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Development and performance of a hybrid loading simulator for earthen dams

P. Kumar & B.V.S. Viswanadham
Department of Civil Engineering, IIT Bombay, Mumbai, India

ABSTRACT: The objective of this paper is to present the development and performance of a hybrid (flooding and pseudostatic) loading simulator for evaluating the performance of water retention type dams (WRTDs) in a geotechnical centrifuge. The developed simulator consists of a screw-jack gearbox based mechanism on one side and a hinge on the other side to produce horizontal inertial accelerations at enhanced gravity levels. In addition, it consists of a water pumping unit to simulate water flooding on the upstream side of WRTD. The developed simulator can investigate the behaviour of small-scale models with vertical to 1V:2H slopes subjected to a maximum horizontal seismic coefficient (K_H) of 0.36. In the present study, calibration and performance of the developed simulator were demonstrated in a 4.5 m radius large beam geotechnical centrifuge facility available at IIT Bombay, India. A constant high flood level (HFL), steady-state seepage, and inertial instability conditions within an earthen dam are presented through centrifuge model tests at 30g.

Keywords: centrifuge test, earthen dam, hybrid loading, reservoir filling, pseudo-static.

1 INTRODUCTION

The past few decades have seen a rise in the cases of dam failures due to natural and anthropogenic activities, severely damaging the natural and built environment. The study conducted on nearly 3500 tailings dams worldwide by Martin et al. (2002) reveals the alarming annual rate of failure being approximately 1 in 1000 compared to the conventional earthen dams with 1 in 10,000. Very recent failures include Brumadinho tailings dam in Brazil in 2019 and Cadia dam in NSW, Australia in 2018 . The primary causes of failure are natural (earthquake and rainfall), followed by piping or seepage, overtopping, slope instability, foundation failure, structural defects, and operational ambiguities, as reported by Rico et al. (2008).

The seismic design of a WRTD is based mainly on the concept of inertial forces using the pseudostatic method, where knowledge of K_H is desirable. Many researchers have recommended various K_H values based on the judgement and lessons learned from past failures (Terzaghi 1950, Seed 1979). Jibson (2011) and Andrianopoulos et al. (2014) mention that choosing the appropriate K_H value is crucial for safe and robust design. Given this and the lack of experimental data, prompted the authors to develop a simulator for a geotechnical centrifuge to study the response of a small-scale model of WRTDs when subjected to hybrid loading conditions in an enhanced gravity environment.

2 BASIC PRINCIPLE

The simulator has been developed for enhanced gravity environment to serve two purposes: to induce (a) pseudo-static loading and (b) upstream (u/s) flooding and drawdown. For the pseudo-static loading, the centrifuge model is tilted to an angle (α) at a constant rate about a pivotal point. The tilting angle α and K_H acting on the centrifuge model are related by Eqn. (1).

$$K_H = \text{Tan}\ \alpha \qquad (1)$$

For flooding operation, the water from the onboard storage tank placed at a lower elevation is pumped to the u/s side of the centrifuge model (at a higher elevation) at desired rates. The suction capacity of the pump allows the water to reach the impeller, and the rotating vanes impart kinetic energy to the water to lift the desired elevation. The drawdown can be triggered under gravity field using a solenoid valve arrangement.

2.1 Review of the existing setups

Vagneron and Adams performed the initial tilting table experiments on reinforced earth walls to simulate pseudostatic conditions at 1g followed by the shaking table tests conducted by Richardson and Lee (1975) for the same models and compared with the analytical results from Mononobe-Okabe theory. Ohishi et al. (1995) developed the tilting table set up for an enhanced gravity environment to study the response of embankments constructed with cohesive volcanic material and compared the results with shaking tale tests. Some more studies on reinforced soil walls and embankments using tilting table at Ng were reported by Koseki (1998) and Izawa and Kuwano (2010). Very recently, Wolinsky and Take (2019) used the tilting table set up to determine instability conditions leading to strain softening in loose dry granular soils, particularly the shallow landslides. However, the studies on stability and deformation behaviour of retention type dams and embankments subjected to steady-state seepage and pseudo-static loading conditions have not been addressed to date. This prompted the authors to design and develop a hybrid loading simulator for centrifuge-based studies for potential application to WRTDs.

2.2 Scaling laws

The scaling laws for the model (m) and the prototype (p) were taken into consideration during the design and development of the hybrid loading simulator. The parameters included tilting angle (α) and seismic coefficient (K_H) for tilting operation, whereas the u/s water head (h_F), duration of water filling (t_F), and rate of filling (R_F) for reservoir filling operations. The tilting angle (α) is a dimensionless parameter, so its scale factor is taken as unity. Due to tilting, K_H acts on the centrifuge model, and its scale factor is given by Eqn. (2).

$$\frac{(K_H)_m}{(K_H)_p} = \frac{(\tan\alpha)_m}{(\tan\alpha)_p} = 1 \qquad (2)$$

The scale factor for u/s water head (h_F) is expressed as shown in Eqn. (3). The scale factor for the duration of water filling (t_F) is considered similar to the duration of seepage (t_s) and is expressed as shown in Eqn. (4). The rate of filling (R_F) is defined as the ratio of the head (h_F) developed over a period of time (t_F), and the scale factor is expressed as shown in Eqn. (5).

$$\frac{(h_F)_m}{(h_F)_p} = \frac{1}{N} \qquad (3)$$

$$\frac{(t_F)_m}{(t_F)_p} = \frac{(t_s)_m}{(t_s)_p} = \frac{1}{N^2} \qquad (4)$$

$$\frac{(R_F)_m}{(R_F)_p} = \frac{(h_F)_m}{(h_F)_p}\frac{(t_F)_p}{(t_F)_m} = N \qquad (5)$$

It is to be noted that the developed setup only imparts inertial loading to simulate pseudo-static slope stability and do not replicate the cyclic nature of the earthquake.

3 DESIGN DETAILS AND COMPONENTS

The developed simulator is shown in Fig. 1, comprises a screw-jack, two-stage gear train, a geared motor, a C-section base plate, and hinges as part of the tilting assembly. The water pump, water storage tank, solenoid valves, and network of pipes form part of the flooding assembly for reservoir filling or drawdown. The design of the hybrid loading simulator was in accordance with the technical requirements of the large beam geotechnical centrifuge of 4.5 m radius at IIT Bombay, Mumbai, India (Chandrasekaran 2001).

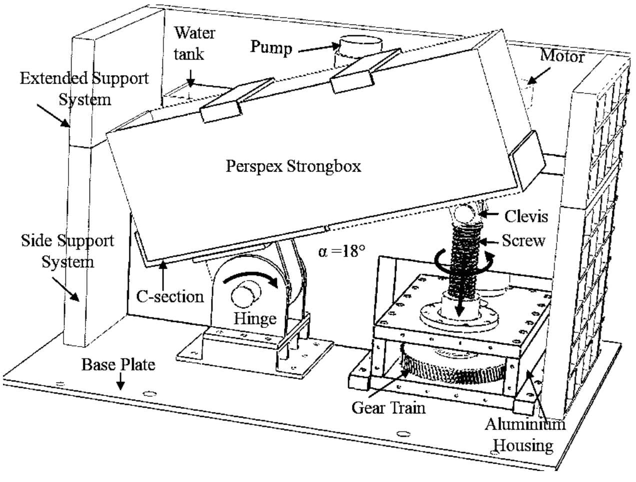

Fig 1. Schematic representation of the developed simulator.

3.1 Tilting Assembly

Various components of the tilting assembly are designed for 60g level. The screw-jack is made of EN19 carbon steel material, has a nominal diameter of 65 mm and a pitch of 12 mm. During tilting operation, the screw remains in a stationary position. A phosphor bronze nut attached to the gear train is the rotating part and holds the screw. The gear train is made of helical gears with case-hardening steel. A planetary geared motor attached to the bell housing imparts initial rotation of 30 rpm (at 24 V DC, 26 Ampere) to the pinion (input gear), which gets further reduced to 0.5 rpm at the output shaft (or nut) after a two-stage reduction with a final speed ratio of 47.38. A clevis at the top of the screw facilitates in linear motion of the screw and tilting.On the other side, a hinge is provided to facilitate rotation. It is made of 15 mm thick MS plates, and a stainless steel pin of 60 mm diameter serves as a pivotal point for rotation. A 15 mm thick MS plate in the form of a C-section serves as the platform to rest the strongbox container. Both sides (towards hinge and gear train) are firmly bolted to the C-section plate to form a tilting assembly.

3.2 Flooding Assembly

An impeller based regenerative type axial pump is used to lift the water from a rectangular container made of mild steel material that serves as a water storage tank (capacity 21 litres). The pump has a top speed of 2800 rpm at a maximum input supply voltage (V_{in}) of 24 V DC and a current of 35 Ampere. The choice of water pump has been made considering the requirement of delivery head, discharge, initial suction at high gravity. These pump characteristics vary with the variation in V_{in}. A network of pipes along with solenoid valves facilitates in maintaining constant water elevation in the storage tank and the u/s side enclosure, delivery of water, collection of seepage water, drawdown operation, etc.

3.3 Other Components

The other components that facilitate in smooth functioning and operations of the simulator includes (a) double pole double throw relay switch placed close to the axis of rotation of the centrifuge is designed to facilitate input supply to either motor or the pump; (b) control unit placed in the control room outside centrifuge chamber facilitate in regulating V_{in} ; (c) rear Aluminium support consists of enclosures for housing motor vertically, resting and clamping the pump vertically, and the water tank; (d) strongbox container having internal dimensions of 950 mm (L), 250 mm (B), and 350 mm (H) for constructing the instrumented soil model; (d) a camera assembly that houses digital GoPro camera for capturing images of front elevation of the centrifuge model, and rotates with the rotation of hinge; and (e) side support system is provided on three sides to contain the test package and protect from outside interference.

4 SALIENT FEATURES AND MERITS

The developed hybrid loading simulator has various salient features and advantages. Firstly, it can model flooding, drawdown, steady-state seepage, and tilting operations for WRTDs. The rate of filling ranges from 0.5 m/day to 2.5 m/day (in prototype dimensions at 30g), and the rate of tilting ranges from 0.2°/min to 0.8°/min. It has a lightweight Aluminium strongbox container for housing the soil model with slope inclinations as gentle as 2H:1V (for an earthen dam). The setup is robust as it is designed for operations up to 60g. While in-flight, all the operations of the developed simulator can be controlled from an outside control room. The versatile applications of the simulator involve testing of raw water reservoir, tailings dam, ash dyke, waterfront structure, structures on inclined slopes like landslides etc.

5 PERFORMANCE OF THE SIMULATOR

5.1 Model Preparation and Instrumentation

For the centrifuge test, an earthen dam model having a height of 240 mm, crest width of 150 mm, and side slopes inclination of 1H:1V was considered. The earthen dam rests on an impermeable base of 50 mm thickness and has a horizontal drain (HD) on the downstream (d/s) side for seepage control with a normalized length (L_d/H) of 1.31 and normalized thickness (t_d/H) of 0.083. The dam model was prepared in the strongbox shown in Fig. 1. After placing the impermeable base layer, the pore pressure transducers were placed at the toe (PPT1), 220 mm (PPT2), 320 mm (PPT3), 420 mm (PPT4), and 505 mm (PPT5) from the u/s toe. The wooden fixtures were then placed to attain geometry. The shell zone was constructed using the silty sand material (classified as SP-SM as per USCS) in 6 layers of 40 mm thickness, each compacted at a maximum dry unit weight of 19.75 kN/m^3 and water content of 7.5% (standard Proctor). The effective cohesion, angle of internal friction, and coefficient of permeability (k) of the shell zone material are 8 kPa, 33°, and 1.54×10^{-6} m/s, respectively. Further, HD was constructed using the sand pluviation technique with sandy material (classified as SP) at 85% relative density and has k of 1.5×10^{-4} m/s. In addition to this, L-shaped markers were embedded after each layer, on the slope faces, and on the crest to record vertical and horizontal movements. After model preparation, displacement transducers were placed on the crest to record crest settlements. Finally, the model test package was mounted on the swing basket and necessary connections (mechanical, electrical, and hydraulic) were checked before starting the centrifuge.

5.2 Analysis and interpretation of centrifuge tests

In the present study, the centrifuge tests on earthen dam was conducted at 30g due to (a) earthen dam having a factor of safety close to unity at HFL and (b) capability of the pump used to induce flooding. The phreatic surface has intercepted the HD between t_s = 2.2 days to 2.5 days. The HFL reached at 7.5 days with the maximum $u/\gamma H$ at the u/s side and at the toe being 0.37 and 0.12, respectively. The steady-state seepage condition was maintained till t_s = 16 days before subjecting to tilting. Fig. 2 shows the variation of pore-water pressure (PWP) for the earthen dam model during the tilting stage. The observations from u_{PPT2} and u_{PPT3} depict that steady-state seepage condition was maintained even during the tilting stage. The reduction in u_{PPT4} and u_{PPT5} evidenced movement of the phreatic surface away from the d/s face. At about $\alpha = 15°$ (or $K_H = 0.27$), a sudden rise in PWPs u_{PPT4} and u_{PPT5} was detected. The d/s side was observed to undergo failure at $\alpha = 15.5°$ (or $K_H = 0.28$), having maximum $u/\gamma H = 0.34$ and $u_{toe}/\gamma H = 0.08$. Following this, the tilting operation was stopped, and the centrifuge was brought to 1g.

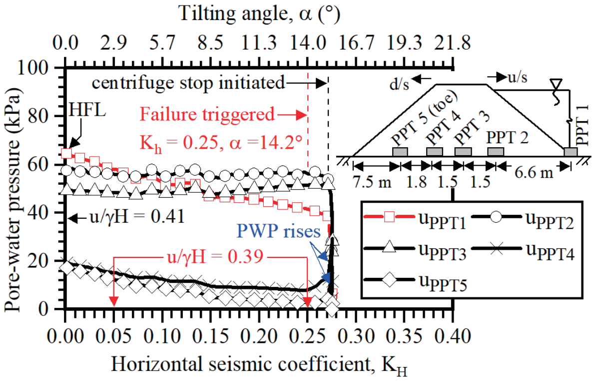

Fig 2. Variation of pore-water pressure during tilting stage.

Fig. 3 depicts deformation response of earthen dam model at penultimate stage captured during in-flight conditions. No slope face movements (S_f) were observed until $\alpha = 0°$ and initiated only after $\alpha = 10.3°$ (or $K_{H,yield}$

= 0.18). This value of K_H when deformation of the slope just initiates owing to factor of safety of unity is known as seismic coefficient at yield ($K_{H,yield}$). The maximum value of K_H subjected to the earthen dam model is known as $K_{H,max}$. In the present study, the earthen dam model was observed to deform at $K_{H,yield}$ = 0.18. The d/s side slope collapsed at $K_{H,max}$ = 0.27. The $S_{f,max}$ (in prototype dimensions) was observed at normalized height (Z/H) of 0.09 and were 0.012 m at α = 12°, 0.26 m at α = 15.3°, and 0.51 m at α = 15.4°, respectively. Here, Z is measured vertically upwards from the toe of the dam.

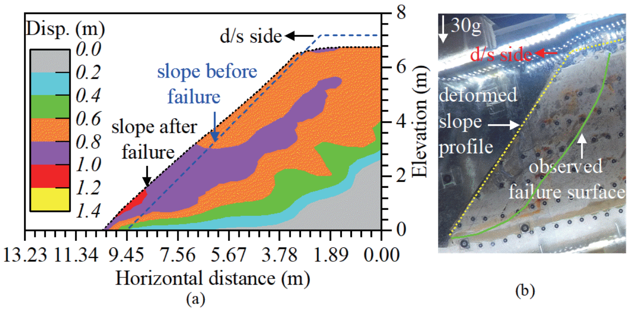

Fig 3. Deformation response of centrifuge model at penultimate stage (α = 15.4°): (a) Resultant displacement contours from DIA and (b) Front elevation image.

The crest settlement (s_c) observations from DIA were also in line with the values recorded with LVDTs. The observed values of $s_{c,max}$ (in prototype dimensions) were 0.09 m at α = 14°, 0.18 m at α = 15.2° and 1.5 m at α = 15.4°.

6 CONCLUSIONS

In the present paper, the design and development of a hybrid loading simulator for inducing reservoir filling, flooding, drawdown, steady-state seepage, and pseudo-static loading conditions for a geotechnical centrifuge at an enhanced gravity environment is presented. The basic principle involved in the design is discussed, with a focus on the various parameters for tilting and filling, as well as the governing scaling factors. The various components of the hybrid loading simulator along with advantages over existing simulators, are discussed in detail. Further, setup was used to ascertain the response of an earthen dam subjected to reservoir filling and pseudo-static loading conditions at 30g. A constant rate of reservoir filling was observed with a subsequent build-up of PWP within the dam body. The HFL was attained and maintained by the water pump, steady-state seepage condition was established. Following this, the tilting operation was initiated, and the dam experienced catastrophic failure at α =15.4° or $K_{H,\ max}$ = 0.27. In addition, the developed simulator can be used for understanding the stability and deformation behaviour of other similar water retention type structures like raw water reservoirs, ash dykes, waterfront structures, etc.

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