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Prediction of karst for tunnelling using fuzzy assessment combined with geological investigations

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ABSTRACT

This paper presents a method for predicting karst features before and during tunnel construction. The prediction of karst consists of two components: an initial karst prediction using a fuzzy assessment system to evaluate the underground karst state and an updating karst prediction where appropriate geological investigation methods are selected based on the assessment of underground karst state. The investigation results are then used to update the underground karst state. The initial assessment system is based on a fuzzy comprehensive evaluation method. Nine influence factors are selected as the evaluation indices for the underground karst state, and each index is quantitatively rated to four grades. The membership of the evaluation index is determined by using a membership function, and the weights of these indices are distributed by using a fuzzy Analytical Hierarchy Process. The fuzzy transform principle and maximum membership degree principle are applied to determine the underground karst state level. Based on the assessment result, several techniques for geological investigation, including the seismic reflection method, ground penetrating radar, infrared water detection, transient electromagnetic method, and advance probe boreholes, are recommended to predict the location, size, and distribution of karst features ahead of tunnel faces. These geological investigations have different characteristics and can be combined to improve the accuracy of the geological prediction. The appropriate combination of investigation methods is selected using the assessed underground karst state, and the investigation results are also used as the input to update the underground karst state. The proposed method can improve the prediction of karst in tunnelling. An application of this method was performed in the Doupengshan tunnel project.

1. Introduction

Tunnel construction in karst terrain is fraught with problems associated with the unexpected location, irregular geometry, and unpredictable dimensions of karst structures (Alijia et al., 2013). Many cases around the world have shown that karst is the major challenge for tunnelling in karst areas since the presence of karst features can lead to economic, safety-related, and environmental problems (Casagrande et al., 2005; Filipponi, 2015; Zini et al., 2015). The prediction of karst features is critical for the reduction of risk for tunnel construction.

Recently, several methods have been developed for predicting and assessing the karst risk. Computer simulation of the expert decision-making process was used to construct a karst disaster prediction system (Zhang et al., 1993). A ground investigation method named Karst-ALEA based on the knowledge of the speleogenesis processes and 3D modeling was applied to assess the risk of karstic rock masses at the planning stage (Filipponi, 2009; Filipponi and Jeannin, 2010). Some researchers used statistical data of karst features to assess karst hazards (Kaufmann and Quinif, 2002; Waltham and Fookes, 2003; Galve et al., 2011; Zini et al., 2015). These established assessment systems are useful for predicting karst features, but they can only provide overall and approximate guidance for construction. Underground karst structures have complex characteristics and have random distributions in space. For the safety of tunnel construction, it is essential to obtain specific information about karst structures in advance in order to take countermeasures during tunnelling.

Different site investigation and testing techniques can be used to detect unfavourable geological structures in front of the tunnel face. The investigation techniques in karst terrain mainly include two categories. The first category is geological analysis, including geological surveys (Zini et al., 2015), advance drilling, and borehole tests (Pesendorfer and Loew, 2004). The other category includes geophysical methods such as the seismic reflection method (Asadollahi and Foroozan, 2006; Alimoradi et al., 2008; Sun et al., 2008), ground

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penetrating radar (Collins et al., 1994; Conyers and Goodman, 1997; Chamberlain et al., 2000; Al-fares et al., 2002; Knödel et al., 2007), and the transient electromagnetic method (Knödel et al., 2007; Goldscheider and Drew, 2007). Because each technique/method has shortcomings and restricted application conditions (Waltham and Fookes, 2003; Li et al., 2008; Alijia et al., 2013), the prediction of karst with a single technique/method may not be reliable. Thus, different investigation techniques should be combined to increase the accuracy of prediction.

This paper presents a comprehensive method to predict karst features for tunnelling. The method contains two parts: (1) initial karst prediction via assessment of underground karst state before tunnelling and (2) an updated prediction of karst features by combining the previous assessment results with the geological site investigations that occur during tunnelling. The initial evaluation system for assessing underground karst state is constructed based on a fuzzy evaluation method, and the updated karst prediction relies on the assessment results of the underground karst state and appropriately selected geological investigations. The initial assessment result is used to guide the planning of geological site investigations, and the results of the geological investigations are used to update the initial assessment. This comprehensive method can make the prediction of karst more efficient and economical. A case study is provided to demonstrate the application of this method for karst prediction.

2. Methodology for karst prediction

2.1. Initial karst prediction via assessment of underground karst state before tunnelling

Geological data from maps and other sources can be used to assess the underground karst state in advance of tunnel construction. The underground karst state (UKS) is used to describe the current status of the shape and the scale of the underground karst within a region. The assessment of UKS can be regarded as an initial karst prediction. The evaluation system for assessing the UKS constructed in this paper makes use of a fuzzy evaluation method. The fuzzy method is an effective tool to handle the uncertainties and subjectivities, and fuzzy boundaries (Shi et al., 2014; Zhang et al., 2015; Lu et al., 2016; Liu et al.,2017). The main components of the fuzzy evaluation of UKS are: (a) select evaluation indices, (b) establish index set and evaluation set, (c) construct membership function and fuzzy evaluation matrix, (d) determine evaluation indices weights, and (c) produce a comprehensive evaluation.

2.1.1. Evaluation indices for underground karst state

Karstification is a geological process in soluble rock controlled by the solubility and permeability of the rock and the mobility and aggressivity of the groundwater (Sokolov, 1962). Geologic structures, vegetation cover, climate and other factors also affect karst development (LeGrand and Stringfield, 1973; Stringfield et al., 1979; Ford and Williams, 2007; Li et al., 2013). The underground karst state can be assessed from the status of the factors influencing karst development (Stokes and Griffiths, 2000). Based on the existing research and the statistical information of tunnelling cases in karst terrain, several factors are selected as the evaluation indices to assess the UKS.

(1) Formation lithology

Formation lithology is one of the major factors controlling the karst development because the presence of soluble rock is a precondition for karstification. It is more likely for karst to develop in formations with strong solubility than those with weak solubility. The solubility coefficient t has been recommended to evaluate the contribution of formation lithology to karst development (Zhou et al., 2013). The lithology coefficient t is expressed as:

$$t = \sum_{i=1}^{3} A_i B_i = A_1 B_1 + A_2 B_2 + A_3 B_3 = 0.636B_1 + 0.259B_2 + 0.105B_3 \tag{1}$$

where A_1, A_2 and A_3 represent the contribution of a different lithology to karst development and are determined based on the statistical data and expert judgement as suggested by Zhou et al. (2013). The values of B_1, B_2 and B_3, are the proportions of lithology with strong, medium, and weak solubility respectively and meet $B_1 + B_2 + B_3 = 1$ (Xu et al., 2011). The division of lithologies with strong, medium, and weak solubility are presented in Table 1.

Table 1
Solubility of carbonate rocks (after Mao et al., 2010; Zhou et al., 2013).

Solubility	Weak	Medium	Strong
Formation lithology	Impure carbonate rocks, or impure carbonate rocks interbedded with clastic rocks	Pure carbonate rocks interbedded with impure carbonate rocks or clastic rocks	Pure carbonate rocks

Impure carbonate rock includes argillaceous limestone, argillaceous dolomite, siliceous limestone, siliceous dolomite. Pure carbonate rock includes limestone, dolomite, dolomitic limestone, carbonaceous dolomite.

(2) Hydrodynamic condition

The presence and action of groundwater is the other precondition for karstification. The hydrodynamic condition of groundwater can control the karst development. The groundwater in a karst area is divided into four vertical hydrodynamic zones with different characteristics in karst development (Sokolov, 1967). Based on the general characteristics of karst development in different hydrodynamic zones and the specific groundwater features and runoff condition, the groundwater hydrodynamic condition is quantitatively classified into the four grades through expert evaluation.

(3) Geological structure conditions

Geological structures, including faults, folds, joints, and bedding planes, are key to karst development because they host and guide the underground solution conduit networks (Stringfield et al., 1979; Ford and Williams, 2007). The width of fault fracture zones, the structural features of folds, and the spacing of joints or bedding planes are selected to evaluate the contribution of geological structures to karst development. These three parameters are quantitatively classified into the four grades according to four levels of underground karst state.

(4) Landform and physiognomy

Karst is regarded as a distinctive terrain developed in soluble rock with landforms that relate to underground drainage (Waltham et al., 2005). Negative landforms such as valleys, depressions or dolines influence the recharge of groundwater and can reflect the development and occurrence characteristics of karst water. The proportion of the ground surface with negative landforms is selected to assess the contribution of landform and physiognomy to karst development, and it is quantitatively divided according to four levels of underground karst state (Li et al., 2013).

(5) Attitude of rock formation

The attitude of strata in a rock formation also influences the karst development because it affects the permeability of a rock formation and the seepage characteristics of groundwater. The permeability of a rock