Research Article

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Dynamic characteristics of tailings dam with geotextile tubes under seismic load

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Abstract: Geotextile tubes are one of the emerging and promising technologies to build fine-grain tailings dams. In this study, shaking table model tests are conducted to evaluate the seismic performance as characterized by horizontal acceleration and displacement of the tailings dam subject to horizontal peak ground accelerations (HPGAs). The test results indicate that the tailings dam is sustainable, whereas the whole dam tends to slide forward. Test results reveal a W-pattern variation of acceleration amplification coefficient (A_m) at the same elevation despite different HPGA, whereas A_m on the geotextile tubes exhibits minimal changes with increasing HPGA. A_m inside the dam is highly variable in terms of the elevation and the specific position. The maximum vertical displacement occurs at the top of the geotextile tubes as the side of the geotextile tubes tilting upward. The highest horizontal displacement is observed in the middle section of the geotextile tubes, resulting in an overall convex deformation pattern. Two reinforcement schemes are proposed accordingly including strengthening the drainage and installing the anti-slide piles. The dynamic behaviors of the tailings dam subject to earthquakes from this study can serve as guidance for seismic design and technology promotion.

Keywords: tailings dam, geotextile tubes, seismic load, shaking table model test, dynamic response

1 Introduction

The mining industry produces an extremely high volume of tailings as solid wastes during grand-scale mining and mineral processing [1]. In 2020 alone, the estimated phosphate ores unearthed worldwide was as high as 290Mt with 30–40% of the phosphate ore mass that were discarded as tailings [2]. In 2019, the tailings emissions reached nearly 1.2 billion tons in China exclusively [3]. Further concerns are also raised by the considerable number of tailings containing useful components that have not been recovered effectively. Without a proper recycling and recovery process, tailings not only imposes a severe burden as a waste source but also incurs serious environmental pollution to the nearby farmland and rivers [4]. Therefore, an effective method is highly desirable to process tailings properly. Besides the usage as building materials, mines' goaf fillings, and coastal land preparation, tailings should be properly stored in special reservoirs. More than 12,700 tailings reservoirs had been constructed in China till 2019, and the number is still increasing [3].

The tailings reservoir is a special industrial construction, which is considered as one of the three major control projects within a mine. Safe operation of the tailings reservoir plays a crucial role in the production of the ore dressing plant [5,6]. It is especially true in light of that the tailings reservoir is a major hazard source [7,8]. A number of factors influence the failure mechanism of a tailings dam, such as seismic liquefaction, slope instability, amounts of rain, and overtopping [9]. The historical major failures of tailings ponds that have occurred in China since 1962 [10] are summarized in Table 1.

With the continuous improvement of the beneficiation technology and recovery rate [11], tailings have become less coarse with decreasing portions of particles larger than 0.074 mm and increasing fine particles smaller than 0.03 mm [12]. Fine-grained tailings feature poor water permeability after storage, long consolidation time, low mechanical strength, and incapability of dissipating excess pore water pressure [13]. The upstream method of dam construction,

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Table 1: Major failures of tailings dams in China

Name of dam	Tailings types	Construction method	Year of failure	Fatalities
Huogudu, Yunnan Tin Group Co., Yunnan province	Tin	Upstream	1962	171
Niujiaolong, Shizhuyuan non-ferrous metals Co., Hunan province	Copper	Upstream	1985	49
Longjiaoshan, Daye iron ore mine, Hubei province	Iron	Upstream	1994	31
Dachang, Nandan Tin mine, Guangxi province	Tin	Upstream	2000	28
Zhenan Gold mine, Shanxi province	Gold	Upstream	2006	17
Xiangfen tailings pond, Shanxi province	Iron	Upstream	2008	277
Xinyi Zijin Tin mine, Guangdong province	Tin	Upstream	2010	28

which has been widely used in China for decades, is simple and easy to manage [14]. However, a large number of coarse particles are often required to construct tailings embankment for the upstream method [15]. If the traditional upstream storage method is used for fine-grained tailings, common problems [16] such as dam construction difficulty, poor drainage of the dam body, the slow slope of the sedimentary beach, and poor stability are often encountered [17].

Therefore, improving the stability of tailings dam poses as a challenge for mine operators [18]. Ye *et al.* [19], Zhang and Wang [20], and Xue [21] studied the application of geofabriform method damming technology in tailings dams and have suggested that geotextile tubes in the tailings dam construction are an effective remedy for all these problems.

The geosynthetic has been considered as a premium geotechnical engineering material to build reinforcements [22,23]. The geotextile tube made of geotextile sheets can also be used for soil strengthening [24–26]. Tubes can be filled with tailings slurry through the hydraulic transport process [27]. After the slurry is consolidated, the geotextile tubes are accumulated to form a dam or other types of geotechnical structures. In recent years, geotextile tubes are widely adopted in building dike enforcement [28], dewatering of soils/slurry with high water content to control flood and prevent beach erosion [29]. Kim *et al.* [30,31] conducted the tension force analysis of geotextile tubes by half cross-section test and studied the use of clay slurry filled geotextile tubes to construct dikes. Dorairaj and Osman [32] presented practices and emerging opportunities in bioengineering for slope stabilization in Malaysia. Man *et al.* [33] conducted an experimental study on permeability characteristics of geotubes for seepage analysis on the safety assessment of dams. Oyegbile and Oyegbile [34] studied the applications of geosynthetic membranes in soil stabilization and coastal defense structures. Cholewa *et al.* [35] evaluated the stability of modernized bank protections in a culvert construction.

Tailings dams are expected to function similarly as a general reservoir or river embankment. The application of geotextile tubes in the construction of tailings dams enhances the stability of the dam. The successful experiences of design and construction of conventional water storage dams avail economical and safe construction of tailings dams.

Figure 1 gives a zoomed-in partial view of a prototype tailings dam constructed with geotextile tubes in Yunnan province of China, while Figure 2 is a schematic of a cross-section of such a tailings dam.

Due to rapid drainage, low investment, and maintenance costs of geotextile tubes, many researchers have explored the application of the geotextile tubes in the

(a)

(b)

Figure 1: Zoomed-in partial view of tailings dam constructed with geotextile tubes in Yunnan province: (a) interior and (b) exterior.

Figure 2: Schematic of a cross-section of tailings dam constructed with geotextile tubes.

construction of tailings dams. Specifically, Yang et al. [10] studied the successful application of geotextile tubes in the construction of tailings dam raise through comprehensive geotechnical investigation and stability analysis of the tailings embankment. Li et al. [36,37] studied the mechanical performance of geotextile bags filled with tailings based on the slope sliding and unconfined compression tests, suggesting that the friction coefficient between geotextile bags increased with decreasing moisture content of tailings inside the bags. Additionally, the elastic modulus of a single geotextile bag experienced an increase before decreasing and finally increasing again as the vertical pressure rose. Assinder et al. [38] introduced a geotextile tubes system filled with tailings as the structural elements to establish raises for mine tailings storage facilities. Nsiah and Schaaf [39] introduced the potentials of biological geotextiles in erosion and sediment control during gold mine reclamation in Ghana.

However, very limited studies have been reported to identify the dynamic characteristics of the tailings reservoir constructed using geotextile tubes subject to seismic load along with even fewer reports on tailings dam failure by shaking table tests.

According to the statistical analysis by the World Commission on Dams (ICOLD), since the early 20th century, more than 200 cases of tailing accidents have been recorded with most of them related to earthquakes [40,41]. It is understood that the saturated tailings are prone to liquefaction due to the earthquake, which leads to local dam breaking [42,43].

To promote the general application of geotextile tubes in constructing tailings dams, seismic sustainability of such tailings dam is vital for design in a country like China that is susceptible to strong earthquakes [44,45]. To investigate the instability mechanism of the tailings reservoir under seismic load, understanding the dynamic characteristics of the tailings reservoir under the potential action of an earthquake is a prerequisite [46–48].

In this study, the variation law of acceleration and displacement, i.e., the dynamic characteristics, of the tailings

reservoir constructed with geotextile tubes under seismic load is investigated through a large-scale shaking table model test. The instability mechanism of the tailings reservoir under seismic load is analyzed. The research results are expected to provide a theoretical basis and reference for the design and safe operation of the tailings reservoir and promote the application of the tailings dam constructed with geotextile tubes.

2 Test overview

2.1 Test setting

The tests are conducted at the Civil Engineering Test Center of the Institute of Disaster Prevention of China Earthquake Administration. One of the key test equipment for this research, the shaking table, is an electrohydraulic servo two-way shaking table with dimensions of 3.0 m × 3.0 m and a maximum load capacity of 20 tons, operating frequency range of 0.4–80 Hz, a maximum overturning moment of 400 kN·m, and a maximum displacement of ±20 cm. Other specifications of the shaking table include a maximum speed of 80 cm·s⁻¹ and a maximum horizontal acceleration of 2.0 g at full load. A 128-channel dynamic acquisition system is used for data acquisition.

2.2 Model design

Figure 3 shows the designed model box in the present tests. Considering the size and maximum load of the shaking table, the test model box is designed to be 2.7 m × 1.0 m × 1.0 m. The two long sides (Side A and Side B) of the model box, as shown in Figure 3, are made of plexiglass for visual observation and one of the short sides is left open to input load. The bottom edge and

Figure 3: Test model box.

the other short side of the model box are made from steel plates. The model box is reinforced with 120 channel steel connecting sides A and B of the box. The model box is fixed to the shaking table with six bolts.

The geotextile tube structure is 40 cm wide and 80 cm high with a slope ratio of 1:1, consisting 16 layers of $20\text{ cm} \times 20\text{ cm} \times 5\text{ cm}$ geotextile tubes filled with fine tailings.

Similar test materials as those at the construction site of a prototype tailings dam in Yunnan Province are adopted. The physical parameters of the tailings, the particle composition, and the basic mechanical parameters of the geotextile are given in Tables 2–4.

In conventional shaking table tests, quantitatively measuring the actual seismic response of soil through the soil shaking table tests is challenging due to the difficulty in recording the gravity acceleration directly [49]. It is understood that the similarity-law is satisfied only in geometry and kinematics instead of mechanical behavior [50]. In view of this, in this study, the mechanical behavior of the tailings dam is not studied quantitatively. The main parameters of similarity according to the structural similarity Buckingham π theorem are deduced as in Table 5.

In the current test, eight pore pressure sensors (K1–K8) are installed at two different positions in each layer of totally four layers along the height of the tailings dam. Eighteen accelerometers are deployed, including twelve 941B accelerometers placed in the tailings denoted as J1–J12. Accelerometer are deployed at two different

Table 3: Size and composition of tailings

Particle size range (mm)	≤ 0.019	≤ 0.037	≤ 0.05	≤ 0.074
Mass percentage (%)	56.64	68.44	73.29	79.89

Table 4: Mechanical parameters of geotextile

Test projects		Unit	Average value	Reference standard
Mechanica properties	Mass per unit area	$\text{g} \cdot \text{m}^{-2}$	151	GB/T13762-2009
	Thickness (2 kPa)	mm	0.62	GB/T13761.1-2009
	Breaking strength	$\frac{T}{W}$	1,520	GB/T3923.1-2013
			1,210	GB/T3923.1-2013
	Elongation at break	$\frac{T}{W}$	20.3	GB/T3923.1-2013
			18.7	GB/T3923.1-2013

positions in each layer of totally six layers along the depth. Four piezoelectric acceleration sensors are also positioned along the height of one side of the geotextile tube structure, which are indicated by JY1–JY4. Devices K1, K2, J3, J4, and JY1 are installed at the same height as that of K3, and K4, J5, J6, and JY2 are located at the same height. Again devices K5, K6, J7, J8, and JY3 are arranged at the same height with K7, K8, J9, and J10 and JY4 are at the same height. Other two 941B accelerometers are placed on each of two sides along the input acceleration direction of the shaking table to measure the actual triggering acceleration of the shaking table. Five ejector pin displacement meters are also deployed on one side of the geotextile tubes structure, which are denoted by W1–W5. W1–W5 are placed at elevations of 25, 40, 55, 70, and 75 cm, respectively. The sensor layout is shown in Figure 4.

In the shaking table test, the seismic excitation is usually distorted due to the limited size of the model box, thus the reflection and refraction of seismic wave

Table 2: Physical parameters of tailings

Unit weight	Void ratio	Compression modulus	Compression factor	Consolidated quick shear strength	
γ ($\text{kN} \cdot \text{m}^{-3}$)	e	E_s (MPa)	a (MPa^{-1})	c (KPa)	φ ($^\circ$)
20	0.63	12.1	0.15	16	21

Table 5: Primary similitude coefficients of the model

Parameter	Similarity relation	Scale factor (prototype/model)
Density ($\text{kg}\cdot\text{m}^{-3}$)	C_ρ	1
Acceleration ($\text{m}\cdot\text{s}^{-2}$)	C_a	1
Length (m)	C_1	20
Time (s)	$C_1^{0.5}$	4.472
Frequency (Hz)	$C_1^{-0.5}$	0.224
Displacement (m)	C_1	20

on the model box [51] and rigid constraint on soil deformation around the boundary of the model box. As a result, the seismic energy and the deformation of soil cannot be reliably recorded.

The rigid model box adopted in this test is straightforward to build and can sustain large loads. However, the critical drawback of rigid containers lies in the extremely substantial reflection of a seismic wave at the boundary, thereby seriously negating the reliability of the test results. Bhattacharya et al. [52] suggested that the wave reflections could be alleviated or even averted completely by lining the container walls with an appropriate absorptive material. Various types of flexible materials have been attempted as reactive artificial boundaries, such as 20 cm polystyrene sheets wrapped with polyethylene film, 4 cm thick conventional foam sheet, 10 cm conventional foams, 5 cm thick polystyrene foam board, polystyrene foam board, and 22.5 cm thick geo-foam [53–55] to reduce the wave reflection in shaking table tests.

Accordingly, in this study, after the model box is fixed to the shaking table, a 1,000 mm × 800 mm × 100 mm sponge mat sealed with a water-impermeable film is inserted between the tailings and the model box. The test model contains a thin layer of tailings on the bottom of the model box and multiple marking lines on the model box for the geotextile tubes to be laid in positions. A layer of geotextile tubes is paved with tailings before soaking with water. The tubes are also laid out for the second layer with specific inclination following the marking line. The tailings are laid with water. Other upper layers are placed similarly. The moisture content of each layer is measured to be about 30%. Sensors are deployed in the specified positions during the dam construction. To measure the displacement in the vibration process, marker balls are placed at different heights adjacent to both sides of the model box allowing observation from outside. After the model dam is built, water is added for saturation, followed by one day of maturing. The piled model is shown in Figure 5.

(a)

(b)

(c)

Figure 4: Typical sensor layout of shaking table test: (a) model dam; (b) schematic of longitudinal profile of model; and (c) top view of model.

2.3 Loading procedure

To derive the resonant frequency of the overall test equipment, white noise test is first performed before the input of the seismic wave. The white noise consists of a

Figure 5: Illustration of model construction.

horizontal peak ground acceleration (HPGA) of 0.05 g with a duration of 80 s and frequency contents in the range of 0–50 Hz. Fourier analysis of amplitude against frequency for this input is shown in Figure 6. The initial natural frequency of the dam model is derived to be 4.76 Hz.

Earthquake load can usually be represented by horizontal seismic wave. Thus, the input seismic wave in this test is a one-way horizontal WoLong wave observed in Wenchuan earthquake in China, which has the largest peak acceleration in the main shock records. A typical seismic time-history of acceleration and the Fourier spectrum are shown in Figure 7(a) and (b), respectively. The predominant frequency of the input seismic wave is observed to be 2.4 Hz. Due to the restriction

Figure 6: Typical example of Fourier spectrum in white noise tests.

(a)

(b)

Figure 7: Seismic wave time-history and the Fourier spectrum: (a) Seismic wave time-history and (b) Fourier spectrum.

of the experimental condition, a single predominant frequency of the input motion, which approximates the most unfavorable conditions, is used to study the stability of the model dam in this paper.

The initial natural frequency of the dam model is higher than the predominant frequency of the input motion. As the vibration magnitude increases, the model dam will be damaged, resulting in gradually decreasing natural vibration frequency. When the natural frequency of the model dam approaches to the predominant frequency of the input seismic wave, the model dam inclines to damage substantially by resonance.

To identify the specific wave intensity to initially incur dynamic damage to the tailings dam and the failure mode, the seismic load is imposed with an amplitude of 0.1, 0.2, 0.6, 0.8, 1.0, 1.2, 1.6, 2.0 g, respectively, of the

same time-history evolution pattern of the acceleration. Due to the precision limitation of the hydraulic jack, the peak accelerations of the actual output of the shaking table are 0.1, 0.3, 0.6, 0.7, 0.9, 1.0, 1.3, and 1.5 g, respectively. The acceleration of the shaking table acts as the horizontal seismic ground acceleration loads, indicated by HPGA. A subsequent test cannot be implemented until the excess pore water pressure of the tailings is completely dissipated from the previous test. The failure magnitude of the dam is evaluated based on equation (1).

$$\alpha = \frac{D_{\max}}{H_t} \quad (1)$$

where $D_{\max}$ is the maximum horizontal displacement of the dam and H_t is the total height of the dam. When $\alpha > 0.1$, the dam is rated as a failure [56].

3 Failure mode analysis

3.1 Test observations

The overall evolution process as well as the model dam before testing are given in Figure 8. Based on the observations from the vibration tests, with small input of HPGA, such as 0.1 or 0.3 g, the whole dam body moves with the model box without relative displacement. No obvious cracks, vertical displacement or horizontal displacement are observed in the dam.

From Figure 8(b), as the HPGA increases, cracks appear on the top of the model dam along with perceivable vertical and horizontal displacements. When HPGA reaches 0.6 g, the upper 1/3 height of the dam vibrates strongly. Simultaneously, the corresponding geotextile tubes begin to move inside the dam before the dam reaches the failure limit and begin to crack at the end of the load cycle. The observation reveals that the tailings in the dam vibrates and compacts with a remarkable vertical settlement to reach a maximum as high as 60 mm. The model is subsequently detached from the sponge mat of the model box with a maximum separation width of 70 mm, where liquefaction takes place as indicated by a small amount of water exudation. The cracks continue to extend to run through the overall dam structure to reach the top of the dam. Eventually, the maximum crack width reaches 22 mm as shown in Figure 8(c).

As the vibration continues, the amount of water exuded and the area of liquefaction increase as shown in Figure 8(d). The entire dam slides outwards with the

upper geotextile tubes tilting upward under the vibration. Variable displacements at different locations are observed. The horizontal displacement of geotextile tubes in the middle of the dam is larger comparing to those at the top and bottom, resulting in an overall central convex deformation pattern.

At the end of the load step, the liquefaction area extends to the entire top surface of the dam as the upper tailings of the dam are in a mortar state as shown in Figure 8(e). The geotextile tubes slide off from each other and the conspicuous convexity of the central geotextile is observed, as seen in Figure 8(f). In addition, the upper geotextile tubes are lifted upwards as shown in Figure 8(g). From Figure 8(h), the entire dam slides outwards to the edge of the model box without collapse of the dam body.

3.2 Discussions on results

The shaking table model tests demonstrate that, subject to earthquake, the tailings dam constructed with geotextile tubes can develop cracks and liquefy with geotextile tubes sliding off from each other. As the load step approaches to the end, the dam slides forwards as a whole to the edge of the model box without collapse. Major observations from the tests are as follows.

- (1) Due to the supporting effect by the geotextile tubes on the slope surface, cracks are observed on the top of the dam only. The geotextile tubes effectively prevent the cracks from spreading to run through form sliding plane. At end of the test, the dam slides forwards as a whole without collapse, suggesting that the geotextile tubes can effectively improve the stability of the dam.
- (2) At present, the prevailing seismic reinforcement measures for tailings dams can be summarized as follows:
 - (a) Reduce the penetration line, such as setting vertical drainage wells, horizontal drainage layers, and vertical and horizontal combined drainage measures, etc.;
 - (b) Reinforce the structure of the tailings dam, for example, building anti-slide piles at the foot of the tailings dam and reinforcing the dam body;
 - (c) Compact the tailings dam, such as adding a secondary compaction;
 - (d) Other methods, such as the gravel pile method, improve the construction technology of the dam, and a comprehension of the aforementioned methods have also been applied.

Figure 8: Failure process of tailings dam: (a) tailings dam model before testing; (b) cracks appears on top of the dam; (c) test model separates from model box with increasing crack width and small amount of water exudate; (d) increasing amount of water exudate and area of liquefaction; (e) liquefaction area covers entire top surface of dam; (f) geotextile tubes slide off from each other with conspicuous convexity of central geotextile tubes; (g) exterior of upper geotextile tubes lifts upwards; and (h) entire model slides toward edge of model box.

In light of the aforementioned reinforcing methods, according to the failure mode and liquefaction from the current tests, two reinforcement schemes are proposed:

(1) Strengthening drainage

In order to control the impact of seismic liquefaction on the stability of the tailings dam, additional

drainage measures, such as setting up sufficient vertical drainage wells and horizontal drainage channels in the reservoir area, should be engaged. Drainage pipes and other drainage instruments in the geotextile tubes can be installed to improve the permeability of the dam, and thus, reduce the saturation line.

(2) Setting up anti-slide piles

The current shaking table test reveals that the dam tends to displace forward as a whole. Some anti-sliding piles can be deployed at the bottom of the geotextile tubes to reduce the slippage of the tailings dam.

More researches are desired to examine the reinforcement effect and the dynamic behaviors of the reinforced structure in the future.

4 Analyses of test results

4.1 Acceleration response of dam

4.1.1 Acceleration at top of dam

4.1.1.1 Acceleration time-history

The acceleration time-histories at J11, J12, and JY4 with respect to HPGA of 0.6 g are shown in Figure 9.

From Figure 9, acceleration time-histories at J11, J12, and JY4 demonstrate similar trends despite different acceleration peaks subject to similar HPGA input. The magnitude for the peak acceleration response depends highly on the specific position in view of that the measurement at JY4 is much smaller than those at J11 and J12.

4.1.1.2 Acceleration amplification factor A_m

The acceleration amplification factor A_m is defined as the ratio of the maximum acceleration of each measurement point to the input peak acceleration of the shaking table surface. Figure 10 shows the A_m at J11, J12, and JY4 subject to different HPGAs.

A_m at J11 and J12 demonstrates an approximately W-pattern with increasing HPGA. The failure process can be divided into four stages:

- (1) In stage one, the deformation of the whole dam is relatively small and the cracks begin to appear.

Figure 9: Acceleration time-histories of dam crest subject to HPGA = 0.6 g: (a) at J11; (b) at J12; and (c) at JY4.

Figure 10: Amplification factor A_m at J11, J12, and JY4 against different HPGA.

At $HPGA = 0.1$ g, A_m at J11 and J12 is similar to be 1.313, which is the highest value of A_m in the overall test, which is considered attributed to the high stiffness to refrain substantial horizontal displacement of the dam. Due to the micro-cracks inside the dam incurred by the vibration, A_m then slightly decreases with an increase of HPGA until HPGA reaches 0.3 g. The evolution patterns at J11 and J12 basically coincide, indicating that the accelerations at J11 and J12 at this stage are basically similar to indicate a stable and integral stage of the dam body.

- (2) Stage two is registered as that the cracks are pushed to close by vibration, and the dam body enters into the initial failure stage.

When $HPGA = 0.6$ g, the dam body is vibrated to compact. A_m at J11 and J12 increases to 1.135 and 0.940, respectively, when the dam body enters the ultimate failure state. The large difference between A_m at J11 and J12 indicates internal segregation of the failing dam body.

- (3) During stage three, the cracks develop rapidly and the dam collapses.

As the HPGA increases, the dam begins to fail along with the drastic decrease of A_m . When HPGA reaches 1.0 g, A_m at J11 and J12 are 0.517 and 0.459, respectively. The maximum horizontal displacement of the dam, D_m , is 112 mm. The total height H_t of the dam is 800 mm. According to the failure assessment criterion, $D_m/H_t = 14\% > 10\%$, the dam body is considered to be damaged.

- (4) During stage four, the tailings are compacted again under the vibration.

After the failure of the dam, the tailings are compacted again under the vibration, A_m increases again gradually.

Generally, J11 and J12 exhibit larger A_m than JY4 regardless of different HPGA inputs. The HPGA has little effect on the measurement at JY4 due to that the bottom of the bag body slips at the beginning of the vibration. Since the vibration is influenced solely by the friction between the tubes, whereas the friction coefficient is a fixed value, A_m at JY4 remains unchanged throughout the test.

The peak accelerations of the dam crest at J11 and J12 against different HPGA inputs are shown in Figure 11. The curve by Idriss [57] for ground surface response acceleration against bedrock input acceleration is also presented in the plot as reference, which is based on post-earthquake studies of the 1985 Mexico City and 1989 Loma Preta earthquakes. From Figure 11, the three acceleration response curves demonstrate similar trends. In the initial stage of vibration, the peak acceleration of the dam crest is above the 45-degree oblique line with an amplified acceleration. As the vibration increases, the peak acceleration of the dam crest decreases below the 45-degree line with non-amplified acceleration.

4.1.2 Internal acceleration in the same layer

Figure 12 displays A_m evolutions against the HPGA at different elevations, indicating a similar response trend of A_m to those at J11 and J12 as shown in the Figure 10. Similarly, the failure process experiences four stages, which confirm the above-mentioned initiation and evolution of the dam failure. In other words, when the accelerations at two different positions on the same layer begin to differ and the difference accumulates continually, it indicates that the dam body begins to fail.

4.1.3 Acceleration of dam slope

Figures 13 and 14 show that A_m at JY1, JY2, JY3, and JY4 exhibits minimal changes with the increasing HPGA. It can be interpreted as that the acceleration response of geotextile tubes on the slope surface is governed by the friction between geotextile tubes. At the beginning of the vibration, sliding displacement occurs between the bottom of the geotextile tubes and the model box. With

Figure 11: Curves of peak acceleration at J11 and J12 of dam crest vs variable HPGA.

the intensified vibration, an interlayer slip takes place between the geotextile tubes. Therefore, the vibration intensity of the geotextile tubes is determined exclusively by the friction between the geotextile tubes.

4.1.4 Internal acceleration of dam

Figures 15–18 show distributions of A_m at different measurement points along vertical elevations.

From Figure 15, A_m has an alternative decrease-increase-decrease trend (W-pattern) with the increasing dam height. The highest A_m of all measurements is incurred by input of HPGA of 0.6 g.

Figure 16 shows W-pattern of evolution A_m with increasing HPGA. When HPGA is less than 0.6 g, A_m at the dam crest J11 exhibits the maximum value. On the other hand, when HPGA is greater than 0.6 g, A_m at J5 yields the maximum value instead. Thus, the maximum A_m does not necessarily appear at the dam crest.

Figure 17 depicts the W-pattern evolution of A_m with the increasing elevation, which conforms to the overall structural deformation pattern. The value of A_m is different from that in Figure 16, indicating that A_m is variable with respect to different locations.

As shown in Figure 18, no substantial increase of A_m is incurred until HPGA reaches 0.6 g. A_m at J4, J8, J10, and J12 reaches their respective maximum at HPGA of 0.6 g before decreases with the further increase of HPGA. Maximum A_m is often observed at the crest along the vertical elevation when HPGA is relatively small. However, as the HPGA increases, the maximum A_m tends to shift from one location to another instead of fixing at a specific one.

(a)

(b)

(c)

Figure 12: Amplification factor A_m at similar elevations against variable HPGA: (a) elevation of 25 cm; (b) elevation of 55 cm; and (c) elevation of 70 cm.

Figure 13: Amplification factor A_m at JY1, JY2, JY3, and JY4 against variable elevation.

Figure 16: Amplification factor A_m at J1, J3, J5, J7, J9, and J11 vs variable HPGA.

Figure 14: Amplification factor A_m at JY1, JY2, JY3, and JY4 against variable HPGA.

Figure 17: Amplification factor A_m at J2, J4, J8, J10, and J12 against variable elevation.

Figure 15: Amplification factor A_m at J1, J3, J5, J7, J9, and J11 against variable elevation.

Figure 18: Amplification factor A_m at J2, J4, J8, J10, and J12 vs variable HPGA.

4.2 Responses of dam

Figure 19 shows the vertical displacement time-histories of the geotextile tubes at various elevations. From Figure 19, the vertical displacement increases with increasing elevation, suggesting that the vertical displacement at the dam crest is the largest. The vertical displacement at the bottom of side A (elevation below 50 cm) exhibits minimal change as the HPGA increases. The vertical displacement increases with the increase of HPGA at elevation higher than 50 cm. When HPGA is 1.3 and 1.5 g, the displacements are negative at the elevations of 25 and 40 cm, indicating an upward displacement and tilt occur in the geotextile tubes during the late stage of the test. This trend is consistent with the observations as shown in Figure 8(g).

Figure 19: Vertical displacement of geotextile tubes against variable elevation: (a) side A and (b) side B.

Figure 20 depicts the horizontal displacement time-histories of the geotextile tubes at variable elevations.

From Figure 20, the horizontal displacements exhibit minimal changes with the increase of the elevation before HPGA reaches 0.6 g. With further increase of HPGA, the horizontal displacements increase steeply in the middle section of the dam at the elevations of 25, 40, and 50 cm, especially when HPGA is 1.3 and 1.5 g. This trend indicates that the geotextile tubes have the maximum horizontal displacement in the middle of the slope and protrudes outwards, which is consistent with the findings as shown in Figure 8(f).

5 Discussions

- (1) The tailings dam with geotextile tubes is a flexible structure with high deformation modulus, tensile strength,

Figure 20: Horizontal displacement of geotextile tubes along elevation: (a) side A and (b) side B.

and damping, thus high capacity to consume seismic energy. It is because when the tailing dam fails, the dam tends to slide forward as a whole while maintaining overall stability and seismic performance.

- (2) The tailings dam in this study is composed of geotextile tubes and tailings. According to the construction manner and characteristics of potential forces, the tailings dam can be considered as one special type of retaining wall with the geotextile tubes acting as the panel of the retaining wall. The ratio of the horizontal displacement to the height of the dam is used to evaluate the stability of retaining walls in this study. More efforts beyond the current research are desirable to identify more relevant evaluation criteria for this type of tailings dam.
- (3) The stability of soils is susceptible to a variety of deteriorating factors. In this study, the small test dam is inlaid with dozens of cables to connect sensors. The cables themselves can serve as reinforcement to enhance the stability of the dam against seismic loadings. The reinforcing effect of the cable may be considered equivalent to that of the geotextile tubes with greater friction to construct the tailings dam.

6 Conclusion

The shaking table tests with different horizontal peak ground accelerations (HPGA) are performed on the model tailings dam constructed with geotextile tubes at a slope ratio of 1:1 and a full-slope height of 800 mm. Test results and a comparative analyses suggest that the test model box serves the purpose well for investigating the dynamic characteristics of tailings dam constructed with geotextile tubes subject to earthquake loads. The present study sheds light on the dynamic behavior of the tailings dam constructed with geotextile tubes to provide references to the seismic design of tailing dams constructed with geotextile tubes.

Based on the test results, the following conclusions are drawn:

- (1) Though the tailings dam constructed with geotextile tubes develop cracks and liquefy under the earthquake, as the geotextile tubes slides off from each other, the dam slides forwards as a whole without collapse. Accordingly, two reinforcement schemes of strengthening drainage and setting up anti-slide piles are proposed for this type of dam.
- (2) The acceleration amplification coefficient at specific elevation of the dam exhibits a W-pattern with increasing HPGA. When the internal vibrations at different locations

become inconsistent, the dam body is considered to begin failing. When the ratio of the maximum horizontal displacement $D_{\max}$ to the total height of the dam H_t , i.e., $D_{\max}/H_t$ exceeds 0.1, the dam is rated as a failure.

- (3) The acceleration amplification coefficient on the side of the geotextile tubes demonstrates minimal changes since the bottom of the tubes structure slips at the beginning of the vibration due to fixed friction coefficient.
- (4) The acceleration amplification factors inside the dam are both elevation and position-dependent, and the maximum value does not necessarily appear at the dam crest.
- (5) The vertical displacement at the dam crest of the geotextile tubes registers the maximum of the overall dam, while the highest negative vertical displacement occurs at middle section of the dam, indicating that one side of the geotextile tubes tilts upwards. The largest horizontal displacement is spotted at the middle section of the geotextile tubes, indicating a convex deformation pattern of the dam.

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