GEO-CENTRIFUGE TEST IN THE EVALUATION BEHAVIOR OF SOIL - STRUCTURE SYSTEM UNDER EARTHQUAKE LOADING

THÍ NGHIỆM MÁY LY TÂM ĐÁNH GIÁ ỨNG XỬ CỦA HỆ ĐẤT - KẾT CẤU DƯỚI TÁC DỤNG CỦA TẢI TRỌNG ĐỘNG ĐẤT

NGUYEN ANH DAN[a,*]
[a]University of Transport and Communications, Hanoi, Vietnam
[*]Tác giả đại diện: *E-mail*: nadan@utc.edu.vn
Ngày nhận 15/10/2023, Ngày sửa 11/12/2023, Chấp nhận 17/12/2023
https://doi.org/10.59382/j-ibst.2023.vi.vol4-1

Abstract: *Earthquakes are often difficult to predict and have the potential to cause great damage to people and property, most of which are related to the collapse of the soil-structure system and geotechnical problems. Currently, to evaluate the dynamic behavior of structures and ground under the effect of earthquake load experimentally, there are two main methods: the 1-G shaking table model experiment (1-G shaking table test) and the centrifuge model experiment (geo-centrifuge test). Different from the 1-G shaking table test, the model is accelerated to an appropriate level in the centrifuge test. Thus, the self-weight of the soil and structure can be increased correspondingly at the appropriate rate, and the behavior of the soil-structure system can be described similar to reality.*

Keywords: *centrifuge test, soil-structure system, earthquake, shaking table test, geotechnical engineering*

Tóm tắt: *Các trận động đất thường rất khó dự báo và có khả năng gây ra các thiệt hại lớn về người và tài sản, trong đó phần lớn liên quan đến sự sụp đổ của hệ đất – kết cấu cũng như các sự cố liên quan đến địa kỹ thuật. Hiện nay, để đánh giá ứng xử động của kết cấu và nền đất dưới tác dụng của tải trọng động đất bằng thực nghiệm, có hai phương pháp chính đó là sử dụng thí nghiệm mô hình bàn rung 1-G (1-G shaking table tests) và thí nghiệm mô hình máy ly tâm (geo-centrifuge tests). Khác với thí nghiệm bàn rung 1-G, trong thí nghiệm máy ly tâm, mô hình được gia tốc đến cấp độ thích hợp, do đó trọng lượng bản thân của đất và kết cấu có thể được tăng lên tương ứng với tỷ lệ nguyên mẫu và ứng xử của mô hình có thể được mô tả tương tự như thực tế.*

Từ khoá: *Thí nghiệm máy ly tâm, hệ kết cấu - đất, động đất, thí nghiệm bàn rung, địa kỹ thuật*

1. Introduction

For the 1-G shaking table experiment, the model is placed at the bottom fixed table system, and the input motion is transmitted through the hydraulic actuator. However, the main drawback of this experiment is that it is difficult to fully describe the actual behavior of the system because of the difference in stress due to self-weight between the experimental model and the prototype. The basic idea of the geo-centrifuge experiment is to place the model in a machine system that can be accelerated to an appropriate gravity level to simulate the prototype stress field. Therefore, it brings many advantages, such as reducing model size and more realistically describing the response of the soil-structure system. By conducting experiments with small-scale models, model fabrication is also easier, which can reduce preparation time and effort [1].

The advantages of experiments using geo-centrifuge test is that the deformation and strength properties of the soil are fully considered, and results from centrifuge model testing are useful for verifying numerical simulations. Therefore, it is possible to predict the behavior of the soil-structure system during an earthquake. The application fields of centrifuge modeling were also expanded from traditional geotechnical problems to more complex geotechnical systems. Modeling technology using centrifuges is currently being applied in many different fields of geotechnical engineering, such as foundations, retaining walls, marine structures, earthquake-related issues, geoenvironmental studies, etc. With the development of advanced technologies in centrifuge equipment and data acquisition, the number of geotechnical centrifuges has increased rapidly, and there are now more than 100 centrifuges in operation worldwide [2].

2. Principle of the geo-centrifuge test and scaling law

The basic idea of modeling the geotechnical system using the centrifuge is to simulate soil stress at the prototype scale in the physical model by increasing acceleration. As depicted in Figure 1, if the model is created with a reduced scale of 1/N, the test must be conducted at N times earth gravity. In this way, the stress generated at any location of the model is the same as that at the corresponding point of the prototype. Experimental models are often made with the same shape as the actual structure but at a smaller scale so we can accurately obtain the structural behavior [1].

Model experiments are designed based on similarity laws derived from the fundamental equations governing the phenomena of interest. The basic scaling law of geotechnical centrifuge testing stems from the need to ensure stress similarity between the experimental model and the corresponding prototype. When acceleration N times earth gravity (g) is applied to a material with density ρ, the vertical stress σ_v at depth h_m in the model is calculated as:

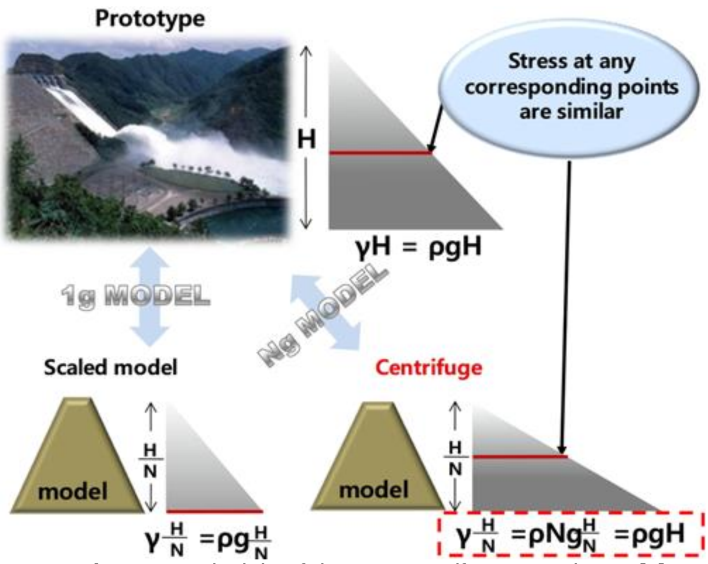

Figure 1. *Principle of the geo-centrifuge experiment [1]*

$$\sigma_{vm} = \rho N g h_m$$

In the prototype scale, assume that the density of soil is ρ, the vertical stress at depth h_p, is:

$$\sigma_{vp} = \rho g h_p$$

When the test is conducted with the same density of soil and accelerated with N times of earth gravity, the vertical stress at depth Hm in the model scale is:

$$\sigma_{vm} = \rho N g h_m$$

The concept and main aim of the geo-centrifuge experiment are that the vertical stress of soil in the prototype is the same as that at a corresponding location in the physical model. We have:

$$\sigma_{vm} = \sigma_{vp} \text{ , then } h_m = \frac{h_p}{N}$$

And the scaling factor for linear dimension is 1:N.

2.1 Basic scaling law

The basic scaling factors for the physical parameters in centrifuge testing are derived based on dimensional analysis using this linear dimensional scale. Since the mechanical properties of the geomaterial used for the centrifuge model are identical to those of the prototype material, its physical parameters can be easily determined. In cases where structural components, such as pile foundation, need to be simulated in the centrifuge model, the design of those components must consider various physical parameters that govern the behavior of the structure. For example, the bending stiffness of the pile foundation is the main parameter to simulate the behavior when the structure is subjected to horizontal loads, so it must comply with the appropriate scaling factor. Table 1 shows the scaling factors for the basic quantities in the centrifuge model.

Table 1. *Basic scaling factors in centrifuge model test*

Item	Scaling factors
Stress, modulus	1
Density	1
Length, displacement	1/N
Gravity	N
Strain	1
Force, load	$1/N^2$
Mass	$1/N^3$
Time	1/N
Velocity	1
Acceleration	N

2.2 Generalized scaling law

Conducting the geo-centrifuge test using the basic scaling factor is very useful in modeling the behavior of the geotechnical system. However, there is a fact that currently, many centrifuges are working in the low g field, and the dimensions of the container normally limit the size of the model. Therefore, using these facilities to perform experiments for a large geotechnical system is difficult if the basic scaling law is applied. Iai et al. [3] proposed the generalized scaling law that allows the use of the currently available centrifuges for modeling large geotechnical systems. This law is based on the concept of two-stage scaling with the acceptance that a prototype can be scaled into two stages, as presented in Figure . The contents of two-stage scaling are as follows [4]:

(1) First stage: the prototype is scaled into an intermediate virtual model based on the scaling relations in the 1g field using the scaling factor μ (prototype /virtual model).

(2) Second stage: the intermediate model is scaled into a physical model based con conventional scaling relations in the centrifugal field with a scaling factor η (virtual model/physical model).

In this way, the real scaling factor $\lambda=\mu\eta$ (prototype model/ physical model) is divided into two smaller scaling factors μ and η. Therefore, the geo-centrifuge test can be conducted with a small scaling factor η which can be chosen suitable for each centrifuge device. In theory, the selection of the scaling factors μ and η is optional, but in practice, it should be selected value of η as the capacity of the earthquake simulator used in the test.

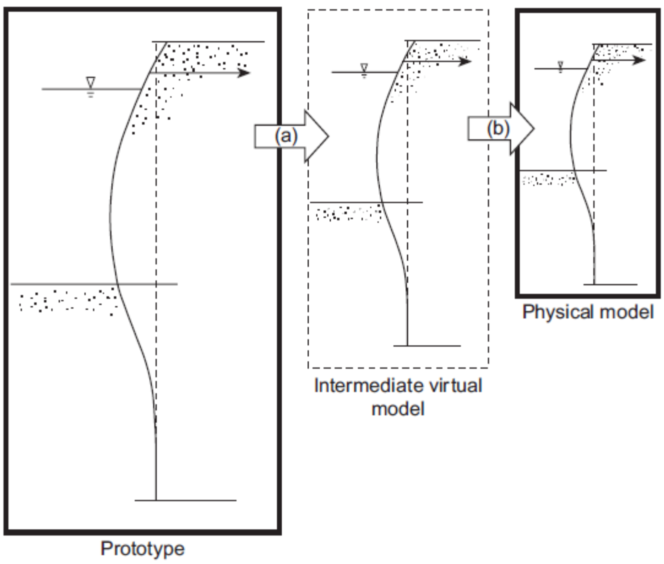

Figure 2. *Concept of two-stage scaling [3]*
(a) scaling relations for the 1g field; (b) scaling relations for the centrifugal field

Table 2 lists the scaling factor for the 1g model test [5]. The equations in the second column are used in general for all kinds of soil; these scaling factors are calculated from the scaling factor for length (μ), density (μ_ρ), and strain (μ_ε). In reality, the soil used for the experiment is normally the same as the prototype. Thus, the scaling factor of density μ_ρ = 1, and the relation is shown in the third column with the title "Type I". The scaling factor of strain can be determined based on the stress-strain relation from laboratory tests. If the laboratory test data is unavailable, it normally assumes that the shear modulus at the small strain (10^{-6}) is proportional to the square root of the confining pressure [3]. It leads to "Type II", which is suitable to apply for the centrifuge test with models using the sand. For the model test using loose sand or clay, "Type III" is suggested.

Table 2. *Scaling factors for 1g model tests [3]*

Quantity	Scaling factor for 1g test	Scaling factors in practice		
		Type I	Type II	Type III
		$\mu_\rho = 1$	$\mu_\varepsilon = \mu^{0.5}$, $\mu_\rho = 1$	$\mu_\varepsilon = 1$, $\mu_\rho = 1$
Length	μ	μ	μ	μ
Density	μ_ρ	1	1	1
Time	$(\mu\mu_\varepsilon)^{0.5}$	$(\mu\mu_\varepsilon)^{0.5}$	$\mu^{0.75}$	$\mu^{0.5}$
Frequency	$(\mu\mu_\varepsilon)^{-0.5}$	$(\mu\mu_\varepsilon)^{-0.5}$	$\mu^{-0.75}$	$\mu^{-0.5}$
Acceleration	1	1	1	1
Velocity	$(\mu\mu_\varepsilon)^{0.5}$	$(\mu\mu_\varepsilon)^{0.5}$	$\mu^{0.75}$	$\mu^{0.5}$
Displacement	$\mu\mu_\varepsilon$	$\mu\mu_\varepsilon$	$\mu^{1.5}$	μ
Stress	$\mu\mu_\rho$	μ	μ	μ
Strain	μ_ε	μ_ε	$\mu^{0.5}$	1
Stiffness	$\mu\mu_\rho / \mu_\varepsilon$	μ / μ_ε	$\mu^{0.5}$	μ
Permeability	$(\mu\mu_\varepsilon)^{0.5} / \mu_\rho$	$(\mu\mu_\varepsilon)^{0.5}$	$\mu^{0.75}$	$\mu^{0.5}$
Pore pressure	$\mu\mu_\rho$	μ	μ	μ
Fluid pressure	$\mu\mu_\rho$	μ	μ	μ
EI	$\mu^5\mu_\rho / \mu_\varepsilon$	μ^5 / μ_ε	$\mu^{4.5}$	μ^5
EA	$\mu^3\mu_\rho / \mu_\varepsilon$	μ^3 / μ_ε	$\mu^{2.5}$	μ^3
Bending moment	$\mu^4\mu_\rho$	μ^4	μ^4	μ^4
Shear	$\mu^3\mu_\rho$	μ^3	μ^3	μ^3
Axial force	$\mu^3\mu_\rho$	μ^3	μ^3	μ^3

Table 3 shows the generalized scaling factors for the centrifuge model test. The generalized scaling factors can be determined by multiplying partitioned scaling factors of the virtual 1g field by centrifugal. Other generalized scaling factors are also can be derived from some basic quantities, including scaling factors for length (λ), density (λ_ρ), strain (λ_ε), and acceleration (λ_g).

Table 3. *Generalized and partitioned scaling factors for centrifuge model tests*

Quantity	Generalized (prototype/ physical model)	Partitioned (prototype/ physical model)	Partitioned	
			Virtual 1g field (prototype/ virtual model)	Centrifugal field (Virtual model/ physical model)
Length	λ	$\mu\eta$	μ	η
Density	λ_ρ	μ_ρ	μ_ρ	1
Time	$\left(\lambda\lambda_\varepsilon / \lambda_g\right)^{0.5}$	$(\mu\mu_\varepsilon)^{0.5}\eta$	$(\mu\mu_\varepsilon)^{0.5}$	η
Frequency	$\left(\lambda\lambda_\varepsilon / \lambda_g\right)^{-0.5}$	$(\mu\mu_\varepsilon)^{-0.5} / \eta$	$(\mu\mu_\varepsilon)^{-0.5}$	$1/\eta$
Acceleration	λ_g	$1/\eta$	1	$1/\eta$
Velocity	$\left(\lambda\lambda_\varepsilon\lambda_g\right)^{0.5}$	$(\mu\mu_\varepsilon)^{0.5}$	$(\mu\mu_\varepsilon)^{0.5}$	1
Displacement	$\lambda\lambda_\varepsilon$	$\mu\mu_\varepsilon\eta$	$\mu\mu_\varepsilon$	η
Stress	$\lambda\lambda_\rho\lambda_g$	$\mu\mu_\rho$	$\mu\mu_\rho$	1
Strain	λ_ε	μ_ε	μ_ε	1

Quantity	Generalized (prototype/ physical model)	Partitioned (prototype/ physical model)	Partitioned	
			Virtual 1g field (prototype/ virtual model)	Centrifugal field (Virtual model/ physical model)
Stiffness	$\lambda\lambda_\rho\lambda_g / \lambda_\varepsilon$	$\mu\mu_\rho / \mu_\varepsilon$	$\mu\mu_\rho / \mu_\varepsilon$	1
Permeability	$\left(\lambda\lambda_\varepsilon / \lambda_g\right)^{0.5} / \lambda_\rho$	$\left[(\mu\mu_\varepsilon)^{0.5} / \mu_\rho\right]\eta$	$(\mu\mu_\varepsilon)^{0.5} / \mu_\rho$	η
Pore pressure	$\lambda\lambda_\rho\lambda_g$	$\mu\mu_\rho$	$\mu\mu_\rho$	1
Fluid pressure	$\lambda\lambda_\rho\lambda_g$	$\mu\mu_\rho$	$\mu\mu_\rho$	1
EI	$\lambda^5\lambda_\rho\lambda_g / \lambda_\varepsilon$	$\left[\mu^5\mu_\rho / \mu_\varepsilon\right]\eta^4$	$\mu^5\mu_\rho / \mu_\varepsilon$	η^4
EA	$\lambda^3\lambda_\rho\lambda_g / \lambda_\varepsilon$	$\left[\mu^3\mu_\rho / \mu_\varepsilon\right]\eta^2$	$\mu^3\mu_\rho / \mu_\varepsilon$	η^2
Bending moment	$\lambda^4\lambda_\rho\lambda_g$	$\mu^4\mu_\rho\eta^3$	$\mu^4\mu_\rho$	η^3
Shear	$\lambda^3\lambda_\rho\lambda_g$	$\mu^3\mu_\rho\eta^2$	$\mu^3\mu_\rho$	η^2
Axial force	$\lambda^3\lambda_\rho\lambda_g$	$\mu^3\mu_\rho\eta^2$	$\mu^3\mu_\rho$	η^2

3. Experimental equipments

The principle diagram of the geo-centrifuge system is depicted in Figure 3. Generally, it consists of an earthquake simulator and a data acquisition system connected with a centrifuge. When the centrifuge works at centrifugal acceleration N(g), the earthquake simulator rotates horizontally, and the acceleration applied to the model also increases to Ng. In this way, the self-weight of the entire model increases, and stress also increases to a value the same as that at the prototype condition [6].

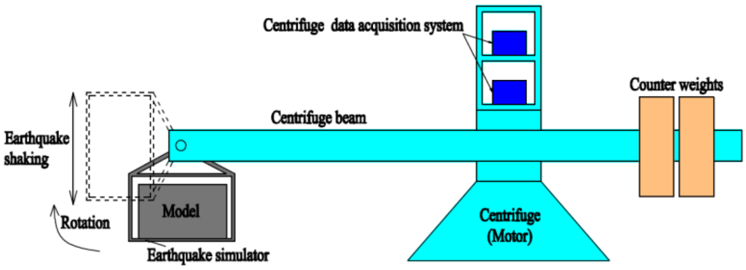

Figure 3. *Principle diagram of centrifuge machine system [7]*

Figure 4 illustrates the geo-centrifuge system in the Geotechnical Centrifuge Testing Center, KAIST, South Korea. It includes an electrohydraulic earthquake simulator mounted on the centrifuge. The centrifuge has an effective radius of 5 m and a maximum capacity of 240 g-tons. The earthquake simulator is a unique apparatus capable of modeling seismic problems on a centrifuge in Korea. It can generate earthquake excitations lasting approximately 2 s, with model frequencies ranging from 40 to 300 Hz. The main specifications of the centrifuge and earthquake simulator are listed in Table 4 [1,8,9].

Figure 4. *Centrifuge in the KAIST, Korea [4]*

The experimental model is usually manufactured and installed in a separate, specialized container and then installed into the earthquake simulator on the centrifuge. There are two commonly used types of containers: hard-bounded and soft-bounded containers (equivalent shear beam container - ESB). A hard-bounded container cannot absorb reflected waves generated by the structure, while a soft-bounded container can absorb these waves to represent boundary conditions more closely to reality. Figure 5 introduces two types of these containers used at KAIST.

Table 4. *Main specifications of geotechnical centrifuge at KAIST [8]*

Item	Specification
Centrifuge	
Platform radius	5.0 m
Max. capacity	240 g-tons
Max. acceleration	130 g with 1,300 kg payload
Max. model payload	2400 kg up to 100 g
Platform dimensions	1.2 m (L) × 1.2 m (W) × 1.2 m (H)
Earthquake Simulator	
Payload Dimension	0.67 m (L) × 0.67 m (W) × 0.65 m (H)
Max. Model Payload	700 kg
Centrifuge Acceleration Range	10-100 g
Max. Shaking Acceleration (No Payload)	40 g
Max. Shaking Acceleration (Full Payload)	20 g
Max. Displacement	6.5 mm
Max. Velocity	1.0 m/s
Loading Frequency Range (Random Vibration)	40-300 Hz
Loading Frequency Range (Sine Burst)	40-200 Hz

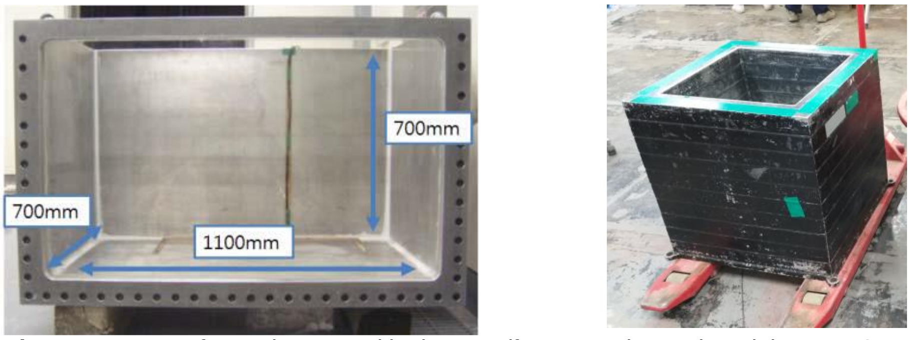

Figure 5. *Types of containers used in the centrifuge experimental models at KAIST*

Figure 6 is an example of the model fabrication and installation process for the centrifuge test of the gravity wall in the equivalent shear beam container. The sand raining system controlled the relative density of sand. A metal block modeled the gravity wall. The model was setup with several measuring equipment such as the potentiometer (measure the horizontal displacement), LVDT (measure the vertical displacement), accelerometer (measure the accelerations), etc.

Figure 6. *Fabrication and installation of models on the centrifuge*

4. Advantages and limitations of geo-centrifuge test

4.1 Advantages

The fundamental reason for using a centrifuge in a soil mechanics problem is that it offers the only means by which a small-scale physical model can be subjected to self-weight stress levels with both strain and boundary conditions compatible with those existing within a full-scale field structure. In centrifuge testing, correct modeling of variables such as compression, yield, transient flow of pore fluid, and complex stress-strain relationships, including anisotropy, can be achieved. The superposition of loads and the change in water level can be easily adjusted during centrifugal testing, providing a better insight into prototype behavior in a very short period. This technique can easily model the problem of cracking of dams. The centrifuge can also model dynamic problems such as liquefaction due to earthquake or blast shocks.

4.2 Limitations

Since the objective of the centrifugal model testing is to predict the behavior of a full-scale prototype, it is desirable to know the limitations of the testing technique so that a realistic interpretation of the data, with necessary corrections, can be made [10]:

+ Variation of acceleration field: Because the acceleration field in the centrifuge is radial and not parallel as earth gravity, the stress field in the model may not be compatible with that in the prototype. The error can be reduced by increasing the radius of the centrifuge so that the maximum tangential dimension of the model subtends the minimum possible angle at the center of rotation;

+ Stress history: It is important in centrifugal testing to ensure that the stress at each point in the model is identical to that at the corresponding point in the prototype and that stress and strain cycles and over-consolidation pressure are similar and correctly modeled. Generally, this task is not easy, and it may be impossible to model complex ground conditions. However, it is possible for soils of moderate uniformity to maintain similarity by obtaining a sample from the site that shares the stress history of all the soil intended to be modeled;

+ Time effect: There are two ways in which time may affect the similarity between the prototype and the corresponding model in centrifugal testing. One type of time effect is the time the model spends in an unsteady state while accelerating to and decelerating from its intended speed. The result creates a stress history in the model with no counterpart in the prototype. The second effect of time is related to the loading rate, which significantly affects the shear strength, especially for clay soils;

+ Size effect: Size effect is especially important when an attempt is made to model soils with a macroscopic structure, which influences soil strength. Concerning centrifugal model testing, macroscopic features must be sufficiently small in the model to permit stresses and deformations compatible with those occurring in the full-scale prototype. Special attention should be given to heavily overconsolidated soils whose behavior is significantly influenced by micro-fissures and progressive failure. However, the size effect can be ignored for normally consolidated or slightly overconsolidated clays;

+ Other effects: There are other effects of secondary importance that are either inherent in soil testing in general or cannot be made to conform with centrifugal modeling laws. Side friction and boundary conditions are problems that are inherent in any soil testing method and must be considered in centrifugal model testing. Chemical processes, such as soil stabilization and other processes, may significantly affect soil behavior, but these effects are independent of the model scale and cannot be simulated by an accelerated time scale.

5. Conclusion

The paper introduced an overview of the geo-centrifuge experimental model, which included the advantages and limitations, to evaluate the response of the soil-structure system under the effect of earthquake loading. Although a miniature model is used, the experiment can more closely describe the behavior of the soil–structure system by accelerating to an appropriate level. This is a modern experiment that can be applied to many different types of projects in the fields of structure and geotechnical engineering. The experimental results give us an overview and detail of the problems occurring in the soil-structure system during earthquakes, and it can be used to verify the numerical models.

REFERENCES

[1] D.S. Kim, N.R. Kim, Y.W. Choo, G.C. Cho (2013), *A newly developed state-of-the-art geotechnical centrifuge in Korea*, KSCE J. Civ. Eng. 17, 77–84. doi:10.1007/s12205-013-1350-5.

[2] T. Kimura (1998), *Development of geotechnical centrifuges in Japan*, in: Centrifuge 98, Tokyo: pp. 945–954.

[3] S. Iai, T. Tobita, T. Nakahara (2005), *Generalised scaling relations for dynamic centrifuge tests,* Geotechnique. 55, 355–362. doi:10.1680/geot.2005.55.5.355.

[4] A. Nguyen, Y.S. Kim, G.O. Kang (2022), *Comparison of dynamic behavior of caisson-type quay wall before and after renovation using geo-centrifuge test*, in: 10th Int. Conf. Phys. Model. Geotech., KAIST, Daejeon, Korea.

[5] S. Iai (1989), *Similitude for shaking table tests on soil-structure-fluid model in 1g gravitational field*, Soils Found. 29, 105–118. doi:10.3208/sandf1972.29.105.

[6] A.D. Nguyen, Y.S. Kim (2022), *Earthquake Resistance of Caisson-Type Quay Wall Renovated by Grouting and Deepening: Geo-Centrifuge Test,* in: Proc. 4th Int. Conf. Sustain. Civ. Eng., Hanoi, Vietnam: pp. 463–471.

[7] A.D. Nguyen (2022), *Geo-centrifuge Test and Numerical Analysis for Developing Renovation Technology of Caisson-type Quay Wall by Grouting and Deepening,* Chonnam National University.

[8] D.S. Kim, S.H. Lee, Y.W. Choo, J. Perdriat (2013), *Self-balanced earthquake simulator on centrifuge and dynamic performance verification,* KSCE J. Civ. Eng. 17, 651–661. doi:10.1007/s12205-013-1591-3.

[9] J.G. Ha, S.H. Lee, D.S. Kim, Y.W. Choo (2014), *Simulation of soil-foundation-structure interaction of Hualien large-scale seismic test using dynamic centrifuge test,* Soil Dyn. Earthq. Eng. 61–62, 176–187. doi:10.1016/j.soildyn.2014.01.008.

[10] M.M. Al-Hussaini (1976), *A centrifuge model testing of soils: A literature review.*