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Seismic performance of earth-core and concrete-faced rock-fill dams by large-scale shaking table tests

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ABSTRACT

Two of China's highest earth-core rock-fill dams (ECRDs) and concrete-faced rock-fill dams (CFRDs) were simulated by large-scale earthquake simulation shaking table tests in this work. A series of staged tests were performed, including white noise, different types of earthquake excitations with different magnitudes etc. The seismic performance of the ECRD and CFRD models were analyzed and investigated. The test results indicated that reservoir impoundment influenced the structure and seismic characteristics of the ECRD model much more than the CFRD model. The average fundamental frequency of the CFRD decreased less than the ECRD model when subjected to strong excitation. The acceleration amplification factors decreased as the input peak acceleration increased. The maximum acceleration occurred at the top of the ECRD model, while it occurred at 0.6–0.9 dam height of the CFRD model. Seismic residual deformations of the two models were very small. When subjected to strong earthquake excitation, the residual deformation of the CFRD model was smaller than that of the ECRD model. The dominant failure pattern of the two models was shallow sliding at the height of 3/4 on the downstream slope. The above analysis indicated that seismic performance of CFRD was superior to ECRD.

1. Introduction

In recent years, a large number of earth-core rock-fill dams (ECRDs) and concrete-faced rock-fill dams (CFRDs) have been constructed and put into operation in different parts of the world. For instance, Western China, despite of rich hydropower resources, is an undeveloped area with poor transportation, complex topographical and geological conditions, even often with deep overburden. ECRDs and CFRDs become priorities due to their good adaptability to topography and geology, low cost of local materials, simple and not time consuming construction process etc. Dam height in China is ever increasing. Some dams are designed over 200, and even 300 m, such as Shuangjiangkou ECRD (314 m), which will become the world's highest ECRD, as well as Lianghekou ECRD (295 m), Nuozadu CFRD (261.5 m), Houziyan CFRD (223.5 m) etc. Unfortunately, most of these high dams are located in earthquake-prone areas. To construct super-high earth and rock-fill dams in these areas, hardly any precedent is available in the world. Besides, these reservoirs are always the core ones of the cascade reservoirs, so they may cause great threat to public safety in the case of an earthquake.

ECRD and CFRD are different in materials and zoning. ECRD makes use of low permeable clayey core for waterproofing, whereas CFRD uses reinforced concrete face slab on upstream slope [1]. Different materials and zoning make different seismic responses and failure process in the earthquake, which are very important for dam safety. Based on a few case studies, some researchers believe that due to the high shear strength of compacted rock-fill and the lack of pore water pressures, CFRD behaves better during earthquakes compared with ECRD [2–3]. However, this has not been fully testified yet. Most of the previous seismic behaviors studies of both the dam types have relied on theoretical and numerical analyses [3–9]. Due to the lack of systematic dynamic response records of high rock-fill dams subjected to strong earthquake, it is quite difficult to validate these dynamic approaches and numerical codes.

Moreover, two types of model tests are applicable in the study of seismic behaviors of the dams: centrifuge tests and shaking table tests. Kim et al. [1] investigated the seismic behaviors of ECRD and CFRD by dynamic centrifuge tests. Compared with shaking table tests, centrifuge tests are better in stress levels. However, the small model size makes similitude of soil grain size less satisfied [10]. As a result, large-scale shaking able tests are considered preferable for the present study, not only for the investigation of the seismic behaviors of dam models, but also for the validation of varied theoretical approaches and numerical codes commonly adopted in practice. Lin et al. [11] studied seismic

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slope behavior by large-scale shaking table model tests. Kong et al. [12] investigated the dynamic failure phenomena of homogeneous rock-fill dam and CFRD by shaking table tests, and discussed the effect of concrete slab on slope stability. Torisu et al. [10] probed into the seismic performance of both earth-core and a surface membrane fill dam models by shaking table model tests, and assessed the permanent displacements of the rock-fill dam. Liu et al.[13] calibrated a numerical model to estimate earthquake-induced deformations by small-scale shaking table tests. Nevertheless, in the previous model tests, the model sizes were still very small due to the restriction of the equipment, which may result in remarkable size effect and the distortion of the test results.

This work aims to explore and analyze the seismic behaviors and failure pattern of ECRD and CFRD by large-scale shaking table tests respectively, and make a comparison of the dynamic performance of the two dam types. The tests were carried out at the State Key Laboratory of Structure and Disaster Prevention in China Construction Science Research Institute. Two dam models were made to simulate Shuangjiangkou ECRD with a height of 314 m and Houziyan CFRD with a height of 223.5 m. A series of staged tests were performed on the dam models respectively. Based on the results of the tests, the fundamental frequency, the acceleration response, residual deformation and failure mechanism of the dam were analyzed.

2. Method of shaking table tests

2.1. Model preparation

The tests were performed by using 6-axis $6\times6\ m^2$ shaking table, which is the largest and most advanced earthquake simulation shaking table in China. The maximum capacity is up to 800 KN, with an operating frequency range of 0.1–50 Hz. The shaking table can simulate maximum horizontal ground acceleration of 1.5 g, and maximum vertical ground acceleration of 0.8 g.

In this study, two typical dam models of ECRD and CFRD were made. The prototype dams were Shuangjiangkou ECRD and Houziyan CFRD, which were both located at the upstream of the Dadu River in Sichuan province of western China. The maximum height of Shuangjiangkou ECRD is 314 m, the upstream dam slope is 1:2.0, with a 5 m wide berm, and the downstream dam slope is 1:1.9. The installed capacity is 2000 MW. While the maximum height of the Houziyan CFRD is 223.5 m, and the installed capacity is 1700 MW. The upstream dam slope is 1:1.4, and the downstream slope become gentler and gentler from bottom to top, changing gradually from 1:1.2 to 1:1.6. Besides, additional rock-fill zone was designed to protect the dam heel. The basic earthquake intensities of the two dam sites are 7 degree (in prototype scale). The Shuangjiangkou ECRD and Houziyan CFRD are typical high rock-fill dams in the same earthquake-prone area, so the dam models were made to stimulate these two dams.

The two dam models were designed following by the maximum dam height profiles of the prototypes, as shown in Fig. 1. The model boxes were made of 2 cm thick steel plates with reinforcement. The inner size of the two boxes was 5.0 m in length, 2.2 m in width, 1.2 m in height.

The core of the ECRD model was made of clay, and the upstream rock-fill zones were filled with sandstones, while the downstream rock-fill zones were filled with granite. The rock-fill zones of CFRD model were filled with limestone. The materials of the dam models were all collected from the prototype dam sites. However, because the maximum diameter of the prototype rock-fill was more than 400 mm, the gradation of the prototype rock-fill materials couldn't be used directly in the dam models. Therefore, reduced scale material simulation was adopted in the tests.

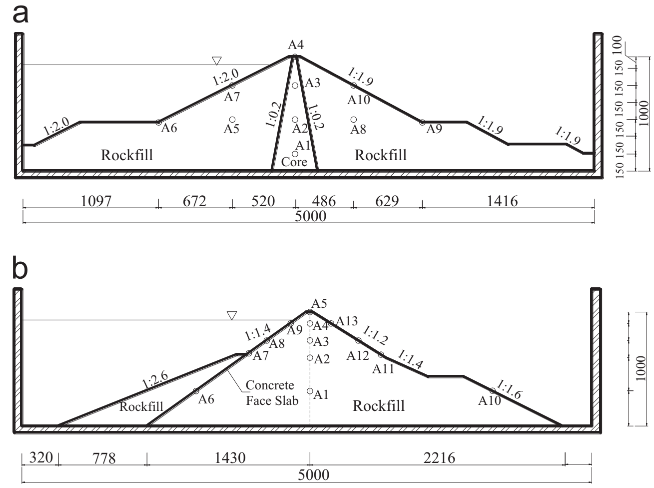

Fig. 1. Layouts of the dam models (mm), (a)ECRD model, and (b)CFRD model.

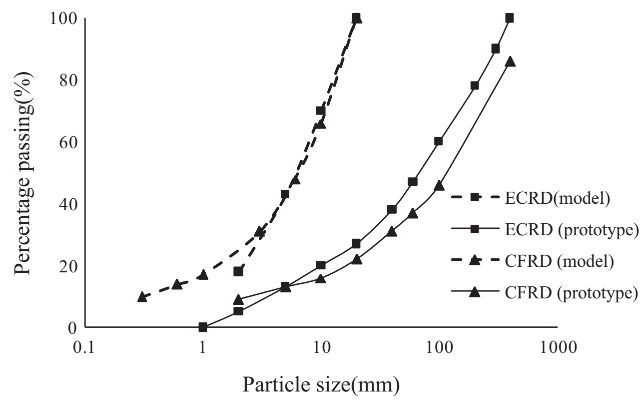

Fig. 2. Rock-fill particle size distribution curves of the prototype and model materials.

Table 1
Material properties of the models.

Properties	Dry density (g/cm^3)	Cohesion (kPa)	Friction angle (deg.)	*K*	*n*
ECRD upstream	2.13	0	46.0	1099	0.565
ECRD downstream	2.06	0	44.0	995	0.570
CFRD	2.07	41.0	38.2	710	0.426

The material gradations of the dam models were determined by similar particle distribution method, with the particle size no more than 20 mm. The rock-fill particle size distribution curves of the prototype and model materials are shown in Fig. 2, wherein the distribution curves of the two dam models were approximately parallel to those of the prototype materials. Table 1 gives the material properties of rock-fill model materials, where K and n were the parameters in the Eq.(1), and the values were measured when the confining pressures were 30 kPa.

$$\frac{G_0}{P_a} = K\left(\frac{\sigma'_0}{P_a}\right)^n \tag{1}$$

where G_0 is the shear modulus, P_a is the atmospheric pressure, and σ'_0 is the mean effective confining pressure.

As the dam models were constructed, 7 horizontal lines were marked in the model boxes and then dams were filled and compacted layer by layer. For the ECRD model, the core was filled