Tunnelling and Underground Space Technology 59 (2016) 157–169

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Numerical analysis of different ventilation schemes during the construction process of inclined tunnel groups at the Changheba Hydropower Station, China

Shuai Shao [a], Xing-guo Yang [b], Jia-wen Zhou [a,*]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, PR China
[b] College of Water Resources and Hydropower, Sichuan University, Chengdu 610065, PR China

ARTICLE INFO

Article history:
Received 3 January 2016
Received in revised form 10 June 2016
Accepted 11 July 2016

Keywords:
Inclined tunnel groups
Ventilation scheme
Numerical simulation
Velocity field
Security distance

ABSTRACT

During the excavation process of underground caverns, the rational selection of the ventilation scheme is very important for the safety and health of construction workers. The flood discharge tunnel groups at the Changheba Hydropower Station are selected as a case to study the design of ventilation schemes in inclined tunnel groups; these groups are characterized by a gradient of approximately 10% and a complex intersecting relationship among the tunnels. The Computational Fluid Dynamics (CFD) method is used to simulate the fluid dynamics in tunnel groups when different ventilation schemes are employed. Four ventilation schemes with the same duct at different positions along the transverse section are formulated, and the scheme approaching the right side with most of the construction adits is adopted in engineering after a comparative analysis, as it offers a well-distributed velocity field and sufficient security distance. The study reveals that flow vortices appear in the tunnels with a long axis length ranging from 5 m to 20 m; the observation that the flow velocity on the transverse sections is away from the heading face indicates that a low-velocity area is always present in the vicinity of an air duct, and the security distance on the upstream side is 60% shorter than on the downstream side with the same air-blower when the tunnels have a 10% gradient. In addition, when the excavation distance rises 200 m, the ventilation condition in the tunnels, especially in the areas around tunnel intersections, is greatly improved by the completion of pilot tunnels and shafts in advance.

1. Introduction

With the rapid development of social economy and science technology, the use of underground space has become an important component of urban transportation, mining, hydrogen storage, nuclear and hydropower engineering, and other fields. Regarding functions of certain urban societies and environments, underground space development has significant advantages relative to surface space development (Chow, 1989; Versteeg and Malalasekera, 1995; Parra et al., 2006). Moreover, with the substantial increases in requirements for mineral resources, increasing numbers of surface mines have been transferred to underground space (Álvarez et al., 2001; Vega et al., 2008; Huang et al., 2011). In addition, the most promising solution to the problem of large-scale energy storage (which appears to be novel today) is underground hydrogen storage (Álvarez et al., 2002; Betta et al., 2010; Wang et al., 2011; Marilena and Giuseppe, 2014). However, during the exploitation of underground space, ventilation problems, such as carbon monoxide poisoning or gas explosions, always emerge in underground caverns. These problems cause enormous economic losses or even great casualties and are usually difficult to solve. Thus, it is necessary to arrange reasonable ventilation schemes during the excavation of underground caverns, with the goals of delivering sufficient fresh air to the heading face and reducing dust and toxic gas concentrations (Hargreaves and Lowndes, 2007; Rohdin and Moshfegh, 2011; Sa et al., 2012; Haque et al., 2015).

At the beginning of the studies for ventilation calculation, the forced ventilation quantity in tunnels can be calculated under the assumption that the length of smoke throwing is the same as the distance from the end of the pipe to the working face (Voronin, 1951). In addition, the research studies also revealed that some parameters, e.g., the maximum distance of the pipeline, required airflow, characteristics of the pipeline and characteristics of the fan, must be known in the design of auxiliary ventilation systems. In addition, when a heading face is not provided with

---

[*] Corresponding author.
E-mail address: jwzhou@scu.edu.cn (J.-w. Zhou).

http://dx.doi.org/10.1016/j.tust.2016.07.007
0886-7798/

an adequate amount of fresh air, the choices are to either replace the fan with a more powerful fan or adjust the pipe layout (Auld, 2004). Nevertheless, the results derived from conventional methods are unreasonable because the foundations of these methods are turbulent diffusion, turbulence deformation theory, and the hypothesis that the airflow and pressure values are determined at a fixed moment and for a certain position of the underground structure (Likar and Cadez, 2000; Wang, 2004; Onder and Cevik, 2008; Rout et al., 2014). Therefore, current studies focus on the use of Computational Fluid Dynamics (CFD) in regard to the ventilation in underground caverns because of its reliability, reasonability and convenience. Research involving the model of gas dilution after blasting and the condition in which workers can return to the blasted area has been developed based on CFD (Torno et al., 2013). Some semi-empirical equations have been proposed to calculate the effective length of the airflow impacting (L_e) by means of CFD (Diego et al., 2011; Nan et al., 2015). The ventilation characteristics with different inlet/outlet angle of the jet fan have been performed (Ji et al., 2011; Lee et al., 2014). Considering the influence of time, dust behavior in auxiliary ventilation systems has been studied (Toraño et al., 2011). Wang et al. (2012) studied the effects of deflected angles of jet fans in a curved tunnel. However, extensive studies on the ventilation has been conducted on different aspects in horizontal tunnels, little research has been done about the ventilation of inclined tunnel groups, actually, the gradient has great influence on ventilation efficiency.

The purpose of this study is the determination of the ventilation scheme through the analysis of air flow behavior under different ventilation schemes during the excavation process of the inclined tunnel groups at the Changheba Hydropower Station. The fluid dynamics in the tunnel groups under different ventilation schemes are simulated using the CFD method. A practical ventilation scheme is determined from the comparative analysis of the fluid dynamic characteristics under different ventilation schemes. The effectiveness of the practical ventilation scheme is validated by field monitoring results regarding the quality of air flow. Some useful conclusions and suggestions are presented for the design of ventilation schemes in inclined tunnel groups.

2. Background

2.1. Project overview

The Changheba Hydropower Station, which is the 10th level hydropower station for cascade development of the Dadu River, is located in Kangding County, Sichuan Province in Southwest China. The project contains the core rockfill dam, which is one of the largest rockfill dams in China; its maximum height rises 240 m. Fig. 1 depicts the diversion and discharge tunnel groups at the Changheba Hydropower Station. As shown in Fig. 1, the Changheba Hydropower Station has three flood discharge tunnels, three diversion tunnels, several traffic tunnels and a vertical air shaft at the right bank. The diversion and discharge tunnel groups are very complex, with different shapes, sizes and inclinations.

The tunnels of small size (such as the air shaft) are excavated as a full section. However, the tunnels with large size (such as the diversion tunnels and flood discharge tunnels) are divided into several sections and stages during the excavation process; in addition, the complex cross relationship of the tunnel groups should be considered. Moreover, the excavation process of the flood discharge tunnels consists of two sections, the inlet section and the outlet section; Fig. 2 shows the flood discharge tunnel groups at the Changheba Hydropower Station. Each flood discharge tunnel is divided into two layers (upper layer I and lower layer II) during the excavation process, and the reasonable selection of ventilation scheme is especially important during the upper layer I excavation process, when the ventilation of the tunnel is only achieved through mechanical measures. Due to the effects of the excavated distance and the delayed completion of pilot tunnels and shafts, the middle sections of the discharge tunnels are excavated from construction adit #1-1, and the upper layer I excavations of the discharge tunnels are divided into three stages: stage I.1, stage I.2 and stage I.3.

2.2. Flood discharge tunnel groups

The three flood discharge tunnels are parallel to each other; the separation distance between discharge tunnel #1 and discharge tunnel #2 is 59 m, and the separation distance between discharge tunnel #1 and discharge tunnel #3 is 111 m. Furthermore, these three discharge tunnels are inclined with a gradient of approximately 10%, which has a great impact on the reasonable selection of a ventilation scheme for the tunnel groups during the excavation process. The excavation works for the middle sections of three flood discharge tunnels start from the intersection with construction adit #1-1 (as shown in Fig. 2); these excavations progress towards the upstream and downstream directions at the same time. Here, the *x* direction is defined to be along the horizontal axial direction of the discharge tunnel (downstream is defined as the positive *x* direction, and upstream is defined as the negative *x* direction); the z direction is defined as the vertical direction, and the *y* direction is along the radial direction of the discharge tunnel in the horizontal plane. The zero point in the *x* direction is defined at the intersection of construction adit #1-1 and discharge tunnel #1 (as shown in Fig. 2).

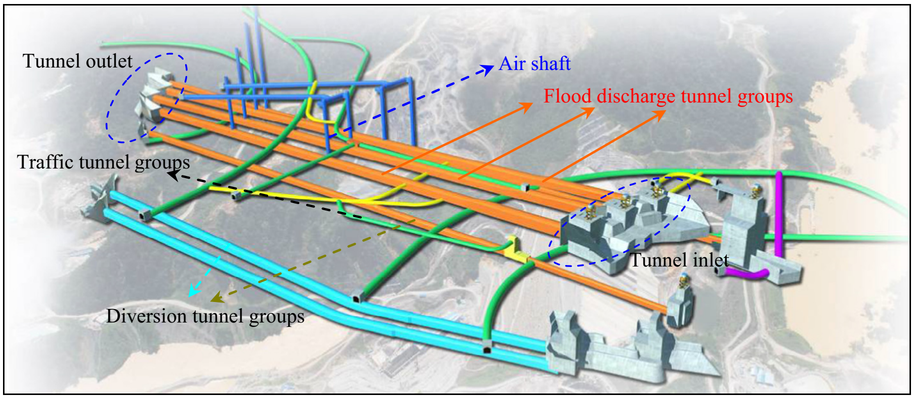

Fig. 1. Visualization of the diversion and discharge tunnel groups at the Changheba Hydropower Station.