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Seismic damage assessment and mechanism analysis of underground powerhouse of the Yingxiuwan Hydropower Station under the Wenchuan earthquake

Xiaowei Wang[a,b], Juntao Chen[a,b,*], Ming Xiao[a,b]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[b] Key Laboratory of Rock Mechanics in Hydraulic Structural Engineering, Ministry of Education, Wuhan University, Wuhan, China

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ABSTRACT

The Yingxiuwan underground powerhouse is one of the closest large-scale underground structures from the epicenter of the Wenchuan earthquake and suffered significant damage during this earthquake. What makes this case even more interesting is that the seismic damage is mainly distributed in the upper part of the concrete structure in the underground powerhouse. A full three-dimensional dynamic finite element model of the underground structure and rock system is adopted to make a reasonable assessment for the seismic damage observed in the field and to study the damage characteristics and mechanisms of the underground powerhouse. Additionally, to approximate actual field conditions, the oblique incidence of seismic waves and the rock-structure interaction (RSI) are both considered in this study, and their effects on the seismic response are evaluated. The numerical results indicate that the oblique incidence of the seismic wave and the RSI both contribute to a larger seismic response, and the results compare well with the field observations when the two are considered. The damage distribution of the concrete structure is mainly dominated by the structure feature itself. The main cause of the severe damage in the upper structure is due to the lack of sufficient constraints on it, which leads to a large deformation in the upper structure.

1. Introduction

In southwest areas of China, a series of seismic damage of underground structures, even for deep-buried underground powerhouses, were observed during the Wenchuan Earthquake with magnitude of 8.3(Mw) on May 12, 2008 in China. As a kind of typical deep-buried underground structure in rock, underground powerhouses are widely accepted to be strongly seismic resistant due to the constraint effects of the surrounding rock unless they are crossed by active faults [1,2]. Nevertheless, the damage observed at Yingxiuwan underground powerhouse provides sufficient evidence to suggest that their seismic safety is still an important and emergent issue.

Although compared to surface structures, underground structures (e.g. tunnels, caverns, etc.) are well known to suffer appreciably less earthquake-induced damage and such damage is generally assumed to decrease with the increasing buried depth [3], this does not mean that the structural damage can be completely avoided under strong seismic conditions. In fact, the importance of seismic design for underground structures has been realized by many researchers after several strong earthquakes, including the 1955 Kobe Earthquake in Japan [4], the 1999 Chi-Chi Earthquake in Taiwan [5], the 2004 Mid-Niigata Prefecture Earthquake in Japan [6] and the 2008 Wenchuan Earthquake in China [7–9]. The seismic performances of underground structures have also been investigated mainly by the following methods: investigation and statistics [10–12], scaled model test [13,14], numerical simulation [15–20] or a combination of any two of the three methods [8,21,22]. Among these methods, numerical methods are the most widely employed because they are of low cost and can simulate complex boundary conditions. Many researchers have developed various numerical models in the past years to study the seismic response of underground structures, such as the time domain finite element models adopted by Refs. [8,15,17,20,22], DDA method used by Zhang et al. [18], and distinct element method by Refs. [16,19]. Those numerical modeling techniques have raised our knowledge on seismic behavior of underground structures.

According to the previous works, a number of parameters are summarized as particularly relevant to the seismic response of underground structures, such as distance to the epicenter, magnitude, overburden, peak acceleration, duration of the earthquake, type and strength of rock, etc. Most of these works are focused on tunnels;

* Corresponding author at: State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China.
E-mail address: chenjt000@163.com (J. Chen).

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however an underground powerhouse is a more complex large-scale structure, and it is generally composed of complicated geometry and a large cross-section with several long span and high sidewall caverns. Therefore, whether the above experiences can be entirely applicable to and meet the design requirements of underground powerhouses remains unknown. Because of the geometrical and material complexity of underground powerhouse and the uncertainty of seismic excitation, many researchers conducted two dimensional (2D) or three dimensional (3D) numerical models to analyze the seismic behavior [16–19,22–24]. In their studies, Zhang et al. [18] and Chen et al. [23] studied the seismic response of underground powerhouse assuming elastic material behavior for the surrounding rock. This linear assumption simplifies the dynamic analysis and cannot properly reflect the seismic damage. More appropriate inelastic dynamic analysis for underground powerhouses can be found in Refs. [16,17,19,22,24]. Although those works can effectively promote the seismic design, most of them did not consider the effects of the incident angles of seismic waves and/or the rock-structure interaction (RSI). In fact, both the incident angles of seismic waves and the RSI have been proved to significantly influence the seismic response of underground caverns [25,26]; thus, systematic and sufficient studies on the response performance of large-scale underground caverns, until recently, are still far from enough [27]. Additionally, the large mass of the concrete structure in an underground powerhouse, which is proven to be relatively more vulnerable to be damaged than the surrounding rock and may suffer serious functional failure under strong earthquakes [22,28], was rarely considered in previous works. Therefore, further studies are undoubtedly required.

In this study, the damage observed at the Yingxiuwan underground powerhouse, which is 8 km away from the epicenter of the Wenchuan Earthquake, is presented and analyzed in detail. Then a more complex numerical model compared to the above works, was established to study the seismic response process of the concrete structure of the underground powerhouse; in this model both the oblique incidence of seismic waves and the RSI are considered and their effects on the seismic response are evaluated. Finally, the damage characteristics and mechanisms are detailedly analyzed and summarized.

2. A brief description of the Yingxiuwan Hydropower Station

The Yingxiuwan hydropower station is located at Yingxiu town of Sichuan province in China and just 8 km away from the epicenter (31.00°N, 103.40°E) of the 5.12 Wenchuan Earthquake, as shown in Fig. 1. Its underground powerhouse is located on the left bank of the Minjiang River and mainly consists of several caverns with different sizes and functions, such as the main powerhouse, the auxiliary powerhouse, the main transformer cavern, and so on. Those caverns are deeply buried in hard rocks with a horizontal buried depth of 50–100 m and a vertical buried depth of 150–200 m. Among the caverns, the main powerhouse is of the largest scale with dimensions of 52.8 m × 17.0 m × 37.2 m and owns three generator units with a total capacity of 135 MW. In the main powerhouse, there are concrete structures such as lining, floors, crossbeams, columns, generator hood and turbine pier, etc.

According to geological prospecting, the geological units of the study area are mainly composed of diorite, granodiorite and granite rocks in the Indo-Chinese epoch and the Yanshan period, and there is no large fault in the study area and only several small faults without new activity control the joint fractures in the rock mass. The Beichuan-Yingxiu Fault [29], where the main shock of the Wenchuan Earthquake occurred, is the nearest large fault, and it is approximately 400 m away from the study area. Strong seismic activity along the fault strongly affected the seismic intensity of the study area of XI degree during the Wenchuan Earthquake (see Fig. 1). As shown in Fig. 1, the Yingxiuwan underground powerhouse is one of the closest large-scale underground structures from the epicenter. Thus, the underground powerhouse can be assumed to have experienced a prototype destruction test during this earthquake, and its seismic damage analysis can unquestionably improve the current knowledge about the seismic performances of large-scale underground structures.

Two relevant characteristics of the earthquake are regarded to contribute to its strong destructiveness. One is the large amplitude, while the other is the long duration. The largest peak acceleration of this earthquake was recorded at Wolong station, which is the closest ground motion station to the epicenter and the underground powerhouse (see Fig. 1), and is located on the ground conditions similar to those of the underground powerhouse. As shown in Fig. 2, the peak accelerations of recorded at the station in the east–west (EW), north-south (NS), and vertical (UD) directions are 957.7, 652.9 and 948.1 gal [30], respectively. Additionally, the recorded duration of the earthquake is nearly 180 s and the acceleration experienced a relatively violent fluctuation process in the period of 20–80 s. Thus, the 60 s acceleration time-history is intercept for the numerical simulation in this paper.

3. Damage investigation of the underground powerhouse

Due to the close distance from the epicenter, the Yingxiuwan underground powerhouse suffered significant damage during the Wenchuan earthquake. The damage attracted the attention of researchers of the seismic design of underground powerhouses and offered a valuable opportunity to study its seismic performance systematically. Thus, our research group has conducted several field investigations after the earthquake and the damage of the underground powerhouse, according to the investigation results, is described in detail as follows.

The entrance of the traffic tunnel and the exit of the tailrace tunnel suffered the most severe damage as they were almost completely collapsed or buried by landslide, as shown in Figs. 3 and 4. These damages to portal structures under a strong earthquake can be expected and have been widely reported [8,31]. The interior of the powerhouse, or its deep-buried parts in other words, suffered moderate structural damage except for being flooded (see Fig. 5). Although there was no obvious surrounding rock instability, which also verified the seismic ability of an underground powerhouse, cracking and spalling were extensively observed on the reinforced concrete structures in the underground powerhouse. Non-penetrating cracks with limited length and width were found on the sidewalls and top arch of the secondary lining of the main powerhouse (see Fig. 6). Moreover, there were approximately90 cracks on the arch before the earthquake and parts of them experienced a further prolongation during the earthquake. Additionally, newly generated cracks (nearly 2 mm in width) occurred on the surface of the lining.

Since the rock-anchored crane beam is no-load during the earthquake, no obvious structural damage was observed. However, inward deformation of the sidewall caused the scraping of the crane and the sidewall, which led to the inoperability of the crane (see Fig. 7). The damage to the generator floor and turbine floor was in the form of diagonal closed cracks that locally resulted in visible broken and uplift (see Fig. 8). Moreover, many cracks with length of approximately 1.5 m, width of nearly 1 cm and depth of 5–7cm, occurred on the turbine pier and generator hood, as illustrated in Fig. 9. Those cracks, according to the results of ultrasonic testing, were pinched out or closed at their bottom. Additionally, steel corrosion or even distortion locally appeared at the cavern intersection, where the concrete was cracking and peeling (see Fig. 10). It should be noted that the other caverns also suffered significant cracking damage (see Figs. 11 and 12), mainly in the form of closed cracks and surface shedding with large extensions.

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