**Proceedings of the 4th ACPMG 2024**
4th Asia-Pacific Conference on Physical Modelling in Geotechnics
11-13 December 2024, Abu Dhabi, UAE

# Modelling tailings dam in a geotechnical centrifuge using a hybrid loading simulator

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**ABSTRACT:** Many earth and tailing storage facilities have failed in the last ten years. Aside from seismic activity, seepage and slope instability are the most frequent causes of failure. The present research work examines the performance of a scaled down model of water retention type (WRT) tailings dam subjected to a high gravity environment. A large beam geotechnical centrifuge with a radius of 4.5 meters, located at the Indian Institute of Technology Bombay, India, is employed. For tailings dams and other water retention-type structures, a reliable in-flight simulator was custom-designed with the consideration of the pertinent scaling laws to simulate (a) reservoir filling and drawdown, (b) steady-state seepage, and (c) inertial or pseudo-static loading conditions at high g-levels. The simulator is capable of producing a maximum tilting angle of 20° (equivalent to horizontal seismic coefficient of 0.36) with tilting rates varying from 0.2°/min to 0.8°/min at enhanced gravity levels and reservoir filling at the rate of 0.5 m/day to 2.5 m/day. To measure pore-water pressure (PWP) and surface settlement, respectively, and ensure the long-term stability and integrity of the tailings dam, the centrifuge models have been instrumented with pore pressure and displacement sensors. In addition, the front elevations of the centrifuge models were taken using an on-board digital camera so that digital image analysis (DIA) could be performed to infer failure patterns, surface settlements, and slope face movements. Effectively illustrating the tailings dam's performance, the results also define the slip surface and failure pattern and measure the horizontal seismic coefficient ($K_{Hyield}$ and $K_{Hmax}$), a vital design parameter associated with inertial loading.

## 1 INTRODUCTION

A tailings dam is typically an earth-fill embankment dam used to store by-products of mining operations after separating the ore from gangue. Globally, the mining industry generates billions of tonnes of this refuse each year only to get stored in a tailings storage facility (TSF). The tailings have often been disposed of and stored by constructing dams, embankments, lagoons, and dykes either as a water retention type (WRT) (like conventional earthen dam) or a raised embankment (upstream, centreline, or downstream construction) type structure.

Currently, no database or world census on TSFs can provide information on the different characteristics of tailings dams, such as location, kind, year of construction, height, storage capacity, tailings composition, danger category, etc. As of December 2020, the number of TSFs globally is projected to be around 30,000 (https://worldminetailingsfailures.org), based on reliable national compilations and data on global mineral production. On the other hand, the most updated database with the recent TSF failure available on the internet is an excel sheet from the Center for Science in Public Participation (CSP2) (http://csp2.org/tsf-failures-from-1915). David Chambers has compiled information from previously presented databases and the recent incidents bringing the total incident count to 368 (as of July 20, 2022). Figure 1 depicts different modes of failure in tailings dam. Statistics from 354 incidents were used to determine the distribution of failure causes based on ICOLD cause classification. Overtopping was responsible for more than 20% of the incidents, slope instability or earthquake for more than 15%, structural inadequacy for 9%, seepage or internal erosion for 8.2%, and foundation inadequacy for 7%. Mine incidents and external erosion accounted for nearly 3.4% of the incidents, while the remaining 19.8% were classified as unknown.

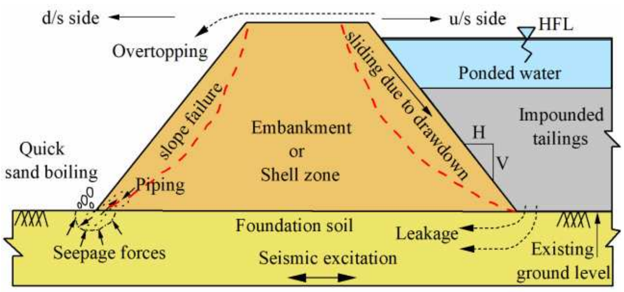


*Figure 1. Various modes of failure in a WRT tailings dam.*

The first-of-its-kind coal tailings dams in the centrifuge were tested by Al-Hussaini et al. (1981)

to study their long-term performance. The models were constructed with truncated slopes owing to space constraints, but the phreatic surface is not much affected and can be neglected for scaling less than 100g (Sutherland and Rechard, 1984), but the drawdown rates and PWP at the bottom of the upstream slope can deviate from normal as observed by Beckett et al. (2016). Cowherd et al. (1993) observed that coarse coal tailings act as free draining material almost throughout the design life of the embankment. The effectiveness of drains for the stability of levees under different rates of flood levels is studied by Saran and Viswanadham (2018).

The present study aims at long-term stability assessment of instrumented WRT tailings dam subjected to operational loading conditions in a 4.5 m radius large beam geotechnical centrifuge. The research work deploys a state-of-art hybrid loading simulator in a 40 g-level environment for seepage and inertial loadings.

## 2 DESIGN AND DEVELOPMENT OF MODEL TEST PACKAGE

The simulator consists of a screw jack gearbox-based mechanism with a pivotal hinge to produce a maximum tilting angle of 20° ($\approx K_H = 0.36$) with tilting rates ($\delta$) varying from 0.2°/min to 0.8°/min at enhanced gravity levels. The setup can safely withstand gravity as high as 60g and carry a maximum load of 100 kN at a torque of 3000 N-m. The simulator can accommodate small-scale models of 1V:1.5H to nearly vertical slope dimensions and has an impeller-based pumping system for simulating reservoir filling operations.

### 2.1 Tilting Analogy

To study the behaviour of a geotechnical structure subjected to inertial loading, the small-scale model is tilted to a small angle ($\alpha$°) in a geotechnical centrifuge at Ng-level. The inertial force developed due to the model's tilting is identical to the seismic pseudostatic force (= $K_H \times$ weight of the sliding mass, W). Figure 2 illustrates the application of the analogy for a WRT dam and the subsequent variation of basic parameters and force vectors for pseudostatic condition demonstrated in-situ and during tilting (Kumar and Viswanadham, 2022). On comparing normal and tangential forces from in-situ and experimental conditions and solving for $K_H$, equation 1 is obtained.

$$K_H = \tan\alpha \qquad (1)$$

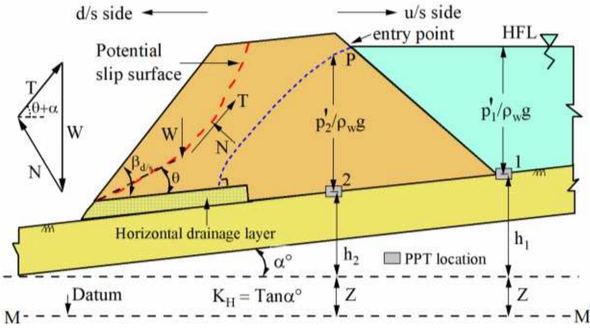


*Figure 2. Schematic of a WRT tailings dam subjected to tilting and associated forces.*

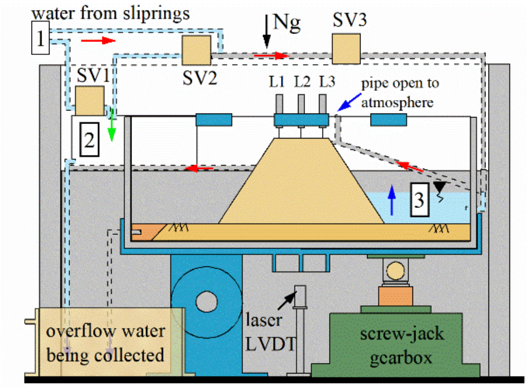
Based on inertia, Terzaghi (1950) presented stability of natural slope, dam and embankment subjected to seismic condition by considering pseudo force, known as the pseudostatic method or seismic coefficient method (Seed, 1979).

### 2.2 Mechanical Design

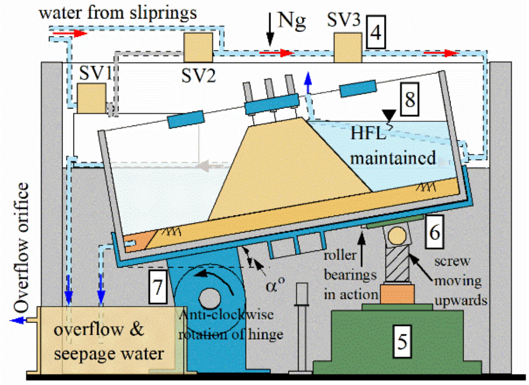
The mechanical design of the simulator includes designing a screw jack, nut, helical gear train assembly, C-section plate, and hinge assembly. ***Screw Jack:*** The initial input requires the design load, screw travel length, and lifting speed. The single start (n = 1) screw is made up of carbon steel (EN19), having a mean diameter of 58.5 mm and pitch of 12 mm. The torque required to raise and lower the screw jack design load is computed as per design procedure in Shigley and Mischke (1996). The design also accounts for tensile or compressive stress and torsional shear stress. ***Nut:*** The Phosphor Bronze (PB2) nut threads share the load equally, they are checked for bearing, crushing, and shear failure. Safety from buckling of the screw is considered at the static position and at the raised position. ***Gear Train:*** A two-stage helical gear train, case-hardening steel (20MnCr5), is custom-designed to transmit a torque of 3000 N-m to the screw jack for a final speed ratio of 47.38 at 60g. The procedure adopted for the design of the helical gear train follows the American Gear and Manufacturers Association standards, as documented by Shigley and Mischke (1996). ***Hinge Assembly**:* The hinge is designed as a pin connection for zero moment and free rotation. The entire load is distributed to two structural plates of 15 mm thickness over a width of 150 mm and transferred to a 60 mm diameter pin and then to a stable base through another similar pair of plates. ***C-section Plate:*** It is designed like a uniformly loaded over-hanged beam because a hinge supports the C-section plate at one end and a screw jack at the other. Further, it can carry the maximum design load from the model at 60g without any deformation.

## 2.3 Sequence of Operations

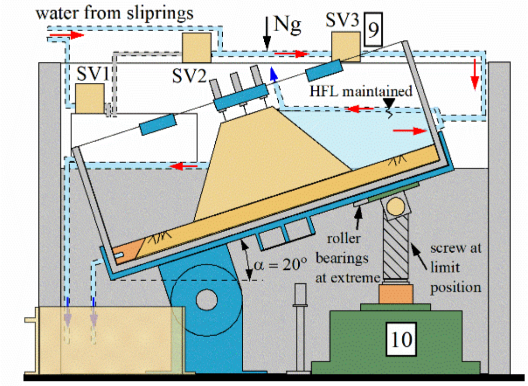
Figure 3 depict schematic view of the developed simulator and the sequential processes involved in simulating steady-state seepage and inertial loading conditions. In the depictions mentioned, step-by-step processes are shown with moving components in relative stages, they would assume in-flight during the centrifuge model testing.



(*a*) At the onset of flooding (α = 0°)



(*b*) During tilting (α = 10°)



(c) At limit position (α = 20°)

*Figure 3. Sequence of testing tailings dam at high gravity using developed simulator.*

As the model test package reaches desired g-level, the water through the slipring is activated (step 1) using a solenoid valve to fill the water storage tank connected to the pump (step 2). The DPDT relays are triggered one by one by operating switches (S1 and S2) connected to the power supply unit placed in the control room. When the input voltage supply is directed towards the impeller pump, water filling on the upstream side is initiated, as shown in Figure 3a (step 3). This stage is in operation till steady-state seepage condition is established (step 4). After this, the supply is directed towards the motor (step 5) for raising the screw jack assembly (step 6), as shown in Figure 3b. Simultaneously, the hinge on the other side of the screw jack also rotates with the rise in the screw during tilting operation (step 7). To maintain HFL during the tilting stage, a separate solenoid valve (SV3) is used (step 8). When the model attains failure or screw reaches maximum α (= 20°), whichever occurs earlier, the input voltage to the motor is reduced to zero and centrifuge model is brought to normal gravity (Steps 9 and 10). The screw jack assembly is then lowered (Fig. 3c).

## 2.4 Calibration Details

The developed simulator is thoroughly tested for the functionality of its components before performing calibration using the above operational sequence. In the present study, (a) the screw jack is calibrated to determine the tilting and lowering rates (in °/min), and (b) the impeller pump is calibrated to determine the reservoir filling rate (volume of water/min). From experimental point, the above parameters are crucial to a WRT dam for developing a water head on the upstream side, maintaining steady-state seepage, and monitoring its performance when subjected to inertial loading. Given this, the simulator has been calibrated in normal and high gravity environments at variable motor input voltages. The tilting rate is observed to vary in the range of 0.2°/min to 0.8°/min and variation of the upstream water head is observed to be non-linear, from 0.5 m/day to 2.5 m/day, mainly due to shape of the upstream reservoir.

## 3 MODELLING CONSIDERATIONS

Geotechnical centrifuge modelling is an avenue for studying small-scale models of WRT dams and other geotechnical structures by maintaining similar prototype stress conditions in a high-gravity environment. The time required to induce seepage in the model WRT dam makes it more popular to study the seepage-stability response when subjected to hybrid loading conditions. Relevant scaling laws for modelling reservoir filling and inertial loading for WRT dam model in a geotechnical centrifuge are summarised in Table 1.

*Table 1. Summary of scaling laws for modelling WRT dam.*

| Parameters | M/P |
|---|---|
| Dam height (H) or geometry (L, B), m | 1/N |
| Upstream and downstream slopes (α, β), ° | 1 |
| Unit weight of the soil (γ), kN/m$^3$ | N |
| Cohesion (c), kN/m$^2$ | 1 |
| Angle of internal friction ($\phi$), ° | 1 |
| Pore water pressure (u), kN/m$^2$ | 1 |
| Seepage time ($t_s$), sec | 1/N$^2$ |
| Coefficient of permeability of soil (k), m/sec | N |
| Upstream water head ($h_F$), m | 1/N |
| Duration of water rising ($t_F$), day | 1/N$^2$ |
| Rising rate ($R_F$), m/day | N |
| Tilting angle (α) | 1 |
| Inertial or pseudostatic coefficient ($K_H$) | 1 |
| Inertial force ($F_H$ ), kN | 1/N$^2$ |

Note: N is scale factor or gravity level attained in centrifuge experiment; M: model; P: prototype

## 4 CENTRIFUGE MODEL TESTS

Centrifuge modelling technique was adopted in the present study to evaluate the performance of a small WRT dam having a height of 7.2 m (in prototype dimensions), side slope inclinations of 1H:1V, and blanket drain for seepage control at 40g. Figure 4 shows the model test package mounted on the swing basket.

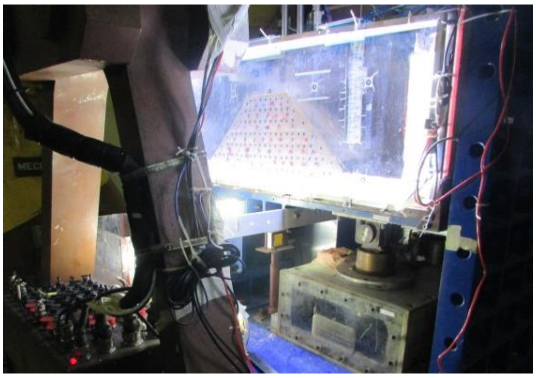


*Figure 4. Model test package mounted on the swing basket.*

### 4.1 Material Properties

The shell zone and the internal drain materials adopted in the present study resemble the materials obtained directly from the field. The silty sand used for the shell zone has 20% fines content and specific gravity of 2.61. The maximum dry density (MDD) of 19.75 kN/m$^3$ and optimum moisture content (OMC) of 7.5% are obtained from the standard Proctor compaction test. For the soil specimens moist-compacted at MDD and OMC, a coefficient of permeability of 1.54×10$^{-6}$ m/sec is obtained from the falling head permeability test, and the effective cohesion (c') and angle of internal friction (ϕ') are obtained as 8 kPa and 33° by conducting consolidated-undrained triaxial compression tests. The fine sand used for internal drains has a specific gravity of 2.67. The maximum and minimum void ratios are obtained as 0.94 and 0.64, respectively. For the fine sand specimens at a relative density of 85%, a coefficient of permeability of 1.5×10$^{-4}$ m/s is obtained from the constant head permeability test, and the effective cohesion (c') and angle of internal friction (ϕ') are obtained as 0 kPa and 33° from direct shear tests.

### 4.2 Model Preparation

The WRT dam model is constructed in a specially designed Aluminium strongbox. Figure 5 shows cross-section of the model dam used in present study. After compaction of the impermeable base layer, five miniature pore pressure transducers (PPTs) were placed to monitor the development of the water head on the upstream side and within the dam section. Further, L-shaped plastic markers made from thin plastic sheets (20×10 mm) were embedded after each soil layer within the front elevation and along the inclined slope faces to determine relative displacements with respect to the permanent markers. A pinch of red colour food dye was placed at specific positions to visualize and trace the progress of wetting front or water flow within the WRT dam during hybrid loading conditions.

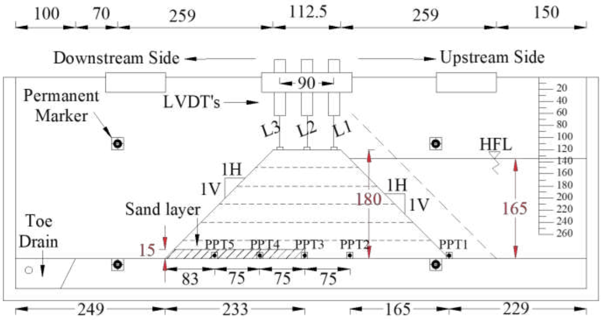


*Figure 5. Schematic cross-section of WRT dam model used in the present study for testing at 40g (all dimensions are in mm).*

After completing the dam model, the Aluminium container was placed firmly on the C-section plate. The linear variable differential transformers (LVDTs) (three nos.) were placed along the crest to record surface settlements such that LVDT L1 is at the crest towards the downstream side, L2 is at the centre of the WRT dam, and L3 at crest towards the upstream side. The model test package was mounted on the swing basket, and all necessary connections were established. Figure 6 shows various transducers used in the present study.

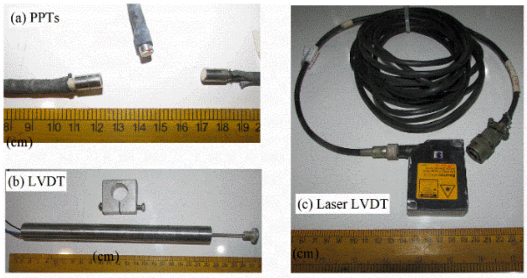


*Figure 6. Various transducers used in the present study.*

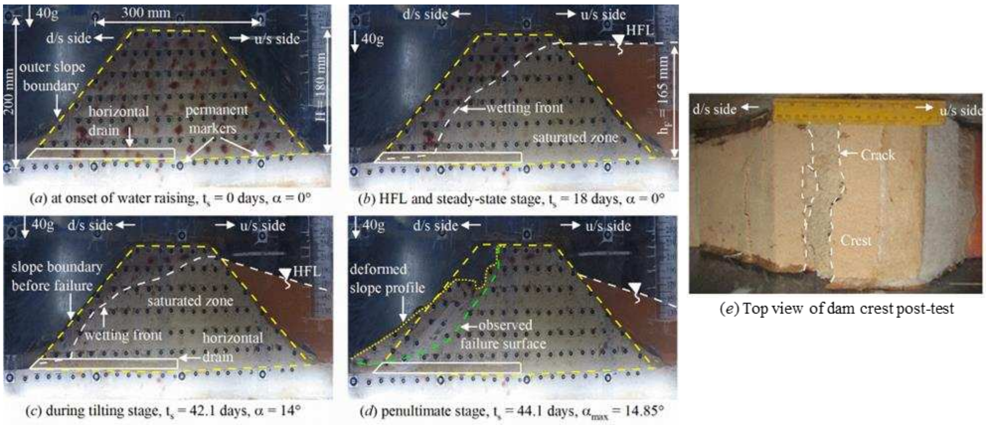
## 4.3 Response of WRT Dam Model

Figure 7 depicts the front elevation view of the WRT dam models just before the centrifuge test with the permanent markers placed at intervals of 150 mm (horizontally) and 200 mm (vertically) on the inner side of the front perspex sheet (Fig. 7a). The maximum HFL is kept at 6.6 m (in prototype dimension) from the top of the impermeable base layer (Fig. 7b). The front elevation images captured using the digital camera are analyzed using Image-J software (Image J, 2012) and interpreted to deduce surface settlements, slope face movements and displacement contours. The tell-tales observed during the post-test investigation are used to verify and support the analyzed data.

When subjected to reservoir filling, the WRT dam with internal drain was stable during the reservoir filling stage compared to a fully clogged internal drain that failed catastrophically before reaching HFL (Kumar and Viswanadham, 2022). The model was subjected to inertial loading conditions by tilting the base of the model (Fig. 7c) and witnessed failure at some value of tilting angle ($\alpha$) or horizontal seismic coefficient ($K_H$). A clear distinction between the sliding wedge and the intact mass is visible (Fig. 7d), indicating the development of slip surfaces. As observed, the plane-strain condition prevailed in the model, as indicated in Figure 7e, by the detachment zones and cracks on the dam's crest and the downstream side slope that runs along the width of the centrifuge model and the Aluminium strongbox. In upstream and downstream toe regions, the water content exceeds 90%, indicative of model soil reaching saturation.

The HFL ($\approx 0.917H$) was attained after seepage time of 6.5 days and maintained until a steady-state seepage condition was established for a minimum of five days. The upstream water pressure was observed to be 64.15 kPa before and during the tilting stage. During the steady-state seepage, the average PWPs were registered as $u_{PPT2}$ of 55.68 kPa, $u_{PPT3}$ of 42.87 kPa, $u_{PPT4}$ of 18.91 kPa, and $u_{PPT5}$ of 17.6 kPa, respectively. The PWPs registered at $\alpha = 8°$ were $u_{PPT2} = 51.83$ kPa, $u_{PPT3} = 40.65$ kPa, $u_{PPT4} = 10.53$ kPa, and $u_{PPT5} = 8.86$ kPa. Compared to PWPs at $\alpha = 8°$, the PWPs at the end of $\alpha = 14.84°$ registered a reduction due to tilting of the WRT dam model by 17% for $u_{PPT2}$; by 21% for $u_{PPT3}$; by 69% for $u_{PPT4}$; and by 77% for $u_{PPT5}$. Beyond this point (i.e. $\alpha = 14.84°$), model failed within three days of maintaining a constant tilting angle (Fig. 8a). Figure 8b shows the variation of PWP for the model dam.

After processing the batch of images, multiple nodal points were generated for every L-shaped marker, which were used to obtain relative displacements for computing face movements and surface settlements. For the dam model in the present study, negligible surface settlements were observed during the static condition (i.e. $\alpha = 0°$), as depicted in Figure 8c, whereas, dam model witnessed distress at $\alpha > 0°$. The WRT dam model at 40g attained FS = 1 at $\alpha_{yield} = 10.3°$ ($K_{Hyield} = 0.180$). The displacement values are observed to be insignificant until $\alpha = 14.5°$. The $s_{c\ max}$ and $s_{f\ max}$ observed was 1.91 m and 2.65 m, respectively at $\alpha_{max} = 14.84°$, as depicted in Figures 8c-8d.



(*a*) at onset of water raising, $t_s = 0$ days, $\alpha = 0°$

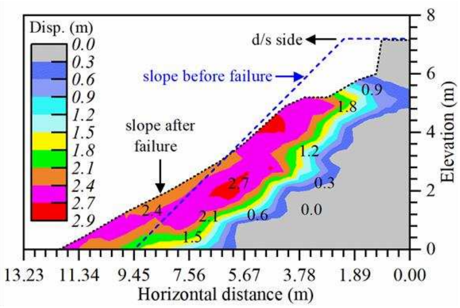
(*b*) HFL and steady-state stage, $t_s = 18$ days, $\alpha = 0°$

(*c*) during tilting stage, $t_s = 42.1$ days, $\alpha = 14°$

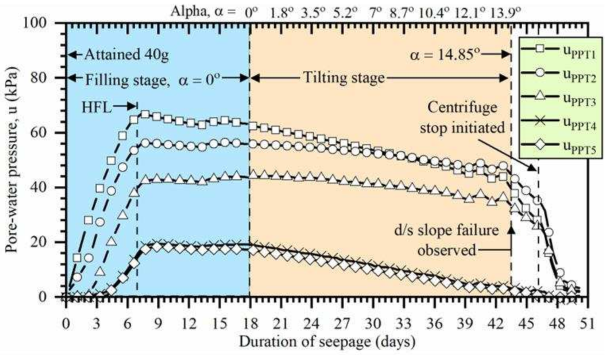
(*d*) penultimate stage, $t_s = 44.1$ days, $\alpha_{max} = 14.85°$

(*e*) Top view of dam crest post-test

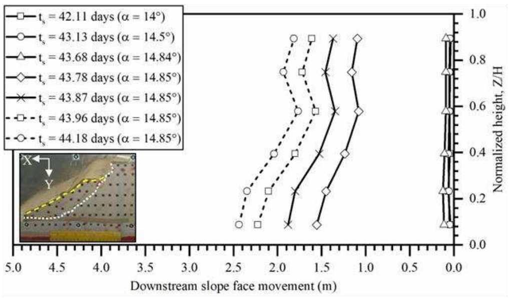
*Figure 7. View of the front elevation of Model dam at various stages of hybrid loading.*



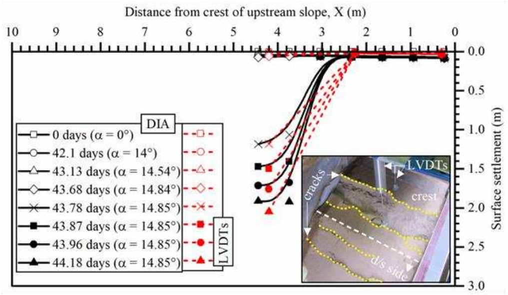
(a) Deformation contours



(b) Porewater pressure records



(c) Slope face movements



(d) Crest surface settlements

*Figure 8. Results obtained from centrifuge model test for the model dam.*

## 5 CONCLUSIONS

The present study presents a hybrid loading simulator designed to investigate water retention type structures in a high gravity environment. The simulator can experimentally evaluate the influence of $K_H$ induced by the inertial loading. The versatility of the simulator to produce varying filling and tilting rates becomes advantageous for geotechnical structures like earthen dams, levees, ash dykes, tailings dams, raw water reservoirs etc. and can give more insights into the response of geo-structures under variable loading conditions.

## 6 ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by Board of Research in Nuclear Sciences (BRNS) in Mumbai, India, for their support with grant no. 36(2)/15/07/2016-BRNS/36007. The authors are also grateful to staff members at the NGCF, IIT Bombay, Mumbai, India, for their assistance with this research.

## REFERENCES

Al-Hussaini, M. M., Townsend, F. C., Schofield, A. N., and Goodings, D. J. (1981). Centrifuge Modeling of Coal Waste Embankments. Journal of the Geotechnical Engineering Division, ASCE, 107, no. 4: 481-499.

Beckett, C., Fourie, A. B., and O'Loughlin, C. D. (2016). Centrifuge Modelling of Seepage through Tailings Embankments." International Journal of Physical Modelling in Geotechnics, 16, no. 1: 18-30.

Center for Science in Public Participation (CSP2) database. "Tailings dam failures from 1915 to 2022." http://csp2.org/tsf-failures-from-1915 (Accessed July 21, 2022)

Cowherd, D. C., Miller, K. C., and Perlea, V. G. (1993). Seepage Through Mine Tailings Dams. In Third International Conference on Case Histories in Geotechnical Engineering, vol. 1, 26: 463-468, University of Missouri-Rolla, USA, https://web.archive.org/web/20201205124507/https://scholarsmine.mst.edu/icchge/3icchge/3icchge-session02/26/

ImageJ (2012). User Guide. National Institutes of Health, USA, version 1.52a.

Kumar, P. and Viswanadham, B.V.S. (2022). Design and Development of Tilt Table Based In-flight Simulator for Pseudostatic Loading in a Geotechnical Centrifuge. Geotechnical Testing Journal, ASTM, 45, no. 5: 936-960.

Saran, R.K., and Viswanadham, B.V.S. (2018). Centrifuge Model Tests on the Use of Geosynthetic Layer as an Internal Drain in Levees. Geotextiles and Geomembranes, 46, no. 3: 257-276.

Seed, H.B. (1979). Considerations in the Earthquake-Resistant Design of Earth and Rockfill Dams." Géotechnique, 29, no. 3: 215-263.

Shigley, J.E. and Mischke, C.R. (1996). Standard Handbook of Machine Design. Mc-Graw-Hill Book Company, USA. Webpages https://worldminetailingsfailures.org (Accessed July 21, 2022)

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*The paper was published in the proceedings of the 4th Asia-Pacific Conference on Physical Modelling in Geotechnics and was edited by Tarek Abdoun. The conference was held from December 11th to December 13th 2024 in Abu-Dhabi, United Arab Emirates.*