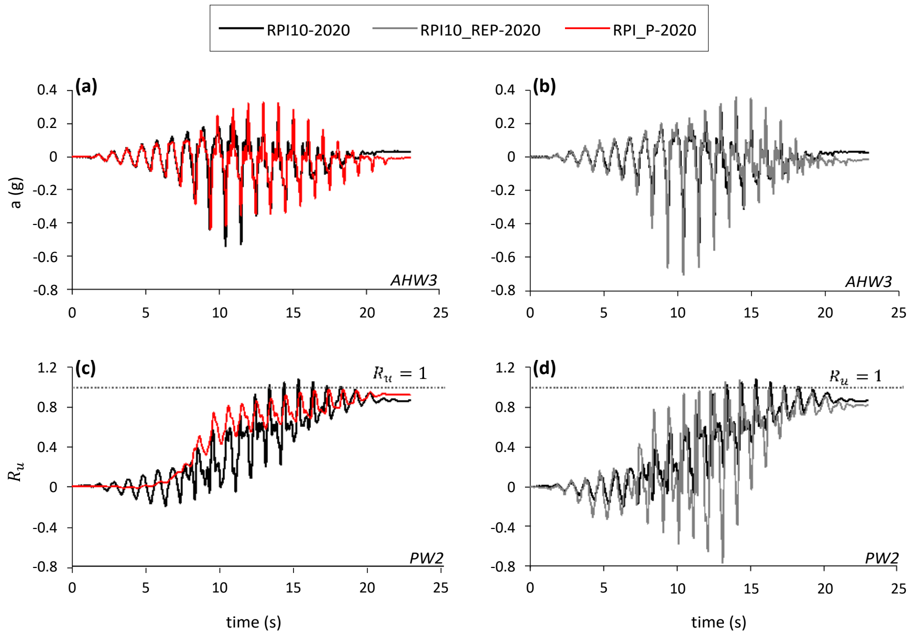

Fig. 4 Comparison of the response in terms of acceleration and excess pore pressure ratio (R_u).

Consistently with the acceleration results, RPI_REP-2020 developed significantly stronger dilation adjacent to the wall compared to RPI10-2020, which may be attributed to localized difference in relative density or soil disturbance. This discrepancy between the two seemingly identical models underscores the inherent challenge in physical mod-eling to accurately replicate localized soil conditions during model building, particu-larly in areas under strong soil-structure interaction (SSI) influence.

The pilot model test exhibits earlier and more rapid accumulation of settlements (Fig. 5a) and seaward wall lateral displacements (Fig. 5b) compared to RPI10-2020. It is postulated that the initial seaward rotation of the sheet-pile wall towards the excavated side in the pilot test created a bias in its response, thus favoring its outward rotation. As shown in Fig. 5b, the sheet-pile wall in all model tests did not re-center during its oscillation, but rather it accumulated permanent seaward displacements. Nevertheless in the pilot model test, it is evident that the range of oscillation for the sheet-pile is slightly smaller, which indicates its increased inability to rotate towards the backfill.

Both in terms of settlements (Fig. 5a) as well as in terms of lateral displacements for the sheet-pile wall (Fig. 5b), RPI10-2020 and RPI_REP-2020 exhibited high consistency both in terms of accumulation rate as well as ultimate displacement. This further corroborates the high degree of achieved repeatability between the two model tests.

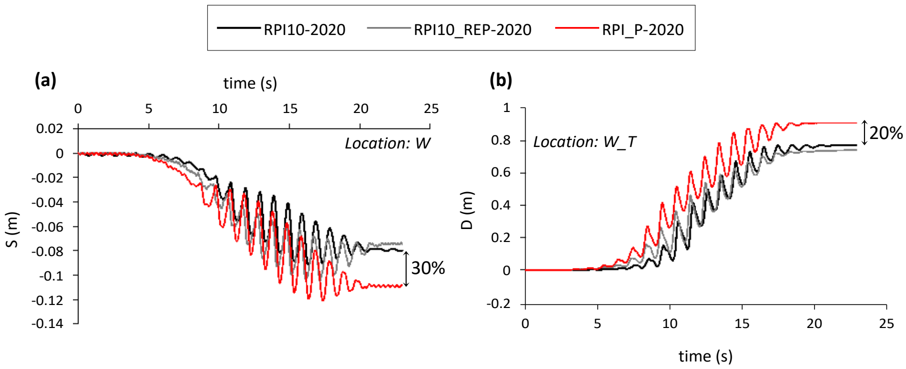

Fig. 5 Comparison of the response (a) in terms of settlements and (b) in terms of sheet-pile lateral displacements.

4 Conclusions

Three experiments were performed at RPI as part of the LEAP-2020 experimental campaign, investigating the system response of a floating rigid sheet-pile quay wall supporting a liquefiable sand deposit. Installation of the floating sheet-pile wall was especially challenging, and its installation in the pilot model test introduced an imperfection to the model, by allowing the wall to rotate towards the excavated side. This rotation further increased during spin-up, accentuating in this way the initial rotation of the wall prior to shaking.

Improvement of the model building technique minimized such imperfections, leading to the benchmark (RPI10-2020) and the repeatability model (RPI_REP-2020) to have highly consistent response both for the soil settlements as well as for the sheet-pile wall displacements. RPI_REP-2020 revealed a stronger dilative response com-pared to RPI10-2020, which further underlined the inherent limitations of accurately reproducing soil conditions in a model, especially close to the structure.

On the other hand, the initial rotation of the sheet-pile wall led to significantly milder dilative response compared to RPI10-2020, which was associated with larger settlements and larger lateral displacements.

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