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Analysis of factors influencing tunnel deformation in loess deposits by data mining: A deformation prediction model

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ABSTRACT

Due to the special properties of loess, the deformation of tunnels constructed in loess is generally large and easily induced. To control deformation during construction, the degree of influence of multiple factors on tunnel deformation is analyzed by data mining and a deformation prediction model is established, based on tunnels along the Menghua railway of China. Both objective environment and manual operation are considered. The surrounding rock level, groundwater condition, burial depth, excavation method and support close time are selected as the main factors influencing tunnel deformation. The influence degree of each factor is calculated through mining statistical data collected from the project. Finally, using influencing factors as evaluation indices, a Rough set-extension model for predicting loess tunnel deformation is established and tested. Results obtained via the prediction model are in good agreement with field observations. The study quantifies the influence degree of each selected factor on deformation of the loess tunnel, which in turn can help in deformation control efforts. Moreover, the Rough set-extension model realizes a multi-criteria prediction of the loess tunnel's deformation and provides a practical guide for construction of similar projects.

1. Introduction

Loess is composed of yellow silty sediments formed by wind transport during the Quaternary period. Loess is mainly distributed in arid to semi-arid mid-latitudes areas of the northern hemisphere. China's loess deposits (Kukla and An, 1987) are mainly distributed in the arid to semi-arid areas north of the Kunlun Mountains, Qinling Mountains, Mount Tai and Mount Lu. The Loess Plateau of China is the largest loess deposit in the world. Following the adoption of the "The Belt and Road" strategy (Liu, 2015), construction of a number of tunnels has begun through the Loess Plateau of China.

It has been widely recognized that deformation of tunnels through loess deposits is generally large, commonly producing landslides. To control tunnel deformation, an examination of the factors influencing tunnel deformation is crucial. The deformation of a tunnel is affected by various factors, including geological conditions and construction operations.

Loose particle-packing with high porosity and a significant amount of macroscopic pores make up the loess metastable structure (Gao, 1988; Liu et al., 2012). Loess's metastable structure is dominated by a variety of weak or short range bonds between skeleton particles, including matric suction (capillary force), clay, soluble salts and less soluble agents (Matalucci et al., 1970; Rogers et al., 1994). Loess has low shear strength and great compressibility with relatively small changes in stress (Derbyshire and Mellors, 1988; Gao, 1988; Rogers et al., 1994; Kruse et al., 2007). When water content increases, the unsaturated loess matric suction is reduced, force on the tunnel supports is increased and the radius of plastic zone increases (Feda, 1988; Xue et al., 2014). Therefore, the physical, mechanical and deformation properties of loess have a significant impact on tunnel deformation. However, the properties of loess are closely related to the geologic age, transfer processes and sedimentation manner (Jefferson et al., 2003; Reznik, 2007). Especially, sedimentation conditions control the geotechnical behavior of soil to a high extent and loess constituent grains are influenced by their weight and have the same slope with the sedimentation environment (Rezaiy et al., 2011). The geological conditions commonly vary during tunnelling with significant changes in the surrounding rock type, burial depth, and groundwater condition.

As for manual operation, the properties of loess determine the excavation that will cause the minimum amount of deformation. Selecting an appropriate excavation method for a tunnel through loess is a key factor for successful construction of the tunnel (Li et al., 2016). The New Austrian Tunnelling Method (NATM) (Rabcewicz, 2008) is relatively simple, adaptive, cost effective and technically feasible (Fang

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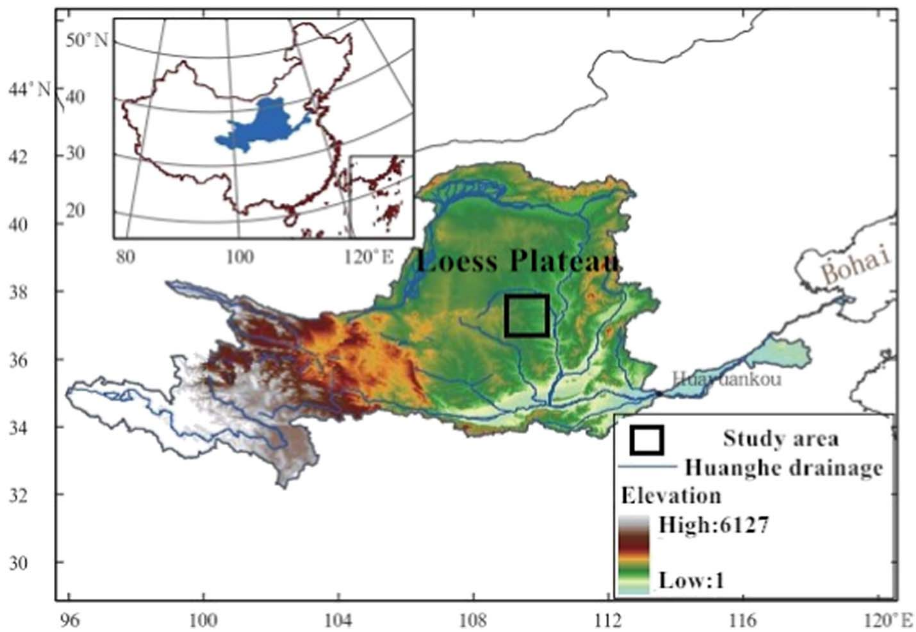

Fig. 1. Map showing the location of study area and the Loess Plateau of China.

et al., 2012). NATM has been widely adopted for tunnel construction in the Loess Plateau of China. The sequential excavation method (SEM), in which the tunnel face is partitioned into several temporary drifts, promotes face stability and reduces ground displacement (Sharifzadeh et al., 2013). The diversity of excavation methods and actual operations by workers also has an impact on deformation of loess tunnels. The above studies respectively examined factors influencing deformation of loess tunnels, which provides the basis for selecting the main influencing factors in this paper.

Soil structure has a direct effect on the mechanical properties of soil (Kruse et al., 2007). Kruse et al. discussed different effects of soil structure on soil mechanics in three case studies. In addition, they pointed out that it was possible to realize the incorporation in the engineering practice of effects of common types of soil structure with the widespread availability of techniques such as numerical modeling. The mechanical characteristics of collapsible soils depend on soil void ratios and moisture content (Reznik, 2007). Jiang et al. (2014) characterized the microstructural evolution of saturated natural loess under triaxial tests and pointed out that the cementation bonds, of which breakage is influenced by stress path and confining pressure, play important roles in the strength and deformation behavior. Growing particle size heterogeneity, varying particle orientations and increasing microstructural damage are the main causes of the alternation in shear strength (Hu et al., 2001). Chen et al. (2017) carried out the dynamic triaxial testing of loess to explore the relationship between the dynamic elastic modulus and confining pressure and found the microstructural parameters had greater correlation with macroscopic strength based on grey relationship theory. Li et al. (2016) conducted a series of in-situ tests and numerical simulations to reveal displacement characteristics and obtain optimal construction approaches for large-span loess tunnels in China. Özbek et al. (2003) carried out the graphical analysis of deformation values measured in the Kızlaç T3A tunnel, which is excavated through a sequence composed of sandstone–shale alternation, sandstones and dolerite dykes, and realized the prediction of the lithological transitions ahead of the face, which was used to determination of the tunnel support system. Sharifzadeh et al. (2013) used three-dimensional finite element modeling to determine excavation method, excavation sequence and optimum trailing distance between different excavation stages in soft ground urban tunnelling according to the deformation characteristics of the tunnel.

Previous studies have made a significant contribution to understanding deformation mechanisms in and the optimal approach to loess tunnelling (e.g., Hu et al., 2001; Kruse et al., 2007; Sharifzadeh et al., 2013; Jiang et al., 2014; Li et al., 2016). However, as described above, the actual tunnel deformation in loess deposits is affected by the combined action of multiple factors. Little has been done to explore how much each factor contributes to the overall deformation of loess tunnels. Therefore, this paper aims to examine the main factors influencing loess tunnel deformation in the Menghua railway of China and predict the amount final deformation. The specific process is as follows.

1. Select surrounding rock level, groundwater condition, burial depth, excavation method and support close time as the main factors affecting deformation of the loess tunnel;
2. Collect displacement monitoring data and values of influencing factors from the excavated tunnel sections;
3. Based on displacement monitoring data, evaluate the final deformation of each section by establishing the Delphi-extension model;
4. According to the division standards, construct the decision table with the evaluated deformation grades and collected values of influencing factors to calculate influence degree (weight) of each factor on deformation using rough set theory;
5. Use the obtained weights and division standards of factors to establish a deformation prediction model of the tunnel using extension theory;
6. Apply the prediction model to a tunnel under construction to test the model's accuracy.

This study quantifies degree of influence of each selected factor on deformation of the loess tunnel, which highlights the main factor controlling the deformation. Moreover, the rough set-extension model utilizes a multi-criteria prediction for the loess tunnel's deformation and helps in support design and making preparatory support arrangements during tunnelling.

2. Overview of the project

Menghua Railway is currently the largest scale coal line in China. It starts at Haolebaoji station in Inner Mongolia and ends at the Ji'an station in Jiangxi Province. The Menghua Railway is 1837 km long and has a design capacity of 200 million tons per year.