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Geotechnical aspects and seismic damage of the 156-m-high Zipingpu concrete-faced rockfill dam following the Ms 8.0 Wenchuan earthquake

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ABSTRACT

Damage to the Zipingpu concrete-faced rockfill dam (CFRD) with the maximum height of 156 m was induced by the great May 12, 2008 Wenchuan earthquake with a magnitude of Ms 8.0. The dam is the first CFRD over 150 m high experiencing the strong shallow earthquake of IX degree in the world. The seismic damage to the dam raised a number of questions concerning the safety of the dam as well as the adequacy of design criteria. Extensive investigation has been carried out accordingly and is summarized in this paper. The purpose of this paper is to document geotechnical aspects of the design and seismic damage during earthquake, and in particular to highlight key experiences and lessons learned. Analysis of the instrumental records during the earthquake and results of the subsequent surveys following the quake yield three key conclusions as follows. (1) The earthquake motion mainly caused significant seismic non-uniform deformation of the embankment and damage to the face slabs, structures on the crest and downstream stone masonry. The predominantly longitudinal seismic motion intensified the interaction between the embankment and the abutments. The seismic deformation of the embankment and the strong interaction between the abutments and embankment were believed to have been responsible for damage to face slabs. Seepage through the dam increased, but was not significant, due to water-seal damage in the concrete face and peripheral joints. In general, the damage to the dam, although serious in some parts, was minor as a whole and was reparable. (2) Several design considerations contributed to the safety of the Zipingpu dam. Shallow-angle slopes on the downstream dam face were used to enhance the stability of the dam. Most significantly, the adequate zoning and well-compacted rockfill enabled effective deformation control of the embankment, thus greatly reducing the seismic deformation during ground shaking and ensuring the safety of the seepage control system. The performance of the Zipingpu dam during the earthquake evidenced the success of the design. (3) Overall, the Zipingpu CFRD was structurally stable and safe even though it was subjected to seismic shaking at a greater magnitude than the design seismicity. High CFRDs are feasible in seismic regions of western China if adequate design considerations are implemented to alleviate as much damage as possible during major earthquakes.

1. Introduction

China is the country with the largest number of high-embankment dams built in the world. The embankment-type dam has several advantages, including high adaptability to different topographic and geologic conditions, wide availability of materials, and simple and fast construction [1]. It has become the world's most common type of high dam in recent decades. The concrete-faced rockfill dam (CFRD) is a type of high-embankment dam favored by dam engineers. By the end of 2011, about 600 CFRDs were either completed, under construction or in planning, in nearly 100 countries. About 50% of these are located in China, where there are 48 CFRDs over 100 m high that are complete, 20 under construction and 27 in planning [2].

China is rich in hydropower resources, and about 70% of the total hydropower resources are concentrated in the west of China. However, these regions are well known for their high seismicity, both in terms of earthquake magnitude and frequency. Most of the high-embankment dams in China are built in high seismicity

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regions, where seismic safety becomes a control factor in design. Before the Wenchuan earthquake, only some embankment dams below the height of 100 m had been subjected to severe earthquake damage. The Zipingpu CFRD is the first dam of this type over 150 m high subjected to a seismic intensity of 9, during the Ms 8.0 Wenchuan earthquake of May 12, 2008. The damage to the dam resulting from the strong and long duration of shaking immediately raised great concerns regarding the safety of the dam and downstream communities [3–5].

Extensive investigations of geological hazards in the reservoir and damage to the Zipingpu dam were conducted [4,6–18]. A description of the investigations and discussions on the Zipingpu dam is presented herein with emphasis on the geotechnical aspects of the design and seismic damage as well as some key experiences and lessons learned. This paper is an extension of the keynote paper published in GeoShanghai International 2010 [19].

2. General description of the Zipingpu hydraulic project

2.1. Project location

The Zipingpu hydraulic project, situated 60 km northwest of Chengdu City, Sichuan Province, is the lowest of the upstream cascade developments in the Minjiang River. It was categorized by the design codes of China to be a first-class large-scale water control project with the main functions of irrigation and water supply, and other benefits from power generation, environmental protection and tourism. The normal reservoir water level is at an elevation of 877 m with a corresponding storage capacity of 1.112 billion m^3. The total installed capacity is 760 MW. The project mainly consists of a CFRD, a spillway, two flood discharge and flushing tunnels, a scour sluiceway and a power house with four generator units.

2.2. Geology

The topography of the Zipingpu region comprises low and moderate mountainous terrain formed by tectonic denudation. The CFRD lies on the end of a U-shape river bend, which has been incised by the Minjiang River, as shown in Fig. 1. The dam is in the Shajinba section, downstream of the Minjiang River. The river valley cross-section is an unsymmetrical V shape. The region is underlain by Upper Triassic lacustrine coal grits and shales with a typical flysch sedimentary formation. The rocks are characterized by vertically alternating coarse and fine particles and laterally significant variations in particle size and lithology. About 49% of rocks are medium and fine sandstone, 37% are siltstone and 14% are bone coal or argillaceous shale.

Tectonic movement has produced the Shajinba syncline, fault zones including faults F2, F2-1, F3 and F4, and interlayer shear weakness zones including L8–L14 (Fig. 1). Interlayer crushing weakness zones are well-developed in the syncline. The fault F3, lying 360 m downstream from the dam axis, comprised of mylonite, fault gouge and tectonic lenses of sandstone. The materials are poorly cemented and easily disintegrate on exposure to water. The interlayer shear weakness zones L8–L14 result from strong tectonic deformation where soft shales have been crushed, sheared and dislocated between hard sandstones. The interlayer shear weakness zones are large scale in terms of both length and width.

2.3. Seismicity

China is located between two of the world's large active belts. One belt, seismically very active, passes through the center of the country from north to south and is part of the China–Pacific Seismic belt and the Mediterranean Seismic belt. The other passes

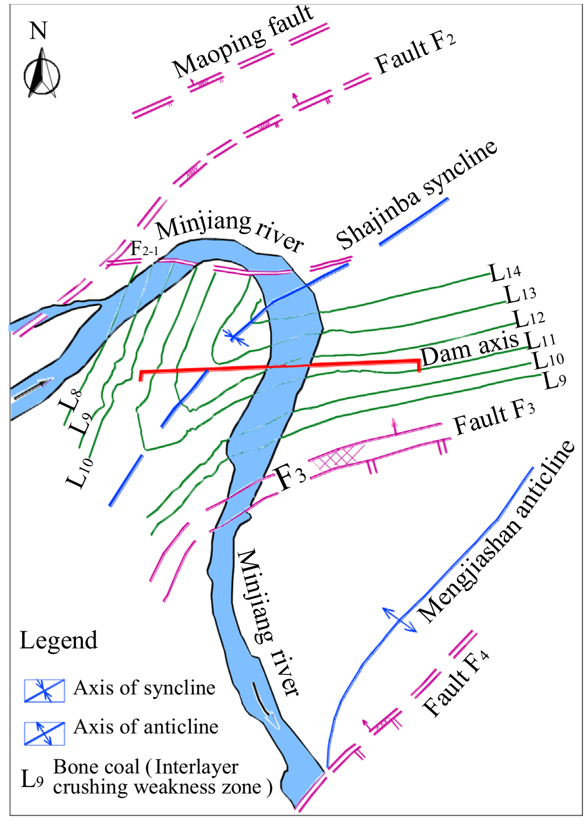

Fig. 1. Geology of the Zipingpu hydraulic project.

through northern China from east to west. The Wenchuan Earthquake of May 12, 2008 resulted from an oblique dextral-thrust motion in the Longmenshan tectonic fault zone within the first seismic belt. The Longmenshan tectonic fault zone is located at the eastern margin of the Tibetan Plateau and adjacent to the Sichuan Basin. This plateau margin may be amongst the steepest, with a relief of 5 km over a distance of less than 50 km, as shown in Fig. 2. It is a major thrust zone that has been repeatedly reactivated in the India–Asia collision. However, historically the maximum earthquake magnitude in this area never exceeded Ms 6.5. It may be the long-term accumulation of energy in the Longmenshan Fault zone that rendered the Wenchuan earthquake the largest event in the past three decades in China. Some studies (e.g. [20–22]) correlated this event with triggering stresses near the Beichuan thrust fault caused by Zipingpu water reservoir, while others (e.g. [23]) suggested that the reservoir probably did not play a role in the occurrence of this earthquake.

3. History of the dam and conditions prior to the earthquake

3.1. Geology and foundation conditions

The general layout of the dam is shown in Fig. 3. A spillway is located on the right abutment. A power house is located on the right base downstream of the dam. The dam rests mostly on recent alluvium consisting of erratic boulders and gravel. However, the alluvium in a zone of about 100 m width downstream from the plinth was excavated as shown in Fig. 4, so that the plinth and half of the upstream dam rests on bedrock. A grout curtain beneath the plinth provides seepage control. The remaining alluvium attains a maximum thickness of 14 m beneath the dam, which was considered to be an acceptable foundation for the dam. Underlying the alluvium are interbedded stiff medium-fine sandstones, siltstone and in some