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Rock mass collapse mechanism of concealed karst cave beneath deep tunnel

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ABSTRACT

Local collapse of the surrounding rock often occurs during tunnel construction in a karst area, particularly when the rock pillar between the tunnel and the karst cave is very thin. The collapse of the surrounding rock in tunnel construction is sudden and may lead to great economic loss or even loss of life. To predict the collapse of rock mass where a tunnel is excavated above a karst cave, an analytical expression of the collapse surface is derived from variational calculation in the framework of the upper bound theorem. Based on the analytical solution, the shape of the collapse surface is plotted to investigate the effects of rock parameters on the collapse surface of the rock mass where a karst cave exists beneath a tunnel. According to the changing law of the collapse surface varying with the distance between tunnel and cave, the computational formula of the minimum safety thickness for preventing the collapse of rock pillar is derived. To evaluate the validity of the proposed method in this paper, we compared the analytical solution with numerical solution. The comparison result indicates the analytical solution matches up with the numerical solution very well, which suggests that the analytical approach proposed in this paper is valid.

1. Introduction

Karst is a common landscape widely distributed in the southwest of China. With the rapid development of infrastructure in China since the start of this century, large numbers of highway and railway tunnels have been constructed, especially in mountainous regions. However, since most mountainous regions are in the southwest of China, the probability of encountering a karst cave for tunnel excavation in these areas is very high. As karst caves are common at different depth underground, it is likely that the rock pillar between tunnel and cave is very thin for the tunnel excavation adjacent to the karst caves in practical engineering. In some cases, there is water or other fillers in the cave. Due to the excavation-induced disturbance, the thin rock pillar cannot bear the huge pressure produced by fillers in the cave, causing the fillers to break into the tunnel. The inburst of the fillers may lead to the occurrence of local collapse of the rock mass around the tunnel. Since the location of the concealed karst cave cannot be determined accurately in the engineering investigation phase, the position of the local collapse around the tunnel is difficult to predict. Furthermore, as the occurrence of local collapse is sudden and instantaneous, the builders do not have time to escape. Thus, if there is no proper precautionary measure, the local collapse may cause serious economic losses and even human casualties.

As the damage of local collapse for tunnel construction in karst areas is so great, the study on this subject has drawn the attention of many investigators. Based on a fluid–solid coupling method and strength reduction method, Zhao et al.[1] established a fluid–solid coupling model to study the stability of a rock pillar on a concealed karst cave ahead of a roadway. Using this model, they calculated the safety thickness of a rock pillar for preventing water inrush from a concealed karst cave. By investigating the distribution of karst landscape in China, Cui et al.[2] described the feature of each karst area in China and analyzed the potential geo-hazards during tunneling in karst areas. They also proposed a treatment technique which can be used to handle the karst cave of those adjacent to a tunnel before tunnel excavation and verified the effectiveness of this technique by a case study. Since a collapse of the residual soil over bedrock cavities is a common accident during construction in a karst terrain, Eric et al.[3] presented a dimensionless stability chart to evaluate the stability of the residual soil near existing cavities based on numerical analyses. As there is no available method to predict the risk of water inrush in the karst tunnel, Li et al.[4] constructed an attribute synthetic evaluation system to evaluate the risk of water inrush in karst tunnels in the framework of attribute mathematical theory. Later on, Li et al.[5] used the geographic information system technology to establish a risk assessment model for water inrush in the karst tunnel. Two types of risk assessment methods, assessment with no geological flaws and assessment with geological flaws were presented by the authors, and

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the reliability of this model was validated by water inrush cases in the auxiliary tunnel in a hydropower station.

However, analytical approaches regarding local collapse of a tunnel excavated in karst areas are rare in literature. Similar to the formation of local collapse for a karst tunnel, the sinkholes formed from the sudden collapse of an underground cavity are common in limestone areas. To assess the stability of the ground where there are underground cavities, Augarde et al.[6] calculated the rigorous bounds of true collapse loads by employing finite-element limit analysis technique. Their results, which are verified by comparison with closed-form solutions, can help engineers to determine the influence region of sinkholes. Linker and Klar[7] constructed a theoretical model of the sinkhole-induced strain profiles, which can be used to generate a database of signals for detecting sinkhole formation in elastic-plastic soil. Another similar issue to sinkhole is tunneling-induced surface settlement, which is often encountered in a shield tunnel drilled in a shallow stratum. On the basis of actual collapse mode of a shallow tunnel, Yang and Huang[8] constructed a curved failure mechanism for shallow tunnels. Employing the variational approach and upper bound theorem, they obtained the analytical solution of a collapse surface, which can be used to predict the possible position and region for the potential collapse of a shallow tunnel. To predict ground movements caused by shallow tunneling in soft ground conditions, Pinto and Whittle[9] presented a closed-form analytical solution based on idealized modes of uniform convergence and ovalization. Their solutions have two advantages: they provide a more comprehensive framework for understanding ground deformation on one hand and they need fewer input parameters during the calculation process on the other.

This paper is concerned with predicting the collapse of rock mass where a karst cave exists beneath a deep highway tunnel. Based on the mechanical characteristics of the collapse for rock mass at the tunnel base, we constructed a failure mechanism, the velocity field of which is kinematically admissible. Using this failure mechanism, an objective function composed of the external rate of work and the rate of internal energy dissipation is constructed in the framework of the upper bound theorem. With the variational approach, the analytical expression of the collapse surface is derived. The research presented here can be used to determine the position and range of the potential collapse surface, which helps engineers to estimate the stability of rock mass at the bottom of the tunnel above a karst cave.

2. Failure mechanism of rock mass for a karst cave beneath a tunnel

Due to the blasting disturbance or other factors in tunnel construction, the collapsing block is moving downwards with velocity v relative to the rest of surrounding rock, and the two parts are separated by a narrow transition layer of plastic deformation. In this process, the detaching surface (also called collapsing surface) is formed. As the interface between the collapsing block and the remaining surrounding rock is rough, the detaching surface is an irregular curved surface resulting from the friction on the interface. This means that the curves which make up the detaching surface cannot be described by any predefined equation. Consequently, how to construct a failure mechanism conforming to the failure characteristic of the detaching surface in a kinematically admissible field is an issue confronting many investigators. Fortunately, an analytical approach developed by Fraldi and Guarracino[10] provides an effective means for calculating the analytical expression of the detaching surface.

According to their approach, the failure mechanism is composed of an arbitrary curve and the analytical expression of this curve can be derived from a variational calculation. Thus, one of the biggest advantages for the approach proposed by Fraldi and Guarracino[10] is that there is no need to assume any linetype which is used to constitute the detaching surfaces in a kinematically admissible velocity field. Furthermore, the final result of the detaching surface derived from variational calculation is not described by standard curves such as log-spirals, which makes the result conform to the collapse observed in actual engineering.

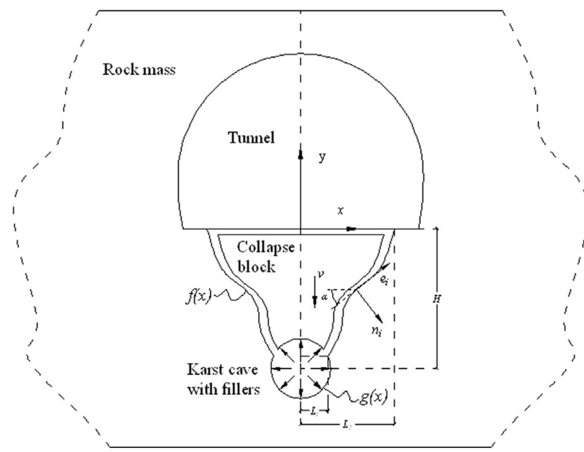

Fig. 1. Rock mass failure mechanism of a karst cave beneath a tunnel.

In view of the advantage of this method, by using an arbitrary curve, we constructed a failure mechanism formed from the collapse of rock mass between the tunnel and the karst cave. As shown in Fig. 1, there is a karst cave beneath a deep multi-circular road tunnel, and a collapse block constituted by an arbitrary curve $f(x)$ extends from the tunnel base to the karst cave roof. Furthermore, the shape of the karst cave is simplified as a circle for mathematical convenience. Suppose the equation of the circle is $g(x)$ and the distance from the centre of the circle to the tunnel base is H. The collapse block moves downwards with vertical velocity v owing to the effect of gravity, causing the collapse in the tunnel base.

Though the application of upper bound theorem for investigating the collapse of the surrounding rock in tunnel construction has numerous advantages, several assumptions should be made before this theorem can be used. Firstly, the material is perfectly plastic and obeys an associated flow rule; secondly, the geometric deformations of the body in the kinematically admissible field are insignificant, which means the collapsing block can be regarded as a rigid body. According to these assumptions, the rate of energy dissipation and the external rate of work which constitutes the virtual work equation can be derived in the subsequent calculation.

3. Upper bound solution of collapse surface

As illustrated in Fig. 1, the plastic deformation occurs from the smooth sliding of adjacent surfaces of a collapsing block and the surrounding rock. The rate of energy dissipation which is produced by the plastic deformation is confined to this region. Since the dissipation of energy in a plastic deformation field can be computed from the plastic stress/strain rate relation, it is necessary to calculate the plastic stress/strain rate in the plastic flow field. Hoek–Brown failure criterion which is widely used to estimate the strength of rock mass is a suitable yield function to describe the plastic flow rule of rock mass in a karst region. The rate of energy dissipation is composed of normal and shear parts, and the Hoek–Brown failure criterion represented by normal and shear stresses is:

$$\tau = A\sigma_{ci}\left(\frac{\sigma_n - \sigma_{tm}}{\sigma_{ci}}\right)^B \tag{1}$$

where σ_n is the normal stress, τ is the shear stress, A and B are material constants, σ_{ci} is the uniaxial compressive strength and σ_{tm} is the tensile strength of the rock mass. According to Fraldi and Guarracino,[10] the rate of dissipation of energy per unit area in the plastic flow field subjected to the Hoek–Brown failure criterion can be demonstrated as: