KSCE Journal of Civil Engineering (2013) 17(1):77-84
DOI 10.1007/s12205-013-1350-5

Geotechnical Engineering
www.springer.com/12205

TECHNICAL NOTE

A Newly Developed State-of-the-Art Geotechnical Centrifuge in Korea

Dong-Soo Kim*, Nam-Ryong Kim, Yun Wook Choo***, and Gye-Chun Cho******

Received October 14, 2010/Accepted June 14, 2012/Published Online July 15, 2012

Abstract

The first large scale geotechnical centrifuge in Korea has recently been developed at KAIST under the Korea Construction Engineering Development (KOCED) Collaboratory program. A 5 m platform radius, 240 g-tons state-of-the-art geotechnical centrifuge has been installed in a new facility. The centrifuge has the unique feature of an automatic balancing system and includes parts for general testing purposes such as fluid rotary joints, slip rings, a fiber optic rotary joint and an Ethernet network system. In addition, a four degree-of-freedom in-flight robot can be equipped to simulate complex construction or in-situ testing process during centrifuge flight. In order to simulate earthquake motion during operation, a self-balancing type biaxial shaking table has also been developed. Since the KOCED program promotes collaboration and remote use, tele-presence and tele-participation environments have been implemented in this facility.

Keywords: *physical modeling, geotechnical centrifuge, KOCED, shaking table, in-flight robot*

1. Introduction

In the field of geotechnical engineering, reduced-scale physical modeling is often conducted within a large centrifuge in order to provide correct scaling of the self-weight stresses (Schofield, 1980; Taylor, 1995; Gaudin *et al*., 2009). Major soil properties that govern mechanical behavior such as strength and stiffness depend on the effective stress level, and hence reduced small-scale models cannot replicate the field scale behavior. When the models are accelerated within a centrifuge, the self-weight of the soil can be raised to field conditions so that the entire behavior of the model can be similar to that of full scale geotechnical structures.

Physical modeling using a centrifuge has various advantages in the analysis of geotechnical systems. The geotechnical centrifuge is sometimes called "the site next door" because it gives an opportunity to easily simulate field conditions. By conducting experiments with reduced scale models, centrifuge modeling can reduce consumption of time and effort in preparation. It is also easier to make a model than to conduct full-scale tests while the centrifuge also provides more accurate and realistic stress conditions in the model system than a 1-g experiment. The centrifuge is useful for verifying numerical simulations and has the advantage that the deformation or strength characteristics of the soil under consideration can be fully adopted. The application area of centrifuge modeling has also expanded from traditional geotechnical engineering problems to more complex geotechnical systems. Physical modeling technology using a centrifuge is currently applied in various geotechnical engineering fields: foundation systems, earth structures, offshore systems, earthquake related problems, geoenvironmental studies, etc (Kimura, 1998). With the development of advanced technologies in centrifuge equipment and data acquisition, the number of geotechnical centrifuges has increased rapidly and there are currently more than 110 centrifuges in operation worldwide.

Several cases have reported applications of physical modeling using geotechnical centrifuges in Korea. However, these studies only applied this approach to traditional and basic problems, for example, slope stability, consolidation, etc. With recent economic growth and demand for new construction technology, there are new demands for advanced physical modeling techniques in the geotechnical engineering field in Korea. Despite the continually increasing need for centrifuge experiments, the number of centrifuge facilities with advanced capabilities is still insufficient.

In 2008, a state-of-the-art geotechnical centrifuge facility with advanced testing equipment was established in Korea. This article presents a general overview of KOCED Geotechnical Centrifuge Testing Center at KAIST. The facility includes a 5 m platform radius geotechnical centrifuge, an in-flight biaxial shaking table, a four degree-of-freedom in-flight robot and general modeling equipment. This facility is expected to provide a unique oppor-

*Member, Professor, Dept. of Civil and Environmental Engineering, KAIST, Daejeon 305-701, Korea (E-mail: dskim@kaist.ac.kr)
**Member, Senior Researcher, Infrastructure Technology Center, K-water Institute, Daejeon 305-730, Korea (Corresponding Author, E-mail: namryong @kwater.or.kr)
***Member, Research Professor, Dept. of Civil and Environmental Engineering, KAIST, Daejeon 305-701, Korea (E-mail: ywchoo@kaist.ac.kr)
****Member, Professor, Dept. of Civil and Environmental Engineering, KAIST, Daejeon 305-701, Korea (E-mail: gyechun@kaist.edu)

tunity to perform diverse experimental research for geotechnical engineers in Korea, and research and development will be further activated in this area. The main purpose of this article is to introduce the major testing equipment of KOCED Geotechnical Centrifuge Testing Center. Research activities of the Center, as well as fundamental aspects of geotechnical centrifuge modeling are presented.

2. Geotechnical Centrifuge Modeling

2.1 General

The basic idea of physical modeling of geotechnical systems using a centrifuge is to accelerate a reduced scale geotechnical structure to the appropriate high g-level to simulate the prototype scale stress field in the model structure. When the model is made on a reduced scale of 1:N, it is accelerated at N times Earth gravity. In this case, the stress level at any point of the model will be similar to the corresponding point of the prototype, as shown in Fig. 1. The centrifuge models are built according to the same shape of the prototype structure at a reduced scale so users can observe the structural behavior of the model easily. Since large scale centrifuge equipment has become available in geotechnical engineering, it has been applied to various geotechnical problems.

2.2 Principles of Centrifuge Modeling

Scaled model experiments must be designed based on similarity laws derived from fundamental equations governing the phenomena of interest. The basic scaling law for geotechnical centrifuge testing is derived from the need to ensure stress similarity between the model and corresponding prototype. When an acceleration of N times Earth gravity (g) is applied to a material of density ρ, the vertical stress σ_v at depth h_m in the model is given by:

$$\sigma_{vm} = \rho N g h_m \quad (1)$$

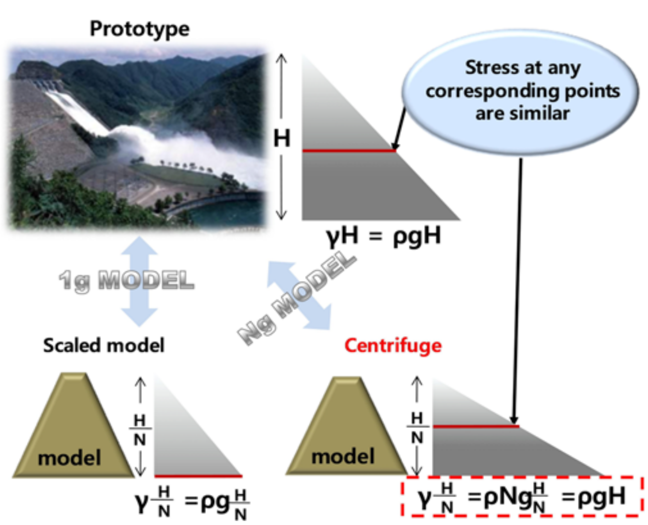

Fig. 1. Concept of Physical Modeling using a Geotechnical Centrifuge

Table 1. Scaling Factors for Basic Quantities in Centrifuge Modeling

Item	Scaling Factor	Item	Scaling Factor
Stress, modulus	1	Force, load	N^{-2}
Density	1	Mass	N^{-3}
Length, displacement	N^{-1}	Diffusion time	N^{-2}
Gravity	N	Stress wave velocity	1
Strain	1	Dynamic acceleration (earthquake)	N

In the full scale prototype, indicated by subscript p, the vertical stress is expressed by:

$$\sigma_{vp} = \rho g h_p \quad (2)$$

From the fundamental concepts underlying centrifuge modeling, the vertical stresses at the model and the prototype are identical: $\sigma_{vm} = \sigma_{vp}$ and $h_m = h_p N^{-1}$, and the scale factor for linear dimensions is 1:N. Basic scaling factors for physical quantities in centrifuge testing are derived based on a dimensional analysis using this linear dimension scale. Since the mechanical properties of the geomaterial used for general centrifuge model are identical to those of the prototype material, its physical quantities can be easily derived. In a case where structural components, such as a pile foundation, need to be simulated in the centrifuge model, the design of those components must consider the different physical quantities that are governing the behavior of the structure. For example, the bending stiffness of the pile foundation is the key parameter for simulating behavior when the structure is subjected to lateral loading, and hence it must follow the appropriate scaling factor. Table 1 shows scaling factors for basic quantities in centrifuge modeling. Most of the scaling factors for the modeling can be derived from those factors.

3. KOCED Centrifuge Testing Equipment

3.1 Geotechnical Centrifuge

The geotechnical centrifuge installed at the facility is Model C72-2 manufactured by ACTIDYN SYSTEMES SA (Elancourt, France) and its installation was completed in March 2008 (Fig. 2). General specifications of this 5 m radius, 240 g-tons beam centrifuge are listed in Table 2. There are about 110 geotechnical centrifuges in operation in the world and the centrifuge at KAIST is one of the 10 biggest centrifuges in terms of maximum capacity (Fig. 3). The centrifuge has an asymmetric design and is balanced by a massive counterweight at the opposite side of the testing model. The design philosophy of the asymmetric single basket enables reduction of the aerodynamic drag force, and hence operation is optimized for minimum electrical power consumption.

Figure 4 illustrates the layout of the mechanical components and control parts of the KOCED geotechnical centrifuge. The electric power supply, located outside of the centrifuge chamber, controls the centrifuge operation by supplying electricity to two AC motors. The operational speed or g-level is decided based on received commands and settings from the operator PC and cen-

Fig. 2. KOCED Geotechnical Centrifuge

Table 2. Specifications of KOCED Geotechnical Centrifuge

Item	Specification
Platform radius	5.0 m
Max. capacity	240 g-tons
Max. acceleration	130 g with 1,300 kg payload
Max. model payload	2,400 kg up to 100 g
Platform dimensions	1.2 m (L) × 1.2 m (W) × 1.2 m (H)
Power consumption	220kW for full capacity operation
Fluid rotary joint	4 lines – water & pneumatic (700 kPa) 6 lines – hydraulic oil (20 MPa)
Electrical slip rings	8 lines for electrical power supply 30 lines for signal transmission 4 channels for video transmission
Fiber optic rotary joint	1 GHz, 2 passages

trifuge status data. The motors are connected to the driving pulley inside the conical pedestal by a rubber belt enabling rotation of the arm. The unbalanced force between the model and counterweight sides is measured at two of four anchors. The unbalanced force can be adjusted in two different ways: by moving primary counterweights with a motor at low g-level and by a hydraulic system at high g operation.

Signal slip rings and a fiber optic rotary joint are incorporated at the top of the centrifuge for data transmission. Brush type signal slip rings with 30 conductors for signal transmission and 4 high frequency video channels are available. By Ethernet connections via the fiber optic rotary joint, users can avoid noise problems induced from slip rings and have greater flexibility in composing experimental systems. At the bottom of the centrifuge, there are a total of five fluid rotary joints for hydraulic oil pressure, air and water supply lines. There are a total of 10 channels in the rotary joints: six 20MPa channels for hydraulic oil for the biaxial shaking table and general hydraulic actuators, two 700kPa channels for water supply and two 700kPa channels for pneumatic pressure. These supply lines directly go through the rotary joint to the user experimental platform and they are also connected to equipment such as the shaking table. It is important to have fluid supply lines for centrifuge experiments

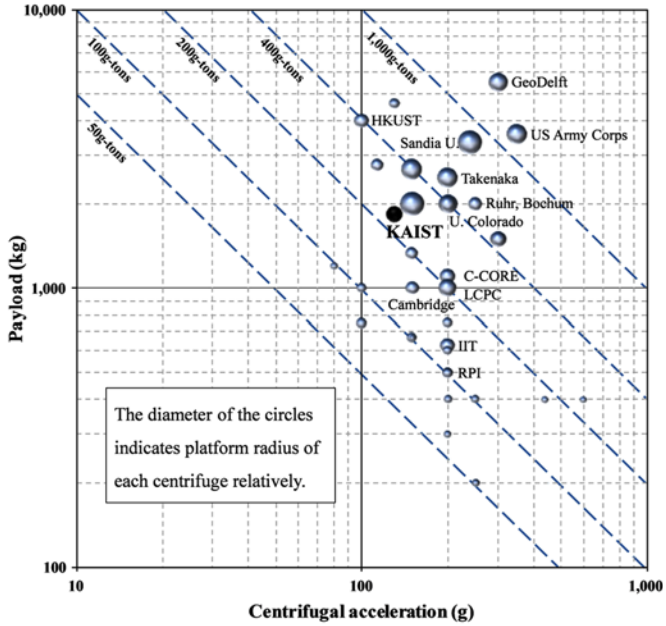

Fig. 3. Major Geotechnical Centrifuges in the World (Drawn with data from ISSMGE TC-104 Physical Modelling in Geotechnics)

that require pneumatic pressure or water supply.

3.2 Centrifuge Data Acquisition System

The Centrifuge Data Acquisition (DAQ) System is installed in the centrifuge near the rotating axis and is directly connected to a local network via a gigabit fiber optic rotary joint. This configuration is now common in most beam type centrifuges, whereas signal slip rings were used for data transmission in the early years of centrifuge testing.

The Centrifuge DAQ System at KAIST is developed by combining National Instruments PXI series A/D boards and controllers, and SCXI series signal conditioning units. This system is widely used in many centrifuge facilities due to its flexibility to configure the system according to the user's requirements. A relay switch to control switches and equipment and four 500 kS/s high-speed simultaneous data acquisition cards for measuring the shear wave velocity of soil are prepared. The NI SCXI signal conditioning units are located at the centrifuge user platform so multiple transducers can be easily connected to the DAQ hardware. It is aimed at the capability to record a total of 192 channels for accelerometers, strain gages, LVDTs and voltage type inputs at 100,000 samples per second simultaneously.

3.3 Four Degree-of-Freedom In-Flight Robot

Since the first four degree-of-freedom in-flight robot for simulating complex processes was introduced by Laboratoire Central des Ponts et Chaussées (LCPC) in France (Derkx *et al.*, 1998), its usefulness has been recognized by the physical modeling research community. Several cases of its development and application in centrifuge tests have been reported (Ng *et al.*, 2002; Zehgal *et al.*, 2002). This on-board robot is installed on the

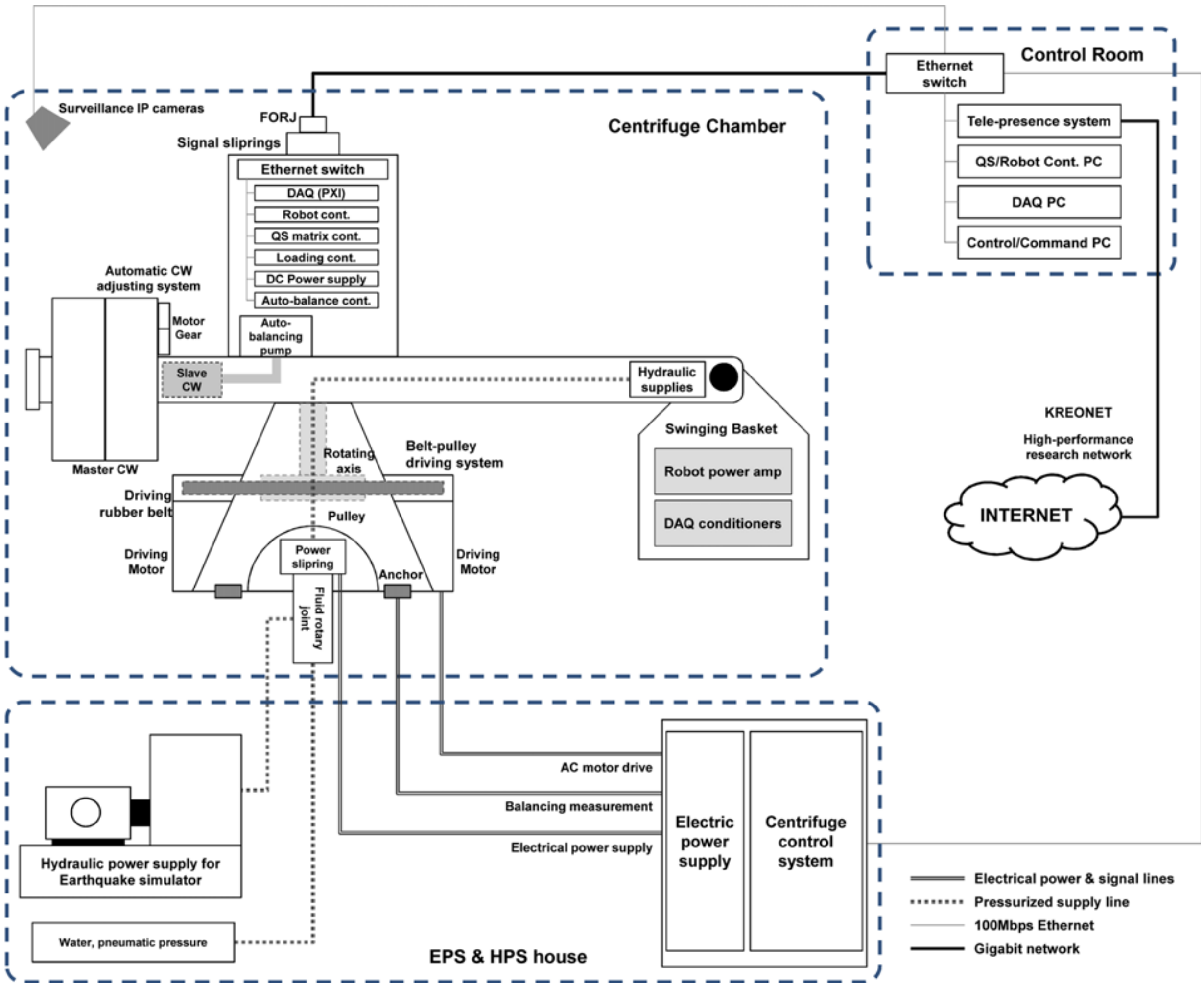

Fig. 4. Configurations of KOCED Geotechnical Centrifuge Operation Systems

top of the model container and is able to take a tool to any location along three linear directions *X*, *Y*, *Z*, and to rotate in one direction, θ_Z. It simulates various construction processes such as pile driving, loading, or excavation remotely while operating the centrifuge.

Figure 5 shows the robot at KOCED Geotechnical Centrifuge Testing Center. The robot can utilize four different tools at the same time and its performance specifications are summarized in Table 3. The maximum centrifugal acceleration for operation of the robot is 100 g. Positioning of the robot head is achieved via movement along the guided rails in three linear directions controlling individual AC motors. The user can define the sequence of motion by either pre-programming or by real-time command.

The tool holder is located at the bottom of the standard head. The robot can take any tool from a four-tools-storage compartment. The robot can grab any of the tools from the storage area for operation as the head of each tool is made with a standardized interface. The standard head provides flexibility for use of the robot. Each tool, such as a cone penetrometer for example, is attached at the bottom of the standard head. The electrical connections are provided by three 10-conductor connectors. Connections for hydraulic, fluid and pneumatic circuits are also provided. Once the robot grabs a tool, the interface is interlocked and electrical signals are transmitted to the connectors at the main frame of the robot. The user can connect to the Centrifuge


Fig. 5. Four Degree-of-Freedom In-Flight Robot at KAIST

Table 3. Performance Specifications of Four Degree-of-Freedom In-Flight Robot

Item	Specifications			
	X	*Y*	*Z*	θ_Z
Stroke	0.8 m	0.6 m	0.5 m	±175º
Maximum speed	50 mm/s	50 mm/s	50 mm/s	5º/s
Loading capacity	±1 kN	±1 kN	±5 kN	±5 Nm
Accuracy	±1.0 mm	±1.0 mm	±1.0 mm	±0.5º

Table 4. Specifications of Biaxial Shaking Table

Item	Specifications
Shaking type	Electro-hydraulic servo type
Shaking direction	Two prototype horizontal
Max. model payload	700 kg
Payload dimensions	0.65 m (L) × 0.65 m (W) × 0.7m (H)
Max. shaking acceleration	20 g for full payload
Experimental frequency range	40 to 300 Hz

DAQ System or other controllers from the mainframe for measurement or control purposes.

3.4 Biaxial Shaking Table

Recently, a considerable amount of research on geotechnical earthquake engineering using centrifuges has been undertaken throughout the world. In-flight shaking tables for geotechnical centrifuges are operated using servo hydraulic systems. Because of the scaling law, the frequency characteristics of ground input motion for the shaking tables must be *N* times the prototype ground motion. Therefore, the maximum operating frequency range of these shaking tables is usually as high as 300 Hz.

Generally, most in-flight shaking tables for centrifuges are uni-directional, while earthquake motions are multi-directional in nature. For this reason, biaxial shaking tables have been developed at several universities internationally. HKUST in Hong Kong and RPI in the USA have developed horizontal biaxial shaking tables (Shen *et al*., 1998; Zehgal *et al*., 2002), and UC Davis in the USA developed a horizontal-vertical biaxial shaking table.

The shaking table at KAIST is a self-balanced bi-directional horizontal shaking table (Fig. 6). The entire system is built in an integrated basket dedicated solely to the shaking table, and consequently the usual static basket must be removed for installation of this shaking table to the centrifuge. This shaking table is designed for operation under 100 g centrifugal acceleration and the maximum shaking acceleration level is 20 g at the model scale. Experiments using this system must be designed according to proper scaling principles considering the frequency response and allowable simulating acceleration capacity, because the response of this system depends on both payload and frequency of input motion. The specifications of this biaxial shaking table are listed in Table 4.

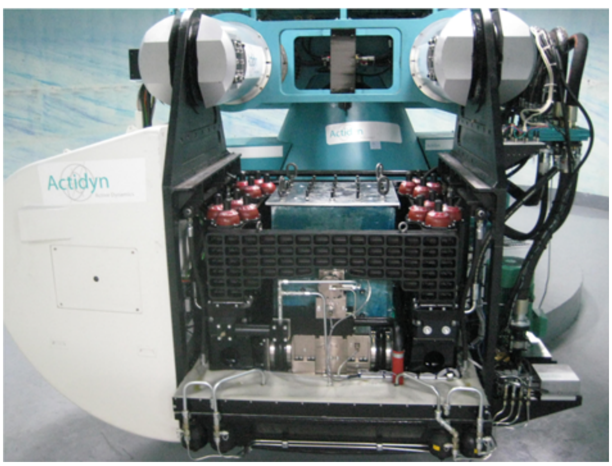

Fig. 6. Biaxial Shaking Table of KOCED Geotechnical Centrifuge

The in-flight shaking table at KAIST is a bi-directional horizontal type and has been designed based on dynamic balancing principles (Perdriat *et al*., 2002). There are two counterweights with similar mass as the experimental model on the shaking table and dynamic balancing is achieved by reciprocal actuation of the model and the balancing counterweight. In this system, X and Y axis balanced motion is obtained by close loop control of two parallel pairs of actuators. Dynamic balancing is important not only for simulating accurate input motion but also for reducing the risk of damaging mechanical parts of the centrifuge itself.

3.5 Accessories

Various types of model containers and modeling equipment required for model construction were prepared for the centrifuge. Rectangular and cylindrical rigid containers for static problems and Equivalent Shear Beam (ESB) type containers for dynamic problems can be used to simulate appropriate boundary conditions. An automatic sand rainer, a vacuum clay mixer and a soil consolidation system are available at the facility. Various types of transducers such as pore pressure transducers, accelerometers, LVDTs are equipped and a 60,000 fps high speed camera to capture video for dynamic event is available as well.

4. Telepresence – KOCED Cyberinfrastructure

The KOCED Collaboratory is planned and built as distributed facilities and resources for dispersed users. Therefore, KOCED provides a supporting system not only for research collaboration, but also for management and administration of the facilities and services. The system that integrates the administration system with the collaboration system is known as the KOCED Cyber-Infrastructure (CI) system (Kim *et al*., 2008).

KOCED CI provides many diversified versions of collaboration services such as multi-party bidirectional teleconferencing, web casting of seminars and experiments, remote control and monitoring, dispersed and collaborative design, online bidirectional lecturing, an expert consultants network, etc. One of the main features of this system is a real time streaming service of experimental data from the testing site to remote users. Video constitutes important data from physical model tests, especially for a geotechnical centrifuge and the results from the measurement

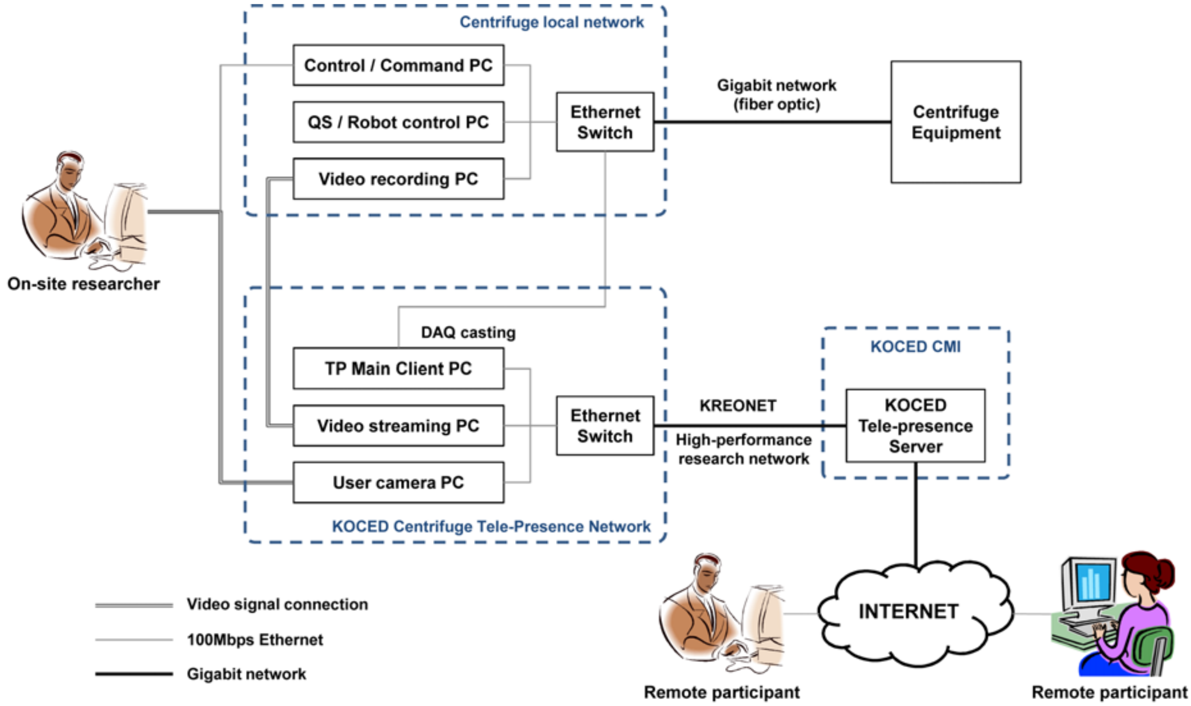

Fig. 7. Configuration of Telepresence System in KOCED Centrifuge Operation Network

system also need to be transmitted to remote users. Therefore, the centrifuge control and monitoring system has been integrated with the KOCED CI system in the facility. Fig. 7 illustrates the configuration of the centrifuge network for the KOCED CI system. In this system, remote users can participate in on-site experiments and real-time experimental data can be provided.

5. Research Activities on Physical Modeling at KAIST

Since the installation of the centrifuge equipment in 2008, several experimental research projects related to geotechnical centrifuge modeling have been carried out at KAIST. Following the first experiments on geophysical visualization of shear wave velocity in the testing model, various research projects on physical modeling have been conducted with the centrifuge equipment: concrete faced dams, earthquake problems, offshore foundations, gas hydrate-bearing sediment, foundation systems, etc., as listed in Table 5. Fig. 8 shows experimental models used for the research projects. The testing center and research staff have been available to support external researchers in conducting experimental projects as well as in industrial engineering practice.

6. Conclusions

The state-of-the-art facility of the KOCED Geotechnical Centrifuge Testing Center has been introduced in this article. With advances in testing equipment and monitoring systems, more complex geotechnical structures can be simulated in the centrifuge and construction processes in the field can also simulated during experiments. With the evolution of instrumentation technology, geotechnical centrifuge modeling can play a key role in understanding physical phenomena and mechanical behavior of geotechnical systems. As geotechnical engineering faces new challenges such as issues related to offshore engineering, energy and environmental problems, there will be potential application areas in which physical modeling technology using the centrifuge

Table 5. Major Research Activities on Physical Modeling Studies at KAIST

V_S tomography in centrifuge testing model (Kim and Kim, 2010) • Measurement system development - Fig. 8(a) • Applications in centrifuge testing models
Modeling of earth structures and performance evaluation (Choo *et al.*, 2010; Kim *et al.*, 2011) • Modeling of concrete faced gravel-filled dams (CFGD) • Evaluating draining performance in damaged cases – Fig. 8(b) • Seismic performance evaluation • Simulating natural disaster and performance verification
Geotechnical earthquake engineering problems (Lee *et al.*, 2010) • System identification of the in-flight shaking table • Effect of embedded foundation on the spectral response – Fig. 8(d) • Seismic evaluation of underground structure
Modeling offshore foundation systems (Kim *et al.*, 2009) • Simulating installation process of suction caisson
Monitoring hydrate dissociation processes in hydrate-bearing sediments (Lee, 2010) • Measuring V_S and electrical resistivity while dissociation process
Foundation systems (Park *et al.*, 2010) • Bearing capacity of piled-raft foundation – Fig. 8(c) • Load distribution characteristics according to arrangement of piles

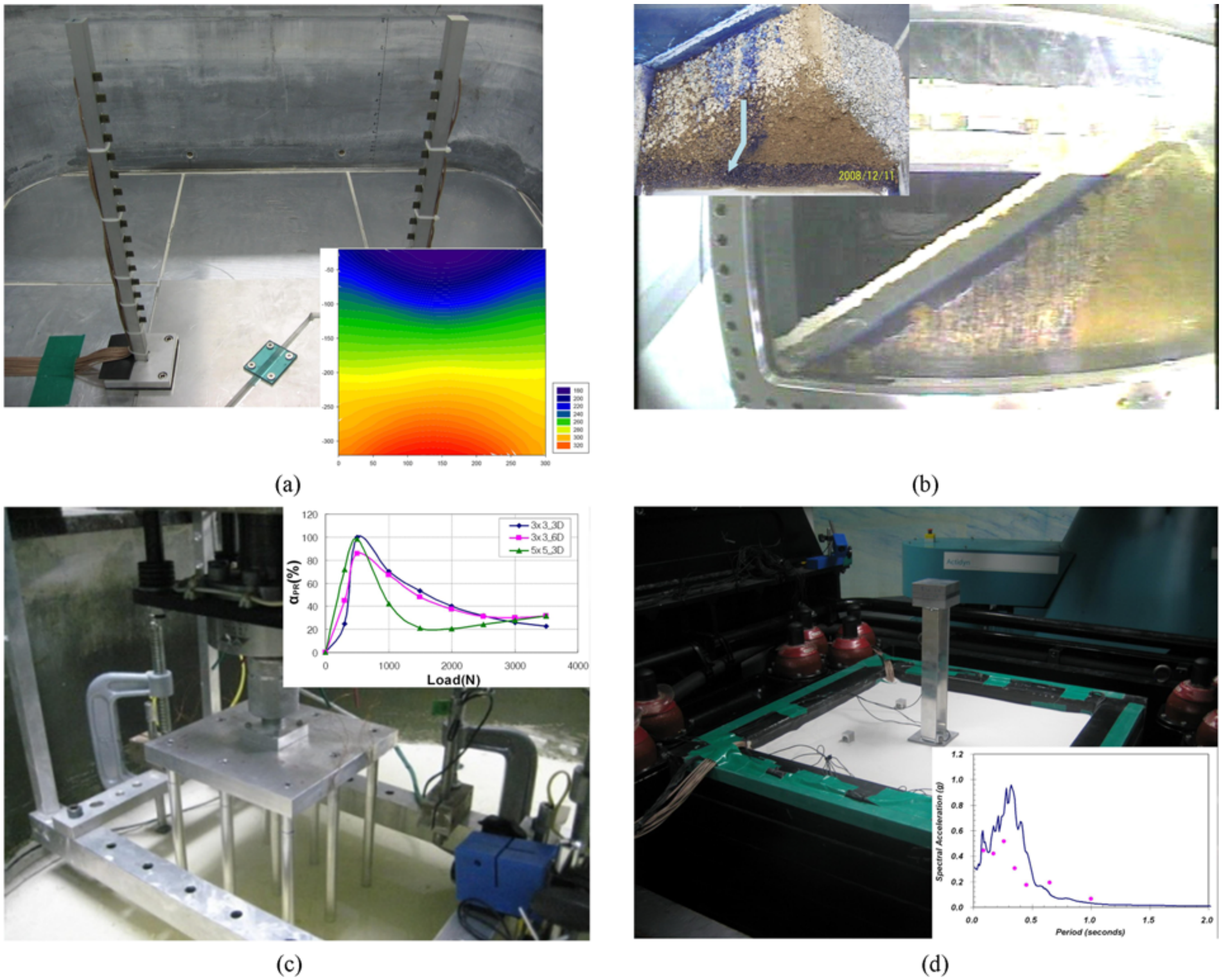

Fig. 8. Experimental Studies with KOCED Geotechnical Centrifuge: (a) V_S Tomography (Bender element array for V_S tomography and a V_S tomogram for a uniform sand model), (b) Modeling of Dams (CFGD modeling and evaluating drainage performance of the material; Model in flight condition and excavated model after experiment), (c) Piled Raft Foundation (Installation and loading test; Load supported by piles varies with arrangement), (d) Soil-Foundation-Structure Interaction (Seismic behavior of buildings under various foundation conditions; Comparison between response spectrum at the surface and structural response measured from the physical model experiment)

can be applied. In this context, the centrifuge testing equipment is expected to provide unique opportunities for studying various types of geotechnical problems. Since the KOCED program provides a shared research environment, research on physical modeling using the geotechnical centrifuge is expected to be activated in the Korean civil engineering community, and international collaboration using the KOCED CI environment will also be promoted.

Acknowledgements

This work is a part of a research project supported by Korea Ministry of Land, Transport and Maritime Affairs (KMLTM) through KOCED Geotechnical Centrifuge Center at KAIST. The authors wish to express their gratitude for the financial support. The authors also gratefully acknowledge the KREONET service provided by Korea Institute of Science and Technology Information.

References

Choo, Y. W., Kim, D. S., Kim, K. H., Shin, D. H., Im, E. S., Cho, S. E., and Park, H. G. (2010). “Effect of drainage zoning and deeply placed plinth on CFGD.” *Proceedings of the 7th International Conference on Physical Modelling in Geotechnics*, Zurich, Switzerland, pp. 1177-1182.

Derkx, F., Merliot, E., Cottineau, L. M., and Garnier, J. (1998). “On-board remote controlled centrifuge robot.” *CENTRIFUGE 98*, Tokyo, Japan, pp. 97-102.

Gaudin, C., White, D. J., Boylan, N., Breen, J., Brown, T., De Catania, S., and Hortin, P. (2009). “A wireless high-speed data acquisition system for geotechnical centrifuge model testing.” *Measurement Science and Technology*, Vol. 20, No. 9, pp. 1-11.

Kim, S., Choo, Y. W., Kim, D. J., and Kim, D. S. (2009). “Centrifuge study on installation of suction pile in sand and silt.” *Proceedings of 22th KKCNN Symposium on Civil Engineering*, Chiang Mai, Thailand.

Kim, N. R. and Kim, D. S. (2010). “A shear wave velocity tomography system for geotechnical centrifuge testing." *Geotechnical Testing Journal*, Vol. 33, No. 6, pp. 434-444.

Kim, M. K., Lee, S. H., Choo, Y. W., and Kim, D. S. (2011). "Seismic behaviors of earth-core and concrete-faced rockfill dams by dynamic centrifuge tests." *Soil Dynamics and Earthquake Engineering*, Vol. 31, No. 11, pp. 1579-1593.

Kim, J. K., Park, Y. S., Kim, D. S., Cheung, J. H., Lee, S. H., Kwon, S. D., Kim, T. H., Kim, C. Y., and Shin, S. (2008). "KOCED collaboratory program: Progress report." *14th World Conference on Earthquake Engineering: Innovation Practice Safety.* Beijing, China.

Kimura, T. (1998). "Development of geotechnical centrifuges in Japan." *CENTRIFUGE 98*, Tokyo, pp. 945-954.

Lee, K. R. (2010). *Engineering properties of sediment samples from the Ulleung Basin, East Sea and physical modeling of gas hydrate-bearing sediments*, Master's Thesis, KAIST, Daejeon, Korea.

Lee, S. H., Kim, S. H., Choo, Y. W., and Kim, D. K. (2010). "Dynamic centrifuge modeling for evaluating seismic loads of soil-foundation-structures." *Proceedings of KGS Fall National Conference*, Gyeonggi, Korea (in Korean).

Ng, C. W. W., Van Laak, P. A., Zhang, L. M., Tang, W. H., Zong, G. H., Wang, Z. L., Xu, G. M., and Liu, S. H. (2002). "Development of a four-axis robotic manipulator for centrifuge modeling at HKUST." *Physical Modelling in Geotechnics: ICPMG '02*, Newfoundland, Canada, pp. 71-76.

Park, J. O., Choo, Y. W., and Kim, D. S. (2009). "Evaluation of bearing capacity of piled raft foundation on OC clay using centrifuge and numerical modeling." *Journal of Korean Geotechnical Society*, Vol. 25, No. 7, pp. 23-33 (in Korean).

Perdriat, J., Phillips, R., Nicolas Font, J., and Huntin, C. (2002). "Dynamically balanced broad frequency earthquake simulation system." *Physical Modelling in Geotechnics: ICPMG '02*, Newfoundland, Canada, pp. 169-173.

Schofield, A. N. (1980). "Cambridge geotechnical centrifuge operation." *Géotechnique*, Vol. 20, No. 3, pp. 227-268.

Shen, C.K., Li X. S., Ng, C.W.W., Van Laak, P.A., Kutter, B.L., Cappel, K., and Tauscher, R. C. (1998). "Development of a geotechnical centrifuge in Hong Kong." *Proceedings of the International Conference CENTRIFUGE 98*, Tokyo, Japan, pp. 13-18.

Taylor, R. N. (1995). *Geotechnical centrifuge technology*, Blackie Academic, London, UK.

Zehgal, M., Dobry, R., Abdoun, T., Zimmie, T. F., and Elgamal, A.-W. M. (2002). "NEES earthquake simulation and networking capabilities at RPI centrifuge." *Proceedings of the Seventh U.S. National Conference on Earthquake Engineering (7NCEE)*, Boston.