Design and manufacturing of geotechnical laboratory tools used in physical modeling

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Abstract: The experimental activities in geotechnical laboratories are highly recommended to be developed annually. Both postgraduate and undergraduate students’ research skills are to be improved. In this paper, three main important machines are designed in a geotechnical lab in Wasit University. Uniaxial small shaking table, mechanical pluviator, and pile’s model loading machine are fabricated and tested. The shaking table is capable of carrying load up to 1 ton and reproducing a sinusoidal motion containing frequencies up to 10 Hz. The pile’s model loading machine is capable of pushing the specimens (pile length up to 60 cm) in the granular soil in very-low-speed rate (i.e. 0.3mm/min), whereas the designed pluviator catches the density range between 28% and 73%. The measured acceleration response and the amplification noticed during wave propagation to the model surface shaking showed great results, and they were consistent with historical records (i.e. approximately 1.6). Great repeatability and highest degree of uniformity are also observed for the prepared models of sandy layers using the new mechanical pluviator from the measured cone resistant (i.e. cone penetration test results for prepared cohesionless specimens). It was also noticed that the design used for the shaking table gave very well prediction for the input motion, confirming...
that side walls of the container were not strongly affected on the laterally reflected wave.

Subjects: Testing; Vibration; Manufacturing Engineering; Civil, Environmental and Geotechnical Engineering

Keywords: Shaking table; model tests; sand; earthquakes; pluviator

1. Introduction

Earthquakes are one of the worst disasters which affect directly human lives annually around the world. Thousands of people die and billions of dollars are lost by the governments after such a disaster (i.e. Kobe earthquake 1995, Chi-Chi earthquake 1999, and Tohoku earthquake 2011). Most of the infrastructure and big projects are strongly influenced by earthquakes (i.e. dams, wastewater treatment plants, and nuclear power plants). Gravity dams are one of these big projects that may incur direct damage due to an earthquake which may both increase the probability of loss of human life and restrict and disrupt rescue operations.

Researches in geotechnical field and the water source engineering field witnessed distinguishable developments in the methods and techniques of studying the engineering problems concerning dynamic effects and seismic performance of structural elements and problems. The simulating of real earthquakes on different hydraulic structures model (i.e. gravity dams, multi-story building, and slopes) under principles of physical modeling has increased in the last two decades. The physical modeling is one of these techniques that can be used to investigate the behavior of such an important structure under earthquake loading. The physical modeling principles are widely used in many studies which were conducted on different small-scale models representing different prototype scales around the worlds [1-6] (Knappett, Reid, Kinmond, & O'Reilly, 2010; Donlon & Hall, 1991; Ghobarah & Ghaemian, 1998; Harris, Snorteland, Dolen, & Travers, 2000; Tinawi, Leger, Leclerc, & Cipolla, 2000) and among. Different parameters were measured and investigated under both real earthquakes (i.e. Bairrao & Vaz, 2000; Tinawi et al., 2000; Rosca, 2008 and amongst) and single-frequency, sinusoidal waveform (i.e. Proulx & Paultre, 1997; Al-Qaisi, 2016).

The seismic performance of structures and the dynamic response can be verified by several techniques. Both geotechnical centrifugal apparatus (under N-g values) and shaking table (under 1-g) are the commonly used techniques in different research centers and universities in the world. In hydraulic structures, the acceleration response, seismic displacement (i.e. sliding), and the hydrostatic pressure along the upstream face and the amplification at both the bottom and top of the dam are the most investigated parameters during a uniform earthquake excitation. Large- and medium-size shaking tables have been designed and widely increased in few decades in the laboratories of both the research centers and universities around the world to solve many problems under single gravity (i.e. 1-g) and provide an investigation of destructible effect (i.e. Harris et al., 2000; Nakamura, Sekine, & Shirae, 2011). Tens of studies were performed using the shaking table. Shuang, Zuo, Zhai, Xu, and Xie (2016) carried out a shaking table test on concrete structural building subjected to earthquake shakings. Željana et al. (2017) performed on the 5m×5m shaking table at the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje, Macedonia, within the ongoing HRZZ SeimoNuMod project. Razieh et al. (2016) conducted a series of shaking table tests on the 1:2 scaled masonry walls in the Laboratory of the Earthquake and Structure Research Center of Amirkabir University of Technology. It has dimensions of 2.5 m × 4 m and consists of four main parts including hydraulic jack, deck, power pack, and control system. It is characterized by a single degree of freedom, and it can simulate harmonic waves up to 20 Hz frequency and 1.5g acceleration. Lin, Cheng, and Yang (2018) carried out shaking table test on the seismic response of a combined retaining structure at China Merchants Chongqing Communications Technology Research and Design Institute Co. Ltd. The dimensions of the table were 6.0 m ×3.0 m, and it could perform 3D and six-degree-of-freedom ground motion. The maximum acceleration was 1.0g with the frequency ranges between
0.1 and 50 Hz. Ling et al. (2005) used large-scale benchmark shaking table tests to present an experimental study of the earthquake performance-reinforced soil-retaining walls at the Japan National Research Institute of Agricultural Engineering. The shaking table with 6 m × 4 m dimensions is able to accommodate a load of up to 500 kN with a maximum acceleration of 1g in all directions. In China, in the Construction Science Research Institute, a 6 m × 6 m shaking table is constructed to investigate a wide range of engineering problems concerned with earthquakes effects. It can carry loads up to 80 tons (Chen, Kato, Tsunaki, & Mukai, 2009). In the State Key Laboratory of Disaster Reduction, Civil Engineering, Tongji University, China, multi-function shaking table has been built and installed to study many problems in civil engineering.(Xiao, Haitao, Yong, & Juyun, 2015). It has four movable tables (4 m × 6 m each) in three degrees of freedom. Two main tables have a payload limits up to 70 tons each, whereas the other two tables with 30 tons each (longitudinal, rotational, and transversal). The National Laboratory for Civil Engineering (LNEC) in Lisbon, Portugal, has 400 kN of 5.6 m × 4.6 m 3D shaking table with maximum displacement reaches to 175 mm for all the three axes (Emílio et al., 1989).

Many studies were conducted using physical modeling to investigate different engineering problems using cohesionless soil in both dry and saturated states. To prepare the model, and because the sand cannot be densified by compaction (granular soil is densified by vibration), the air pluviation technique is widely used in the research laboratories (i.e. Al-Baghdadi, Brown, Knappett, & Al-Defae, 2017; Al-Defae & Knappett, 2014). The uniform soil specimen along the model depth can be achieved using this technique (Rad & Tumay, 1987).

Due to significant amount of seismic and dynamic engineering problems that can be investigated and understood using the shaking table, this paper focuses and represents details of newly designed and tested small uniaxial shaking table (for performing single-frequency waveform with multi-magnitude) and mechanical pluviator to be used for sand model preparation using pluviation technique which they manufactured in the laboratories of University of Wasit, College Of Engineering, to advance the experimental activity in engineering laboratories and enhance the research facilities for both undergraduate and postgraduate students. It was designed and fabricated to carry loads up to 1 ton from simple steel material, gearbox, servo motor, and other important accessories.

2. Methodology
The methodology of this paper included designing of some important equipment that was widely used in physical modeling in geotechnics (i.e. the shaking table and the pile’s model loading rig machine) and the model preparation technique for testing this equipment. Full description of the shaking table is shown in detail in the next subsections, whereas a brief summary of the pile (penetrometer) installation models and the pluviator is described below.

2.1. The designing of uniaxial shaking table
The main body of the shaker consists of steel frame and one-direction movable platform (as a basket carrying the container of the model). When the servo motor runs, the movement will transfer to the gearbox which in turn moves the platform in uniaxial (horizontal) direction. In fact, the mainframe was fixed into the ground to prevent any unfavorable reaction for the model during the excitation of the sinusoidal wave that may lead to reflect the propagation wave particularly close to the boundary of the model. The facilities of this shaking table are of 0.8 m × 1.2 m and platform mass of approximately 10 kN, maximum allowable model weight of 10 kN, range of frequency from 0 to 20 Hz, maximum acceleration amplitude of 1.2g, and maximum displacement of 14 mm.

The energy efficient servo actuator controlled with an electrical signal from lab-view subroutine via computer to indicate the magnitude of the shaft movement is the main part of this shaker. Sinusoidal waveform or simple harmonic motion can be instructed to the servo motor via data physics, and this makes the platform of the shaking table move. The potentiometer resistance
inside the servo changes as the motor rotates, and this should be regulated by the amount of movement and the direction (clockwise or counterclockwise) which is controlled by the control circuit.

To decrease the load on the servo motor, a power transmission system or gearbox is used to convert the rotating servo motor into the shaking platform. Four screw base dampers have also been fixed at the shaker base to prevent any vertical movement that may be generated due to fast vibration of the platform during operation. Four main high-resistance pulley systems are also attached at the base of the shaker’s platform, and they move in one direction along the smooth trench. Furthermore, these rollers or pulleys are to allow movement of the shaker base that contains the weight of the model basket in one direction (horizontal). All the joints, connections of different parts, and different bolts and nuts are used as well. Actuator specifications have been tabulated in Table 1. Details of the shaking table and both the gearbox and the servomotor are shown in Figure 1, whereas the shaking table is shown in Figure 2.

The upper part or the movable shaker base that can carry the container or the model of the test manufactured from high-strength steel base (10 mm) to prevent any vertical or undesirable movement during the shaking with four main pulleys. The shaking system contained the main actuator (motor) with the specification tabulated in Table 1.

Motors are chosen with certain speed–torque characteristics to match speed–torque requirements of various loads (maximum load of 10 kN). A motor must be able to develop enough torque to start, accelerate, and operate a load at rated speed on the mechanical system necessary for the generation of the sinusoidal wave. Rubber strap transfers rotational motion generated from motor to the iron rod of 60 cm length and 6 mm thickness, moving along its longitudinal axis by a large pulley to turn the rotary motion. A 40-cm-long and 8-mm-thick iron rod converts the drag and pull movement from the previous rod into a horizontal movement to generate a desired sinusoidal wave.

### 2.2. Pile (penetrometer) model loading machine

Newly designed and manufactured compression machine is used to push the penetrometer in the prepared sandy layer (full details of this machine are not mentioned in this paper). This machine can be able to apply very small penetration speed (i.e. 0.3 mm/s), and it was designed and manufactured for using in small projects of investigating the behavior of screw piles and cone penetration results for both clay and sand in both saturated cohesive and cohesionless soils. Details of this machine are shown in Figure 3.

### 2.3. The pluviator and sand preparation

The air pluviation technique has been widely used by researchers for preparing uniform or consistent cohesionless soil model to achieve a desired relative density and duplicate the actual deposit state in the prototype scale. This technique has widely been used in geotechnical

| Specification | Grade                        |
|---------------|------------------------------|
| Type          | HIWIN 1,000 W                |
| Tcs           | 27.5 Nm                      |
| Prtd          | 2.81 kW                      |
| Nrtd          | 3,500 rpm                    |
| Vs            | 640 Variable Damper Control (VDC) |
| Rm            | 2.1 Ω                        |
| Weight        | 14.5 kg                      |
laboratories around the world (i.e. Lauder, 2011; Al-Defae, Caucis, & Knappett, 2013; Bertalot, Brennan, & Villalobos, 2013). This technique has been preferred to many techniques due to many advantages such as (i) easy model preparation; (ii) easy instrument installation; and (iii) can achieve uniform soil layers. The pluviator consists of a v-shaped movable container and has pulley wheels and moves back and forth on frictionless bar’s guide, and the soil (sandy soil) falls down from an opening (slot) in the bottom of the container (hopper). Sand falling height, slot size, and the sandy soil properties are strongly affecting the relative density of the prepared deposits (Chen et al. 1998; Madabhushi, Houghton, & Haigh, 2006; Chian, Stringer, & Madabhushi, 2010).

Figure 1. The main parts of the shaking table.

Figure 2. Fixed and movable parts of the shaking table.
In this paper, new mechanical pluviator is designed and fabricated to prepare the soil foundation underneath in the physical modeling of concrete dam (will be tested dynamically later). As the relative density of the cohesionless soil (silica sand here) is strongly influenced by the falling height, the pluviator contained a designed rope crane and attached to the mainframe so that the container can be raised up and down to achieve the desired height. This mechanical pluviator can achieve uniform sandy layers with relative densities that vary from 28% to 71%, and this represents the threshold’s range of loose-to-dense state of sediments. The width of the c-shaped pluviator was 590 mm along the slot, and this covers the width of the container that will be used in certification of the soil density (i.e. cone penetration test [CPT] in the next sections). Full details of this v-shaped container and the pluviator with the rope crane of mechanical movement are shown in Figure 4.

2.4. The designed transparent container
The medium-size rigid container has one transparent (glass) side and is used in the shaking test (under sine waveform which is described later), whereas rigid container from galvanized steel is used during the CPTs. The dimension of the first container was 1,800 mm length, 700 mm width, and 1,050 mm depth (i.e Figure 5), while the second was square (750 mm) and 800 mm in depth (shown in Figure 3). The purpose of this one transparent side (made from glass with thickness...
10 mm) of the first container is monitoring the soil-dam behavior during the shaking as well as taking a short video and pictures using high-speed camera.

To decrease the reflection of the transmitted wave in the soil during the shaking, the internal walls of the first container were covered with high elastic rubber (10 mm) and can be able to absorb the wave reflection within the soil layers and through the water pressure. The rubber layer was tested using simple Matlab subroutine using the saturated soil properties, i.e. specific gravity, soil unit weight, void ratio, angle of internal friction, and maximum densities with motion characteristics, i.e. peak acceleration besides the rubber properties like the thickness, shear stiffness, and the increasing rate of shear stiffness with soil depth. This container was designed, manufactured, and calibrated to develop the research capabilities of undergraduate and postgraduate students to investigate the seismic performance of different structural models.

2.5. Sand properties
The properties of the sand that was used in this paper as a cohesionless soil are very close to the HST95 silica sand’s properties. First, it was dried in an oven for 24 h. Then, it was sieved on #10 sieve to extract the large-size particles. Main physical properties were determined in the laboratory to compare the properties with HST95 silica sand that was widely used in the University of Dundee (Al-Defae et al., 2013; Bertalot et al., 2013; Al-Defae & Knappett, 2014). Maximum and minimum densities were measured in accordance with ASTM D4254 and D4253, respectively, whereas the specific gravity, Gs, was determined in accordance with D854-14.
The prepared sand was classified according to the Unified Soil Classification System (USCS). It was poorly graded sand with clay (i.e. SP-SC). Figure 6 shows the particle size distribution for the prepared sand. It was clearly shown from the figure that the sand particle size is consistent with both HST95 silica sand and Ottawa sand which were commonly used in different research centers and researches in geotechnical physical modeling (i.e. Salgado, Bandini, & Karim, 2000; Knappett et al., 2010; Al-Baghdadi et al., 2017; and Chen et al., 2015). Table 2 shows the main physical properties of the sand used in this paper besides the properties of both HST95 silica sand and Ottawa sand.

3. Results and discussion
Results of the experimental work of this paper included the results of the equipment’s testing that was mentioned above. The results of the pluviator test, CPT by installation and loading of the penetrometer using the loading rig machine, and the preliminary shaking table test using miniature accelerometer.

3.1. The pluviator test
As explained earlier in this paper, the main factors affecting uniform relative density of the sandy layer are the size of the slot (opening size which varies between 2 and 7 mm) and the sand falling height from the v-shaped container and the back and forth movement speed during the deposition process. Due to the difficulty to achieve the desired density of sandy layer (Al-Defae et al., 2013), many trials were conducted on the pluviator using known volume box to investigate how the relative densities of the sandy layer (Dr) change as the pluviator’s v-shaped container slot changes. Thus, the desired specimen densities were achieved by changing the height, slot opening, and the flow rate of the falling sand. The height of the container was fixed at 1.1 m at the preliminary tests, whereas the slot size was changed from 2 to 7 mm. It is clearly shown in Figure 7 that the relative density, Dr, is strongly influenced by the falling height and the blade width. Comparison with the studies of both

![Figure 6. One-face transparent container with wave absorbed rubber.](image)

| Table 2. Physical properties of used sand |
|------------------------------------------|
| The property | This sand | HST95 Silica sand | Ottawa sand |
| Specific gravity, $G_s$ | 2.67 | 2.63 | 2.64 |
| Shape | Rounded | Rounded | Rounded |
| Mean particle size, $D_{50}$ | 0.28 | 0.15 | 0.32 |
| Coefficient of uniformity, $C_u$ | 2.85 | 1.9 | 1.68 |
| Coefficient of gradation, $C_z$ | 1.32 | 0.95 | 1.08 |
| Minimum dry unit weight, $γ_{d,min}$ | 14.8 | 14.7 | 14.9 |
| Maximum dry unit weight, $γ_{d,max}$ | 19.1 | 19.2 | 19.5 |
Bertalot et al. (2013) and Al-Defae et al. (2013) (Collington HST95 silica sand is used with 1 m falling height) showed a good agreement particularly for relative density 55% and above. The same behavior was observed by Rad and Tumay (1987) particularly for medium and dense sand.

It can be concluded from Figure 5 that the loose, medium, and dense states are used to verify the pluviation or deposition technique, and the CPTs are conducted on sandy soil layers to observe how the relative density state of cohesionless soil affected the results of the CPTs which was replicated the variation of the relative density.

3.2. CPT

The CPT was conducted on prepared sandy layers using pluviation technique to understand and investigate the repeatability of soil layer preparation. Three tests were prepared and tested (i.e. loose, medium, and dense prepared models) to investigate how the sand penetration effect on resistance behavior of penetrometer in pluviaed specimens. The CPT was 500 mm in length and 31 mm in diameter with 60° apex angle, and it was built with 5 kN small load cell fixed between cone tip and the core to measure the sand resistance. Full details are shown in Figure 8.

A newly designed and manufactured compression machine is used to push the penetrometer in the prepared sandy layer (full details of this machine are not mentioned in this paper). This machine is able to apply very small penetration speed (i.e. 0.3 mm/s), and it was designed and manufactured for using in small projects of investigation of the behavior of screw piles and cone penetration results for both clay and sand in both saturated cohesive and cohesionless soils. Details of this machine are shown in Figure 8.

Arshad, Tehrani, Prezzi, and Salgado (2014) observed that in both loose and even medium dense sand specimens, the penetration resistance tends to be constant earlier than in the dense state when they inspected the CPT outputs using cone penetrometer that was very close to the one used in this paper (i.e. length around 500 mm and diameter 31 mm). The results obtained from this paper were very compatible with the results obtained from Arshad et al. (2014) as shown in Figure 9. The measured final tip resistance at the end of the depth was very close that results particularly for loose specimens. The uniformly increase in the cone tip resistance for all tested specimens with in the depth of soil model (i.e. all densities range) replicated the uniformity in the model preparation using the pluviation technique.

3.3. The shaking table test results

The main purpose of designing this shaker is to investigate the dynamic performance of concrete dam model constructed on sandy layers (which is not shown in this paper). At the preliminary tests results in this paper, the shaker was tested by investigating the measured acceleration from the bottom of the model to the top (i.e. free field amplification should be noticed) to compare the amplification with the expected value. Five accelerometer sensors were distributed from the bottom to the top of the model (i.e. Figure 10) as well as many others were fixed at the model of the dam (not included in this paper), whereas Linear Variable Differential Transformers (LVDTs) (at different positions at the face and at the top of the dam), pore pressure transducers (beneath the dam at different soil depths), and water pressure sensors (to measure the hydrodynamic pressure at the upstream face of the dam) were also used, and they are not included in this paper.

Sinusoidal wave of 0.65g sinusoidal wave is used as an input motion at the base of the container (represents the recorded at the underlying bedrock, i.e. Figure 11). It was observed
from the measured four accelerometers as shown in Figure 11 that the values gave great representation for the expected amplification at the model surface (around 1.6 times the input motion). This value is consistent with the measured value of Brennan and Madabhushi (2009) and Al-Defae et al. (2013, 2013) which showed that there are two distinct effects of this amplification: the site effect (because of the dynamic properties of the soil material, this is strongly influenced by the material property) and a topographic effect (i.e. a geometric effect or effect of ground surface). This confirms that the boundary effects are well modeled with this container and the used rubber layers gave good performance to reflect the lateral cyclic waves during shaking.
4. Conclusion

In this paper, three important and known laboratory machines are designed, manufactured, and tested to improve the experimental capability for the geotechnical laboratory at Engineering Faculty, University of Wasit. The following main conclusions have been drawn:

1. The results of the cone resistance for soil layer in the tested model using miniature CPTs showed well prediction with art-of-literature results. For all relative densities (i.e. low, medium, and dense states), the cone resistance replicates the actual behavior of the tests in-situ. Rapid increase in the resistance is noticed for the shallow depth (up to 35% of the total soil layer), and then the rate of the resistance decreases due to soil densification with depth.

2. The designed loading rig machine can be used for both conventional pile model installation and screw pile models. This technique under very low installation speed rate and screwing the helical piles under low rotational speed rate increments are very important to inspect the load-displacement curve for tested specimens.

3. Single-frequency shaking table machine gave a comparable prediction for the dynamic amplification factor that was investigated from others (i.e. around 1.6). These results
replicate the actual dynamic wave propagation from the base of the model to the surface of the soil. This gives a great opportunity for the undergraduate and postgraduate students to use principles of physical modeling in geotechnic to investigate the dynamic behavior of different simple models under simple single-frequency motion.

(4) The prepared cohesionless soil models using the new mechanical pluviator replicated the actual soil strata in-situ in terms of uniformity. Wide range of relative density can be prepared with more than 1.5 m movement freedom for the v-shaped container, and this is very important in preparing medium-size models (i.e. 1.5 model container length). Both the loose and dense state behavior is captured using CPTs.

(5) Though the dynamic response (using single-frequency motion) of the cohesionless soil is not close to what has to be under real earthquake motion, it gave very well representation, particularly in terms of the dynamic amplification factor.

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References

Al-Baghdadi, T., Brown, M. J., Knappett, J. A., & Al-Defae, A. H. (2017). Effects of vertical loading on lateral screw pile performance. Proceedings of the Institution of Civil Engineers: Geotechnical Engineering, 170(3), 259–272.

Al-Defae, A. H., Cauais, K., & Knappett, J. A. (2013). Aftershocks and the whole-life seismic performance of granular slopes. Géotechnique, 63(14), 1230–1244. doi:10.1680/geot.12.P.149

Al-Defae, A. H., & Knappett, J. A. (2014). Centrifuge modelling of the seismic performance of pile-reinforced slopes. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 140(6), 04014014. doi:10.1061/(ASCE)GT.1943-5606.0001015

Al-Qeisi, Z. A. M. (2016). Optimal design of concrete gravity dams of random soil. PhD Thesis, Baghdad, Iraq: University of Technology.

Arshad, M. I., Tehrani, F. S., Prezzi, M., & Salgado, R. (2014). Experimental study of cone penetration in sillica sand using digital image correlation. Géotechnique, 64(7), 561–569. doi:10.1680/geot.13.P.179

Bairrao, R., & Vaz, C. (2000). Shaking table testing of civil engineering structures—The LNEC 3D simulator experience. In Proceedings 12th World conference on earthquake engineering, Vol. 2. 2129. Auckland, New Zealand.

Bertalot, D., Brennan, A. J., & Villalobos, F. A. (2013). Influence of bearing pressure on liquefaction-induced settlement of shallow foundations. Géotechnique, 63(S), 391–399. doi:10.1680/geot.11.P.040

Brennan, A. J., & Madabhushi, S. P. J. (2009). Amplification of seismic accelerations at slope crests. Canadian Geotechnical Journal, 45(5), 585–594.

Chen, H. T., Lee, C. J., & Chen, H. W. (1998, September 23–25). The traveling pluviation apparatus for sand specimen preparation. Centrifuge 98, Kimura, Kusakabe and Takemura EDS, Vol. 1 Balkema, Rotterdam, pp. 163–168.

Chen, X. L., Kato, N., Tsunaki, R., & Mukai, K. (2009). Prediction of slope failure due to earthquake. Chinese Science Bulletin, Institute of Geology, Chinese earthquake administrations Beijing, China. doi:10.1007/s11434-009-0283-3.

Chian, S. C., Stringer, M. E., & Madabhushi, S. P. G. (2010). Use of automatic sand pourers for loose sand models. In L. Springman & Seward (Eds.), 7th International conference of physical modelling in geotechnics (pp. 117–121). Rotterdam: CRC Press.

Donlon, W. P., & Hall, J. F. (1991). Shaking table study of concrete gravity dam monoliths. Earthquake Engineering and Structural Dynamics, 20, 769–786. doi:10.1002/eqe.4290200805

Emilio, F. T., Duarte, R. T., Carvalhal, F. J., Costa, C. O., Vaz, C. T., & Corrêa, M. R. (1989). The new LNEC shaking for earthquake resistance testing. Memorie LNEC, 757.

Ghobarah, A., & Ghoemian, M. (1998). Experimental study of small scale dam models. Journal of Engineering Mechanics, ASCE, 124, 1241–1248. doi:10.1061/(ASCE)0733-9399(1998)124:11(1241)

Harris, D., Snorteland, N., Dolen, T., & Travers, F. (2000). Shaking table 2-D models of a concrete gravity dam. Earthquake Engineering and Structural Dynamics, 29, 769–787. doi:10.1002/eqe.9845(200006)29:6<769::AID-EQE925>3.0.CO;2-7

Knappett, J. A., Reid, C., Kinmond, S., & O’Reilly, K. (2010). Small-scale modeling of reinforced concrete structural elements for use in a geotechnical centrifuge. Journal of Structural Engineering, 137(11), 1263–1271. doi:10.1061/(ASCE)ST.1943-541X.0000371

Lauder, K. (2011). The performance of pipeline ploughs. Ph.D. Thesis, University of Dundee, UK.

Lin, Y.-L., Cheng, X.-M., & Yang, G.-L. (2018). Shaking table test and numerical simulation on a combined retaining structure response to earthquake loading. Soil Dynamics and Earthquake Engineering, 108, 29–45. doi:10.1016/j.soildyn.2018.02.008

Ling, H. I., Mohri, Y., Leshchinsky, D., Burke, C., Matsushima, K., & Liu, H. (2005). Large-scale shaking table tests on modular-block reinforced soil retaining walls. Journal of Geotechnical and Geoenvironmental Engineering, 131(4), 465–476. doi:10.1061/(ASCE)GT.1943-541X(2005)131:4(465)

Madabhushi, S. P. G., Houghton, N. E., & Haigh, S. K. (2006, August). A new automatic sand pourer for model preparation at University of Cambridge. International conference on physical modelling in geotechnics, ICPMG 2006. Hong Kong: The Hong Kong University of Science and Technology.

Nakamura, T., Sekine, E., & Shirae, Y. (2011). Assessment of seismic performance of ballasted track with large-scale shaking table tests. Quarterly Report of RTRI, 52(3), 156–162. doi:10.2219/itirg.r.52.156

Proulx, J., & Paulin, P. (1997). Experimental and numerical investigation of dam-reservoir-foundation interaction for a large gravity dam. Canadian Journal of Civil Engineering, 24(01), 90–105. doi:10.1139/l96-086

Rad, N. S., & Tunay, M. T. (1987). Factors affecting sand specimen preparation by raining. Geotechnical Testing Journal, 10(1), 31–37. doi:10.1520/GTJ10136J

Rosca, B. (2008). Physical model method for seismic study of concrete dams. Bulletinul Institutului Politehnic Iasi, 14(3), 57–76.

Salgado, R., Bandini, P., & Karim, A. (2000). Shear strength and stiffness of silty sand. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 126(5), 451–462. doi:10.1061/(ASCE)1090-0241(2000)126:5(451)

Shuang, L., Zuo, Z., Zhai, C., Xu, S., & Xie, L. (2016). Shaking table test on the collapse process of a three-story reinforced concrete frame structure. Engineering Structures, 118, 156–166. doi:10.1016/j.engstruct.2016.03.032

Tinawi, R., Leiper, P., Leclerc, M., & Cipolla, G. (2000). Seismic safety of gravity dams: From shake table experiments to numerical analysis. Journal of Structural Engineering ASCE, 126, 518–529. doi:10.1061/(ASCE)0733-9445(2000)126:6(518)

Xiao, Y., Hattao, Y., Yong, Y., & Juyun, Y. (2013). Multi-point shaking table test of the free field under non-uniform earthquake excitation. Soil and Foundation Journal, 55(5), 985–1000. doi:10.1016/j.sandf.2015.09.031
