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Hazard and seismic reinforcement analysis for typical large dams following the Wenchuan earthquake

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ABSTRACT

The primary aim of this research is to analyze the hazards and seismic performance of reservoirs and typical large dams based on a field investigation following the Wenchuan 8.0 earthquake. The current seismic performance standards being achieved are discussed and further suggestions are given for super high dams. Based on field investigations, statistics are also given on damaged small reservoirs and damage severities, due to the many various types of earthquake threat. It is of interest to note that the major structures of the medium-sized hydropower stations on the Minjiang river did withstand the Wenchuan earthquake, despite earthquake intensity exceeding engineering design expectations. All the dams remained overall stable. The Shapai roller-compacted concrete (RCC) arch dam and the Zipingpu concrete-faced rockfill (CFR) dam suffered damage. The main earthquake-induced hazards to the dam structures and to both abutments are detailed. Case study analyses of the hazards and reinforcement provision revealed that: 1) The Wenchuan earthquake proved very dangerous for small reservoirs, with destroyed reservoirs widely distributed. The risk of failure of small dams can be classified into three levels based on field investigation. 2) The damage to and behavior of the large dams in the area affected by the earthquake prove that the Chinese codes relating to the seismic design of large dams are appropriate. 3) Appropriate reinforcement can increase the overall stiffness of abutments, riverbed foundation and the adjacent slopes, further improving the seismic performance of dams. 4) The design and management of emergency responses, to cope with extreme conditions, should be improved, and a unified response platform, covering all hydropower engineering projects in each valley should be established. The effects to be expected and the seismic design measures to be taken still pose great challenges for engineers in respect of large dams.

1. Introduction

Hydropower construction and the energy industry have played an important role in the economic development in China during the last 30 years. Over 2000 dams have been constructed for irrigation, energy production, flood control and recreation purposes. Earth structures such as highway embankments are located in Sichuan province, as well as almost 100 large dams on the fringes of the active seismic zone. Many incidents followed the Wenchuan 8.0 earthquake, with structures subjected to partial or total damage. Since the failure of dams incurs great losses to society (Zhang and Du, 1997; Zhang, 1999; Lin et al., 2011, 2012, 2014; Li et al., 2012; Q.X. Fan et al., 2012; Liang et al., 2013), all countries pay careful attention to dam safety, especially in cases of dam exposure to extreme earthquake loading (PSCG PRC, DL5073-2000, 2000; ICOD, 2004; Lin, 2006; US Army Corps of Eng., 2007). In studying the seismic performance of the different high dam types, field surveys and numerical simulations are important research tools.

The destructive Wenchuan earthquake was of high magnitude (Ms = 8.0). Its seismic source was located at a shallow depth and of long duration. Its influence was widely felt leading to serious secondary geological disasters (Li et al., 2005; Huang and Li, 2008; Parsons et al., 2008; Zheng et al., 2008; Hubbard and Shaw, 2009; Gorum et al., 2011; Tang et al., 2011; Wu et al., 2012; X.M. Fan et al., 2012 and Wang et al., 2013). A unique inventory of 828 dam landslides was triggered, and 1.4% in total of the more than 60,000 mapped seismic slope failures was attributed to this event. 501 landslides blocked the rivers completely, with the remainder only causing partial damming and channel diversions (X.M. Fan et al., 2012). In total, 69,227 people were killed and 374,643 injured, with 17,923 missing. A direct economic loss of 8451 billion RMB was incurred, according to data released by the government on September 25, 2008.

In addition to the serious casualty count and property damage, about 10,000 reservoirs in the seismic region suffered damage. The statistics show that the affected large and medium-sized hydropower stations were mainly located along the Min, Fujiang, Tsingyi, Dadu, Jialing and

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Bailong Rivers (H.Q. Chen et al., 2008; S.S. Chen et al., 2008; Zheng et al., 2008; CHIDI, 2008). The Minjiang river losses reached 3.2 billion RMB, accounting for 71% of all reservoir losses. Seismic damage can be summarized as follows: (1) Small and medium-sized projects were subject to damage, to different degrees. Destroyed reservoirs were widely distributed and proved dangerous. Seismic damage to small and medium-sized dams included crest cracking and local slips. (2) Four high dams in the main seismic region (Figure 1), each of a different type and structural form, performed better than expected. Although close to the epicenter and suffering seismic loading much more severe than the design loadings, the integrity of the body of these dams was maintained. Ancillary facilities, i.e., power houses, diversion projects, flood-relief projects were the main earthquake sufferers. In fact, it is reasonable to believe that the seismic performances of these dams, given the extreme Wenchuan earthquake experience, could provide seismic design guidelines for the several super high dams under construction including the dams of Dagangshan, Baihetan, Wudongde, Songta and Maji in China (She and Lin, 2014).

During the past five years, much research on the stability of slopes and dams following earthquakes have been carried out. For example, Lei (2011) investigated the role of the Zipingpu Reservoir in triggering the Wenchuan earthquake. Zhou et al. (2009a,b) presented the seismic shear wave velocity-based liquefaction evaluation technique for foundation deformations. Zhuo et al. (2013) carried out resistance analysis of the Shapai RCC arch dam based on field monitoring and dynamic finite element analysis. Zou et al. (2013) used a generalized plasticity model to simulate the seismic response of the Zipingpu CFR dam assuming the Wenchuan earthquake. Lin et al. (2009) briefly analyzed the influence on the structural safety of typical large dams of a Wenchuan 8.0 earthquake. Zhang et al. (2014) investigated multi-hazard scenarios and consequences in Beichuan after the 2008 earthquake. All these studies were effective in analyzing the seismic response of dam structures, and obtained many interesting degrees of hazard related results.

The primary aim of the research described in this Paper is to analyze the seismic performance of reservoirs and typical large dams of different types, based on field investigations following the Wenchuan earthquake. Statistics on the distribution of damaged reservoirs and the severity of the damage are given. This information relates the damage severity degree suffered by small reservoirs to the types of earthquakes experienced. Firstly, the seismic regimes experienced by the high dams investigated are classified. Secondly, seismic performances and other comparisons are made between the two typical high dams: the Shapai RCC arch dam and the Zipingpu CFR dam, and also similar high dams abroad. Thirdly, following some discussion, suggestions, appropriate to super high dams regarding ways of assessing seismic risk and on suitable reinforcement criteria are made.

2. Hazard analysis of reservoirs and typical high dams

2.1. Reservoir hazard statistics

After the Wenchuan earthquake, the Ministry of Water Resources and the corresponding functional divisions of the provinces, cities and counties organized a co-investigation. Field investigation and satellite map analysis showed the locations of serious earthquake damage to small reservoirs as well as those reservoirs which had been destroyed. Damaged/destroyed reservoirs occurred in eight provinces, an unprecedented distribution (Table 1). Of the 1803 dams in the Sichuan province, 96% are homogeneous earth dams. In total, 1996 reservoirs in the Sichuan province were damaged in the Wenchuan earthquake. Risk of dam failure can be classified into three grades related to the dam characteristics as shown in Table 2. It is of interest to note that high risk dams accounted for only 3–4% of all dams damaged.

Based on field investigations, reservoir risk assessment statistics show that more than 50% of dam cracking incidences (1425), dam collapses (687), landslides (354), leakages (428), opening up of closed facilities (161), and damage to drainage facilities, spillways, control houses (422) occurred simultaneously. One of the main tributaries of the Yangtze and the Minjiang river, located on the western edge of the Sichuan basin, originates in the Min mountain, in south Sichuan and near the border of Gansu province. In general, the flow is from north to south, the drainage area is 136,000 km^2, stream length is 735 km and natural drop is 3560 m. The upstream Minjiang river with considerable hydropower development capacity, is close to the epicenter

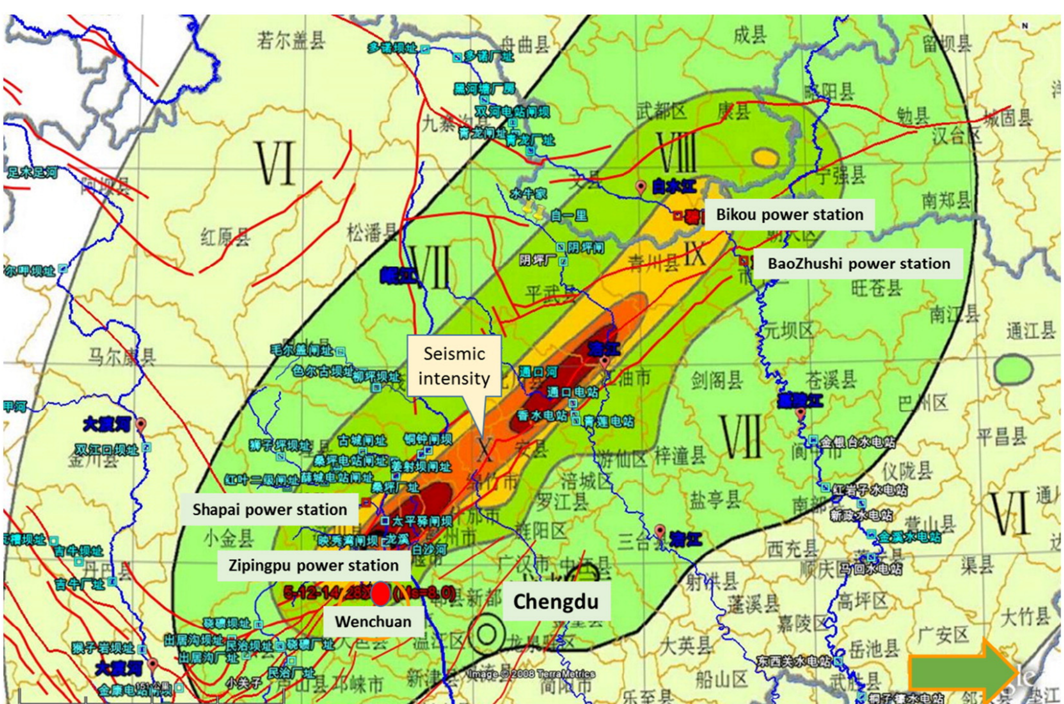

Fig. 1. A map of our typical large dams distributed along the seismic intensity zone.

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