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REVIEW

Recent advances in physical modeling and remote sensing of civil infrastructure systems

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Abstract Natural and man-made hazards are often associated with costly damages to civil infrastructure systems, such as buildings, bridges, Levees, dams, pipelines and offshore structures of all types. The lack of high-quality field and lab data of soil system response have eluded researchers and practitioners until recently. Recent advancements in physical modeling facilities (centrifuge and full scale) and advancement in remote sensing technology are leading to a new reality for the health assessment of soil–structure systems. This new reality is leading to a paradigm shift in the evaluation and modeling of soil–structure systems. Physical modeling, remote sensing and computational simulations are destined to replace the current empirical approaches and will ultimately become the main tool for analysis and design of soil–structure systems. The paper discusses the results of recent research studies utilizing physical modeling to simulate the response of critical soil–structure systems to natural and man-made hazards.

Keywords Infrastructure · Modeling · Sensing

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Introduction

Understanding the field response of soil and soil structure systems is crucial in the control and mitigation of the effects of soil failures. The performance of these systems needs to be reliably predicted, and such predictions can be used to improve design and develop efficient remediation measures. The use of advanced in situ monitoring devices of soil systems, such as the shape acceleration array (SAA) system as well as realistic physical models was found to be the most reliable methods in predictions of soil behavior under static and dynamic loading conditions. Many practitioners found significant differences between scientific numerical soil models and actual field behavior of soil systems. Peck [14] states that these differences come from the fact that science relies on laboratory soil sample tests, while practice is rooted in field performance data and associated empirical studies. Consequently, most practitioners remain skeptical about numerical models developed by geotechnical engineering scientists, mainly because very few models have been properly calibrated with field performance [1–3, 5].

The gap between science and practice poses a huge challenge for designers and practitioners. The answer to this challenge partly resides in the development of tools for short- and long-term health monitoring of existing civil infrastructure. The knowledge gained from this monitoring and analysis would aid in planning for maintenance and rehabilitation of infrastructure systems and could improve the design, construction, operation, and longevity. Critical soil–structure elements of the civil infrastructure which are important to monitor include bridge foundations, abutments, and support systems, retained, reinforced, or stabilized rock and earthen embankments and levees, slopes and mechanically stabilized earth (MSE) walls, and tunnels and tunnel linings [5].

The paper discusses two examples of practical tools, the first from the field and the second from the laboratory that has proven to match as closely as possible the behavior of soil systems under extreme events.

The first tool is the shape acceleration array (SAA) which is a MEMS-based, in-place inclinometer–accelerometer instrumentation system that measures angles relative to gravity, using triaxial micro-electro-mechanical systems (MEMS) accelerometers, which are then used to evaluate inclinations (i.e., deformations). The SAA system uses temperature-calibrated MEMS accelerometers within 30 cm (1 ft) long rigid segments connected by composite joints that prevent torsion but allow flexibility in two degrees of freedom. The SAAs are factory-calibrated and completely sealed, requiring no field assembly or calibration. Because each segment of the SAA contains three orthogonal sensors, arrays can be installed vertically or horizontally. The sensor arrays are transported to the jobsite on an 86 cm (34 in) diameter reel, see Fig. 1, and can be lowered into vertical, or pushed into horizontal, 25 mm (1 in) casing. Wireless SAA data transmission is made possible by the use of an on-site data acquisition system, called a wireless earth station. Similar to traditional probe and in-place inclinometers, data from the SAA represents deviations from a starting condition or initial reading. These data are sent wirelessly, over a cellular telephone network, to an automated server, where data are made available to users through proprietary viewing software and an internet connection [5].

Fig. 1 32 m (104 ft) SAA on shipping reel [5]

The second tool discussed in the paper is centrifuge testing which is a powerful experimental technique that can be used to test soil and soil–structure interaction under static and dynamic loading. Centrifuge testing relies on matching the stresses in scaled models to the stresses in the field, based on the fact that soil is generally a stress dependent material. This is made possible by spinning the soil model in the centrifuge resulting in centrifugal acceleration that is many folds higher than the gravitational acceleration (g) and thus increasing the effective stress at any point in the reduced scale model to match stresses in the field. Figure 2 shows the geotechnical centrifuge available at Rensselaer Polytechnic Institute which is extensively used in experiments related to soil and soil structure systems.

SAA field installation at calibration levee

The calibration levee is located in The Netherlands and was meant for inspection and monitoring technologies for levees. The objectives of this site are: first to develop and validate new sensor techniques, and second to perform full-scale failure experiments on levees to understand their fundamental behavior. This should increase the quality of the levee inspection process and the safety assessment of levees. The final goal is to develop tools to respond to flood threats in a timely manner with appropriate measures. The SAA was the main system for the evaluation of deformation measurements in the uniquely large levee stability test [5].

Quoting from Bennett et al. [5] “The levee for the first production stability test was constructed with a height of

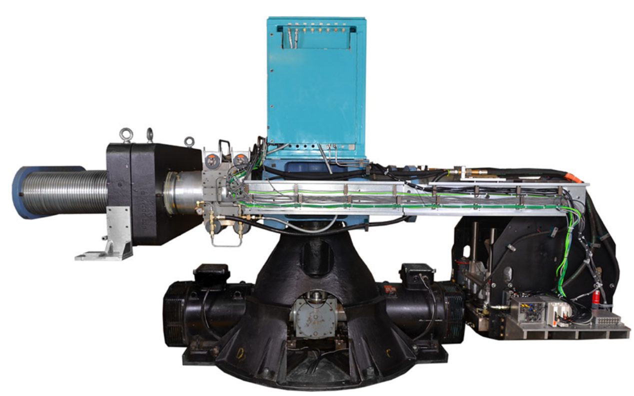

Fig. 2 RPI geotechnical centrifuge [8]

6 m (19.7 ft), a length of 100 m (328.1 ft) and a base width of 27 m (88.6 ft), with a crest width of 3 m (9.8 ft) and side slopes of 1:1.5 (*V*:*H*) on the dry side and 1:2.5 on the wet side. The levee was built parallel to a local canal levee and on top of 1.3–3 m (4.3–9.8 ft) of clay and peat. The levee core is sand, with a thick clay cover. This is the usual configuration of new levees in The Netherlands. For this full-scale testing, using sand inside is an advantage since the levee can be filled with water, which reduces strength and increases the load on the subsoil. An aerial view of the levee on the second day of the test is shown in Fig. 3. A cross section of the levee showing all installed systems is shown in Fig. 4. Some of the systems were installed along the length of the levee, but most of them were concentrated in three cross sections, one in the middle and two 35 m (114.8 ft) away from the middle. The loading sequence to bring the levee to failure is indicated in Fig. 5 and consisted of six stages. First, the bathtub on the wet side was filled, followed by an excavation of 1 m (3.3 ft) on the other side. Second, the excavation was enlarged down to the sand base. In Fig. 5, this phase had just started. Third, the sand core was filled to 2/3 of its height with water. The fourth step was to drain the excavation. In the fifth step, the containers on the crest were filled with water, and finally, in the sixth step, the sand core was filled completely, thus completing this sequence of internal and external loading.

The full-scale stability test began on September 25, 2008. As planned, the test started with the filling of the bathtub, closely followed by the shallow excavation. The second phase of the test, that is, deepening and widening of the excavation (Fig. 6) was completed on the second day of the test. On the third day of the test, the filling of the sand core of the levee from within, through the built-in infiltration tubes, commenced. Because of the apparent variation in permeability, the pore pressures in the sand core increased rather irregularly. After nearly four hours, a section of about 30 m (98.4 ft) in length failed within approximately 40 s (Fig. 6). The SAA measured deformations were confirmed by post-test surveying measurements.

Fig. 3 Aerial view of the stability test levee [5]

This large-scale test demonstrated the easiness of installation and usefulness of the SAA system for real-time monitoring of levees.

Centrifuge testing

Centrifuge model testing is a powerful experimental technique that can be used to test soil and soil–structure interaction under static and dynamic loading. This part of the paper discusses the advanced tools and sensors used at the centrifuge facility at Rensselaer Polytechnic Institute (RPI). It also discusses one of the advanced dynamic centrifuge experiment that has been performed at RPI recently along with the summary of the results.

Tactile pressure sensor

The tactile pressure sensor is a flexible sheet containing sensels, which is a matrix of smaller sensors (Fig. 7). The sensels measure the change in electrical resistance in response to an applied load [7]. It is specifically designed to induce minimal disruption on the pressure pattern of the soil medium. These electrical measurements are converted into pressure through data acquisition hardware and software. The tactile pressure sensor technique was originally used for the analysis of dental applications [15], and it was adopted for geotechnical applications by Paikowsky and Hajduk [12]. Its adaptation for centrifuge testing and comparison to full-scale testing is described by Springman et al. [16]) and Palmer et al. [13] and most recently El-Ganainy et al. [7].

Bender elements

Bender elements are 2-layer piezoelectric transducers that can be used to generate and detect mechanical waves in soil models. Primary and secondary wave velocities can be obtained using the bender elements system. This is accomplished by measuring the time difference between generation and detection of a wave (see Fig. 8). Using bender elements in the centrifuge to measure wave velocities poses a challenge due to the mechanical and electrical noise associated with spinning. There are also several additional challenges that must be overcome to achieve clear results. These include: mitigating the interference between channels when using multiple transducers in the same model; controlling the wave path so that it travels through the soil; and buffering the current produced by the detectors [8].

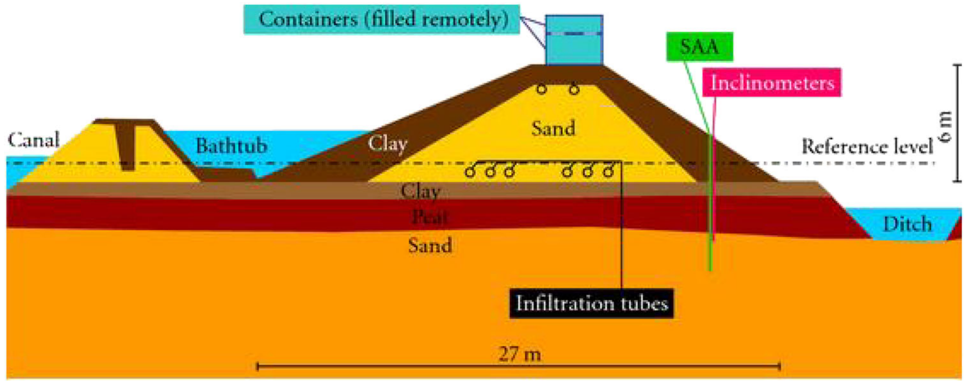

Fig. 4 Cross section of instrumented stability test levee [5]

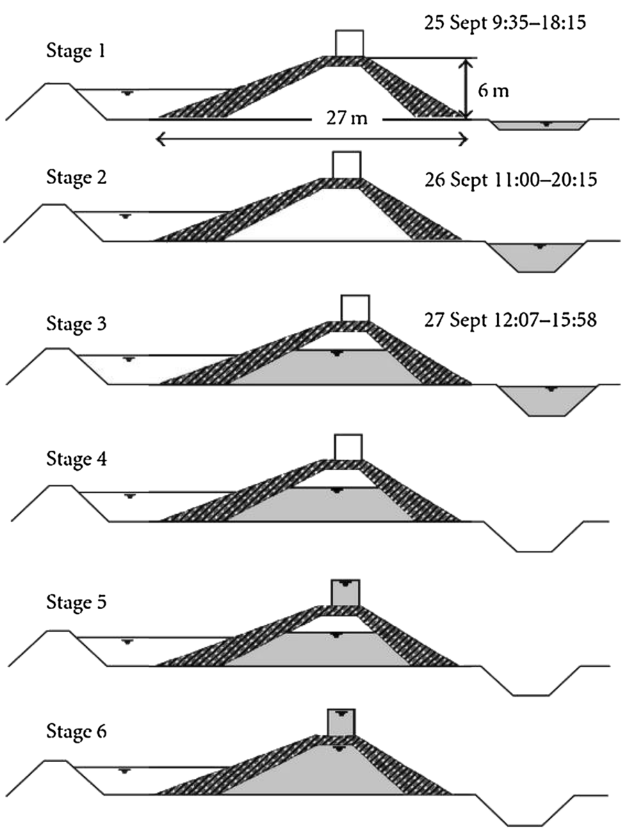

Fig. 5 Six stages of loading sequence [5]

Fig. 6 Levee after failure [5]

Fig. 7 Tactile pressure sensor connected to the handle and to the tactile DAQ computer [8]

2-D laminar container and 2-D shaker

The centrifuge experiment in this paper was conducted in the 2D laminar container shown in Fig. 9. This container was designed to accommodate a wide range of cyclic and permanent deformations in the lateral direction occurring in the dynamic experiments. The RPI 2D laminar container is especially designed to allow motion in the two horizontal directions with minimal friction.

Figure 10 shows the 2D shaker used in the centrifuge experiment discussed in this paper. This 2D shaker can apply earthquake shaking to models in the horizontal plane while spinning at up to 100 g. A wide variety of shakings can be produced with the shaker, including 1D and 2D acceleration time histories comprised of periodic, random, or scaled earthquake signals. The shaker can provide dynamic excitation to soil models by mounting the 2D laminar box or another suitable centrifuge model container on the shaker slip-table (Fig. 11). This enables investigating the behavior of scaled geotechnical or soil–structure systems in response to these complex excitations.

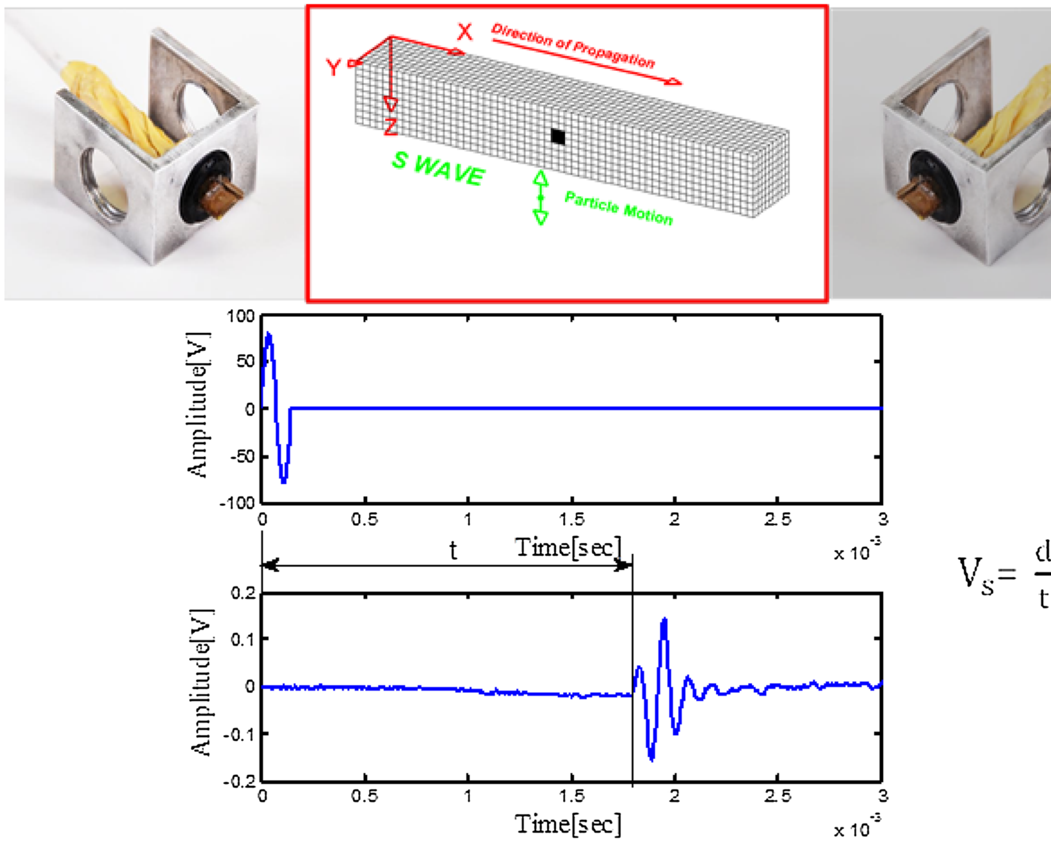

Fig. 8 Sender and receiver bender elements and sent and received waves [8]

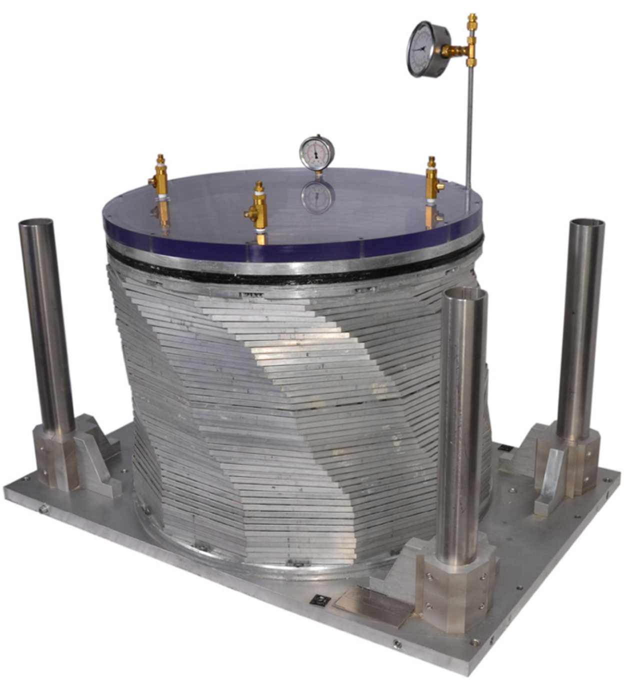

Fig. 9 2D laminar container used in the research [8]

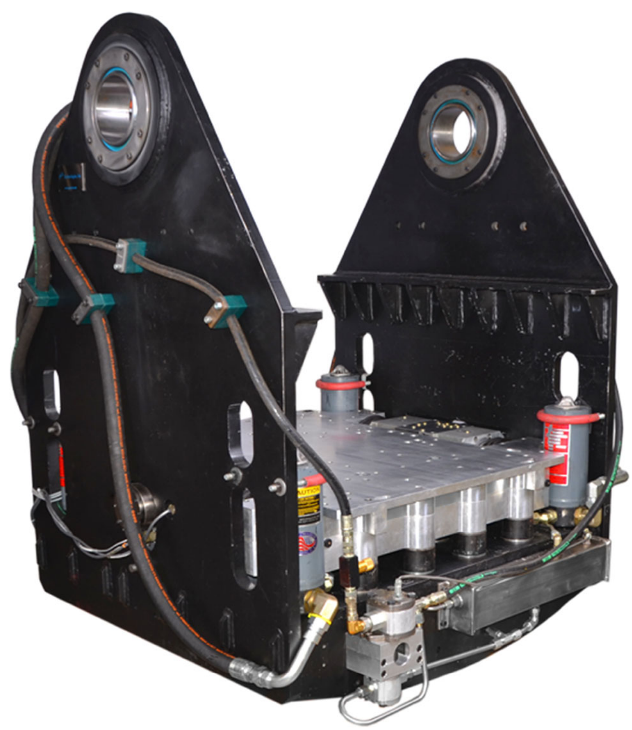

Fig. 10 2D shaker used in the research [8]

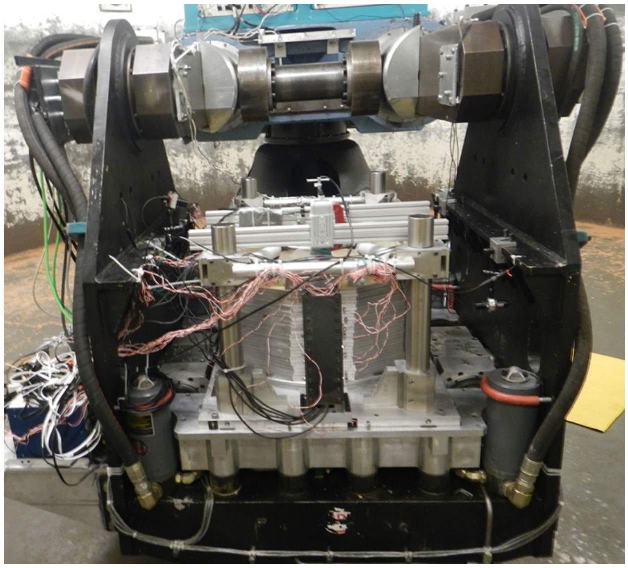

Fig. 11 Prepared soil model in the 2-D laminar container mounted on the 2-D shaker and the centrifuge platform [8]

Centrifuge experiment

In this paper, a long centrifuge experiment was used to study the combined effects of earthquake-induced preshaking and extensive liquefaction on the liquefaction resistance of a saturated clean sand deposit. In this experiment, the base of a 6 m homogeneous deposit was subjected to a total of 37 shaking events of different horizontal base accelerations and durations simulating earthquakes of different magnitudes, with full pore water pressure dissipation between earthquakes. The centrifuge model was subjected to three types of events in an alternating pattern, Events A, B, and C (or D). Events A represent mild earthquake events, Events B represent moderate earthquake events, and Events C represent strong to very strong earthquake events. Full pore water pressure dissipation was allowed after the events before application of the following events [8].

The preparation procedures of the experiment were according to the standard techniques used for saturated tests in the geotechnical centrifuge facility at Rensselaer Polytechnic Institute [4]. In these procedures, the dry sand is pluviated in the box at the desired void ratio; carbon dioxide is then introduced to the model in order to replace the air; and, finally, water is introduced by percolation for 12 h under vacuum to fully saturate the sand deposit [4]. More details about the technique used for model construction can be found in Gonzalez [11] and Abdoun et al. [4].

Figure 12 shows a schematic of the laminar container along with the general configuration of the sensors used. As shown in the figure, the models were instrumented with pore pressure transducers, accelerometers, one vertical LVDT at the ground surface, and bender elements. In this centrifuge experiment, a 6 m prototype depth model of uniform saturated clean Ottawa sand was subjected to a total of 37 base shakings of different intensities and durations (Fig. 13a).

Maximum excess pore pressure ratios and vertical strain in the centrifuge experiment

Figure 13b shows the maximum excess pore pressure ratios, $(r_u)_{max}$, for Events A, B, C and D throughout the experiment. The behavior can be summarized as follows:

- Events C and D always liquefied most of the deposit, as indicated by $(r_u)_{max} \approx 1$ in each Event C and D.
- Events A liquefy the deposit in the beginning, as indicated by $(r_u)_{max} \approx 1$. The liquefaction resistance gradually increases when the deposit is subjected to more and more preshaking, as indicated by lower and lower $(r_u)_{max}$.
- The behavior is totally reset after application of Events C, as indicated by the abrupt jump of $(r_u)_{max}$ for Events A immediately after an Event C. It must be noted that the three Events A immediately after the Event D (S24–S26) had 20–25% lower base acceleration than the rest of Events A. This helps explain why the $(r_u)_{max}$ of Events A was very low immediately after the Event D, compared to Events A that had occurred immediately after Events C.
- For Events B, the soil model experienced high excess pore pressures $[(r_u)_{max} = 0.8–1]$ the first three times an Event B happened. The fourth time that an Event B happened (S22), the whole deposit experienced very low excess pore pressures $[(r_u)_{max} = 0.2]$. After applying the extensive liquefaction shaking Event D, once again the soil deposit liquefied due to shaking Event B S29. However, in the next Events B, again the whole deposit experienced very low excess pore pressure $[(r_u)_{max} = 0.2]$.

Figure 13c shows the permanent vertical strain, $\Delta\varepsilon_v$, due to all shaking events. The behavior of $\Delta\varepsilon_v$ is characterized by the following trends: (1) $\Delta\varepsilon_v$ decreases monotonically with each new Event B and C; (2) $\Delta\varepsilon_v$ decreases monotonically with each new Event A within each 5-Event A sequence; (3) $\Delta\varepsilon_v$ jumps to a higher value for Events A when there is an Event B and C in between; and (4) this jump in $\Delta\varepsilon_v$ is cancelled rapidly by the subsequent Events A, with the net result being a significance decrease in the $\Delta\varepsilon_v$ for Events A between the beginning and the end of the 37-shaking experiment [8].

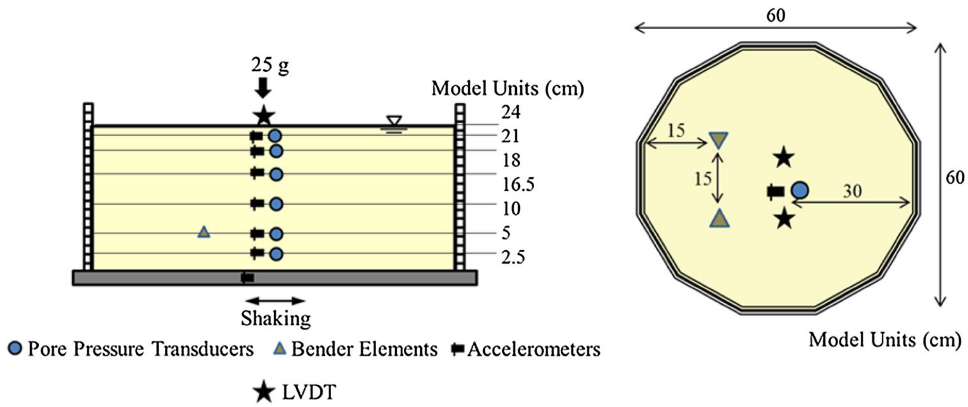

Fig. 12 Setup and instrumentation of the centrifuge model [8]

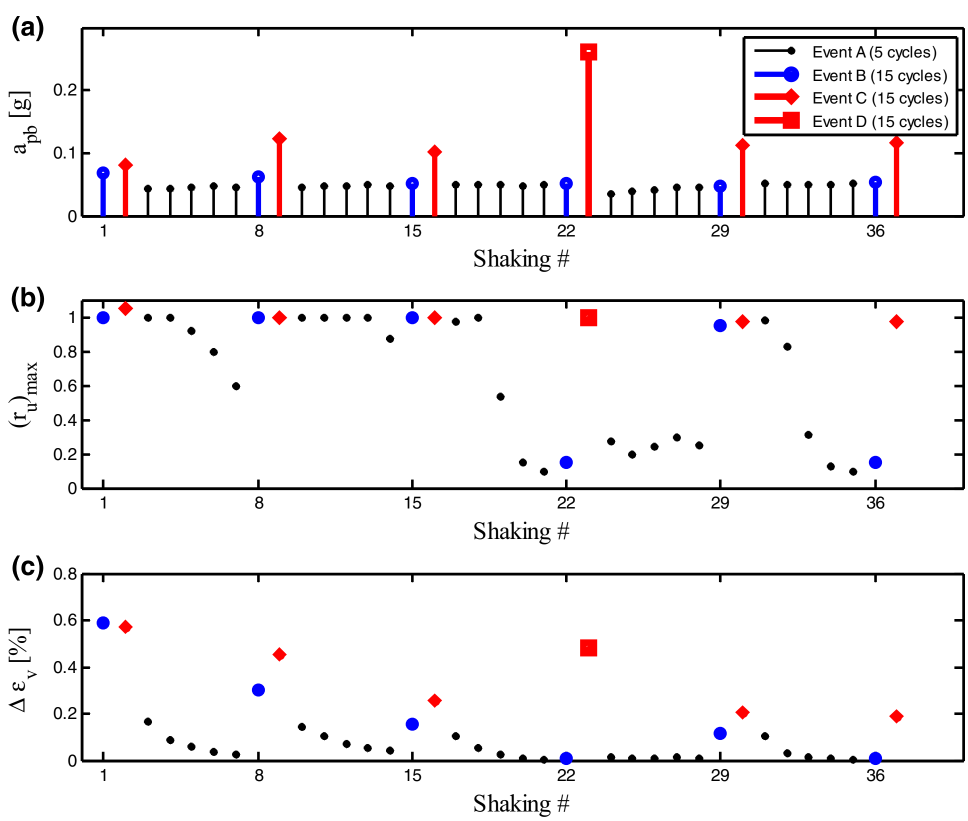

Fig. 13 Experiment 3: histories of maximum excess pore pressure ratios and the permanent vertical strain, $\Delta\varepsilon_v$, of the 37 shakings throughout the centrifuge experiment: **a** shaking sequence; **b** maximum pore pressure ratio for the whole deposit, $(r_u)_{max}$; and **c** the overall permanent vertical strain, $\Delta\varepsilon_v$, of the deposit [8]

Soil densification and evolution of V_{s1} in the centrifuge experiment

Figure 14b shows the change in overall relative density, D_r, of the deposit throughout the experiment. The D_r changed from a starting value of 39% in the beginning of the experiment to an ending value of 69%. The normalized shear wave velocity, V_{s1}, measured before the corresponding events at a depth of 4.6 m is shown in Fig. 14c. It can be noted from the figure that the shear wave velocity generally decreases after Events C and D in most cases, with the decrease being most significant immediately after the Event D, as V_{s1} was decreased from 191 to 168 m/s indicating a significant reduction in the stiffness of the deposit. It must be noted that even though the relative density always increased when the deposit was shaken further, the shear wave velocities increased and decreased depending on the intensity of the shaking, not necessarily reflecting the change in D_r [8].

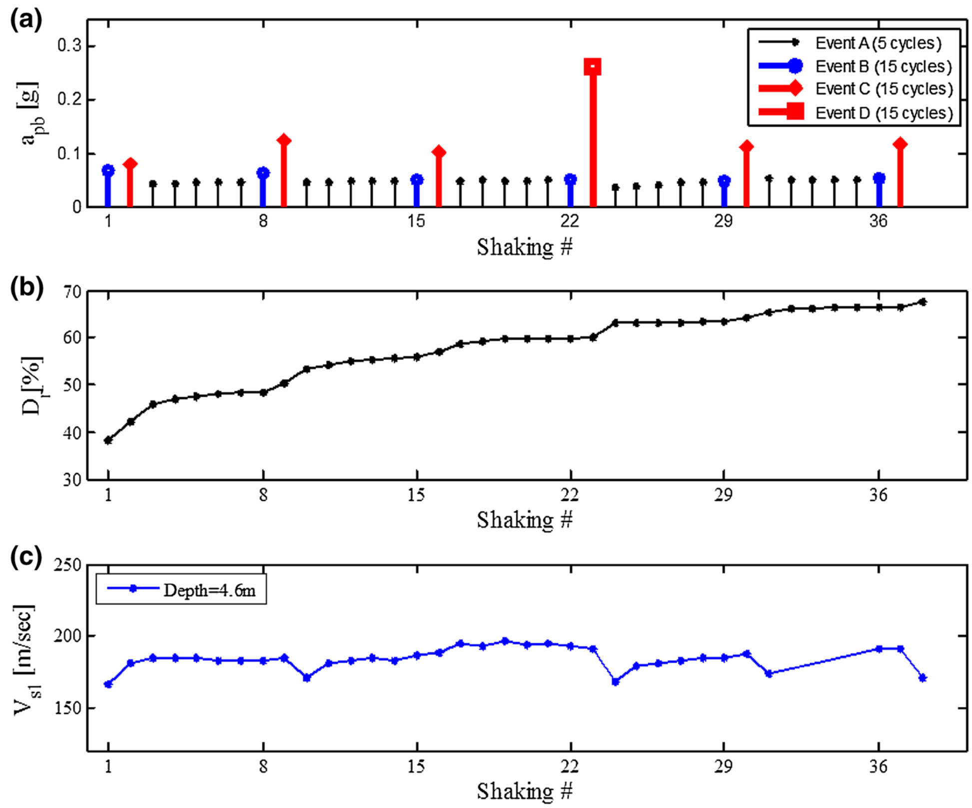

Fig. 14 Experiment 3: histories of relative density, D_r, and of normalized shear wave velocity, V_{s1}, measured before each of the 37 shakings throughout the centrifuge experiment: **a** shaking sequence; **b** values of D_r obtained from the initial D_r and subsequent vertical LVDT measurements; and **c** values of V_{s1} measured at depth of 4.6 m [8]

Field performance versus centrifuge testing

One of the most recent research works performed by the authors and their coworkers is the centrifuge simulation of an instrumented deposit in California; the Wildlife site. The site is located in the Imperial Valley of Southern California, 160 km east of San Diego and close to the US-Mexico border. The site was deposited by flooding around the year 1907. The site is characterized by being located in an earthquake prone zone and has been subjected to dozens of earthquakes since deposition. It has been thoroughly studied and has been instrumented with piezometers and accelerometers by the US Geological Survey (USGS) in 1982, and again in 2005 by the U. of California at Santa Barbara and finally with SAA in 2010 with support from the Network for Earthquake Engineering Simulation (NEES). The response of the site to tens of earthquakes has been recorded by the heavy instrumentation planted there.

The research performed by the authors and their coworkers aimed at investigating the influence of seismic preshaking history on the liquefaction potential of the site. The authors conducted a centrifuge experiment as a simulation of the seismic history of the Wildlife site. The main conclusions reached from analysis of the centrifuge experiment and its comparison with the Wildlife site case history, was that preshaking resulted in increased liquefaction resistance of the silty sand deposit in the site as well as other sites in southern California. This was most dramatically shown by the low pore pressure buildup of the Wildlife critical silty sand layer during the magnitude 7.2, El Mayor-Cucupah earthquake in 2010. That is, the same site that may have liquefied because of an earthquake just after deposition may not liquefy again by a similar earthquake after being subjected to tens of earthquakes throughout its history. This conclusion could not have been reached without integrating the results of the centrifuge experiment with the instrumented field deposit [6, 9, 10].

Conclusions

Based on the examples presented in the paper, it can be concluded that:

- The gap between science and engineering practice is starting to close thanks to the novel field and laboratory testing technologies.
- SAA is a powerful field tool that can provide real-time assessment and health monitoring of critical soil structures.
- Centrifuge testing is the link between lab and practice as it is considered one of the most reliable, low cost tools that can test complicated soil systems subjected to static and dynamic loading.

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