Tunnelling and Underground Space Technology 71 (2018) 382–390

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

A method to estimate the pressure arch formation above underground excavation in rock mass

X.X. Kong[a,b,c], Q.S. Liu[a,b,*], Q.B. Zhang[c], Y.X. Wu[a,b], J. Zhao[c]

[a] Key Laboratory of Safety for Geotechnical and Structural Engineering of Hubei Province, School of Civil Engineering, Wuhan University, Wuhan 430072, China
[b] School of Civil Engineering, Wuhan University, Wuhan 430072, China
[c] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia

ARTICLE INFO

Keywords:
Pressure arch
Arching effect
Underground excavation
Roof stability
Numerical simulation

ABSTRACT

Arching effect has been attributed as a factor of roof stability of underground rock excavations, which affects excavation geometry and rock support. In this paper, a series of numerical investigations were performed using the 2D finite element method (FEM) to study the formation and features of pressure arches. Based on horizontal and vertical stress distributions, three characteristic lines of the arching area were defined, i.e., the outer boundary line, the inner boundary line and the centroid line. It is found that the height of the inner boundary of the arching area is an indicator of the roof stability of underground excavations. Furthermore, detailed parametric studies including the Geological Strength Index (GSI from 20 to 80), the overburden depth (H from 40 m to 420 m), *in-situ* stress ratio (k_0 from 0.8 to 3) and excavation roof rise-to-span ratio (h/B ratio from 0.1 to 0.5) were conducted to discuss their influences on the arching area. The results show that the initial stress state (H and k_0) has more significant effects on the roof stability of underground rock caverns than the GSI and cavern geometry (h/B). A semi-circular roof is optimal design scheme for underground excavation in surrounding mass if only considering the cavern roof stability.

1. Introduction

Arches are well accepted stable structures which have been widely adopted in many buildings and constructions, such as church domes and stone bridges. The arching phenomenon has been observed and described in underground engineering for many decades (Ritter, 1879; Chelapati, 1964; Evans, 1984; Zhao, 2007; Chen et al., 2011). Engesser (1882) proposed 'arching action' above the tunnel roof in cohesion-less ground mass, and clearly formulated the relation between deformation and ground pressure exerted on tunnel linings. IME (1936) made a clear statement that '*The redistribution of weight results in the development of a pressure arch and a somewhat distressed zone therein. The beds within the pressure arch deflect slightly and no longer carry the weight of the superincumbent mass of strata*'. Later, IME (1949) further explained that arches exist above every mine opening and the load of the superincumbent strata was transferred to two abutments. A more precise definition of roof arch was proposed by Terzaghi (1946) that the mechanism of ground arch forming with the development of the loosened ground zone due to tunnel construction could be described by the equal settlement model (shown in Fig. 1). It should be noted that early studies of ground arching are heavily limited to soil material based on Terzaghi's theory and the results of trapdoor experiments, and the theoretical system of the soil arching effect has been established. Arching mechanism has been further improved in terms of theoretical analysis (Handy, 1985; Tien, 1996; Dancygier et al., 2016), numerical simulation (Makai et al., 1997; Lee et al., 2006; Jiang and Yin, 2012), and experimental tests (Paikowsky and Tien, 2002; Eskis et al., 2012; Iglesia et al., 2014).

Arching effect has also been perceived in surrounding rock with underground excavations development. Gerdeen et al. (1977) discovered the favorable effect of the *in-situ* horizontal stress in the formation of the roof arch when analyzing the stability of a bolted mine roof, and Chappell (1979) stated that rock deformation and stress redistribution during excavation might induce ground arching. The peak value of the transferred load was considered as the ability of the arching mechanism (Liang and Zeng, 2002), while the stress transfer in the arching area was also described by the vertical stress redistribution above the spring line by Lee et al. (2006). Yang et al. (2015) proposed the 'pressure arch' as the stress concentration area due to the resistance to the non-uniform deformation of the surrounding rock, and claimed this structure existed beyond the roof. An arching coefficient was proposed by Zhang et al. (2016) to analyze the pressure of the arching

---

[*] Corresponding author at: School of Civil Engineering, Wuhan University, Wuhan 430072, China.
E-mail address: liuqs@whrsm.ac.cn (Q.S. Liu).

http://dx.doi.org/10.1016/j.tust.2017.09.004
Received 19 May 2017; Received in revised form 25 August 2017; Accepted 5 September 2017
0886-7798/

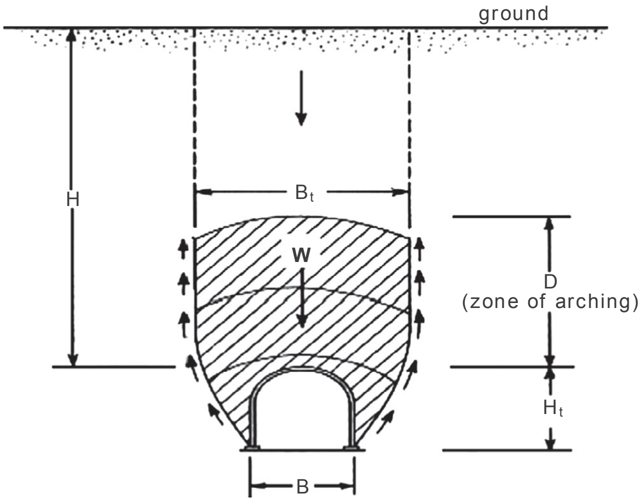

Fig. 1. Zone of loosened ground developed in response to tunnel construction (Terzaghi, 1946).

model and the stability of the underground openings. The above-mentioned methods are essentially continuum methods, however, the formation of pressure arch in jointed rock masses is typically regarded as a discontinuum medium in terms of the Voussoir beam theory (Beer and Meek, 1982; Sofianos, 1996; Hutchinson and Diederichs, 1996) or other methods (Liang et al., 2008; Funatsu et al., 2008; Zhang et al., 2012).

Analysis of the stress distribution clearly illustrated the existence of the pressure arch, and it was also used to indicate the features of the arching area. Jakobson (1958) defined the extent of the arching area that the ratio of the horizontal to the vertical stress was greater than the lateral pressure coefficient. Handy (1985) developed the family of hammock models, such as the path of minor principal stress model. Yang et al. (2015) determined the location of the pressure arch between the inner boundary line where the curve was connected the peak points of the maximum principal stress of the surrounding rock and the outer boundary line connecting the points where the stress variable was equal to 10%. The arching area was also defined by the horizontal and the vertical stresses instead of the principal stresses. Huang et al. (2002) defined the arching zone beneath the inverted principal stress zone within which principal stresses were vertical and horizontal only. The inflection points of vertical stress-depth curves above the tunnel roof were analyzed by Chen et al. (2011) as the reliable indexes to show the development of ground arch.

Although the existence of pressure arches can be illustrated by analyzing stress redistribution, there is no indicator to clearly characterize the nature of the pressure arch area and to build the relationship between this self-stability structure and roof stability in underground rock masses. Furthermore, there is a lack of discussion provided on the factors affecting the properties of the ground arching area and its stabilization mechanism. The insufficient understanding of the arching mechanism in underground excavation impedes consideration of the stabilization mechanism of this self-stability structure in underground engineering and further relevant studies. Thus, it indicates the importance of better understanding of the pressure arch.

This paper aims to gain an in-depth understanding of the arch mechanism of rock structures after excavation based on a series of numerical experiments. With advanced numerical tools, the formation of the pressure arch is illustrated by analyzing the stress redistribution around underground excavations. The comparison between the roof deformation and the location of the inner boundary of the arching area reveals the arch stabilization mechanism. Furthermore, the influencing factors are identified and analyzed in detail. In conclusion, some suggestions are made for the design of profiles of the rock cavern by only considering the roof stability.

2. Numerical model

2.1. Description of calculation model

To obtain a clear understanding of the formation mechanism of pressure arches and their effect on roof stabilization, numerical investigations were conducted by considering various parameters. Some simplifications and assumptions are made as follows: (1) the surrounding rock mass is considered as a homogeneous and elastic-plastic continuum following the Mohr-Coulomb failure criterion; (2) the initial *in-situ* stress is uniformly distributed within the computational domain and the two principal stresses act in the horizontal and vertical directions. Numerical cases are plane-strain models in the commercial software ABAQUS. The 2D numerical mesh and boundary conditions are shown in Fig. 2. The overburden depth H is the vertical distance from the ground surface to the roof of the opening.

Full-face excavation is assumed in all analyses and the effects of the excavation process are ignored. To measure the stress distribution after excavation, 12 measurement lines perpendicular to the surface are located 1 m apart above or near the immediate cavern crown, as shown in Fig. 2.

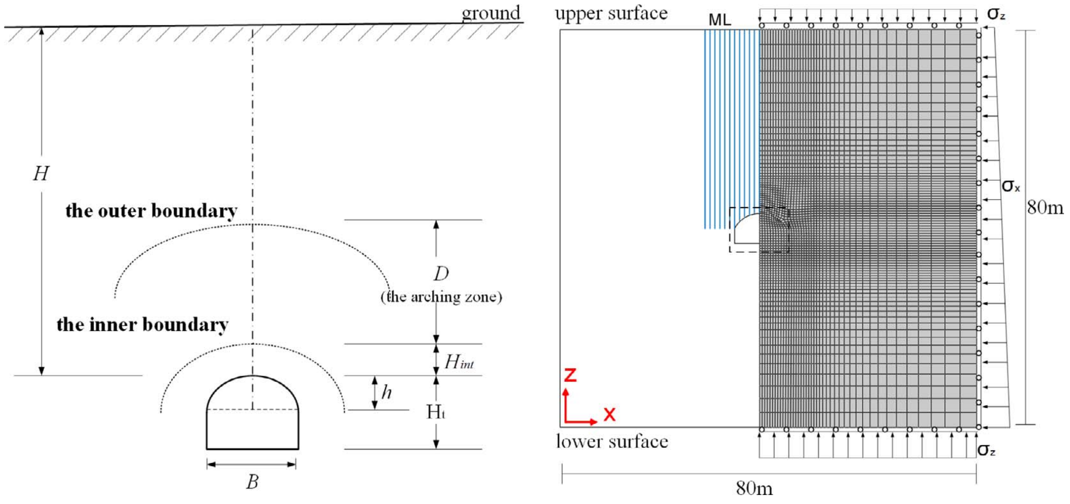

Fig. 2. Boundary constraints on the numerical mesh.