Applications of Geotechnical Centrifuge in Research

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Abstract - *Geotechnical centrifuge modeling is an advanced physical modeling technique for simulating and studying geotechnical problems. It provides physical data for investigating mechanisms of deformation and failure and for validating analytical and numerical methods. Due to its reliability, time, and cost-effectiveness, centrifuge modeling has often been the preferred experimental method for addressing complex geotechnical problems. This paper highlights the applications of geotechnical centrifuge modeling in the research areas of earthquake engineering, geoenvironmental engineering, foundation engineering, and landslide engineering. It is thought that such a study would give a better understanding of applications of centrifuge modeling in various geotechnical research fields and to encourage its application in future research.*

Key Words: Geotechnical research, Centrifuge modeling, Earthquake, Landslide, Foundations, Geoenvironmental engineering

1. INTRODUCTION

Geotechnical centrifuge modeling is a technique for testing physical scale models of geotechnical engineering systems such as natural and man-made slopes and earth retaining structures and building or bridge foundations; and contaminant transport through soil matrix. The scale model is typically constructed in the laboratory and then loaded onto the end of the centrifuge, which is typically between 0.2 and 10 meters (0.7 and 32.8 feet) in radius. The purpose of spinning the models on the centrifuge is to increase the gravitational force equivalent acting on the model so that stresses in the model are equal to stresses in the prototype [1-9]. Figure-1 shows the 9 m radius Geotechnical centrifuge at University of California, Davis, USA [6]. The purpose of spinning the models on the centrifuge is to increase the gravitational force equivalent acting on the model so that stresses in the model are equal to stresses in the prototype. Centrifuge model testing provides data to improve our understanding of basic mechanisms of deformation and failure and provides benchmarks useful for verification of numerical models. Hence more accurate data could be obtained by using geotechnical centrifuge modelling [1, 2].

Objective of this review paper is to describe the application of geotechnical centrifuge in research, experimental setups, and observations of the centrifuge modeling in areas of earthquake engineering, geoenvironmental engineering, foundation engineering, and landslide engineering as observed from various research papers. By presenting these applications, it is hoped to illustrate the role of geotechnical centrifuge modeling in advancing the scientific knowledge of geotechnical research.

Fig -1: Geotechnical centrifuge at UC Davis, USA

2. PRINCIPLE OF CENTRIFUGE MODELING

Fundamental principle of centrifuge modeling is to recreate stress conditions, which would exist in a prototype, by increasing n times the "gravitational" acceleration in a 1/n scaled model in the centrifuge. Stress replication in the 1/n scaled model is approximately achieved by subjecting model components to an elevated "gravitational" acceleration, which is provided by centripetal acceleration ($r\omega^2 = ng$), where r and ω are the radius and angular velocity of the centrifuge, respectively. Thus, a centrifuge is suitable for modeling stress-dependent geotechnical problems [1-9]. Apart from the ability to replicate in-situ stress level in a reduced size model in a centrifuge, one of the benefits of centrifuge modeling is that the use of a small-scale model, resulting in a significant reduction of consolidation time by $1/n^2$.

It is well recognized that soil behaviors are stress-dependent. For an example illustrated in Chart-1, a soil sample A located below the critical state line (CSL) initially, will dilate toward the CSL when it is sheared under a relatively low confining stress (e.g., in a small model test under one Earth's gravity (i.e., 1g=9.81 m/s^2)). By comparison, a sample, B, having the same density (i.e., same void ratio), located at an arbitrary point above the CSL but below or on the normal compression line (NCL), will contract when it is sheared under a higher mean effective stress, p' (i.e., high stress in the field or the centrifuge). It is obvious that the use of test results from sample A for designing prototype problems is likely to be non-conservative and maybe even dangerous because the observed dilative behavior at low stress under 1g conditions will not occur under high stress in the field. Thus, it is vital to simulate the stress level of the soil correctly before carrying out any physical experiment [5, 6]. For centrifuge model tests, scaling laws are generally derived through dimensional analysis, from the governing equations for a phenomenon, or the principles of mechanical similarity between a model and a prototype [1-9]. Some common scaling factors derived and used are summarized in Table 1 [2]. Some of the applications of geotechnical centrifuge in research are described in the following sessions.

Table -1: Common scaling factors for centrifuge

Parameter	Scale factor (model/prototype)
Acceleration	n
Linear Deformation	1/n
Stress	1
Strain	1
Mass	$1/n^3$
Density	1
Unit weight	n
Force	$1/n^2$

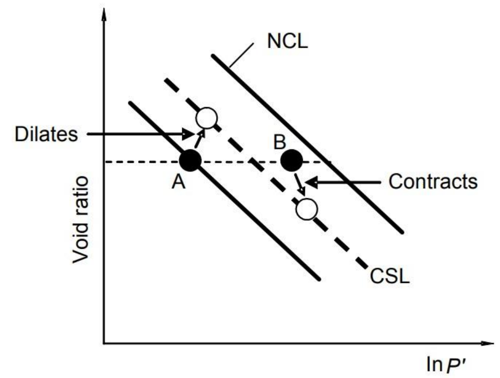

Chart -1: Distinct responses of two soil samples at the same density sheared under different confining stresses

3. EARTHQUAKE ENGINEERING

Simulation of earthquake induced geotechnical problems in centrifuge has grown significantly in the past decade and a variety of challenging problems are now being tackled in various centrifuge establishments all over the world. Considerable experience has been gained in simulating earthquake effects in the centrifuge successfully. Simulation of earthquake conditions in the geotechnical centrifuge requires careful consideration of several factors. These include modeling of base motion, selection of model container with non-reflecting boundaries, and use appropriate fluid in the soil [1]. A research in this field is briefed below:

In this research, the centrifuge test was conducted to study the contributions of fibres in real seismic conditions. All the tests were conducted at a nominal 50 g level. This g level was achieved at a depth of 130 mm (model scale) from the ground surface of models and the variation of g level in models was within ± 6%. Model layout and instrument distribution is shown in Figure-2.

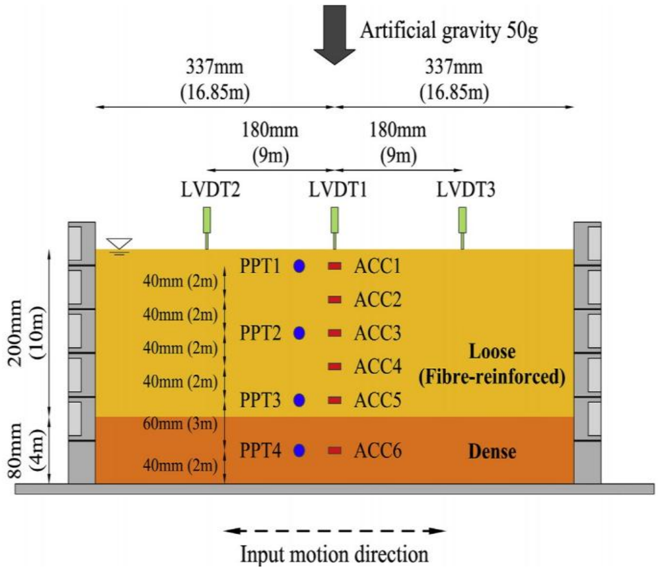

Fig -2: Model layout and instrument distribution

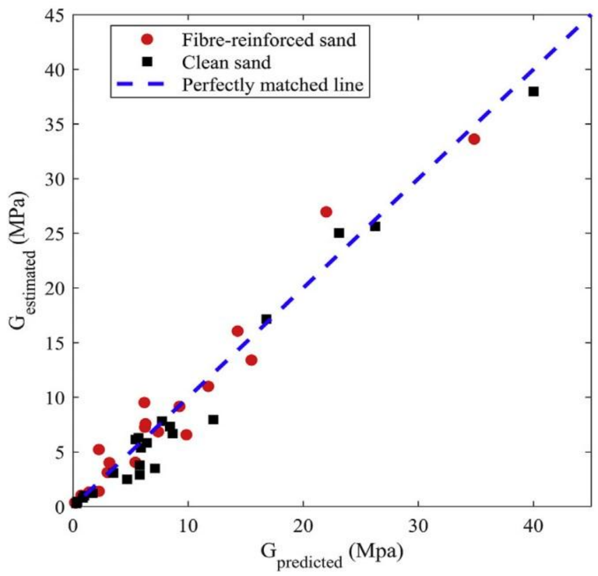

Chart -2: Comparison between estimated and predicted shear moduli

Parameters such as shear moduli, damping ratios, ground surface settlements, acceleration propagation, excess pore pressure generation, stress-strain behavior, etc. were observed from this experiment. Maximum shear strength of both reinforced and unreinforced sample at various effective vertical confining stress is shown in Chart-2. The influence of fibres on increasing shear moduli was verified in centrifuge tests and it was more apparent under lower confining stresses and at larger shear strains [1].

4. GEOENVIRONMENTAL ENGINEERING

Contamination of groundwater is an issue of major concern in residential areas in the vicinity of landfills and waste disposal repositories. It has become necessary to assess the long-term performance of these wastes in disposal sites and the severity of their effect on the geological environment [2]. Physical modeling of subsurface transport processes provides valuable information about the effectiveness of various contaminant and remedial action strategies. Such observations are required both to test and verify existing numerical codes as well as to aid in improving and developing conceptual models for the complex processes involved. Centrifuge modeling, therefore, offers much assistance in identifying the optimum course for environmentally sound waste management and control [9]. One of the recent research in this field is described in the following:

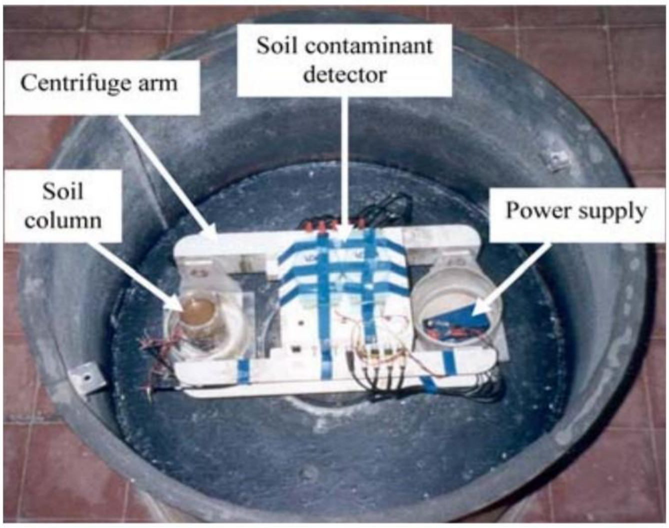

Fig -3: Centrifuge test setup for the chloride diffusion test

This research constituted the modeling of chloride (Cl) diffusion through soils in a geotechnical centrifuge. Acceleration level, N, of 100 g was used for centrifuge modeling of Cl migration through 7.5-m-deep soil strata for a period of 150 and 600 days [2]. Figure-3 shows the experimental setup used for this study. From the centrifuge test results, the Reynolds number, R, and Péclet number, P, were found to be several orders less than unity. This indicated that the dominant Cl transport mechanism in the soil is diffusion. Finite-element modeling was performed, using SEEP/W and CTRAN/W, to validate the experimental results, and excellent matching was obtained. Chart-3 depicts the comparison of the experimental results with computed values. The study also highlighted that geotechnical centrifuge modeling can be used as a viable alternative to field-scale experimentation.

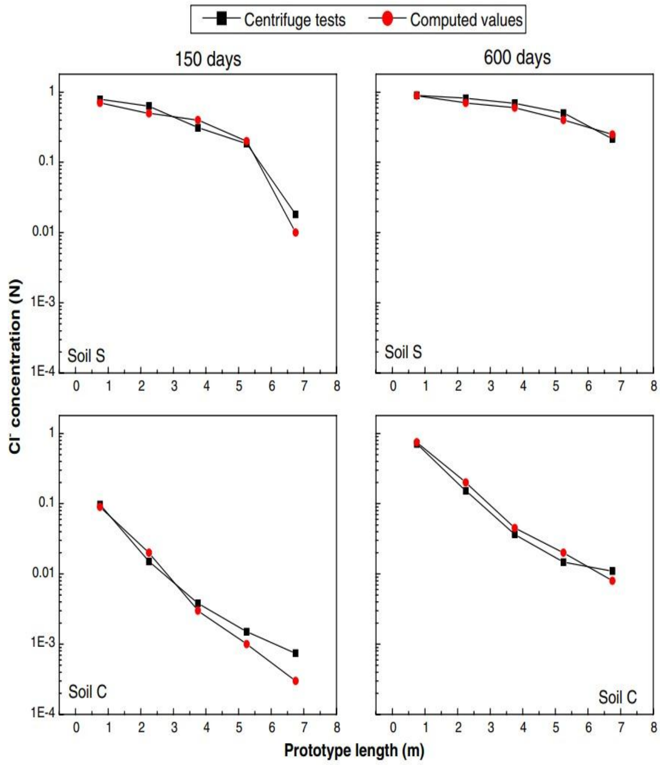

Chart -3: Comparison of centrifuge test results with computed values

5. FOUNDATION ENGINEERING

New generation of offshore structures have higher technical requirements due to their larger capacities or harsh working conditions, which will certainly result in more challenges for the design of the foundations. Increasing the pile diameter is found to be an efficient solution for difficult geotechnical and hydrological conditions in transportation projects. However, the initial cost of steel will increase significantly with the pipe piles with excessive large diameters, and the associated construction and installation will be more difficult. Therefore, a new design of the pile foundation is necessary instead of continuously increasing the pile diameter. For analyzing new designs of the pile, centrifuge modeling was found highly useful [3], [6]. It is shown through a research example as briefed below:

This research illustrated an innovative design for the pile foundation, which constituted an innovative strategy over the traditional pile foundation to achieve higher axial bearing capacity. This was achieved by adding restriction plates inside the pile to help form the soil plug. A series of geotechnical centrifuge tests were carried out to evaluate the load-bearing behaviors of traditional pile foundation and innovative pile foundation with different types of restriction plates. Figure-4 depicts the centrifuge loading system for pile. The pile diameter and shapes of the restriction plates on the soil plug behaviors and pile load-carrying capacity were analyzed. Chart-4 shows the analyzed experimental results from this research work for different pile diameters [3].

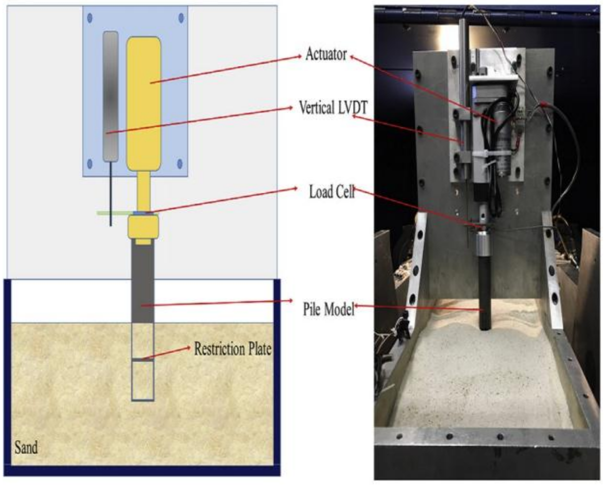

Fig -4: Centrifuge loading system for pile

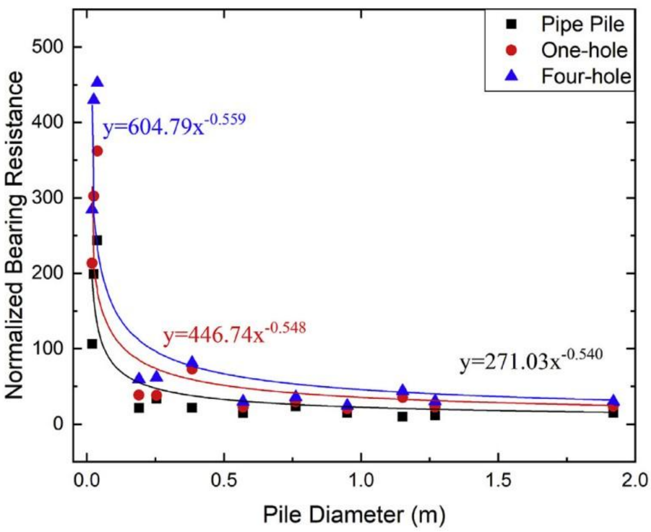

Chart -4: Normalized ultimate bearing resistance with pile diameters

6. LANDSLIDE ENGINEERING

Recent heavy monsoon-triggered flood and landslides in Kerala, India was catastrophic. A natural slope that fails usually has soil properties that are not characterized before the event; however, laboratory tests on landslides are not feasible because of the magnitude of the problem involved. Also on 1g scale model simulations of natural slopes in the laboratory, which are typically less than 1 m high, may not completely represent field conditions as soil behavior is different within a natural slope because of stress confinement, as opposed to a loose state or a state of low-stress confinement in a small model. But shallow landslides can be modeled successfully with the help of centrifuge modeling [4]. One of the researches in this field is described below:

This study focused on landslides resulting from heavy precipitation, such as rainfall from hurricanes. A series of centrifuge model simulations were performed regarding a landslide that occurred during Typhoon Nabi in Japan in 2005. The procedures of simulation on a slope using a sand-clay soil mixture were illustrated in the research. The rainfall event was simulated by applying precipitation in increments to the slope surface until it exceeded that of the field measurements. The instability was examined using an infinite slope analysis[4]. Figure 5 shows the configuration of the centrifuge slope model.

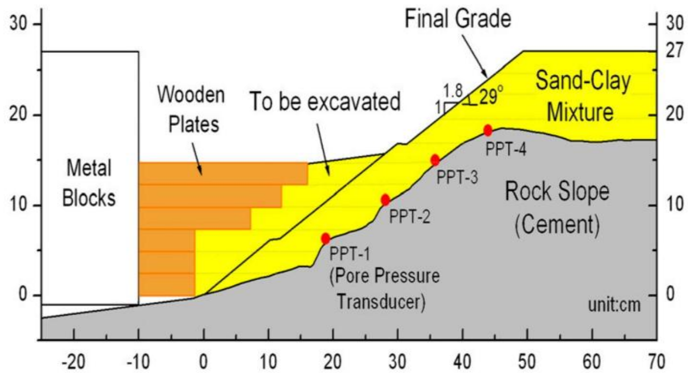

Fig -5: Configuration of the centrifuge slope model

7. CONCLUSIONS

Basic principles and various applications of centrifuge modeling were reviewed with the help of some examples of recent researches. Main focus was given to its application in geotechnical researches in the areas of earthquake engineering, geoenvironmental engineering, foundation engineering, and landslide engineering and were reported briefly. To validate the centrifuge models, numerical/computational tools (such as GeoStudio®, PLAXIS® etc) may be used. Centrifuge models can simulate real life problems economically. Although geotechnical centrifuge was proved to be a powerful physical modeling tool for researchers and engineers, it had some limitations; such as, it was not suitable for investigating soil creep, aging, biodegradation etc.

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BIOGRAPHIES

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