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Characterization of transient groundwater flow through a high arch dam foundation during reservoir impounding

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ABSTRACT

Even though a large number of large-scale arch dams with height larger than 200 m have been built in the world, the transient groundwater flow behaviors and the seepage control effects in the dam foundations under difficult geological conditions are rarely reported. This paper presents a case study on the transient groundwater flow behaviors in the rock foundation of Jinping I double-curvature arch dam, the world's highest dam of this type to date that has been completed. Taking into account the geological settings at the site, an inverse modeling technique utilizing the time series measurements of both hydraulic head and discharge was adopted to back-calculate the permeability of the foundation rocks, which effectively improves the uniqueness and reliability of the inverse modeling results. The transient seepage flow in the dam foundation during the reservoir impounding was then modeled with a parabolic variational inequality (PVI) method. The distribution of pore water pressure, the amount of leakage, and the performance of the seepage control system in the dam foundation during the entire impounding process were finally illustrated with the numerical results.

1. Introduction

Over the last two decades, tens of large-scale arch dams, typically with a height over 200 m, have been designed and/or constructed over deeply cut narrow valleys in southwestern China, such as Ertan (Zhou et al., 2008), Xiaowan (Chai et al., 2004; Lin et al., 2015), Xiluodu (Liu et al., 2013; Fan et al., 2015), Jinping I (Fei et al., 2010; Chen et al., 2015, 2016) and Dagangshan (Zhang et al., 2015) arch dams, to name only a few. Owing to its thin structure, a high arch dam commonly suffers from a high pore water pressure (over 2 MPa) and a large pressure difference in the foundation rocks. Consequently, groundwater leakage, seepage erosion and/or abnormal distribution of uplift pressure frequently occur as a result of insufficient characterization of site conditions and/or improper design of seepage control systems (e.g. Chen et al., 2016). A proper characterization of the permeability of foundation rocks is therefore indispensable (Chen et al., 2010), either based on the site characterization data at the design stage, or based on the field measurement data at the impounding and operation stages, as a key step to better understand and control the groundwater flow behaviors in the dam foundations. To the best of our knowledge, however, a systematic study on the behaviors of transient groundwater flow and the effects of seepage control in a high arch dam foundation under difficult geological conditions has not yet been reported.

This study takes the Jinping I double-curvature arch dam, located in the middle reach of Yalong River, as an example to examine the transient groundwater flow behaviors in the high arch dam foundation. The Jinping I arch dam was completed in December 2013, with a maximum height of 305 m. The impounding of the reservoir began in November 2012, which was separated into four stages (Stages I–IV). In the second stage of reservoir impounding, however, a significant amount of leakage was observed from the drainage holes drilled in the lowest drainage tunnel at the left bank abutment at an elevation of 1595 m. Chen et al. (2016) comprehensively examined the source of leaking, the groundwater flow paths, the performance of grouting curtains, and the effects of engineering treatments of the leakage event on the dam safety by proposing a multi-objective inverse modeling procedure using the in-situ time series measurements of both flow rate and hydraulic head, together with the observations by water chemical analysis, digital borehole imaging and tunnel geological mapping. The transient groundwater flow behaviors in the dam foundation, however, remain to be further investigated. This study

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aims to present the back-calculated permeability of the foundation rocks, the performance of the seepage control systems and the seepage flow behaviors in the Jinping I dam foundation.

2. Site characterization

2.1. Project description

The Jinping I double-curvature arch dam, located on the border between Muli and Yanyuan counties (Sichuan Province, China), is the first level of the cascade of dams in the middle reach of Yalong River. This dam has a maximum height of 305 m and a varying width of 63–16 m from the base to the crest. The dam is a major component of the hydraulic structures in the Jinping I Hydropower Project mainly designed for energy production, sediment trapping and flood control. Fig. 1 shows the layout of the project. The underground powerhouse cavern system is located in the right bank of the mountain about 350 m downstream the dam axis, with a total installed capacity of 3600 MW. The reservoir capacity is about 7.76×10^9 m^3 at the normal pool level of 1880 m.

The river course at the construction site was blocked on December 4, 2006 for the construction of the dam. The excavation of dam foundation started in August 2007 and was completed in September 2009. The first bucket of concrete was poured into the foundation on October 23, 2009, and the construction duration lasted for 50 months. The impounding of the reservoir began on November 30, 2012, and the reservoir water level was gradually elevated to the normal pool level (1880 m) by about 232 m in 21 months, which could be separated into four stages (stages I–IV), as shown in Fig. 2.

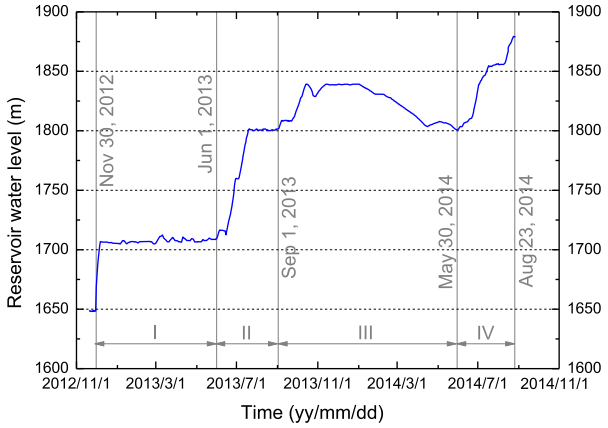

Fig. 2. The reservoir impounding process.

2.2. Geological settings

The Jinping I dam is located in a typical deeply cut V-shaped valley. As shown in Fig. 3, the dam foundation consists of a series of epizonal metamorphic rocks, which belong to the second member (T^2_{2-3z}) and the third member (T^3_{2-3z}) of the Zagunao group of upper to middle Triassic system ($T_{2\text{-}3z}$) (Qi et al., 2004). The rocks in the second member (from $T^{2(1)}_{2-3z}$ to $T^{2(8)}_{2-3z}$), on which the dam foundation is mostly situated, mainly consist of marble, breccia marble, lens of calcareous tuff phyllite and green schist. The third member (from $T^{3(1)}_{2-3z}$ to $T^{3(6)}_{2-3z}$), outcropping at higher elevation in the left bank slope, consists of slate and metamorphosed sandstone. The strata strike almost parallel to the river (N0°–30°E), dipping 25°–45° toward NW.

Several large-scale faults are developed at the dam site, including F_2, F_5 and F_8 in the left bank and F_{13} and F_{14} in the right bank (Fig. 3). Fault F_2, striking N30°–40°E and dipping 40°–56° toward NW, was formed as an associated structure of the shear zone in the second member ($T^{2(6)}_{2-3z}$) of the regional strata. It is about 0.2–0.8 m in thickness and mainly composed of schistose, cataclastic or mylonitic rocks. Faults F_{13} and F_{14}, striking with an angle about 50° to the axis of the machine hall and dipping 60°–80° toward S20°–30°E, are less permeable than the surrounding rocks, acting as low-permeability barriers to the groundwater movement. Besides the geological structures mentioned above, there are

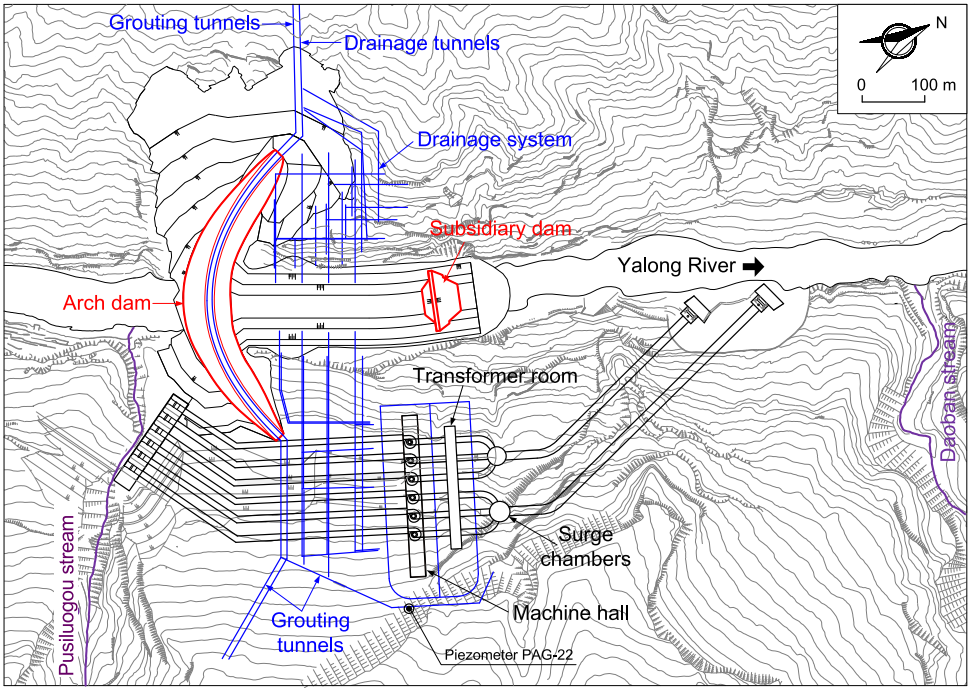

Fig. 1. Layout of the Jinping I Hydropower Project.