The Effect of Ground Water and Its Prediction Methods and Techniques during Tunnel Construction

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ABSTRACT

The effects of ground water within rock mass during tunnel construction are generally presented in this paper. In addition, main predicting methods and techniques for water-irruption during tunnel construction, and principle monitoring methods for ground water during tunnel operation are also introduced. In the case study followed, the numerical analysis method that is used for simulating 3D-seepage field surrounding the large-scale excavation under natural and drainage conditions is proposed. By employing this numerical method, joint effects of seepage and stress on the tunnel stability was analyzed, finally the effect of seepage-controlled measures is also evaluated.

1. INTRODUCTION

The problem of ground water irruption is one of the most serious geological disasters during tunnel construction. For example, there are a total of 415 tunnels constructed along the railway from Chengdu to Kunming in China, among them, 93.5% have involved the water irruption problem. The 4 km long exploring tunnel of the Jinping II hydropower station that is being constructed passed a large-scale regional fault with heavily developed karst caves and geological discontinuities. During the tunnel excavation, several water irruption from karst channels occurred between 2755~2760m, 3580~3600m, and 3900~3948m, with a flow about 0.61m$^3$/s, water pressure about 5MPa, and a total of water flow capacity about 2.78m$^3$/s. In the initial stage of construction of the Huayunshan railway tunnel in 1998, a large number of karst caves and water-irruption spots were found. In the total of 80 of water irruption spots, 20 are extremely larger, with a maximum water flow capacity of $2.4\times10^4$m$^3$/d. Generally speaking, the geological disasters that possibly occurred during tunnel construction mainly include water-irruption, rock burst and high temperature, and so on. Among them, the water irruption is often encountered and the most hazardous (Xu Zemin and Yang Lizhong, 1993). The large water irruption may not only inundate the tunnel and working equipment, but also have the workers’ life in danger. In addition, the heavy drainage scheme after water irruption will cause lots of secondary geological disasters, for example, a strong decline of the underground water level, a shortage of surface water resources and ground settlement. Therefore, an exact prediction for the water flow capacity in tunnel construction is of a great significance.

2. PREDICTING METHODS AND TECHNIQUES FOR WATER IRRUPTION

2.1 Predicting methods of water-irruption

Since the water irruption is caused by various factors associating with each other in a very complicated means, its mechanism is sophisticated. The main predication methods for water irruption presently used can be classified into: Information analysis method, Expert system method, Geographic information system method, Fuzzy mathematics method, Artificial neural networks system method, Nonlinear theory (Jin Dewu, 2000) etc.
(1) Information analysis method. In the early of 1990s, by applying the classical information theory to forecast the water-irruption occurred during tunnel construction, Chinese scholars developed an information model of water-irruption prediction and proposed the Information analysis method for water-irruption prediction (Jin Dewu, 1993). By incorporating various qualitative and quantitative factors that contributed to the occurrence of water irruption into the same information system, the proposed method not only sorts and combines different factors related to water irruption, but also evaluates the prediction results of water irruption. These characteristics cannot be replaced by the single-factor model.

(2) Expert system. Expert system is a computer program system incorporated with a large quantity of technical knowledge and experience, which is provided by one or a group of experts. The expert system applied the artificial intelligence technology to deduce, estimate, and solve problems by simulating the thinking mode of experts. At the end of 1980s, Chinese scholars proposed and developed the Expert system for predicting water-irruption during tunnel construction successfully. After application of this system in over 200 tunnels for predicting water irruption, it has been verified that 90 percent has been successfully predicted (Zhang Minjiang, 1989).

(3) Geographic information system. Geographic information system (GIS) is one type of technology system that is mainly used for managing and studying the space-data recorded. The main purposes of utilizing GIS in the prediction of water irruption in tunnel engineering include: 1) collection and process of the data related; 2) preprocess of information; 3) establishment of the water-irruption model; (4) prediction of partition. The procedures for applying the GIS method are as follows: firstly, according to analysis results of hydrological conditions within rock mass, to choose factors that contribute to water irruption and to generate an area for information storage by plotting a subject map for each factor; secondly, to establish a complex area for information storage by assembling principal factors, and to develop digital model for simulation analysis; finally, to develop a model of water irruption and to predict possible water irruption problem. Chinese scholars have suggested a predicting model of water-irruption with support of the GIS. Presently, the GIS method has been widely used in the prediction of water irruption in China (Zhang Dashun et al., 1994 and Sun Sunan, 1996).

(4) Fuzzy mathematics method. By applying the fuzzy evaluation method of fuzzy mathematics, the Fuzzy mathematics method determines the principle factors affecting water-irruption (such as developing process of geological discontinuities, strength of water-resisting layer, characteristics of water-bearing layer, magnitude of water pressure, conditions of geologic structure etc.), their membership function and corresponding value of effecting weight of each factor. Afterwards, the degree of water-irruption is evaluated by the rule of maximum membership (Liu Chuantao et al., 2001).

(5) Artificial neural networks system. The theory of artificial neural networks is a non-linear science being developed rapidly in world wide in 1980s. Recently, with modification of shortcoming of BP neural networks that exists many local minimum, adoption of the advantage of the genetic algorithm that may local the global minimum, training of neural networks by using generic algorithm. The artificial neural networks for predicting water-irruption have been developed in China (Wang Lianguo and Song Yang, 2001).

(6) Nonlinear theory. It is well known that the nonlinear theory can be used to solve lots of complicated engineering problems. It is believed that the nonlinear theory that includes some important branches, such as fractal theory, chaos theory, dissipation theory, nonlinear dynamics etc., will provide an important tool in prediction of water-irruption in the near future.

2.2 Prediction techniques of water irruption

Recently, because of the rapid development of tunnel construction, geological disasters such as rock burst, water-irruption and collapse are becoming serious increasingly. In order to avoid and reduce those disasters, and ensure the safety and fast construction of tunnels, geological prediction is being developed for this purpose. Prediction of water irruption in tunnel construction is also a key area to study in many countries such as the UK, France, Japan and Germany. In China, research on geological prediction during tunnel construction was started at the end of 1950s, and the real application of

1. Geology method. The geology method mainly takes advantage of the geological conditions ahead of a tunnel face to perform the prediction. Those geological conditions mainly include orientation of discontinuities, degree of fragmentation of rock mass, water content of rock mass, volume of water flow (Chen Chengzong, 1995).

2. Advanced drillings. The advanced drillings method is a direct method to predict water-irruption during tunnel construction. This method judges whether a water-transmitted structure exists by determining if water was found in the leading borehole. When water flows out from the borehole, we can measure the water pressure, the capacity of water flow, and their variation with time for the tectonic zone ahead the excavation face.

3. Wave reflection. The wave reflection method mainly makes use of the phenomena that the acoustic wave, supersonic wave, seismic wave, and electromagnetic wave can transmit and reflect in stratum. By receiving reflection signals of these waves by using a signal collecting system, this method may judge the reflection interfaces (such as faults, weak seams, cavities and so on) and water ahead of a tunnel face. At present, the commonly used testing instruments include: acoustic wave detector, seismometer, surface wave detector, geological radar detector, TSP-203 (tunnel seismic prediction), and high-definition geologic detector etc. (Sun Guangzhong and Wu Zhiyong, 1991)

4. Electrical survey method. The electrical survey method, which belongs to the non-contact exploring technology, can avoid the possibility of water irruption in an area with rich water that can be disclosed by drilling. This method is very appropriate to explore the existence of a tectonic structure containing a large amount of water ahead of a tunnel face. It not only provides a more reliable way to explore faults with large water ahead, but also is of great efficiency, convenience, and low-cost (Liu Qingwen, 2001).

5. Hydrogeochemical exploring technology. The hydrogeochemical exploring technology is to predict the water irruption by studying the natural chemical constitution and isotope of underground water, or observing and analyzing the movement and variation of the tracer in the ground water. It has been shown that the technology has a promising application in exploration of the source of the water-irruption, the runoff channel of ground water, the hydro-connection of various water bearing layers, and the water-resistance and water-transmission properties of fault. Presently, research on predicting techniques for water-irruption during tunnel construction is still underway, and is also an important research subject in tunneling engineering. It can be predicted that the comprehensive prediction method based on geological methods that combine all advantages of various prediction methods will be of superiority in the future. In addition, the nuclear magnetic resonance (NMR), some new technologies monitoring temperature of rock mass and water, will be gradually applied in the prediction of water irruption during tunnel construction (He Faliang, 2001).

3. MONITORING AND NUMERICAL SIMULATION METHODS FOR SEEPAGE FIELD OF GROUND WATER

3.1 The monitoring methods for seepage field of ground water

Generally, In order to know the seepage condition of rock mass for tunnels or underground structures in operation, to provide the designer with necessary supports for corresponding layout of seepage-controlled countermeasures, and to protect the safety of underground structures, it is usually necessary to arrange monitoring instruments at some places where the rock mass is greatly affected by ground water flow, to measure the water pressure, and to monitor the seepage field of ground water. The commonly used pore water gauges are of double pipe, air pressure, resistance, vibrating etc. (CECS55-93) Among them, because it can transmit frequency signal, and has a great ability of resisting disturbance, the vibrating pore water gauge is often used (Wu Zhongru, 1999).
With the rapid development of optical fibre technology, the new type of monitoring instrument based on optical fibre technology has been gradually applied to actual projects rather than in laboratory (Liu Xiong, 1999). Recently, in-situ monitoring tests and application research by applying the optical fibre technology have been carried out in many Chinese hydropower projects, such as Gezhouba Project (Jin Keli et al., 2005), Three Gorges Project, and Geheyan Project etc. it has been shown by testing results and research output that the optical fibre osmometer has some merits of small volume, high precision, wide range of measurement etc. It has an obvious advantage and a promising prospect compared to the conventional monitoring instruments.

3.2 The numerical simulation methods for seepage field

By numerical simulation and stress coupling analysis for seepage field based on monitoring information obtained, we can predict the development pattern of seepage field, evaluating the effect of the seepage field on the stability of tunnels and other underground structures, and learning the effect of the seepage-controlled measures. Afterwards, it can provide scientific supports on designing schemes of seepage monitoring and seepage control, and optimizing the supporting design of tunnel.

The currently used seepage models of jointed rock mass include: 1) Double medium model of jointed rock mass; 2) Discrete crack network model; 3) Equivalent continuous medium model (Priest and S. D., 1993). Among them, by applying the theoretical basis of porous medium seepage theory and rich numerical simulation experience, the Equivalent continuous medium model can reflect the basic characteristics of jointed rock mass such as non-homogeneity and anisotropy. It has become the most commonly used model in numerical analysis of seepage field presently (Chai Junrui, 2002).

Numerical method is often used for seepage analysis, and the finite element method is the most commonly used numerical simulation method today. As the problems of underground water are widely existed, much special computer software for this problem has been developed in China and other countries. The seepage analysis programs of STSE-2D and FAPD-3D based on the saturation condition have also been developed by IWHR. Since stress-strain analysis of Geotechnical engineering often involves the problem of ground water, the multi-field coupling model that can simulate seepage is usually included in some large FEM software, such as ANSYS, ABAQUS etc., and some special software for geotechnical engineering analysis, such as GeoStudio and FLAC3D etc.

4. CASE STUDY

4.1 Brief introduction of the Nuozhadu Hydropower Project

The Nuozhadu Hydropower Project is located in the middle of Lancangjiang River, Yunan, China. Its water-diversion and power-generation system are arranged on the left bank. The main caverns such as main generator room, main transformer room, tailrace gate room, and tailrace surge chamber are located in a depth of more than 200 meters. The type of rock mass is slightly weathered or fresh granite. The ground water level in the mountain is about 70 meters above the cavern roof. For safety, four layers of grouting adits are arranged at elevation 821.5m, 755.0m, 690.0m, and 648.0m on the upstream side of the main powerhouse, and an impervious curtain is also grouted. In addition, two layers of drainage galleries are arranged at elevation 605.0m and 575.0m around the main caverns in the project area, and drainage holes are drilled in these galleries, forming a drainage curtain around the underground structures. Moreover, a layer of light water proof membrane is arranged at the top of the main cavern crown, which results in converting seepage water to the side walls and draining them conveniently.

4.2 Model construction

The Contour of natural ground water level is plotted in Fig.1 by using the observation information at different observatory holes. According to the contour of ground water level as shown in Fig.1, boundary conditions of calculation area of the finite element model can be determined. The bottom of
A model, which is at elevation 400m, is set to be impervious. The middle line of the river is specified as the upper stream boundary with given water head; tail water level is set to be controlling water level boundary, and the surface over the downstream water table is specified as possible overflow boundary. In analysis, the grouting curtain is simulated by entity elements. The system of drainage galleries and holes is simulated by given a water head. Finally, the finite element model after discretization includes 14433 elements and 16748 nodes. The 3-D finite element (FE) model of seepage is shown in Fig. 2.

4.3 Result analysis

It can be shown from the analysis results that the ground water level in the area of underground powerhouse has been controlled effectively when the impervious and drainage curtain jointly take effect. In the normal condition, the top of the underground powerhouse is above the underground water table (Fig.3). The underground powerhouse is not inundated by the water flow from upstream and downstream sides; however, wetting still exists in the part of upper wall as shown in Fig. 4. It can be concluded by analysis results of the 3-D FE seepage analysis that the total drainage capacity is 3800 m$^3$/d at least by using drainage system proposed, and there is no risk of seepage failure in the fault zone. Generally, Seepage field and corresponding seepage loads within rock mass can be obtained from the 3-D FE seepage analysis mentioned above. Afterwards, these seepage loads can be coupled into the following 3-D stress-strain FE analysis for underground powerhouse during excavation or after reinforcement.

Following the 3D FE analysis previously mentioned, it can be shown from the analysis results that the distribution density of plastic zone and crack zone of rock mass is increased on the side walls of main caverns prior to and after reservoir filling; the displacement around the caverns is also increased, however the magnitude is allowable. Therefore, if the seepage control system adopted was reasonable, the seepage field would not put much influence on the stability of the hydropower cavern.

5. CONCLUSIONS

The ground water existed in the rock mass has an important influence on the safety of tunnel during construction. Main methods such as information analysis method, expert system method, geography information system method, fuzzy mathematics method, artificial neural networks system method, and nonlinear theory can be applied to predict water-irruption flux during tunnel construction. In addition,
geology method, advanced drillings, wave reflection, electrical survey method, and hydrogeochemical exploration also provide a promising tool for the prediction of water irruption. Underground water seepage field also poses an important influence on the stability and safety of tunnels and large-scale excavations in operation. The distribution of seepage field can be monitored exactly by reasonably arranging advanced monitoring instruments. The evolvement of the seepage field of ground water can be predicted by using numerical analysis methods. The analysis results combined with the monitoring information can be used to evaluate the effect of seepage field on the stability of underground structures. It will provide a scientific support for designing schemes of seepage-controlled countermeasures, optimized tunnel reinforcement.

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