Tunnelling and Underground Space Technology 77 (2018) 1–12

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

An improved numerical simulation approach for arch-bolt supported tunnels with large deformation

Weiteng Li[a,c,*], Ning Yang[a,b], Bo Yang[a], Haiyao Ma[a], Tingchun Li[a,*], Qi Wang[c], Gang Wang[a], Yiteng Du[a], Meixia Zhao[b]

[a] Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention, Shandong University of Science and Technology, Qingdao 266590, China
[b] Jiangsu Vocational Institute of Architectural Technology, Xuzhou 221116, China
[c] Geotechnical & Structural Engineering Research Center, Shandong University, Jinan 250100, China

ARTICLE INFO

Keywords:
Tunnel support
Numerical simulation
Arch support
Anchor bolt broken
Separable arch-rock interaction
FLAC^{3D}

ABSTRACT

Our goal was to develop an effective research tool for tunnels with significant deformations supported by arch–bolt union system. The improved numerical simulation approach is constructed through additional development of FLAC^{3D}. There are four parts that form the approach: a yieldable supporting arch module, a separable arch–rock interaction module, a breakable anchor bolt module, and a practicable surrounding rock module. The yield criterion of the supporting arch was proposed and embedded in the modified beam element via the FISH language programming. A separation criterion is proposed for the arch–rock interaction link, and the separable arch–rock interaction module is realized through modifying the normal-yield attachments of the built-in arch–rock links. A tensile breakage failure criterion is proposed for the anchor bolt using the ultimate elongation ratio δ_f of the whole anchor-free part as the criterion. Taking an actual mining roadway tunnel as the simulation object, two simulation schemes adopting the newly improved approach and the original method were carried out respectively, and comparisons of the results show that: (1) the bending moment and axial force at the yielding moment of the compression-bending element change from independent to related after modification, and the computed deviation of the arch model caused by the shortcomings of the original beam element were effectively suppressed; (2) the separable link is proved effective by the supporting forces curves and arch deformation responses; (3) the breaking property of the anchor bolt is implemented, and the response is sensitive; and (4) the surrounding rock controlling results in the modified model scheme are closer to the actual. The analysis shows that the improved numerical simulation approach is much more reliable for large deformation tunnel behavior with arch–bolt union support, especially concerning the bearing and failure behaviors of the supporting arch and anchor bolt.

1. Introduction

Currently, mining depths for both metal ore and coal have increased beyond 1000 m throughout the world, including mines in Sweden, Canada, Australia, and South Africa. Certain metal mines have even reached depths greater than 3000 m (Sun and Wang, 2000; He et al., 2014). By early 2015, nearly 60 coal mines in China had mining depths that exceeded 1000 m (including 7 coal mines deeper than 1200 m); deep coal mining is now imperative (He, 2014; Kang, 2014). Meanwhile, there are lots of roadway tunnels excavated in muddy, weakly cemented soft rock stratum (in Neimeng and Ningxia in west China, e.g.) (Zhao et al., 2014), swelling soft rock (e.g., in the Longkou mining area in east China.), and other special strata with water or faults. Under high ground stress and the other previously mentioned special situations, the traditional support form (rock bolt–steel mesh–-shotcrete) can hardly meet the requirement of controlling the stability of the surrounding rock, and thus the arch-bolt composited support (supporting arch + anchor bolts/cables + shotcrete) became the current main support style in these situations. The cross-section forms of the supporting arch mainly include I-section steel, U-section steel (Brady and Brown, 2004; Wong et al., 2013; Tan et al., 2017), and concrete filled steel tubes (CFSTs) (Chang et al., 2014; Zhang et al., 2017; Huang et al. 2018; Wang et al., 2018). Although high-strength arch-bolt union supports were used, under the effects of soft strata, high ground stress, underground water, mining, and even rock burst (Wang et al., 2000; Jiao et al., 2013; Rodríguez and Díaz-Aguado, 2013), the large deformation and failure problems of support structures and surrounding rocks are still very common. Some typical cases are shown in

* Corresponding authors at: Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention, Shandong University of Science and Technology, Qingdao 266590, China.
E-mail addresses: lwteng2007@163.com (W. Li), tchli_sd@163.com (T. Li).

https://doi.org/10.1016/j.tust.2018.03.001
Received 5 June 2017; Received in revised form 5 February 2018; Accepted 1 March 2018
0886-7798/

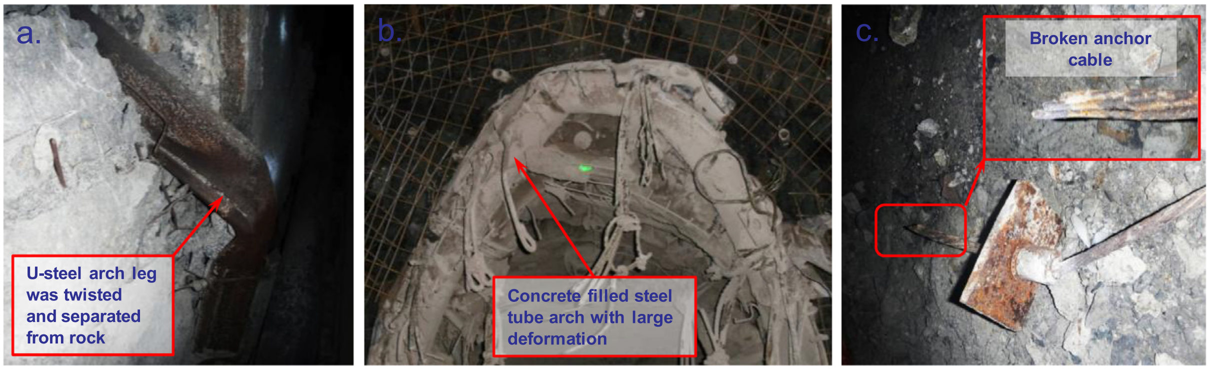

Fig. 1. Typical failure cases of roadway tunnels supported by arch-bolt union style. (a) roadway supported by U-steel arches in a coal mine in east China; (b) roadway supported by CFST arches in a coal mine in west China; (c) broken of anchor cable in a coal mine in mid-eastern China.

Fig. 1, the U-steel arch leg was seriously bent inward and separated from the surrounding rock (Fig. 1a); even in the tunnel using the CFST arch (Fig. 1b), whose bearing capacity is 2 times that of a U-steel arch, the circle tunnel and CFST arches still deformed significantly. In Fig. 1c, this huge deformation was caused by the broken anchor bolts or anchor cables. Similar situations exist in other tunnels such as traffic tunnels, subways, and water conveyance tunnels located in similar complex ground conditions.

The above tunnel support failure problems are very complex, the theoretical analysis method is difficult to operate on this issue, and the model test method cannot be widely used because of its high cost. Currently, numerical simulation is an important and widely used way to study roadway tunnel deformation and support failure mechanisms, and to improve support technology. There are several commercial software programs, such as FLAC^{3D}, ANSYS, and ABAQUS, that are the universally used. At present, the research mainly focuses on the accurate simulation of the mechanical properties of the surrounding rock, and a lot of scholars have developed constitutive models of the surrounding rock based on existing software platforms (Wu et al., 2011; Latha and Garaga, 2012, Li et al., 2013; Pourhosseini and Shabanimashcool, 2014; Fahimifar et al., 2015; Li et al., 2015; Wang et al., 2016). However, little effort has been spent on the support structures themselves, such as the arch supports, rock bolts, or anchor cables (Qi et al. 2004; Schumacher and Kim, 2013; Nemcik et al., 2014; Hegde and Sitharam, 2015; Yu et al., 2016). As a result, there are still obvious deficiencies in the simulation of the mechanical behavior of the support structures; these deficiencies are discussed in the following:

(1) The supporting arches are always simulated by the built-in structure elements in the software platforms, because the use of solid modeling will significantly affect the calculation speed and the results are not easy to manage, although the built-in structure elements usually cannot simulate the real mechanical behavior of the supporting arch accurately. For example, the support arch model established by the beam elements in FLAC^{3D} will significantly amplify the actual bearing capacity because the beam elements cannot yield in the axial direction.

(2) As a result of the mechanical characteristics of the arch shape structure, some parts of the arch structure will separate from the surrounding rock when the deformations reach a certain level (Fig. 1a), and the interaction relation between supporting arch and surrounding rock will be affected by the separating behavior. While, these separating behaviors are always ignored in tunnel support simulations, and thus the reliability of the achieved conclusions relevant to the arch–-rock interaction is reduced.

(3) In tunnels with large deformations, the anchor bolts were subjected to great tensile loads. The anchor bolts will break when the tensile load or tensile elongation became high enough. At present, some anchor cable models address the breakage properties, but they are all refined models for anchor mechanism study on a microscopic scale, and cannot be widely used in real engineering simulations. We were unable to find any research work in the literature on the development of breakable anchor bolt models for the engineering application level.

The research work in this paper is mainly based on the second development platform of FLAC^{3D}. The three previously mentioned problems were first solved through modification of the beam element, link module, and cable element respectively, and an improved numerical simulation approach was then established taking the modifications as the core. Finally, the approach was verified through simulation analysis of a typical real engineering case.

2. General framework

There are four main parts in the improved numerical simulation approach, as shown in Fig. 2.

(1) Yieldable supporting arch module. This task addresses the problem that the beam element in FLAC^{3D} cannot yield in the axial direction; the mechanical properties and yield criterion of the original beam element of the supporting arch will be modified.
(2) Separable arch–rock interaction module. To solve the problem that the arch cannot separate from the surrounding rock in the numerical model, a rock–arch separating criterion will be proposed, and the constitutive model of the built-in link module in FLAC^{3D} will be improved.
(3) Breakable anchor bolt module. To solve the problem that the anchor bolt modeled by cable elements in FLAC^{3D} cannot be broken, a breakage criterion will be proposed based on the elongation ratio of the cable elements, and the axial constitutive model of the cable element will be improved.
(4) Surrounding rock simulation module. To accurately simulate the surrounding rock mechanical characteristics, such as rheology, strain softening, and so on, the corresponding constitutive models of the surrounding rocks will be improved.

The improved numerical simulation of the arch–anchor bolt support in large deformation tunnels will be established as a combination of these four modules. Then the approach will be verified and perfected through real engineering case simulation analysis. However, because there have been many related achievements, the development of the fourth module (simulating the surrounding rock) is currently more mature, there will be no further research on that module in this paper.

3. Yieldable supporting arch based on beam element modifications

According to the FLAC^{3D} user's manual (Itasca Consulting Group Inc., 2005), each beam element is defined by geometric and material parameters. A single beam element is assumed to be a straight segment of uniform asymmetrical cross-sectional properties lying between two