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Seismic responses of high concrete face rockfill dams: A case study

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Abstract

Seismic responses of the Zipingpu concrete face rockfill dam were analyzed using the finite element method. The dynamic behavior of rockfill materials was modeled with a viscoelastic model and an empirical permanent strain model. The relevant parameters were obtained either by back analysis using the field observations or by reference to parameters of similar rockfill materials. The acceleration responses of the dam, the distribution of earthquake-induced settlement, and the gap propagation under the concrete slabs caused by the settlement of the dam were analyzed and compared with site investigations or relevant studies. The mechanism of failure of horizontal construction joints was also analyzed based on numerical results and site observations. Numerical results show that the input accelerations were considerably amplified near the top of the dam, and the strong shaking resulted in considerable settlement of the rockfill materials, with a maximum value exceeding 90 cm at the crest. As a result of the settlement of rockfill materials, the third-stage concrete slabs were separated from the cushion layer. The rotation of the cantilever slabs about the contacting regions, under the combined action of gravity and seismic inertial forces, led to the failure of the construction joints and tensile cracks appeared above the construction joints. The effectiveness and limitations of the so-called equivalent linear method are also discussed.

Keywords: Concrete face rockfill dam (CFRD); Seismic response; Zipingpu; Permanent strain; Construction joint; Viscoelastic model; Finite element method

1. Introduction

A concrete face rockfill dam (CFRD) is a type of dam widely used in hydropower projects all around the world. Concrete slabs, supported and stabilized by the underlying rockfill materials, are connected with the toe plinth by the peripheral joints, so as to form an impermeable system. Due to the excellent adaptability of CFRDs to topographical and geological conditions and the significant economic advantage of using local materials, CFRDs have become quite a competitive alternative to concrete dams. The invention and application of the vibratory compaction method have further and advantageously enhanced the density and moduli of compacted rockfill materials and therefore successfully reduced the unfavorable deformation encountered in early hydraulic fill dams. As a result, the height of modern CFRDs has grown continuously from 100 m to 200 m over the past fifty years (ICOLD, 2010). The highest CFRD in the world to date is the 233-m Shuibuya Dam located in Hubei Province, China (Zhou et al., 2011). China is now planning to face the challenge of constructing CFRDs with a height near or over 300 m.

Unfortunately, China is located between the circum-Pacific seismic belt and the Mediterranean-Himalayan seismic belt, and it has been frequently struck by large earthquakes throughout history. Moreover, large amounts of high CFRDs built, under construction, and under design in China are located in regions of high seismic intensity (Chen, 2015). On May 12, 2008, an earthquake with a Richter magnitude of 8.0 hit Sichuan

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Province in western China, and the well-known Zipingpu CFRD (156 m), which is located about 17 km away from the epicenter, was severely damaged by the earthquake. Post-quake investigations at the dam site show that the dam settled considerably at the crest and some of the concrete slabs were dislocated along the horizontal construction joints due to the seismic excitation (Chen, 2015; Kong and Zou, 2014). Examination and measurement also indicate that the concrete slabs near the dam crest were separated from the cushion layer and the peripheral joints underwent an obvious displacement (Song and Cai, 2009). In addition, the strong earthquake resulted in many visible tensile cracks and compressive failure within the concrete slabs and the parapet walls (Chen, 2015).

Although the damage to the Zipingpu CFRD caused by the earthquake was severe, the dam survived the extremely strong earthquake and its functions were recovered after several months of rehabilitation. This rare case redemonstrated the high resistance of this type of dam to earthquakes and the feasibility of building high CFRDs in regions of high seismic intensity. Since the dam's rehabilitation, substantial attention has been paid to the seismic behavior of high dams, not only in order to deepen the understanding of their seismic behavior but also to improve the design and construction levels (Dakoulas, 2012; Feng et al., 2010; Kong et al., 2012a; Xiong et al., 2013; Zhong et al., 2013).

The objective of this study was to investigate the seismic behavior of the Zipingpu CFRD through numerical simulations on the basis of the equivalent linear method. Special emphasis was placed on the amplification coefficient of the base acceleration and the earthquake-induced settlement of the dam, as well as the gap propagation under the concrete slabs. The mechanism of failure of construction joints was also studied based on numerical analysis and field observations. Although the conclusions obtained from a single case study may not be generally applicable, the results presented in this paper may offer useful insight into the seismic behavior of similar projects.

2. Relevant information regarding Zipingpu CFRD

2.1. Dam materials and construction stages

The Zipingpu CFRD is located in Dujiangyan City, in Sichuan Province, China. The maximum height of the dam is 156 m and the length and width of the crest are 663.77 m and 12 m, respectively. Both the upstream and downstream slope ratios below an elevation of 840 m are 1:1.4 and the downstream slope ratio above this elevation is 1:1.5. Fig. 1 shows the material zones of the dam (separated by the solid lines) and the three stages of construction (separated by the dashed lines). Excluding the cushion layer (IIA) and the transition layer (IIIA), the dam can be partitioned mainly into three different zones: IIIB, IIIC, and IIID in Fig. 1. The mineral contents of rockfill, cushion, and transition materials are all limestone, but with different grain size distributions. The main rockfill (IIIB) and the secondary rockfill (IIIC) have the same origin and grain size distribution. However, the designed densities of both zones are slightly different: the IIIB zone and the IIIC zone were compacted to densities of 2.16 g/cm^3 and 2.15 g/cm^3, respectively.

As shown in Fig. 1, the dam materials were filled to an elevation of 810 m during the first construction stage, 850 m in the second stage, and 884 m in the third stage. In accordance with the construction processes of the dam, concrete slabs (C25) were also cast in three stages. After the filling of dam materials to the designed elevations for the first and second stages, the concrete slabs were cast to elevations several meters below the existing dam crest. After the completion of the third stage, they were cast to an elevation of 879.4 m in order to connect them to the parapet walls. Therefore, two layers of construction joints exist within the face slabs at elevations of 796 m and 845 m. These construction joints are horizontal, and they proved to be vulnerable to dislocation during the Wenchuan earthquake (Song and Cai, 2009).

2.2. Deformation monitoring system

Due to the significance of the Zipingpu CFRD, a total of 56 monitoring gauges were installed along four monitoring lines in the 0+251.00 m section and three monitoring lines in the 0+371.00 m section so as to track the deformation behavior of the dam. Fig. 2 shows the locations of the 34 monitoring instruments in the major monitoring section of 0+251.00 m. During the main shock and aftershocks of the Wenchuan earthquake, most of these monitoring gauges functioned effectively, and provided valuable data for the safety evaluation of the dam. Although the dam was designed to withstand an earthquake with a seismic intensity of 8.0, and the peak bedrock acceleration with an exceedance probability of 0.02 within

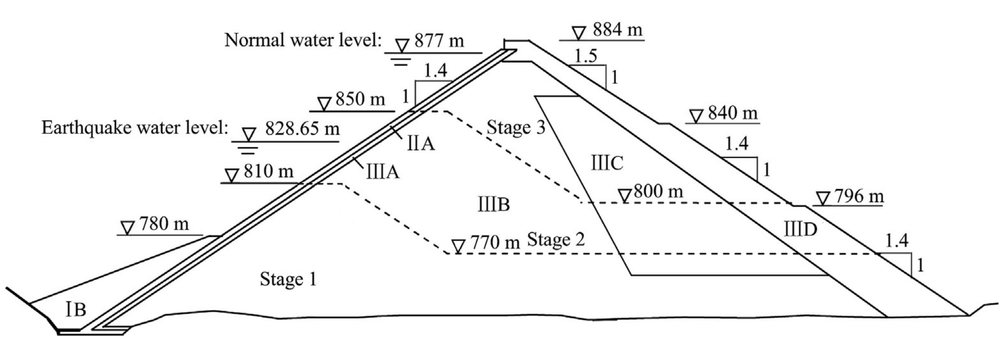

Fig. 1. Typical cross-section of Zipingpu CFRD (0+321.00 m).