Tunnelling and Underground Space Technology 48 (2015) 58–66

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

The external water pressure on a deep buried tunnel in fractured rock

Yong Huang [a,*], Zhimin Fu [b], Jing Chen [c], Zhifang Zhou [a], Jinguo Wang [a]

[a] School of Earth Science and Engineering, Hohai University, Nanjing 210098, China
[b] College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[c] Jiangsu Province Hydrology and Water Resources Investigation Bureau, Nanjing 210019, China

ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form 28 January 2015
Accepted 16 February 2015
Available online 7 March 2015

Keywords:
External water pressure
Rock tunnel
Coupled model
Fractured rock

ABSTRACT

Underground tunnels are increasingly built at greater burial depths for water conservancy and hydropower projects. The safety of these tunnels is threatened by high external water pressure during construction and reservoir operations. In this research, external water pressure was considered to be a relative incremental water pressure, instead of an absolute value: it thus depended on several factors, such as the excavation, lining, and grouting zone of tunnel. The calculation thereof was deduced. Also, a coupled model was used to calculate the external water pressure. This model incorporated a fractured network model (DFN) into an equivalent continuous medium model (ECM). The results showed that calculated hydraulic heads matched measured values when using the coupled model, rather than the continuous model, in the areas where fractures and fault zones were well-developed. Furthermore, external water pressures were predicted using the verified coupled model during the emptying and filling of diversion tunnels with water.

1. Introduction

External water pressure plays an important role in the stability of underground tunnels under high water pressure. It is often defined as the hydrostatic pressure on the lining due to groundwater. The waterproof lining can increase the external water pressure (Wang, 2008), but a drainage system can decrease it (Ponlawich et al., 2009). According to Wang et al. (2008), controlled drainage can reduce the water pressure on the lining. Sometimes, the grouting zone can share a part of load arising from this water pressure (Wang, 2008). In fact, the calculation of external water pressure not only depends on the permeability of the lining, the drainage system, and the grouted zone around the tunnel (Zhang et al., 2011), but also on their construction process (Zhang, 2003). External water pressure is usually considered to be an absolute static water pressure on the lining in the literature; however, here it was considered as being a relative increment related to construction stages such as excavation, lining, and grouting. The design of the lining is mainly based on the initial groundwater level. The groundwater level falls after the tunnel is excavated and rises due to its lining and grouting. If the rising groundwater level overtops the initial groundwater level, the difference in groundwater level, or its additional load, except for the initial groundwater level, must be considered.

Various calculation methods for external water pressure have been developed: the first is the reduction coefficient method (Zhang, 2003), where the coefficient is a constant ranging from zero to one. Therefore, the external water pressure is a product of the coefficient and the hydraulic head from some location to the groundwater table. The reduction coefficient depends on the hydrogeological conditions around the tunnel during its excavation. The second is an analytical method: based on a characteristic water pressure curve, Shin et al. (2007) proposed a new equation to calculate the external water pressure. Also, the relationship of the external water pressure to the discharge from the tunnel was analysed using a theoretical model of a mountainous area with a high water level. External water pressure decreases with increasing tunnel discharge due to the decrease in groundwater level (Wang et al., 2004; Kolymbas and Wagner, 2007; Ponlawich et al., 2009). According to conformal mapping, Huangfu et al. (2010) developed an analytical solution to study the steady seepage field around a circular cross-section underwater tunnel. In their model, the fractured medium was assumed to be a homogeneous, isotropic, aquifer. In fact, there are faults and fractures around deep underground tunnels. For heterogeneous, or anisotropic, aquifers, the analytical solution may be erroneous. The third is a numerical method: a seepage model is used to calculate the external water pressure in a pin-hole system (Shin et al., 2009). A coupled model based on seepage and stress fields was

* Corresponding author at: 1 Xikang Road, Nanjing, Jiangsu Province 210098, China. Tel.: +86 13951876225; fax: +86 2583787234.
E-mail address: hyong@hhu.edu.cn (Y. Huang).

http://dx.doi.org/10.1016/j.tust.2015.02.003
0886-7798/

applied to the calculation of external water pressure in Xiaowan Hydropower Station in China (Bian et al., 2009). When an external water pressure was calculated using these methods, the effect of fractures and fault zones on the external water pressure was often ignored.

The calculation of hydraulic head is important before the determination of external water pressure. Its calculation includes methods such as the ECM, DFN, and dual medium approach. The ECM treats the fractured aquifer as a continuous medium (Carrera et al., 1990; Schoeniger et al., 1997; Schwartz et al., 2010). The DFN approach describes the fractured aquifer as a discrete medium (Long et al., 1982; Cacas et al., 1990; Dershowitz et al., 1991; Huang, 2004). A dual medium approach treats the fractures and rock matrix as two materials with different porosities and hydraulic conductivities (Barrenblatt et al., 1960; Zhou, 2003).

In this research, a coupled model was used to simulate groundwater around diversion tunnels, where fractures and fault zones were represented by a DFN, and the rock matrix and any small-scale fractures were described by an ECM model. Also, external water pressure, which is the product of water density, gravity acceleration and hydraulic head, was taken as being a relative water pressure rather than an absolute value. On the other hand, hydraulic fracturing values can be determined by high pressure water test. So the evaluation is carried out between external water pressure, hydraulic fracturing values and hydrostatic pressure in the diversion tunnels.

2. Description of the study sites

2.1. Study site description

Heimifeng pumped storage power station (HPSPS) is located 25 km north of Changsha City, China (Fig. 1). It has 1200 MW installed capacity, which includes four reversible pumped storage units. It consists of an upper and lower reservoir, an underground power house and waterway system. The catchment areas of the upper and lower reservoir are 1.12 km^2 and 11.2 km^2, and their water levels above sea level (asl) are 400 m and 103.7 m respectively. The elevation of the adjacent mountains ranges from 50 to 395 m asl and the area has a relief generally above 300 m. The buried depth of underground power house ranges from 180 m to 230 m owing to the topographic relief. There are two diversion tunnels (Nos. ① and ②), and the distance between the two tunnels is 46 m. Each diversion tunnel is divided into two sub-diversion tunnels in the flat section of the waterway system. The distance between each sub-diversion tunnel is 23 m. The elevation of the centrelines of these tunnels is 15 m, so are subjected to a high external water pressure during their operating and emptying periods. Precipitation ranges from 458.6 to 2052.5 mm *per annum* with a mean annual precipitation of 1361.6 mm. The air temperature ranges from 4.4 to 24.7 °C, with an annual mean temperature at the study area of 17.2 °C.

2.2. Geology and hydrogeology

Stratigraphic units are composed of granite and granitic pegmatite veins in the late Yanshan, and Quaternary strata (Q). Granitic compositions are involved in monzonitic granite, biotite granite, and K-feldspar granite. The mineral compositions of the granitic pegmatite veins include potash feldspar, quartz, anorthose, and muscovite. The veins strike NE and NW. The width of the veins is about 200 mm. The Quaternary strata consist of an eluvial layer (Q^{edl}), riverbed alluvium (Q^{al}), and a colluvial deposit (Q^{col+dl}). The thickness of layers is about 2 m, 4.5 m, and 5 m, respectively.

Some 56 faults are disclosed within the study area of 1.3 km^2. They can be grouped into three types based on fault orientation. The first group strikes N35–65E and inclines NW with a dip angle of 45–88°. The second strikes N15–40E and inclines SE with a dip

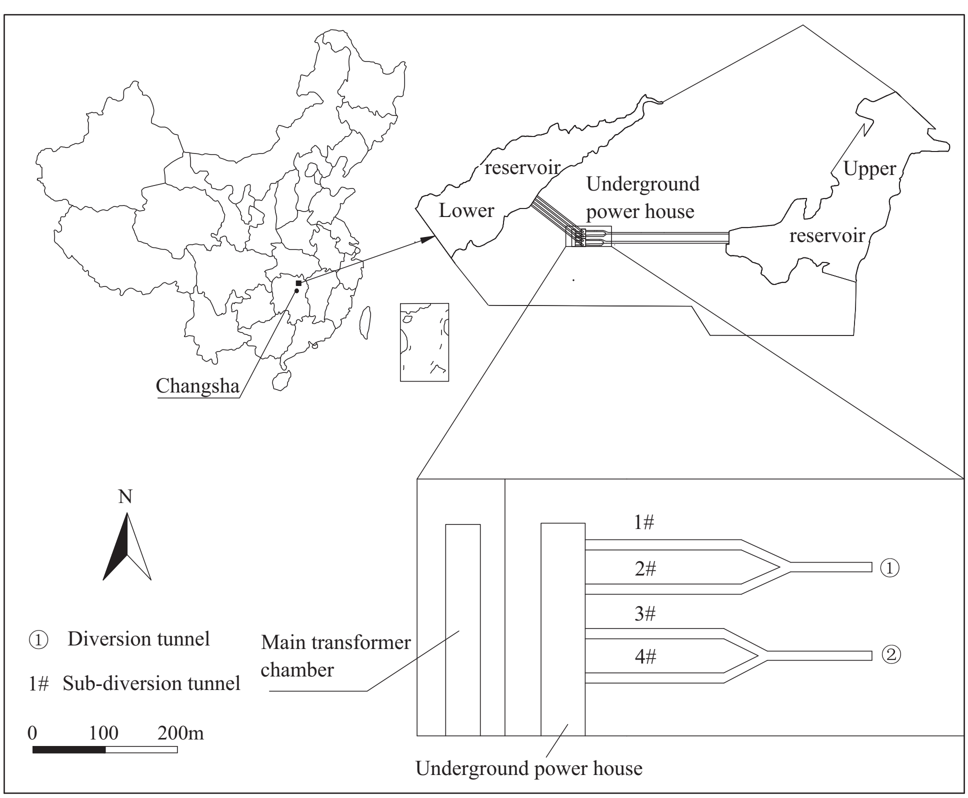

Fig. 1. Location of the study area and the distribution of diversion tunnels.