Physical Modeling of Geotechnical Systems using Centrifuge

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SYNOPSIS : In geotechnical engineering, the mechanical characteristics of soil, the main material of geotechnical engineering, is highly related to the confining stress. Reduced-scale physical modeling is often conducted to evaluate the performance or to verify the behavior of the geotechnical systems. However, reduced-scale physical modeling cannot replicate the behavior of the full-scale prototype because the reduced-scale causes difference of self weight stress level. Geotechnical centrifuges are commonly used for physical model tests to compensate the model for the stress level. Physical modeling techniques using centrifuge are widely adopted in most of geotechnical engineering fields these days due to its various advantages. In this paper, fundamentals of geotechnical centrifuge modeling and its application area are explained. State-of-the-art geotechnical centrifuge equipment is also described as an example of KOCED geotechnical centrifuge facility at KAIST.

Keywords : physical modeling, geotechnical centrifuge, model test, shaking table, in-flight robot

1. Introduction

In 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). The strength and stiffness of soil highly depends on the effective stress level, and so 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 condition so the entire behavior of the model can be similar with the full scale geotechnical structures.

Since Edouard Phillips suggested a centrifuge modeling of 1:50 scale bridge structures in 1869 under recognition of the significance of self-weight body forces to obtain similarity of stress between reduced scale models and prototypes when the same materials were used, there has been rapid evolution in physical modeling research using centrifuge. After the first geotechnical centrifuge applications in the US and USSR in 1930s, the modern age of physical modeling research started in 1960s. Mikasa at Osaka City University started centrifuge research from self-weight consolidation and his research expanded to bearing capacity and slope stability problems. At the same era, Schofield at the University of Cambridge also started using centrifuge on slope stability and consolidation problems.

The centrifuge modeling capabilities had been slowly recognized in the world and those are widely spread after 1985 International Conference in San Francisco. Since the Technical Committee has organized in International Society of Geotechnical Engineering and Soil Mechanics (ISSMGE) in 1985, physical modeling research activities using centrifuge has been more activated worldwide. With advanced technologies in centrifuge equipment and data acquisition, the number of geotechnical centrifuges increased rapidly and currently there are more than 110 centrifuges in operation in the world. The application area of centrifuge modeling also expanded from traditional geotechnical engineering problems to more complex geotechnical systems.

Physical modeling using centrifuge has various advantages in analysis of geotechnical systems. Geotechnical centrifuge is sometimes called "the site next door" because it gives an opportunity to easily simulate field condition. By conducting experiments with reduced scale model, centrifuge modeling can reduce consumption of time and effort in preparation. For example, when consolidation phenomenon of clay is simulated at 100g acceleration in centrifuge, 1 hour of consolidation in the model can represent more than 1 year of consolidation in prototype scale. Also it is easier to make the model than conducting full scale test while centrifuge provides accurate stress condition in the model system than 1-g experiment. Centrifuge is useful for verifying numerical simulation and it has advantage that the deformation or strength characteristics of soil material can be fully adopted. Also interface characteristics between two deferent materials or boundary conditions can be easily simulated in centrifuge models.

Fundamentals of geotechnical centrifuge modeling and the application fields of modeling are introduced in this paper. Especially, geotechnical centrifuge equipment is introduced by the case of KOCED geotechnical centrifuge testing center, which installed most of state-of-the-art testing equipment for geotechnical centrifuge modeling.

2. Geotechnical centrifuge modeling

Basic idea of physical modeling of geotechnical systems using centrifuge is accelerating a reduced scale geotechnical structure to appropriate high g-level to simulate prototype scale stress field in the model structure. When the model is made on reduced scale of 1:N, it is accelerated at N times of Earth gravity. In this case the stress level any point of the model can be similar to the corresponding point of prototype as shown in Figure 1. The centrifuge models are made according to the same shape of the prototype structure at reduced-scale so users can observe the structural behavior of the model very easily.

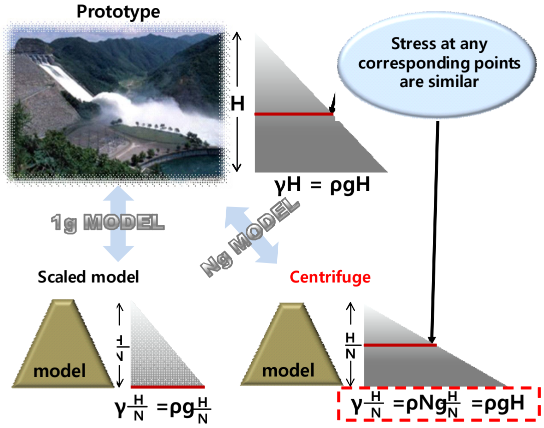

Figure 1. Concept of physical modeling using geotechnical centrifuge

Since large scale centrifuge equipment has been available in geotechnical engineering, it has been applied to various geotechnical problems. From the applications to slope stabilities and consolidation problems, centrifuge modeling has been used for almost every geotechnical engineering field. Applications to foundation engineering and earth structures were the most common in the past. With developments of shaking tables, it has been widely used for earthquake related problems such as structural stability of earth structures and liquefaction analysis. These days, the needs from petroleum industry activate centrifuge researches on offshore foundation systems. Table 2 shows the number of reports on centrifuge modeling published in International Conference on Physical Modelling in Geotechnics and their application area. It shows that physical modeling research using centrifuge is applied to most of geotechnical engineering fields.

More recently, physical modeling techniques using centrifuges are applied to practical design of complex geotechnical structures. For example, new concept of foundation design and its earthquake resistance of Rion-Antirion Bridge in Greece have been verified by centrifuge testing (Pecker, 2006). The design of the foundation at the main tower is basically a mat foundation above soft clay layer which is improved by installation of pile intrusion. The seismic design concept of the foundation systems based on yield design theory, which allows limited sliding failure of the foundation system to prevent collapse of entire bridge structures, has been verified by centrifuge testing (Figure 2).

Table 2. The number of papers dealing with centrifuge modeling in the fields of geotechnical engineering which published in ICPMG 2002 and 2006

case	ICPMG 2006	ICPMG 2002
Physical modeling facilities	6	5
New experimental techniques	18	24
Soil characterization	6	4
Slopes and dams	21	8
Earthquake related problems	7	16
Ground improvement and soil reinforcement	20	13
Offshore systems	13	5
Pipelines	11	7
Shallow foundations	5	4
Pile foundations	39	19
Retaining structures	11	11
Tunneling and underground constructions	11	8
Geoenvironment	6	11
Miscellaneous	56	19

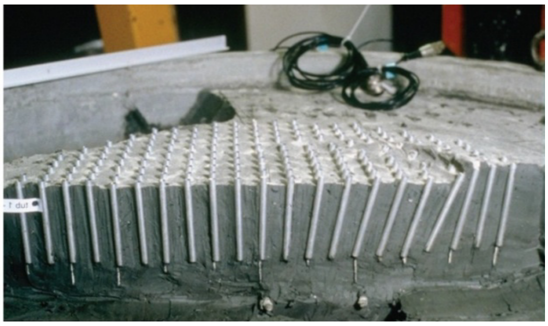
Figure 2. Deformation of the foundation system of Rion-Antirion Bridge after centrifuge test

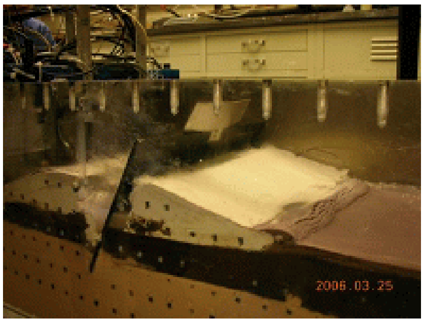

Figure 3. Failure of New Orleans levee (London North)

Physical modeling is also used for replicating natural disaster and for analysis of the failure mechanism. In 2006, intensive investigation had been conducted on the failure mechanism of levees in New Orleans area due to hurricane Katrina in 2005. Centrifuge modeling of levees at London North Avenue and 17th street had been conducted and the failure of the levees was simulated by controlling water level at the canal side (Sasanakul et al., 2006). It was found that the gap between the levee and sheet pile was caused by the water pressure applied to the sheet pile and this water pressure caused huge water flow. This failure mechanism could be confirmed by numerical simulation which considered the gap between the levee and the sheet pile.

3. Principles of geotechnical centrifuge modeling

3.1 Scaling laws

Scaled model experiments must be designed based on similarity laws derived from fundamental equations governing the phenomena to be investigated. The basic scaling law for the 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:

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

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

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

From the fundamental idea of the centrifuge modeling that the vertical stress at the model and the prototype is identical $\sigma_{vm} = \sigma_{vp}$, $h_m = h_p N^{-1}$ and the scale factor for linear dimensions is 1:N. Basic scaling factors for physical quantities in centrifuge testing are derived based on dimensional analysis using this linear dimension scale. Since the mechanical properties of geomaterial used for general centrifuge model is identical with prototype material, those physical quantities can be easily derived. In case that structural components, such as pile foundation, need to be simulated in the centrifuge model, the design of those components must consider what kind of physical quantities are governing the behavior of the structure. For example, bending stiffness of pile foundation is the key parameter for simulating the behavior subjected to lateral loading, so it must follow appropriate scaling factor. Table 3 shows scaling factors for basic quantities in centrifuge modeling. Most of scaling factors for the modeling can be derived from those factors.

Table 3. 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	N^{-3}
Strain	1	Dynamic acceleration (earthquake)	N

3.2 Basic considerations

The Earth gravity is uniform for the practical range of soil depths encountered in civil engineering. However, when using a centrifuge to generate a high acceleration field for physical modeling, there exists a variation in acceleration through the model in vertical direction. From the equation (1), the scaling factor N is generally calculated by the effective centrifuge radius for the model R_e such that:

$$Ng = \omega^2 R_e \qquad (3)$$

where ω is a angular rotational velocity of the centrifuge and the effective centrifuge radius R_e is generally determined as the distance from the rotating axis to one-third of depth of soil layer from the model surface. If the radius to the top of the model is R_t, the vertical stress at depth z_1 in the model can be determined from the following equation.

$$\sigma_{vm}(z_1) = \int_0^{z_1} \rho\omega^2 (R_t + z) dz = \rho\omega^2 z_1 (R_t + \frac{z_1}{2}) \qquad (4)$$

As shown in Equation (4), the vertical stress in centrifuge model shows nonlinear distribution with depth and the difference of stress amplitude in a centrifuge model is compared with prototype in Figure 4. This error can be minimized when the ratio between model soil depth and the centrifuge operational radius is small. Therefore, bigger radius centrifuges have advantages in accurate modeling and model size while small radius centrifuges are convenient to use for repeatable tests.

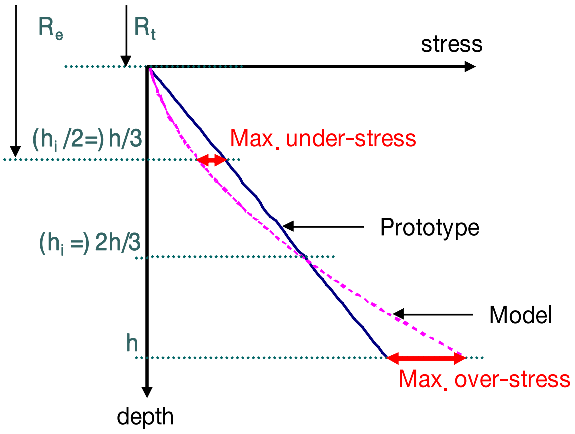

Figure 4. Comparison of stress variation with depth in a centrifuge model compared to prototype (Taylor, 1995)

In centrifuge testing, the particle size of soil sometimes affects the behavior of entire model. If the scaling law is directly applied to the particle size, fine sand particle used in a 1:100 scale might be representing gravel and clay might be representing fine sand. However, stress-strain characteristics of sand and clay are different. These particle size problems can be significant when a centrifuge test is designed at high g level especially when sand or coarse particles are used in limited model dimensions because the stress-strain curve of the material in the model cannot be fully mobilized in the same way with prototype.

Most of centrifuge testing models use the same soil with prototype under guidelines from various research works. Ovesen (1979, 1985) showed that there is some deviation from the common behavior when the ratio of circular foundation diameter to grain size is less than about 15. Tatsuoka (1991) showed it is necessary to consider the ratio of particle size to shear band width. The validation of this effect can be investigated by ‘modeling of model’. By testing centrifuge models of different scale at appropriate acceleration levels corresponding to the same prototype, scaling effect not only for particle size but for general design considerations can be validated, and it is useful to check procedure for centrifuge modeling.

4. State-of-the-art geotechnical centrifuge equipment

A state-of-the-art geotechnical centrifuge equipped with a two-horizontal biaxial shaking table and a four degree-of-freedom in-flight robot has been recently installed at KAIST by Korea Construction Engineering Development Collaboratory Program (KOCED program) of Ministry of Land, Transport and Maritime Affairs of Korea (Kim et al, 2006). With the ultimate goal of strengthening Korea’s international competitiveness in construction technologies, the KOCED Program aims to promote research and development and to set up a nationwide education program to produce highly qualified researchers and practitioners in the various fields of construction engineering (Kim, 2006). In this program, six large scale experimental facilities are being built and operated at the major regional universities and will be interconnected with high performance information network in Korea (KREONET) and KOCED will construct a system that can be controlled and accessed remotely. The geotechnical centrifuge facility at KAIST, as a part of the KOCED program, will be operated on a shared-use basis.

In this section, the state-of-the-art equipment related to physical modeling using geotechnical will be introduced with an example of KAIST case. It includes general idea and capabilities of geotechnical centrifuges, data acquisition systems, and equipments widely used for simulating earthquake motion and construction process

4.1 Geotechnical centrifuge

There are two types of geotechnical centrifuges. In the drum type geotechnical centrifuge, instead of rotating arm, the rotating drum in which a soil specimen is placed along the full periphery of a cylinder rotating about its axis. The effective experimental radius of drum centrifuge is usually less than 1.2m, which is relatively smaller than beam centrifuge. Beam type geotechnical centrifuge, which is the majority of the centrifuges, is composed of rotating arm and swinging basket. Most of the old designs are based on the principle of using a symmetric balanced beam with the possibility of simultaneously using two models of comparable size and mass, one at each end of the arm. More recent design uses asymmetric arm with model container at a long radius balanced by a more massive counterweight at a smaller radius. The most recent technology enables moving the massive counterweight automatically by measuring unbalanced force at each side induced by the model weight, and adjusting fine unbalanced force during experiments by moving additional mass along the rotating arm.

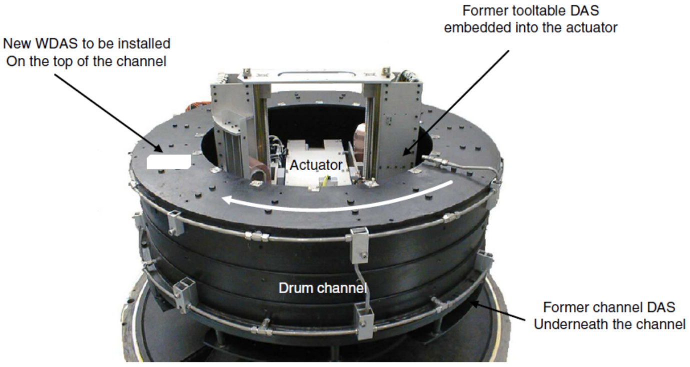

Figure 5. Drum centrifuge at the University of Western Australia (Gaudin et al., 2009)

Figure 6. Beam centrifuge at KAIST

A state-of-the-art geotechnical centrifuge can be explained by the case of KAIST. The centrifuge at KAIST is installed in 2008 by a French manufacturer, Actidyn Systemes SA. This 5m radius and 240g-tons asymmetric beam centrifuge has full automatic balancing system. During the starting stage of the machine lower than 5g, main counterweight with two massive metal parts moves along the rotating arm by a motor to minimize unbalanced moment at the rotating axis between experimental model and the counterweight by measuring unbalance force at the anchor. During the test, automatic unbalance system moves secondary counterweight inside the rotating arm by hydraulic pump to adjust fine unbalance force. Detailed specification of this centrifuge is shown in Table 4.

There are signal slip rings and fiber optic rotary joint at the top of the centrifuge for data transmission. Brush type signal slip rings, which make electrical connections through a rotating assembly, have been widely used for transmitting analog signals from the transducers in the centrifuge experimental model to the data acquisition equipments outside of the centrifuge. While slip rings have been traditionally used for this purpose, fiber optic rotary joint enables gigabit ethernet connection between the equipments in the centrifuge and the control computers outside. These days, PC-based data acquisition system or controller for various accessories is usually installed in the centrifuge and users control those systems remotely from control room. By using fiber optic rotary joint, users avoid noise problems induced from slip rings and can have more flexibility on composing experimental systems. In some centrifuge facilities, people use wireless network instead of fiber optic slip rings.

At the bottom of KAIST centrifuge, there are total five fluid rotary joints for hydraulic oil pressure, air and water supply lines. Those supply lines directly go though the rotary joint to user experimental platform, and they are connected to the equipments such as shaking table. It is important to have those fluid supply lines in case of centrifuge experiments which require pneumatic pressure or water supply.

Table 4. The specification of KAIST geotechnical centrifuge

Item	Specifications
Platform radius	5.0 m
Maximum capacity	240 g-tons
Maximum acceleration	130 g
Maximum model payload	2,400 kg
Experimental platform dimensions	1.2 m (L) × 1.2 m (W) × 1.2 m (H)
Fluid rotary joint	4 channels for 700kPa 6 channels for 20MPa
Electrical slip rings	8 lines for power supply 30 lines for signal transmission 4 lines for video transmission
Fiber optic rotary joint	1GHz, 2 passages

4.2 Data acquisition systems

In case of KAIST, the data acquisition (DAQ) system for centrifuge experiments is installed in the centrifuge near the rotating axis and it is directly connected to local network via gigabit fiber optic rotary joint. This configuration of centrifuge DAQ system is common in most of beam type centrifuge cases while signal slip rings had been used for data transmission in early years of centrifuge testing. More recently, high-speed wireless data acquisition systems (WDAS) have been developed for centrifuge testing (Gaudin et al., 2009). This technology provides advantages in avoiding difficulties for connection between transducers and data loggers, and limitations of signal slip rings in case of drum type centrifuges.

The DAQ system at KAIST is developed by combining brand-new National Instruments PXI and SCXI series. This system is widely used in many centrifuge facilities due to its good flexibility to configure the system as user's requirements. This system basically consists of a computer and PXI-6251 multifunction data acquisition card mounted onboard the centrifuge. Additionally, PXI-2566 relay switch is also installed to control switches and equipments. There are four 500kS/s high-speed simultaneous data acquisition cards, PXI-6123, installed in the DAQ system for measuring shear wave velocity of soil. 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 for 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.

There are multiple channels for video camera signals, by using either on-board computer or electrical slip rings. It gives more flexibility to centrifuge users for recording the experimental images.

4.3 Shaking table for geotechnical centrifuge

Recently, lots 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 have to be N times of prototype ground motion. Therefore, the maximum operating frequency range of those shaking tables is usually up to over 300Hz to 400Hz.

Generally, most of the in-flight shaking tables for centrifuge are unidirectional while earthquake motions are multi-directional in nature. For this reason, biaxial shaking tables are developed at several universities in the world. 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 horizontal-vertical biaxial shaking table.

The in-flight shaking table at KAIST is two-horizontal biaxial type and it has been designed based on dynamic balancing principle (Perdriat, 2002). There are two counterweights with similar mass of the experimental model at the shaking table, and dynamic balancing is achieved by reciprocal actuation of the model and the balancing counterweight. In this system, the X and Y axis dynamically balanced motion is obtained by close loop control of its two parallel pairs of actuators. This offers better performances than any known type of mechanical bearing guidance associated with symmetry of construction. The dynamic balancing is important not only for simulating accurate input motion but for reducing the risk of damaging mechanical part of the centrifuge itself.

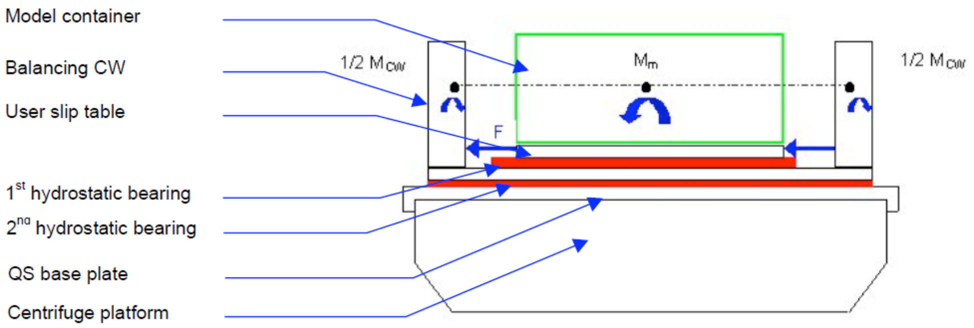

Figure 7. Dynamically balanced shaking table

Table 5. The specification of KAIST biaxial shaking table

Item	Specifications
Shaking type	Electro-hydraulic servo type
Shaking direction	Two prototype horizontal
Maximum model payload	700 kg
Payload dimensions	0.65 m (L) × 0.65 m (W) × 0.6m (H)
Maximum acceleration	40 g
Frequency range	Up to 300Hz

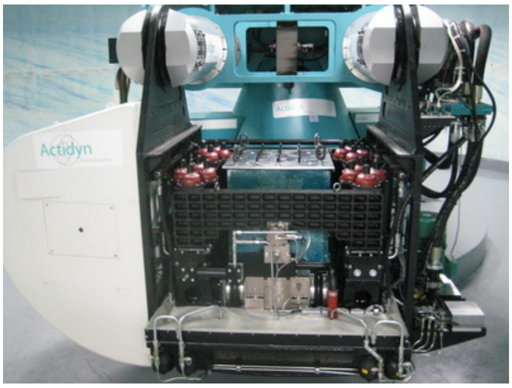

Figure 8. KAIST biaxial shaking table

Figure 9. Hydraulic power supply for the shaking table

4.4 Four degree-of-freedom in-flight robot

In most of geotechnical centrifuge testing, operations on centrifuge models should be done in flight condition in which the stress state is properly simulated. Many tools such as cone, vane, and loading devices have been developed for these purposes. Those are usually installed at a fixed location on the container and to repeat the same test or operation at different points in a model, users have to stop the centrifuge to move the equipment. These stops make loading and unloading cycles to the soil sample that may induce changes in its characteristics, for example, consolidation conditions in clay samples. Furthermore, complex simulations such as pile driving, soil reinforcement and excavation are difficult or impossible to be done in flight condition with limited equipment. Therefore, new concept of equipment which enables various experimental simulations in centrifuge flight condition is highly required.

In this context, four degree-of-freedom in-flight robot has been developed first at Laboratoire Central des Ponts et Chaussées (LCPC) in France (Derkx et al. 1998). This on-board robot is installed on the top of model container and is able to take and position a tool in any location using its four degrees of freedom, three linear directions X, Y, Z, and one rotational direction, θ_Z. It can change tools during a test and enables performing various operations on the model. The in-flight robot is a general purpose device, capable of either following a pre-programmed sequence of activities, or of being operated remotely from an operator's station in real time.

Since the usefulness of the robot was recognized, HKUST and RPI also developed the robot. The experiments using this kind of device have been tried for various cases and its usefulness in simulating construction activities has been proven (Derkx et al. 1998, Ng et al. 2002, Zehgal et al. 2002). KAIST also has developed the robot which can utilize four different tools at the same time.

The development of in-flight robots represents a new and evolving trend in geotechnical centrifuge modeling, which permits a wide array of new research capabilities. This robot will be used to perform various operations such as pile driving, applying static and cyclic loads in each direction, in-situ testing of soil properties using calibrated probes (e.g. cone penetration test, T-bar, shear vane), soil remediation (e.g. sloping and/or level ground reinforcement, vibro-compaction, injection of soil stabilizers), and excavation of soil to simulate construction activities.

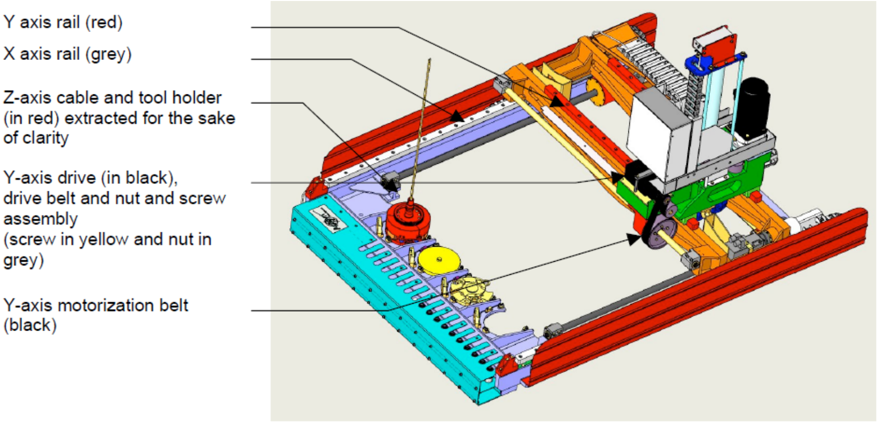

Figure 10. Mechanical assembly of KAIST 4 degree-of-freedom in-flight robot

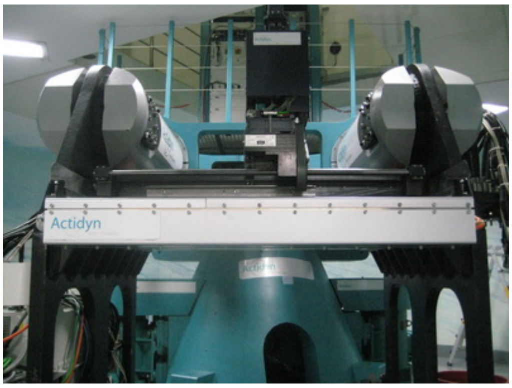

Figure 11. KAIST 4 degree-of-freedom in-flight robot

Table 6. Performance specifications of KAIST in-flight robot

Item	Specifications			
	X	Y	Z	θ_Z
Stroke	0.8m	0.6m	0.6m	270°
Maximum speed	50mm/s	50mm/s	50mm/s	5°/s
Loading capacity	1kN	1kN	5kN	5Nm
Accuracy	±1.0mm	±1.0mm	±1.0mm	±1.0°

Table 7. Robot tools at KAIST

Item	Purpose
Standard head	Providing air, water and hydraulic oil
Tool fixture	Store 4 tools for operation
Pincer tool	Grab and move small parts around the model
Cone penetrometer	Model CPT unit with sensors for tip and sleeve resistance

5. Physical modeling research activities at KAIST

Since the installation of the centrifuge equipment in 2008, there have been several experimental research projects related to geotechnical centrifuge modeling at KAIST. The first experiment for KAIST centrifuge was geophysical visualization of shear wave velocity in model soil. Two bender element arrays were installed for generating and receiving shear waves transmitting in model soil and 16 bender elements were installed at each side every 20mm. 300mm×300mm area between two arrays could be visualized by tomography inversion analysis from total 256 shear wave travel time information and the result shows good agreement with resonant column test. This shear wave information in the model provide relatively accurate deformational characteristics, G_{max}, in-flight condition and it can be used as key parameter for analysis of general centrifuge experimental results.

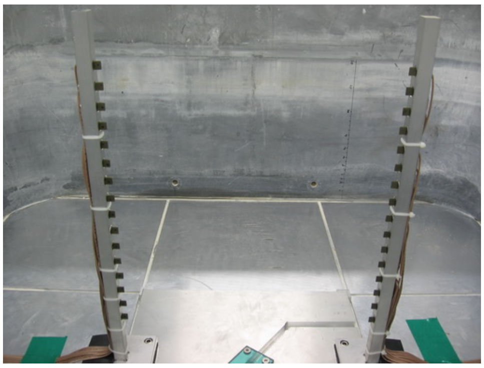

Figure 12. Bender element arrays for V_S tomography

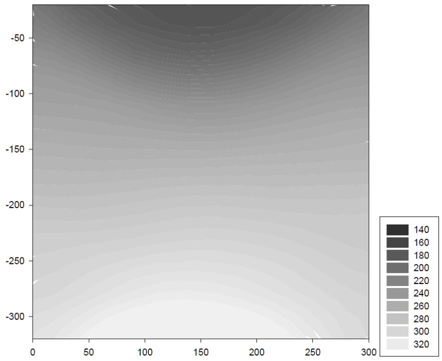

Figure 13. V_S tomography image in a uniform sand layer at 50g

Physical modeling of foundation systems for high-rise buildings or long span bridges is another research topic with KAIST centrifuge. A series of centrifuge experiments were conducted to evaluate bearing capacity of single piles, group piles and piled-raft foundations. The load distribution characteristics in different arrangement of piles in piled-raft foundation could be measured by instrumentations at each pile, and the bearing capacity of the piled-raft foundation could be estimated from the result of single piles and un-piled raft.

The effect unexpected water flow in the concrete faced gravel-filled dam (CFGD) caused by damages at the concrete facing was simulated to evaluate the drainage characteristics according to the selection of fill material. The function of drainage zone beneath the concrete facing composed by gravelly material is to prevent rise of water level in the dam to protect dam by enabling quick drain of water coming in. The effect of planning this zone was compared with a model which doesn't have this selective zone and the water penetration characteristics could be monitored from this test.

Recently, modeling of offshore foundation systems, natural disaster prevention of levee from flooding, soil-foundation-structure interaction, and dissociation of gas hydrate in the seabed are in progress at KAIST. Using the shaking table, the earthquake ground motions of free-field, embedded foundation, and pile-supported foundation, the behaviors of rock-fill and CRFD dams, and the seismic design of subway tunnels will be evaluated. Physical modeling of carbon sequestration progress and earthquake simulation in the centrifuge are new challenges for KAIST in near future.

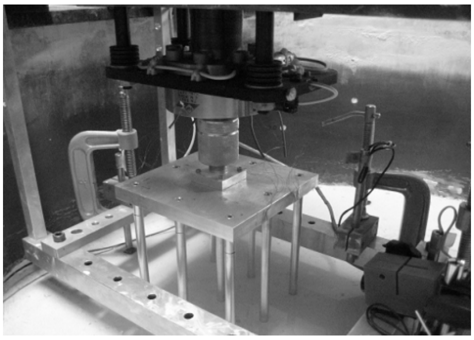

Figure 14. Installation of model piled-raft foundation

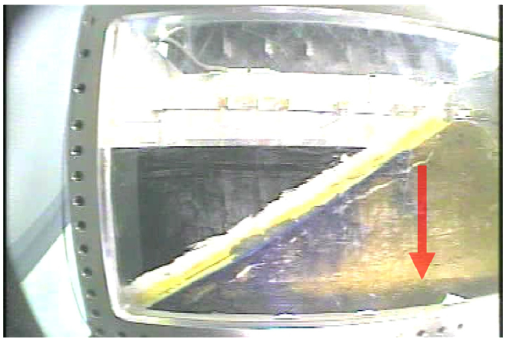

Figure 15. Water penetration test from the cracks at the facing of CFGD

6. Conclusions

Fundamentals and its application area of the geotechnical centrifuge modeling have been explained and state-of-the-art geotechnical centrifuge equipment has been described by an example of KOCED geotechnical centrifuge facility at KAIST. With advances of testing equipment and monitoring systems, more complex geotechnical structures can be simulated in the centrifuge and construction process in the field can also be possible to simulate during the experiment. Evolution of instrumentation technology enables geotechnical centrifuge modeling to be able to play a key role to understand physical phenomena or mechanical behavior of geotechnical systems. As geotechnical engineering faces new challenges such as offshore engineering, energy and environmental problems, there will be potential application area which physical modeling technology using centrifuge can be applied.

With active collaborations between members in ISSMGE TC-2 Physical Modelling in Geotechnics, new technologies for physical modeling and centrifuge testing will be developed and provided to geotechnical engineering society in the world. Under the umbrella of the KOCED program, the share-based use of KOCED centrifuge facility will be activated in Korean geotechnical community.

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