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Physical Modelling in Geotechnics

Applications of KNU centrifuge on geotechnical engineering: Introduction of experimental cases

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ABSTRACT: In 1993, the first beam-type small centrifuge, with a 1.35 m platform radius and a capacity of 20 g-tons, was installed at the Kangwon National University (KNU) in Korea. Since then, various experimental studies of geotechnical problems have been conducted, including those investigating the consolidation of dredged clay, foundation systems, and tunnels. These studies have been valuable for assessing the behavior of geotechnical structures and contributed to the spread of physical modeling in Korea. In this paper, some key results of studies conducted at KNU over the last 30 years are presented.

Keywords: KNU centrifuge, facility, consolidation, foundation, tunnel.

1 INTRODUCTION

Since the small centrifuge was built at Kangwon National University (KNU) in 1993, it has been used in various research fields for approximately 30 years. The KNU centrifuge has a capacity of 20 g-tons with a 1.35 m platform radius. The centrifuge was designed as a beam-type with a basket at both beam ends. One side of the basket is used for mounting the model box, and the other side provides a space to load counterbalancing weights. Steel plates are loaded manually to counterbalance the total weight of the model box. A slip ring with 40 channels was installed at the top of the centrifuge. A rotary joint with two channels and a slip ring for power supply were installed at the bottom of the centrifuge. The technical features of the main centrifuge components are listed in Table 1.

Various studies have been conducted using this centrifuge, such as the consolidation behavior of dredge clay, foundations of port facilities, behavior of piles adjacent to a tunnel, and pile behavior under lateral loading. This paper presents the main findings and experimental techniques from research using the KNU centrifuge.

Table 1. Technical specifications of the KNU centrifuge

Items	Specification
Maximum capacity	20g.ton
Maximum acceleration	200g at 1000 mm radius
Platform radius	1.35 m
Payload dimensions	500 × 500 × 600 mm
Electrical slip rings	40 channels 2 lines for camera (SLR and video)
Fluid rotary joint	2 lines for oil

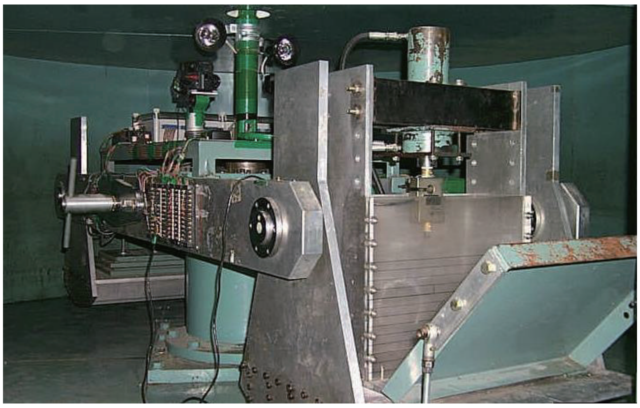


Fig. 1. KNU centrifuge

2 RESEARCH ACTIVITIES ON PYSICAL MODELING AT KNU

The advantages of the small KNU centrifuge include a simplified operating process, ease of sample preparation, and low operating costs of parametric analysis. Generally, smaller soil sample sizes lead to higher uniformity and consistency. With these advantages, several experimental studies have been conducted at KNU including consolidation of dredged clay, foundation systems, and tunneling problems. The authors briefly introduce experimental cases conducted at KNU in this paper.

2.1 Consolidation Behavior of Dredged and Reclaimed Clay

In Korea, coastal reclamation is progressing steadily, owing to the geographical conditions of the limited land area, bounded by the sea on three sides. Since the 1970s, reclamation has led to an area increase of over 2,000 km^2. Thus, because the water depth of the surrounding sea is relatively low, and the coastal seabed is mainly composed of clay, the study on consolidation behavior of very soft ground during reclamation is crucial.

Numerical studies on finite strain consolidation theory (Gibson et al., 1981) and studies for calculating the constitutive relations have been assessed using the KNU centrifuge. For this purpose, more than 30 on-site offshore clays under dredging and reclamation were collected, and self-weight consolidation tests were performed in the centrifuge based on the initial void ratio and thickness of the clay specimen. Figure 2 shows the locations of major Korean ports (Busan, Gwangyang, and Incheon) where offshore clay was collected for centrifuge tests (Jun and Kwon, 2020).

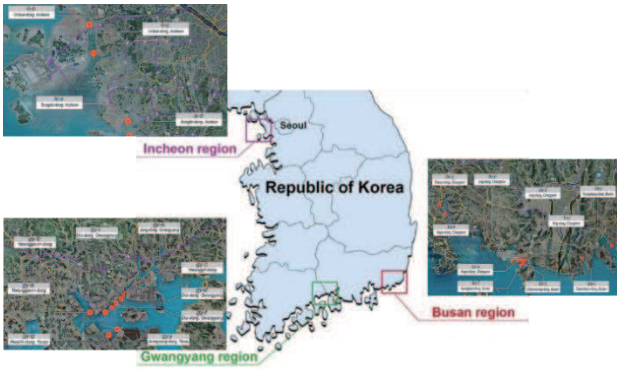


Figure 2. Sampling locations

From a series of centrifuge model tests, the nonlinear constitutive relationship of void ratio–effective stress–permeability, the main factor in the finite strain consolidation theory, was proposed (Yoo et al., 2002). The consolidation settlement induced by centrifugal acceleration was monitored using a video camera, and the excess pore water pressure was measured using pore pressure sensors installed on the soil specimens (Fig. 3). Based on the test results, the site soil properties were evaluated using a constitutive relationship in the form of a power function derived by Somogyi (1980). Table 2 lists the properties of the soft soil obtained using the centrifuge model test.


(a) Consolidation test in centrifuge
(b) Specimen after completion of self-weight consolidation

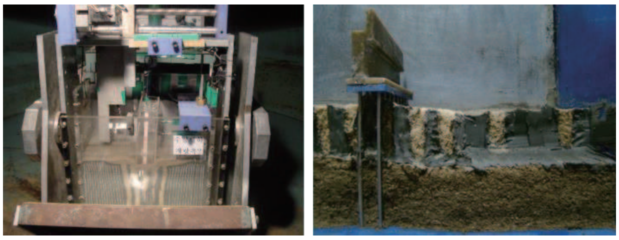
Figure 3. Self-weight consolidation test in KNU centrifuge

Table 2. Experimental conditions and results.

Symbol	Mark	Accel. of Gravity, n (g)	Initial Void Ratio e_0	Atterberg Limits		Constitutive Relationship	
				LL (%)	PI	$e=f(\sigma')$ (σ'; kPa)	$k=f(e)$ (k ; m/day)
Busan Region	bs-a	20~30	4.08~6.80	47.2	20.5	$3.44\ \sigma'^{-0.241}$	$1.42 \times 10^{-5}\ e^{5.22}$
	bs-b	30	4.07~6.78	40.1	16.6	$2.85\ \sigma'^{-0.121}$	$1.17 \times 10^{-6}\ e^{8.22}$
	bs-c	40	5.42~6.78	55.1	27.3	$3.49\ \sigma'^{-0.207}$	$1.74 \times 10^{-5}\ e^{4.06}$
	bs-d	50~60	4.07~5.43	53.8	31.0	$2.32\ \sigma'^{-0.171}$	$1.13 \times 10^{-5}\ e^{5.17}$
	bs-e	50~60	4.34~5.42	54.4	29.5	$2.84\ \sigma'^{-0.175}$	$6.39 \times 10^{-6}\ e^{6.33}$
	bs-f	30~40	4.06~5.41	53.2	24.8	$2.84\ \sigma'^{-0.187}$	$9.91 \times 10^{-6}\ e^{5.34}$
	bs-g	30~40	5.42~6.78	65.6	33.9	$4.20\ \sigma'^{-0.174}$	$9.30 \times 10^{-6}\ e^{4.01}$
	bs-i	50~60	4.08~5.44	69.6	37.9	$4.33\ \sigma'^{-0.222}$	$3.58 \times 10^{-6}\ e^{5.38}$
	bs-j	30~40	4.10~5.46	74.0	39.4	$4.16\ \sigma'^{-0.254}$	$1.03 \times 10^{-6}\ e^{6.03}$
	bs-k	30~50	5.44~10.88	94.3	55.0	$4.58\ \sigma'^{-0.180}$	$1.68 \times 10^{-5}\ e^{3.56}$
Gwangyang Region	gy-a	30~40	4.08~5.43	45.9	24.0	$2.97\ \sigma'^{-0.197}$	$2.67 \times 10^{-6}\ e^{5.52}$
	gy-b	30~40	4.12~5.49	44.9	28.0	$2.66\ \sigma'^{-0.176}$	$8.88 \times 10^{-6}\ e^{6.17}$
	gy-c	30~40	4.07~5.42	44.1	21.0	$2.81\ \sigma'^{-0.175}$	$5.32 \times 10^{-6}\ e^{5.26}$
	gy-d	30~40	4.11~5.48	44.0	25.5	$3.03\ \sigma'^{-0.244}$	$9.72 \times 10^{-6}\ e^{6.10}$
	gy-e	40~50	4.05~8.11	33.8	19.0	$3.16\ \sigma'^{-0.174}$	$4.25 \times 10^{-6}\ e^{7.50}$
	gy-f	30~50	4.08~6.80	79.3	50.5	$3.96\ \sigma'^{-0.294}$	$1.69 \times 10^{-5}\ e^{4.25}$
	gy-g	30~40	4.17~6.95	62.6	35.1	$4.62\ \sigma'^{-0.277}$	$1.15 \times 10^{-5}\ e^{3.75}$
	gy-i	30~40	4.07~5.42	82.7	46.3	$3.77\ \sigma'^{-0.179}$	$8.09 \times 10^{-6}\ e^{5.91}$
	gy-j	40	3.32~5.45	64.5	35.3	$3.71\ \sigma'^{-0.177}$	$1.26 \times 10^{-5}\ e^{3.78}$
Incheon Region	ic-a	60	2.71~4.06	25.5	11.8	$1.76\ \sigma'^{-0.150}$	$1.09 \times 10^{-4}\ e^{5.94}$
	ic-b	50	2.69~4.04	24.8	12.4	$1.50\ \sigma'^{-0.161}$	$3.12 \times 10^{-4}\ e^{4.46}$
	ic-c	30~40	2.71~4.34	33.8	16.8	$2.15\ \sigma'^{-0.139}$	$6.69 \times 10^{-5}\ e^{4.90}$
	ic-d	30~40	4.05~5.40	38.3	15.6	$2.97\ \sigma'^{-0.197}$	$2.67 \times 10^{-5}\ e^{5.52}$

2.2 Research for Port Facility Foundations

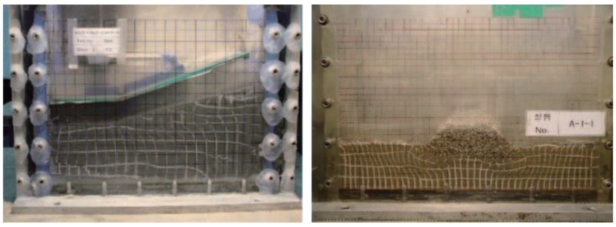
As the Korean coast mainly comprises soft clays, soil improvement is required during the construction of port facilities. Thus, studies have been conducted on soft soil improvements using sand compaction piles (SCPs), replacement methods, and deep cement mixing (DCM). This study focused on the stress distribution and displacement behavior with a replacement ratio of the SCP. After preparing the SCP model using a certain degree of compaction, it was frozen and installed into the soft clay layer. The modeled port structure was carefully placed on the improved layer, and a horizontal load was applied to simulate wave action. Figure 4 shows the soil improvement using the SCP and loading tests (Yoo et al., 2005).



(a) Horizontal loading test (b) Soil improvement with SCP

Figure 4. Centrifuge test for soil improvement with sand compaction pile

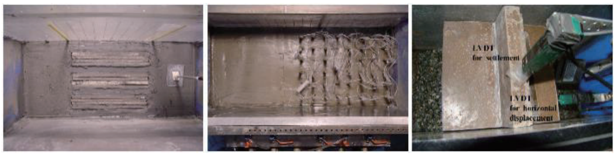
In Korea, excavation and compulsory replacement methods are widely used to construct wharf facilities. The centrifuge model test is used to evaluate soil stability during excavation with respect to slope angle and excavation width. For the compulsory replacement method, the soil failure shape influenced by the placement of gravel, the optimal replacement ratio, and the estimation of the gravel amount to be placed were investigated using the centrifuge. The excavation process was simulated by lifting the loading plate placed on the soft soil after reaching the target g-force level. The centrifuge model test results were compared with those of numerical analysis to improve the reliability of the geotechnical design. Figure 5 depicts the experiments for excavation and compulsory replacement of soft soil for wharf facility construction.



(a) Slope stability of excavated marine clay (b) Settlement due to the compulsory replacement

Figure 5. Simulation of replacement method in the centrifuge

Additionally, research related to soft-soil reinforcement is being actively conducted. The effects of the improvement ratio and strength of the column of the DCM method on ground reinforcement of a caisson foundation were evaluated. Embankment stability on soft clay with a prefabricated vertical drain (PVD) and its behavior induced by breakwater by horizontal loads have also been experimentally evaluated. These studies are used to verify the designs of geotechnical structures in soft soil. Figure 6 depicts representative centrifuge tests conducted at the KNU.

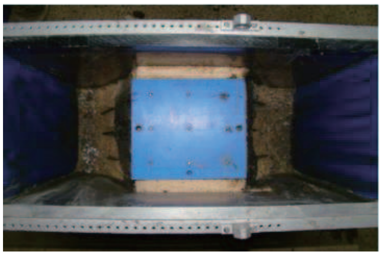


(a) DCM (b) PVD (c) Caisson foundation

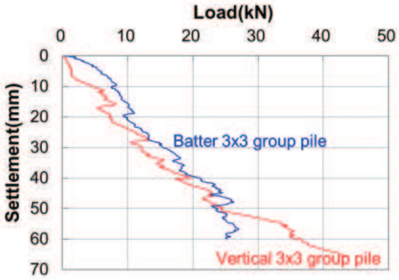
Figure 6. DCM, PVD, and caisson foundation modellings in KNU geo-centrifuge

2.3 Application of Physical Modelling in Foundations and Tunneling

Physical modeling has also been applied in the fields of foundations and tunnels. To date, batter piles have not been successfully used as bridge foundations because of the complexity in bearing behavior and difficulties in construction. Centrifuge model tests were performed to investigate the effect of the batter piles on the bearing capacity of the bridge foundation. The results showed that the batter pile improved the bearing capacity of the bridge foundation compared to a vertical pile at least for relatively low vertical load (~ 25kN). The results also indicated that batter piles could be an option for bridge foundations on a thick soil layer or low-strength soil. Figure 7 shows the batter pile group modeling and a representative load–settlement curve.



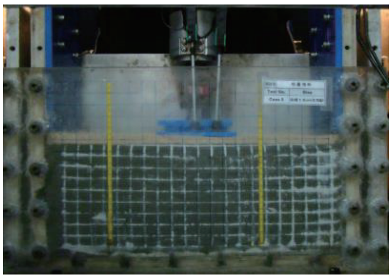
(a) Batter pile group modelling



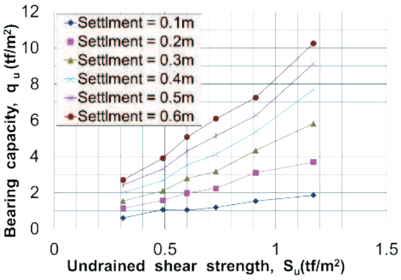
(b) Load-settlement relationship

Figure 7. Bearing capacity of batter pile group for bridge foundation

A study was also conducted to evaluate the trafficability of construction equipment in soft soil, where sand mats and geotextiles had been installed. The soil bearing capacity with consolidation was evaluated, and the available construction equipment for each time lapse was analyzed. Soft soil bearing capacity with change in the undrained shear strength is shown in Fig. 8.



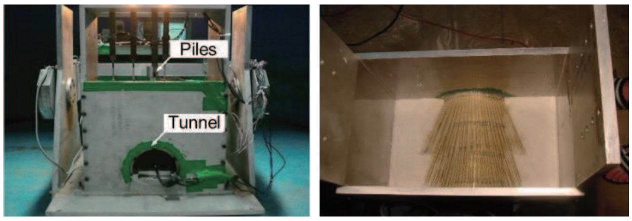
(a) Trafficability modeling



(b) Bearing capacity with undrained soil strength

Figure 8. Trafficability of construction equipment in soft soil

Additionally, a study on tunnel–pile interaction has been performed using the centrifuge. Tunnels and piles were modelled to evaluate the stability of adjacent piles during tunnel excavation. Tunnel excavation was simulated in the centrifuge, and the pile and tunnel displacements were monitored. In addition, a tunnel supporting method that can reduce adjacent pile and tunnel displacements was investigated based on model tests. Subsequently, a suitable tunnel support method was proposed. Figure 9 shows the modeling of the tunnel adjacent to a piled foundation and tunnel support for the centrifuge test.



(a) Trafficability modeling

(b) Bearing capacity with undrained soil strength

Figure 9. Simulation of tunnel-foundation interaction and tunnel reinforcement in centrifuge

3 CONCLUSIONS

Recently, large centrifuges are preferred because of difficulties in the scaling of actual geotechnical structures and the ability to mount intricate instruments. However, small centrifuges have advantages, including a simplified operating process and ease of sample preparation. Efficient experiments are possible for parametric studies, in which a large number of tests are required. Since KNU installed a small centrifuge with a capacity of 20 g-tons in 1993, various geotechnical problems have been investigated. These studies include soft soil consolidation behavior and reinforcement methods, coastal and port structures, deep foundations, and tunnels. The centrifuge model tests have enabled pre-construction design evaluation and prediction of the behavior of geotechnical structures. These studies have contributed to establishing the centrifuge modeling technique and advancing geotechnical engineering in Korea.

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