International Journal of Mining Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

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

3D stability analysis method of concave slope based on the Bishop method

Zhang Tianwen [a,b], Cai Qingxiang [a,*], Han Liu [a], Shu Jisen [a], Zhou Wei [a]

[a] School of Mines, China University of Mining and Technology, Xuzhou 221116, China
[b] Xiaolongtan Mining Administration, Kaiyuan 661699, China

ARTICLE INFO

Article history:
Received 28 May 2016
Received in revised form 7 September 2016
Accepted 20 December 2016
Available online xxxx

Keywords:
Bishop method
Concave slope
Three-dimensional structure
Stability analysis

ABSTRACT

In order to study the stability control mechanism of a concave slope with circular landslide, and remove the influence of differences in shape on slope stability, the limit analysis method of a simplified Bishop method was employed. The sliding body was divided into strips in a three-dimensional model, and the lateral earth pressure was put into mechanical analysis and the three-dimensional stability analysis methods applicable for circular sliding in concave slope were deduced. Based on geometric structure and the geological parameters of a concave slope, the influence rule of curvature radius and the top and bottom arch height on the concave slope stability were analyzed. The results show that the stability coefficient decreases after growth, first in the transition stage of slope shape from flat to concave, and it has been confirmed that there is a best size to make the slope stability factor reach a maximum. By contrast with average slope, the stability of a concave slope features a smaller range of ascension with slope height increase, which indicates that the enhancing effect of a concave slope is apparent only with lower slope heights.

1. Introduction

Slopes exist extensively in nature [1] and from a functional perspective they are divided into natural slopes and engineering slopes, and from the perspective of geometrical morphology they are divided into flat slopes, convex and concave slopes. The stability states and requirements of different slopes are different, for example the stability of engineering slopes is directly related to the safety of personnel and equipment, so there are high requirements for their stability [2–4]. Experts and scholars from both home and abroad have committed themselves to the study of slope stability over a long period and have conducted analysis not only from the aspect of the physical-mechanical properties [5] of the rock mass but also from the aspect of slope structure. A large number of studies have shown that the stability of concave slopes is superior to that of flat slopes but even more superior to that of convex slopes [6]. Most of these studies were carried out based on methods such as experiment and numerical simulation, but few have conducted analysis from the aspect of mechanics.

Gray [7] studied the influence of curvature on slope stability, and found that reducing the curvature of a slope stage surface can improve its stability. In 1970, Piteau and Jennings [8] studied the influence of curvature radius on slope stability in a diamond mine and found that the angle of slopes increases as the plane curvature radius reduces. Hoek and Bray [9] summarized slope design experience around the world and found that when the curvature radius of a concave slope is smaller than the height of the slope, the slope angle could be steepened by 10° compared with the angle predicted by conventional stability analysis; for a convex slope with a plane curvature radius smaller than the slope height, its slope angle should be mitigated by 10° when compared with the angle predicted by stability analysis. All of the above studies indicate that concave structures have major advantages for slope stability.

In 1988, Zhang expanded the 2D Spencer method into 3D and proposed a simple 3D analytical method for concave slopes [10]. Zhu et al. [11–14] analyzed the stability of deep-concave rock slopes and pointed out that for a deep-concave slope which is characterized as an ellipse on a plane, its largest stability slope angle appeared at the semi-major axis end while the smallest safety angle appeared at the semi-minor axis end. Then, under the condition that the stabilities of all positions on the slope were the same, they proposed a method for determining the critical-stability slope surface shape which presented as an elliptic slope on a plane. Han et al. [15] studied concave end-slope mechanics and geometrical

* Corresponding author.
E-mail address: hanliucumt@163.com (Q. Cai).

http://dx.doi.org/10.1016/j.ijmst.2017.01.020
2095-2686/

Please cite this article in press as: Zhang T et al. 3D stability analysis method of concave slope based on the Bishop method. Int J Min Sci Technol (2017), http://dx.doi.org/10.1016/j.ijmst.2017.01.020

characteristics of a strip mine and revealed the coupling rules between key factors such as plane curvature radius and slope height ratio and stability coefficients [16]. Since the 70s of the last century, study achievements of national scholars have further proved that concave slopes had advantages in structure [17].

The 2D analysis method, which is a slope stability analysis method with the most extensive application, is used to handle stability evaluation problems of flat slopes of infinite length with advantages such as simple calculation, accurate results, etc. [18,19]. For general flat slopes, the lateral pressure among soil strips inside the slide mass is the same in the opposite direction, so it can be neglected when stability is being calculated. For concave slopes, there is a certain circular acting force at the two sides of soil strips of the slide mass, and the two sides form a certain included angle, its radial resultant force objectively exists and points to the interior of the slope body, so it will be taken into consideration when stability is being calculated. Hence, the influence of soil lateral pressure on the stability of concave slope cannot be neglected. If it is simplified into a 2D slope disposition, then lateral pressure and structural effect cannot be taken into consideration, and the accuracy of stability analysis results is quite low. This paper describes research conducted on the mechanical calculation of concave slopes and, based on the basic principles of the Bishop method, the stability coefficient computational formula of concave slopes when they experience arc sliding is deduced, and further enrichment of concave slope stability analysis is achieved.

2. Concave slope stability computational formula

During open-pit mining, concave slopes, from the top downwards, form a series of coaxial arcs or elliptic arcs, and the slope crest, slope baseline and slope surface on each bench present concave states on a plane. The geometry of a concave end slope is decided by two parameters which are respectively: arch height a and length b, which is half of the arch span, as shown in Fig. 1. The plane curvature radius R of a concave slope in different positions and arch height, as well as R and length b, which is half of the arch span, has the following functional relationship:

$$(R-a)^2+b^2=R^2 \tag{1}$$

After conversion, the plane curvature radius R of the upper realm is:

$$R=\frac{a^2+b^2}{2a} \tag{2}$$

R takes a derivative with respect to arch height a, and then the following can be obtained:

$$R'=\frac{1}{2}-\frac{b^2}{2a^2} \tag{3}$$

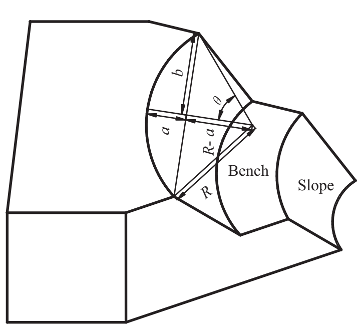

Fig. 1. Concave end slope plane curvature.

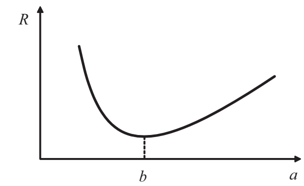

Fig. 2. Relational curve between a and R.

It can be seen from Formula (3) that when $a = b$, R reaches the minimum value b, and its derivative curve is as shown in Fig. 2.

As a basic constituent element of a slope, the concave slope plays a key role in overall slope stability, so this study, starting from the stability of a concave bench, has conducted model establishment and mechanical analysis.

A 3D model is needed to analyze the stability of a concave slope. The traditional limit equilibrium method converts a 3D slope into a 2D plane problem to handle while neglecting the influence of soil lateral pressure on slope stability, which results in a large error in the analysis results. Hence, a 2D model cannot be adopted to analyze the stability of a concave slope. When 3D modeling analysis of a concave slope is being conducted, it is necessary to incorporate the factor of soil lateral pressure and, in addition, the influence of slope curvature radius should be taken into consideration, because when the curvature radii of concave slopes are different, the included angle of soil lateral pressure will change, and so will the radial resultant force; consequently, the influencing degree on slope stability will be different. Hence, it is necessary to conduct mechanical analysis of slices from the 3D angle. The soil strip partitioning method of a 3D concave slope is as shown in Fig. 3.

The slices method was used to conduct modeling analysis of 3D stability of concave slopes. Taking an axis (axis Z) corresponding to the concave slope, with the center line and dθ as an elementary unit, the concave slope was partitioned into several fan-shaped strip columns in the vertical direction. According to differential principles, when dθ tends to 0, fan-shaped columns can be considered as rectangular columns. We took an arbitrary column to conduct analysis and supposed that the slope failure mode was circular sliding. We then partitioned the slide mass along the sliding direction into several vertical slices, assuming that each slice could be approximated as hexahedron, so that the distance from the slice center to the axis of the concave structure was r_i. We took an arbitrary slice to conduct 3D force analysis then, using the Bishop computing method as the basis, we took the soil pressure at two sides of the slice and the concave slope curvature radius as influencing factors and incorporated them into the calculation. We then established a torque equilibrium formula, solved

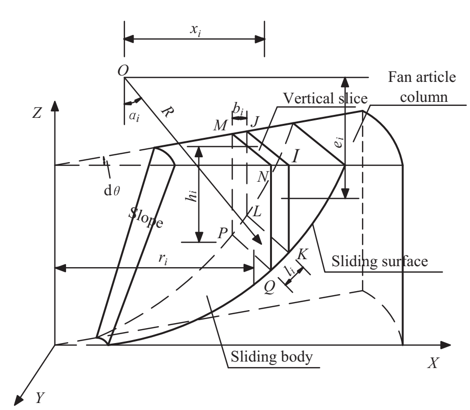

Fig. 3. Partitioning diagram of fan-shaped soil strips.

Please cite this article in press as: Zhang T et al. 3D stability analysis method of concave slope based on the Bishop method. Int J Min Sci Technol (2017), http://dx.doi.org/10.1016/j.ijmst.2017.01.020