Study on early-warning System of Karst Tunnel Collapse

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Abstract: During the construction of karst Tunnel, tunnel collapse often occurs. The establishment of early-warning system of tunnel collapse can effectively ensure the construction safety, but the research is insufficient. Based on the combination of theoretical analysis and engineering practice, this paper puts forward to early-warning system for karst tunnel collapse. (1) The evaluation index system of karst tunnel collapse is composed of anchor axial force, displacement, anchor pull-out force and steel arch stress. (2) The relationship between evaluation index and warning level is determined, and the early-warning system of tunnel collapse is established. (3) The model applied to Chong'anjiang tunnel collapse warning, and achieved good results.

1 Introduction

Tunnel engineering has the characteristics of many risk factors, complex construction technology and huge investment. Compared with other tunnels, the risk of collapse in karst tunnel during construction is higher. In Southwest China, more than 1/3 of the carbonate areas are concentrated, which are easily to form karst areas. Tunnel collapse seriously endangers the safety of construction in Southwest China.

The establishment and application of karst tunnel collapse early-warning system can effectively ensure the safety of tunnel construction and reduce losses. However, the research on the establishment of early-warning system of tunnel collapse in karst tunnel construction is still insufficient.

Wang Tianyu^[1] established a landslide early-warning system based on tunnel characteristics and climate factors. And Zhou Xiaoyong^[2] established a landslide early-warning model based on the mechanical properties of surrounding rock. Ma Shiwei^[3,4] has studied the establishment method of collapse early-warning system for tunnels with weak surrounding rock and loess. Wu

Ke^[5], put forward the establishment mode of landslide early-warning from monitoring measurement and from geological advance prediction. Xue Yiguo^[6] has established an early-warning system for karst tunnels by combining advanced prediction with monitoring measurement.

In this paper, based on the Chong'anjiang tunnel in Guizhou Province, fully considering the characteristics of karst tunnel collapse, the tunnel collapse early-warning system is established.

2 Establishment of karst tunnel collapse early-warning system

2.1 Determination of warning degree

Five color early-warning is established to judge the degree of harm, degree of emergency and development trend of collapse during the construction process. The warning degree is indicated by red, orange, yellow, blue and white, as shown in Table 1.

Table 1 Five color early-warning degree for tunnel geological hazards

Five color warning degree	Warning limit	Explain
Red	Giant warning	The surrounding rock is unstable and the risk of instability is very high
Orange	Severe warning	The stability of surrounding rock is poor and the risk of instability is high
Yellow	Moderate warning	The surrounding rock is basically stable, and the risk of instability is general
Blue	Mild warning	The stability of surrounding rock is good and the risk of instability is low
White	No warning	The surrounding rock is very stable and the risk of instability is very small

2.2 Evaluation index and grade

There are many evaluation indexes that affect the stability of karst tunnel. Based on the relevant research and comprehensive analysis, the indexes of bolt axial force, displacement, bolt pull-out force and steel arch stress are selected to form the evaluation index system of tunnel stability. In order to achieve the purpose of dynamic early-warning, the geological and

topographical factors of the tunnel or the tunnel itself are no longer considered here.

The evaluation indexes are divided into two levels according to the different positions of anchor and different displacement monitoring positions, as shown in Table 2

Table 2 Tunnel stability index system

Primary indicators	Secondary indicators
Bolt axial force	Roof bolt Left haunch bolt Right haunch bolt
Displacement	Vault displacement Peripheral displacement
Stress of steel arch	Stress of steel arch
Pull out force of anchor rod	Qualified rate of anchor rod pullout force

(1) Test of bolt axial force

The axial force test of bolt is mainly used to understand the stress state and axial force of bolt, determine the deformation trend of surrounding rock, and finally evaluate the effect of bolt support. If the

axial force of bolt is too large or too small, it will have adverse effect on the stability of surrounding rock. The risk assessment of bolt axial force test is shown in Table 3.

Table 3 Relationship between bolt axial force and early-warning level

Evaluating indicator	Warning level				
	V	IV	III	II	I
Roof bolt	$0.95N_s \leq N_i < 1.05 N_s$	$0.9 N_s \leq N_i < 0.95 N_s$ Or $1.05 N_s \leq N_i < 1.1 N_s$	$0.8 N_s \leq N_i < 0.9 N_s$ Or $1.1 N_s \leq N_i < 1.2 N_s$	$0.7 N_s \leq N_i < 0.8 N_s$ Or $1.2 N_s \leq N_i < 1.3 N_s$	$N_i < 0.7 N_s$ Or $1.3 N_s \leq N_i$
Left haunch bolt	$0.95 N_s \leq N_i < 1.05 N_s$	$0.9 N_s \leq N_i < 0.95 N_s$ Or $1.05 N_s \leq N_i < 1.1 N_s$	$0.8 N_s \leq N_i < 0.9 N_s$ Or $1.1 N_s \leq N_i < 1.2 N_s$	$0.7 N_s \leq N_i < 0.8 N_s$ Or $1.2 N_s \leq N_i < 1.3 N_s$	$N_i < 0.7 N_s$ Or $1.3 N_s \leq N_i$
Right haunch bolt	$0.95 N_s \leq N_i < 1.05 N_s$	$0.9 N_s \leq N_i < 0.95 N_s$ Or $1.05 N_s \leq N_i < 1.1 N_s$	$0.8 N_s \leq N_i < 0.9 N_s$ Or $1.1 N_s \leq N_i < 1.2 N_s$	$0.7 N_s \leq N_i < 0.8 N_s$ Or $1.2 N_s \leq N_i < 1.3 N_s$	$N_i < 0.7 N_s$ Or $1.3 N_s \leq N_i$

(2) Tunnel convergence displacement

The convergence displacement of tunnel includes vault settlement and peripheral displacement, as

shown in Table 4.

Table 4 Relationship between convergence displacement and warning level

Evaluating indicator	Warning level				
	V	IV	III	II	I
Vault displacement	$U_0<0.6U_n$ no inflection point in the displacement-time curve	$0.6U_n<U_0<0.8U_n$ no inflection point in the displacement-time curve	$0.8U_n<U_0<U_n$ no inflection point in the displacement-time curve	$U_n<U_0$ no inflection point in the displacement-time curve	There is inflection point in the displacement-time curve
Peripheral displacement	$U_0<0.6U_n$ no inflection point in the displacement-time curve	$0.6U_n<U_0<0.8U_n$ no inflection point in the displacement-time curve	$0.8U_n<U_0<U_n$ no inflection point in the displacement-time curve	$U_n<U_0$ no inflection point in the displacement-time curve	There is inflection point in the displacement-time curve

notes: U_0 ——Measured deformation value; U_n ——Allowable deformation value

(3) Pull out strength of anchor rod

The tensile pull-out test of anchor rod refers to the maximum tensile force that the bolt can bear. It is a

comprehensive reflection of the quality of bolt material, processing and construction and installation. Whether the pull-out force of the bolt meets the requirements directly affects the effect of the bolt. When the pull-out force of the bolt is insufficient, it can not play the role of

anchoring the surrounding rock, so the detection of the tensile pull-out force of the bolt is very important.

According to (JTJ 042-94), at least three anchors shall be selected randomly for each installation of 300

anchors, and the three bolts shall be taken as a group for pull-out test in the same section, and another group shall be conducted when the surrounding rock changes.

Table 5 Relationship between pullout resistance of bolt and warning level

Evaluating indicator	Warning level				
	V	IV	III	II	I
Qualified rate of anchor rod pullout force	90%-100%	80%-90%	65%-80%	50%-65%	Less than 50%
(4)Stress of steel arch	support system can be judged by monitoring the stress of steel arch frame in the section.				
The stress of steel arch frame can directly reflect the stability of tunnel support system. The stability of					

Table 6 Relationship between Stress of steel arch and warning level

Evaluating indicator	Warning level				
	V	IV	III	II	I
Stress variation of steel arch (mm/d)	$\sigma \leq 0.8 [\sigma]$	$0.8 [\sigma] < \sigma \leq 0.85 [\sigma]$	$0.85 [\sigma] < \sigma \leq 0.9 [\sigma]$	$0.9 [\sigma] < \sigma \leq 0.95 [\sigma]$	$0.95 [\sigma] < \sigma \leq [\sigma]$

2.3 Determination of alarm degree and limit

The determination of the alarm degree is generally based on the data and change of the monitoring indicators. If the index value falls in a certain alarm

limit area, it is determined as the corresponding alarm degree.

The division of alarm degree and alarm limit is shown in Table 7.

Table 7 The division of alarm degree and alarm limit

Five color warning degree	Warning limit	Explain
Red	Giant warning	The warning level of any index is grade I, or two or more indicators are grade II, and the change trend is increasing
Orange	Severe warning	No warning level is higher than grade I, and there is one index whose warning level is grade II
Yellow	Moderate warning	No warning level is higher than grade II, and there is one index whose warning level is grade III
Blue	Mild warning	No warning level is higher than grade III, and there is one index whose warning level is grade IV
White	No warning	The warning level of all indicators is grade IV.

2.4 Early-warning and treatment

Based on the summary of experts' opinions and

referring to the existing research results, the construction treatment of each early-warning level are determined, as shown in Table 8.

Table 8 Early-warning and treatment

Five color warning degree	Treatment
Red	Stop work and reinforce the process that may cause harm. If necessary, evacuate the non construction personnel in the dangerous area When a large area of overall collapse endangers the safety of construction personnel, all construction personnel shall be evacuated.
Orange	Some processes can be constructed normally, but the processes that may cause harm must be stopped. If necessary, evacuate all non construction personnel in the dangerous area. Continuous monitoring of geological hazards.
yellow	Some processes can be constructed normally, but the process that may cause harm should be slowed down. Continuous monitoring of geological hazards.
Blue	All kinds of working procedures can still be carried out normally, and the monitoring should be strengthened.
white	Normal construction of various processes

3 Engineering examples

3.1 Overview

Chong'anjiang tunnel is a karst tunnel, which is a

separated two-way four lane tunnel, in Guizhou province. The pile number of the left tunnel is zk64 + 270 ~ zk67 + 028, the length is 2758m, and the maximum buried depth is about 337m. The pile number of the right tunnel is yk64 + 270 ~ yk67 + 990,

the length is 2720m, and the maximum buried depth is about 345m.

Taking the tunnel application in a certain mileage section as an example, the accuracy of the model is verified.

3.2 Early-warning results of tunnel collapse

According to Table 2 to Table 6, the early-warning level of tunnel collapse in certain mileage section is determined, as shown in Table 9.

Table 9 Tunnel stability index system

Primary indicators	Secondary indicators	Indicators	Warning level
Bolt axial force	Roof bolt	$1.3N_s \leq N_i$	I
	Left haunch bolt	$1.2N_s \leq N_i < 1.3N_s$	II
	Right haunch bolt	$1.2N_s \leq N_i < 1.3N_s$	II
Displacement	Vault displacement	There is inflection point in the displacement-time curve	I
	Peripheral displacement	$U_0 < 0.6U_n$ no inflection point in the displacement-time curve	V
Stress of steel arch	Stress of steel arch	$0.85[\sigma] < \sigma \leq 0.9[\sigma]$	III
Pull out force of anchor rod	Qualified rate of anchor rod pullout force	90%-100%	V

According to Table 9, the early-warning level of tunnel collapse in certain mileage section is I, Warning degree is red.

In view of the red warning issued in this mileage section, timely measures were taken during the construction process, including: stopping the excavation and closing with C20 shotcrete; adding I22 steel arch protection with the same spacing as permanent steel frame; adding I22 temporary inverted arch, large lock foot and soil nailing according to the monitoring data; radial grouting with $\Phi 42$ self-propelled anchor rod with a length of 4.5 m, spacing of $1.5\text{m} \times 1.5\text{m}$, injection of double liquid slurry.

After the reinforcement measures are adopted, the initial support of each section has a large growth rate in 5-8 days, which is in a slow growth period in 8-20 days, and tends to converge after 20 days.

4 Conclusion

Based on the combination of theoretical analysis and engineering practice, this paper puts forward to early-warning system for karst tunnel collapse.

(1) The evaluation index system of tunnel collapse is composed of anchor axial force, displacement, anchor pull-out force and steel arch stress.

(2) The relationship between evaluation index and warning level is determined, and the early-warning system of tunnel collapse is established.

(3) The model applied to Chong'anjiang tunnel collapse warning, and achieved good results.

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