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Dynamic centrifuge modelling of concrete-faced rock-fill dams subjected to earthquakes

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ABSTRACT: In this study, a series of dynamic centrifuge tests were carried out in the IWHR centrifuge horizontal-vertical shaker to examine the seismic behavior of concrete-faced rock-fill dams (CFRDs) with empty reservoir. The experimental results demonstrate the acceleration amplification behavior both in the rock-fill and along the face slab. The results also suggest that the crest settlement induced by earthquakes is not only influenced by the magnitude of the bedrock acceleration, but also highly determined by the seismic loading history of the CFRD. As for the failure mode of dams, only slight surface sliding may occur near crest as peak bedrock acceleration reaches about 0.36g. In order to examine the variation in the rock-fill dynamic properties, the average shear wave velocity in the rock-fill is determined using the recorded acceleration-time histories. A 50% ~ 60% decrease in the average velocity is observed as the peak bedrock acceleration increases from 0.23g to 0.36g during the initial three tests. However, there is an increase in the average velocity as the peak bedrock acceleration increases from 0.28g to 0.31g during the last two tests. This reflects that the velocity or stiffness in the rock-fill is affected not only by the magnitude of the bedrock acceleration but also by the seismic loading history.

Keywords: CFRD; Dynamic centrifuge tests; Seismic deformation; Shear wave velocity

1 INTRODUCTION

The concrete-faced rock-fill dam (CFRD) has been widely used all over the world thanks to its advantages including complete usage of local embankment materials, simple detailing and construction, short construction period and cost-effectiveness (Cooke & Sherard 1987; Sherard & Cooke 1987; Xing et al. 2006; Seo et al. 2009; Seiphoori et al. 2011). Recent CFRDs include 233 m-high Shuibuya Dam in China, 209 m-high La Yesca in Mexico, 196 m-high Karahnjukar Dam in Iceland and 202 m-high Campos Novos Dam in Brazil. In China, there are more than 170 CFRDs with a height larger than 30 m, 40% of which have a reservoir capacity larger than 100 million m^3, and a large number of high CFRDs are under construction or planned to be built (Yang et al. 2011; Seo et al. 2009; Xu 2010).

It is usually believed that the CFRDs are inherently more resistant to earthquake loading compared with earth-core rock-fill dams due to that severe pore-water pressure build-up and soil strength reduction can hardly occur during earthquake shaking (Sherard & Cooke 1987; Seo et al. 2009; Seiphoori et al. 2011). However, considering that increasing number of CFRDs with high amount of reservoir water and large population in the downstream area are built in high seismic areas, e.g., south-west and north-west China, it is extremely important to guarantee the seismic safety of CFRDs. During Wenchuan earthquake measured 8.0 on the Richter scale in Sichuan Province, China on May 12, 2008, the Zipingpu CFRD experienced obvious damages including crest subsidence, severe horizontal displacement at crest, cracking between downstream slope and dam crest road pavement, crushed damage to the face joints and distortion of steel bars of construction joints in the face slab based on field investigations (Chen et al. 2008; Guan 2009 and Chen & Han 2009). This further aroused public concerns and the attention of geotechnical engineers and scholars in China to the seismic behavior of CFRDs.

This paper aims to examine the seismic behavior of CFRDs, in terms of the acceleration amplification, dam deformation and variations in the dynamic properties of the rock-fills. In order to achieve this, a series of dynamic centrifuge tests were performed using IWHR (China institute of water resources and hydropower research) horizontal-vertical centrifuge shaker. The experimental details are firstly introduced, followed by results and discussions. At last, some conclusions are drawn.

2 EXPERIMENTAL DETAILS

2.1 IWHR centrifuge and horizontal-vertical shaker

The IWHR beam centrifuge has a capacity of 450 g-ton, a radius of 5.03 m, a maximum centrifugal acceleration of 300g and a maximum payload mass of 1.5 ton. As shown in Figure 1, the centrifuge is equipped with a horizontal-vertical centrifuge shaker, which is designed to operate at 100g centrifugal acceleration with a payload mass up to 440 kg. The shaker can simultaneously simulate horizontal and vertical bedrock motions with peak accelerations up to 30g and 20g in the model scale, respectively. The model frequency of input motions is in the range of 10 ~ 400 Hz, and the maximum duration of a shock is 3 s in the model scale. For more details of the centrifuge shaker, please refer to Hou et al. (2014).

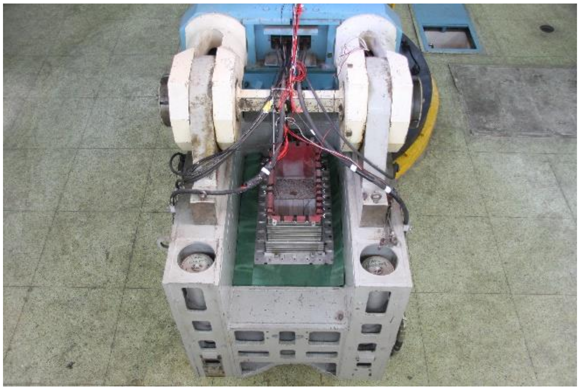


Figure 1. Picture of the IWHR horizontal-vertical centrifuge shaker

Table 1. Summary of the dynamic centrifuge tests carried out in this study

Test No.	**Centrifugal acceleration (g)**	**H_{m0} (mm)**	**a_h (g)**
T1-0.23g	40	210	0.23
T2-0.26g	40	210	0.26
T3-0.36g	40	210	0.36
T4-0.24g	40	210	0.24
T5-0.28g	40	210	0.28

Note: H_{m0} is the height of the dam model and a_h is the prototype peak bedrock acceleration.

2.2 Test series and model design

As shown in Table 1, five dynamic centrifuge tests denoted as T1-0.23g, T2-0.26g, T3-0.36g, T4-0.24g and T5-0.28g were carried out in this study. In all the tests, the CFRD models were subjected to horizontal bedrock motions with different peak values of acceleration but the same waveform as presented in Figure 2, which was a seismic wave recommended by Chinese code (National Energy Administration 2015). PGA increased from 0.23g to 0.36g in the initial three tests (i.e., the first group), and then smaller PGAs 0.24g and 0.28g were used in the last two tests (i.e., the second group). Comparison between the experimental results from the two groups are used to examine the effect of pre-shaking by the relatively strong earthquake in G1-T3-0.36g. Note that the first and second numbers in the denotation of each test respectively represent the excitation sequence number and the peak bedrock acceleration a_h in prototype scale.

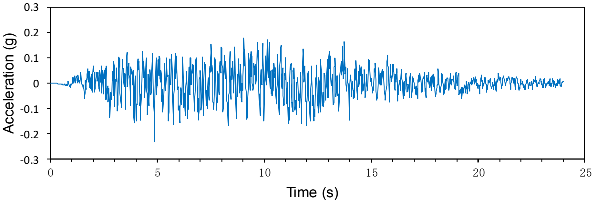


Figure 2. The waveform of the input motion in prototype scale.

Figures 3 and 4 give the picture and schematic drawing of the layout of the test model and instrumentation. The upstream and downstream slopes of the dam model respectively were 1:1.6 and 1:1.8. With a model height (H_{m0}) of 210 mm, the dam model simulates a CFRD with a prototype height (H_0) of 8.4 m at a centrifugal acceleration of 40g. The rock-fill material was prepared by sieving that collected from a dam construction site in China by 10 mm sieve, and the mass fraction of particles finer than 5 mm is 23%. To minimize the friction between the dam model and the side walls of the container, the side walls were firstly covered with petrolatum, and then the rock-fill material was compacted to a density of 1, 990 kg/m^3, which is close to the value used in real project. After that, a cushion layer with a thickness about 5 mm was prepared along the upstream slope using fine sand, followed by the installation of the face slab consisted of 4 cement sheets. Note that each of which has a length of 33 cm, a width of 5 cm, a thickness of 5 mm and a height of 17.3 cm in model scale. The prototype height of the face slab (L_0) is 6.9 m at a centrifugal acceleration of 40g. The elastic modulus was 27.3 GPa, which was close to the general values used at practice in China.

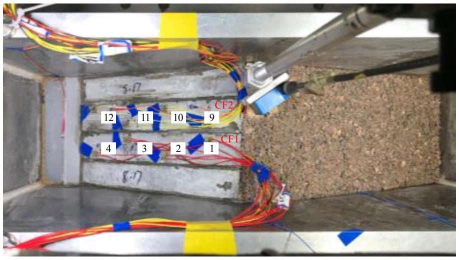


Figure 3. Picture of the centrifuge model

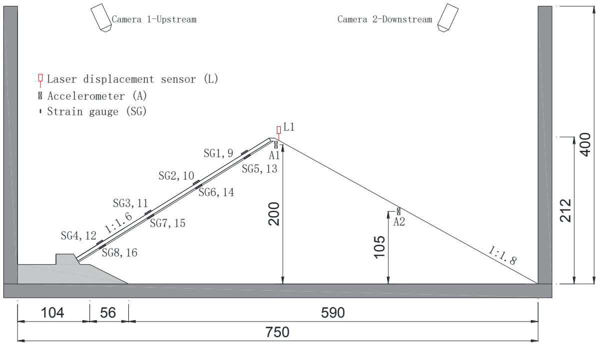


Figure 4. Schematic drawing of the layout of the centrifuge model and instruments

As to the instrumentation, two accelerometers (Model 352A24, PCB Piezotronics, Inc., USA) denoted as A1 and A2 were installed at different heights of the rock-fill to monitor the variation in the horizontal acceleration. The other two accelerometers (Model 3225F5T, Dytran Instruments, Inc., USA), i.e., A3 and A4, were mounted on the outer face of the slab to measure the acceleration normal to the slab. As shown in Figure 3, the heights of the accelerometers from A1 to A4 were $0.95H_{m0}$, $0.5H_{m0}$, $0.80H_{m0}$ and $0.39H_{m0}$. In addition, a laser displacement sensor denoted as L1 was installed at crest to measure the settlement. Moreover, as shown in Figures 3 and 4, the outer and inner faces of the cement sheet CF1 were instrumented with the strain gauges SG-1 to SG-4 and those from SG-5 to SG-8, respectively. The four pairs of strains, i.e., SG-1 & 5, SG-2 & 6, SG-3 & 7 and SG-4 & 8, were used to measure the strain in the face slab at four heights of $0.90H_{m0}$, $0.69H_{m0}$, $0.49H_{m0}$ and $0.28H_{m0}$. The other cement sheet CF2 was instrumented with the strain gauges from SG-9 to SG-16 in a similar way.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental results from the dynamic centrifuge tests are presented and discussed in the following. Note that prototype values are used unless otherwise specified.

3.1 Acceleration distribution and amplification

Figure 5 presents the recorded horizontal acceleration at different heights along the downstream slope and the acceleration of the face slab in the test T1-0.23g. Note that the recorded horizontal bedrock acceleration is also indicated in the figure. In order to present the acceleration distribution in the rockfill and that in the face slab, the peak acceleration values along the downstream slope are normalized by the horizontal peak bedrock acceleration a_h and the peak values of the face slab are normalized by the value measured at the lower height by A4. Figure 6 gives the normalized values or the amplification factors at different locations in all the five tests. The horizontal acceleration in the rock-fill at higher locations is larger than that at lower locations for the tests in both groups, reflecting an acceleration distribution similar to that observed in Cheng & Zhang (2011, 2012). The amplification factor at crest and that at the middle of the slope are in the ranges of 2.02 ~ 2.31 and 1.40 ~ 1.62, respectively. Similer to the amplification behavior in the rock-fill, the acceleration of the face slab also increases with height.

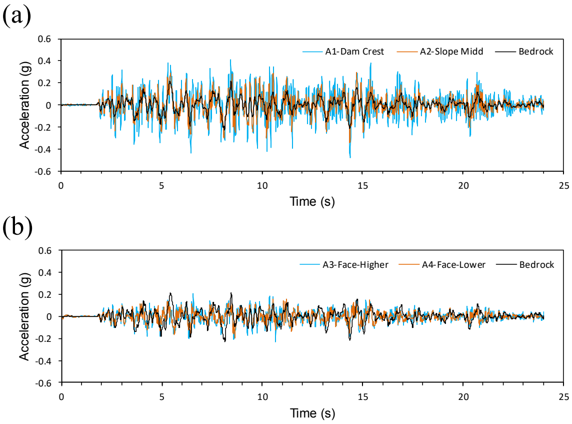


Figure 5. Acceleration records at different heights (a) along the downstream slope and (b) on the face slab for the test T1-0.23g.

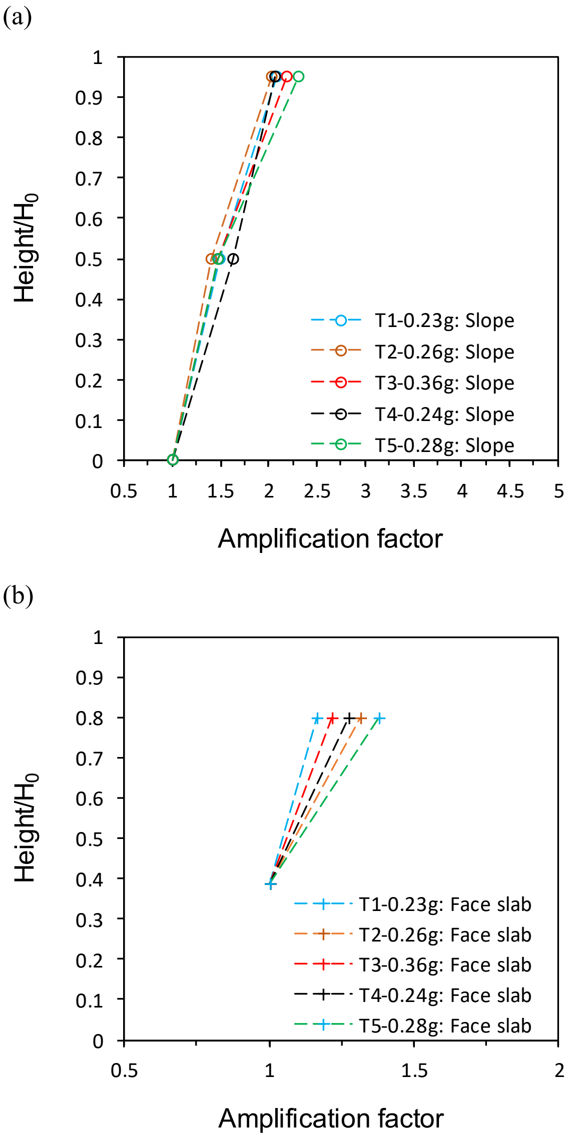


Figure 6. Distribution of the amplification factor of the rock-fill acceleration (a) along the downstream slope and that of (b) the normalized face slab acceleration.

3.2 Dam deformation

The settlement after the stabilization period following the spin-up of centrifuge was smaller than 0.01% of the dam height, reflecting minor static deformation. Figure 7 shows the variation of the crest settlement due to shaking, $\Delta s/H_0$, with the bedrock acceleration a_h. For the tests in the first group, the settlement increases from 0.04% to 0.14% as a_h increases from 0.23g to 0.36g. The same increasing trend is also observed for the tests in the second group. However, the settlement $\Delta s/H_0$ in the second group is much smaller than that in the first group. This indicates that the CFRD which have experienced the a relatively large earthquake during T3-0.36g exhibits smaller settlements during the follwing earthquakes, which is similar to the response observed in the dynamic centrifuge tests by Wang & Zhang (2003) as discussed in the introduction part. The result is also consistent with the behavior in Zipingpu CFRD after Wenchuan earthquake as indicated by the field investigation results in Chen et al. (2008).

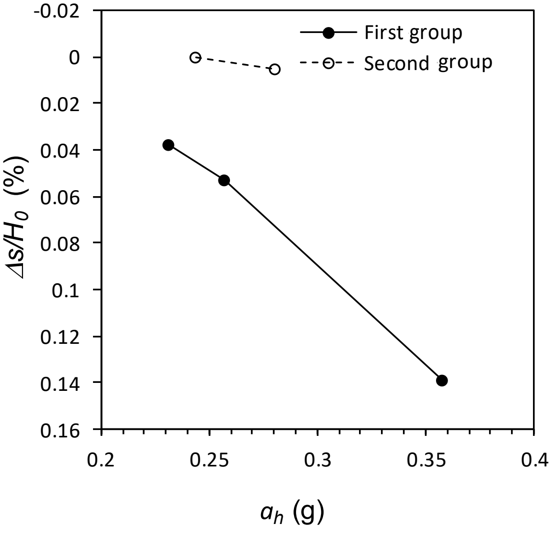


Figure 7. Normalized crest settlements ($\Delta s/H_0$) induced by earthquakes.

As for the movement along the downstream slope, Figures 8a and 8b give the pictures of the downstream slopes before and after T3-0.36g. A slight surface sliding can be visually observed near dam crest, while no sliding has been observed in other tests.

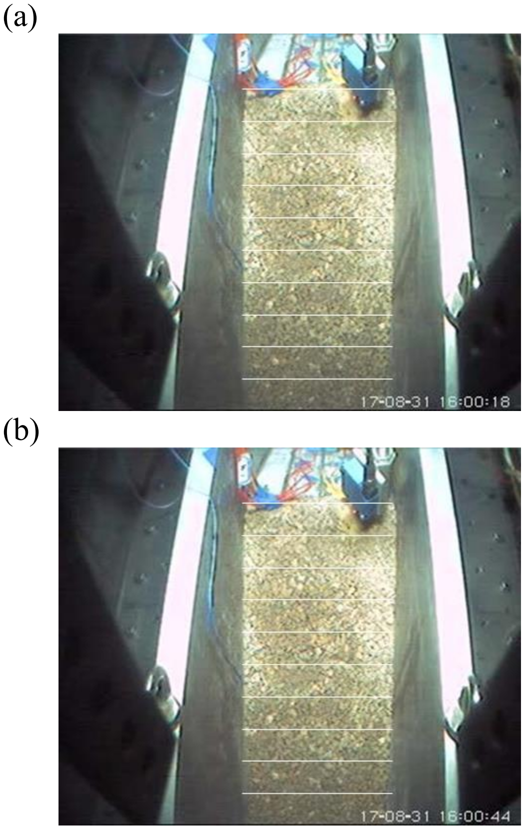
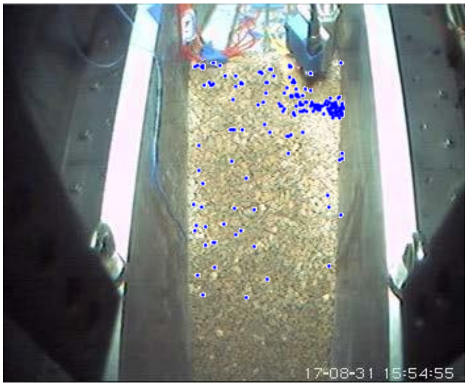


Figure 8. Pictures of the downstream slope taken (a) before and (b) after shaking in T3-0.36g.

In order to demonstrate the sliding locations more clearly, the values of the RGB triplet of each pixel of the picture containing 352 x 288 pixels are obtained. A relatively large difference in the RGB values in the same pixel before and after test reflects the sliding of the material represented by the specific pixel. The difference between the red component values of each pixel in Figures 8a and 8b is firstly calculated, and then the pixels with a difference larger than 20% of the mean value of the red component values in Figure 8a are selected. These pixels are shown using blue dots in Figure 9c. Following the same procedure, the locations of the sliding material during the other four tests are obtained and shown in Figure 9. The figure indicates that slight surface sliding occurs near dam crest at 0.36g while minor surface sliding occurs at smaller bedrock acceleration. Note that similar results can be obtained if another component, i.e., green or blue, is used.

(a)



(b)

(c)

(d)

(e)

Figure 9. Locations of the rock-fill with a relatively large movement shown by the blue dots: (a) T1-0.23g; (b) T2-0.26g; (c) T3-0.36g; (d) T4-0.24g; and (e) T5-0.28g.

3.3 Variation of V_s

The travel time from base to each location of accelerometers can be determined using the cross-correlation method with recorded acceleration-time histories of the bedrock and the specific accelerometer, and then the average shear wave velocity (V_s) along the travel path can be determined. Figure 10 gives the average V_s from base to dam crest and that from base to the middle of downstream slope. As the bedrock acceleration a_h increases from 0.23g to 0.36g by three stages in the first group, the average velocities in the two travel paths decrease by about 60%. The same trend is also observed in the second group. This is caused by the fact that larger shear strain occurs in a relatively stronger earthquake, leading to smaller shear modulus and shear wave velocity. The figure also demonstrates that smaller values of the average V_s are observed in the second group at the same bedrock acceleration, reflecting the pre-shaking effect on V_s.

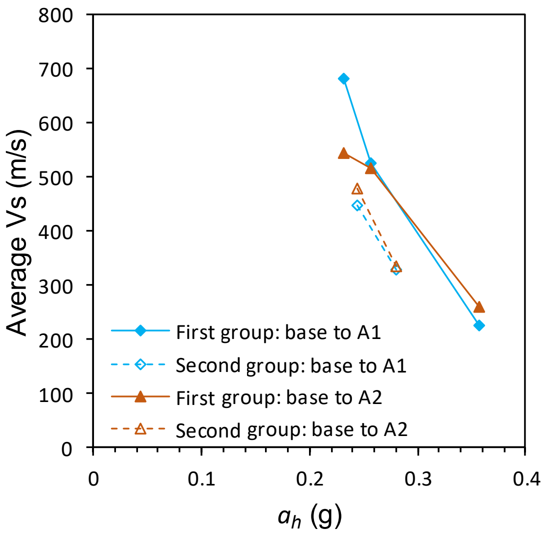


Figure 10. Average velocities in the wave travel paths from base to dam crest (A1) and that from base to the middle of downstream slope (A2).

4 CONCLUSIONS

In this study, the seismic behavior of CFRDs subjected to earthquakes is examined using a series of dynamic centrifuge tests conducted at the IWHR centrifuge horizontal-vertical shaker. The salient findings are summarized in the following.

As for the acceleration distribution mode during earthquakes, the peak acceleration of the rock-fill increases with height along the downstream slope, and the peak acceleration of the face slab also increases with height. In addition, the seismic loading history has minor influence on such an acceleration distribution mode. The amplification factor at crest and that at the middle of the slope are in the ranges of 2.02 ~ 2.31 and 1.40 ~ 1.62 at bedrock acceleration 0.23 ~ 0.36g, respectively.

The crest settlement due to shaking is influenced by the bedrock acceleration and is sensitive to the seismic loading history. For a CFRD subjected of a series of shocks with the associated peak bedrock acceleration increasing from 0.23g to 0.36g, the crest settlement due to shaking increases from 0.04% to 0.14%. However, the CFRD which have experienced the relatively strong shock with a peak acceleration of 0.36g exhibits smaller settlements during the following shocks. As for the movement of rock-fill along the downstream slope, a slight surface sliding occurs near crest as the CFRD is subjected to relatively strong earthquakes with peak bedrock acceleration larger than ~0.36g.

The rock-fill stiffness in terms of shear modulus or shear wave velocity during an earthquake is affected by peak bedrock acceleration and the seismic loading history. As the peak bedrock acceleration a_h increases from 0.23g to 0.36g by three stages, the average velocities in the two travel paths in the rock-fill zone decrease by about 60%. This is caused by the fact that larger shear strain occurs in a relatively stronger earthquake, leading to smaller shear modulus and shear wave velocity.

5 ACKNOWLEDGEMENTS

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