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Mechanism of formation of sliding ground fissure in loess hilly areas caused by underground mining

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ABSTRACT

Based on a shallow-buried coal seam covered with thick loose layers in hilly loess areas of western China, we developed a mechanical model for a mining slope with slope stability analysis, and studied the mechanism of formation and development of a sliding ground fissure by the circular sliding slice method. Moreover, we established a prediction model of a sliding fissure based on a mechanical mechanism, and verified its reliability on face 52,304, an engineering example, situated at Daliuta coal mine of Shendong mining area in western China. The results show that the stress state of a mining slope is changed by its gravity and additional stress from the shallow-buried coal seam and gully terrain. The mining slope is found to be most unstable when the ratio of the down-sliding to anti-sliding force is the maximum, causing local fractures and sliding fissures. The predicted angles for the sliding fissure of face 52,304 on both sides of the slope are found to be 64.2° and 82.4°, which are in agreement with the experimental data.

1. Introduction

In recent years, the coal resources in western China have played a very crucial role in the economic growth because of the rapid exhaustion of mining in eastern China. According to the statistics, the six provinces, Shanxi, Shaanxi, Inner Mongolia, Ningxia, Xinjiang, and Gansu account for approximately 80.7% of the total coal reserves in western China. By the end of the 12th five-year plan, coal demand is expected to increase by more than four billion tons per year. However, the production of coal from the six provinces in western China will be three billion tons per year, which accounts for 75% of the total demand [1]. Mining areas in western China are characterized by widely distributed, shallow-buried coal seams and thick unconsolidated layers [2]. As a result of mining, a series of ecological problems such as surface subsidence, landslides, and soil erosion have become an increasingly serious environmental concern [3–6].

The hilly loess area is one of the typical loess physiognomies in western China, which is mainly distributed in the upper and middle areas of the Yellow River, and is characterized by a fragmentary surface, gully aspect, low vegetation, serious soil erosion, etc. [7]. Ground fissure disasters, caused by underground mining, not only cause irreversible damage to the ecological environment of mining areas, but also threaten mining safety [8–10].

In general, mining fissures are formed by the fracture or collapse of topsoil, which results when surface movement exceeds the deformation strength of the top soil [11]. According to the mechanism of formation, mining fissures can be divided into three types as follows: stretching fissures, collapsing fissures, and sliding fissures [12]. A stretching fissure, which is characterized by being narrow, shallow, and non-sidestepped, develops around the working face, and is formed when the horizontal deformation exceeds the tensile strength of the topsoil. In contrast, a collapsing fissure which is characterized by being wide, deep, and step-type, develops above the working face, and is formed due to the surface subsidence caused by strata breaking. Both types of fissure will change their behavior and shape with time, and will develop to become a sliding fissure, owing to the combined effect of the geological mining environment and geographic and geomorphic conditions.

In this study, a mechanical model of a mining landslide was first developed for the shallow-buried coal seams covered with thick loose layers in hilly loess areas. The mechanism of formation of a sliding ground fissure was studied using slope stability analysis using the circular sliding slice method for the soil slope. Based

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on the results of the above study, a prediction model was established, and its reliability was verified by face 52,304, an engineering example, situated at Daliuta coal mine of Shendong mining area in China. The characteristics of sliding fissures caused by mining under slopes covered with thick loose layers were established, and provided a theoretical foundation and a technical reference for predicting mining fissures in hilly loess areas.

2. Mechanical model of a mining slope

Mining fissures in hilly loess areas are a secondary disaster in shallow-buried coal seam mining, caused by the combined effect of surface breaking and slope sliding [13]. Because the development of mining fissures is attributed to the shape of valleys, in order to elucidate the mechanism of the formation of the sliding fissures in hilly loess areas, a mechanical model for mining slopes was first developed.

A natural slope is stable without any external influence. However, a slope under stress will be affected because of the changes in the earth's crust or human activities, possibly leading to sliding. Underground mining inevitably moves the upper slope, thus forming a continuous fractured surface when the entire or a part of slope reaches a limit equilibrium. Next, the soil on the slope surface separates and slides integrally along the sliding surface under the action of gravity, which is known as a mining landslide [14].

When strata break, the surface of the slope is affected both by mining subsidence and slope sliding. Therefore, except for its own gravity G, the slope will also be affected by the surface's incline and horizontal deformations, which change the entire stress state of the slope. All the mining effects can be categorized into three additional stresses: horizontal stress F_ε, shearing stress F_τ, and vertical stress F_ω, as shown in Fig. 1.

The additional stress of a mining slope can be calculated by using Eq. (1) as follows [15]:

$$\begin{cases} F_\varepsilon = P \cdot (\varepsilon + \varepsilon') \cdot \lambda \cdot G \\ F_\tau = P \cdot \xi \cdot (i + i') \cdot G \\ F_\omega = \eta \cdot G + \eta \cdot C \cdot L \end{cases} \tag{1}$$

where F_ε is the additional horizontal stress, F_τ is the additional shearing stress, F_ω is the additional vertical tensile stress, and P is the mining influence coefficient, which represents the destruction level of the slope layer.

$$P = \frac{MD \tan \alpha}{H_0 F} \tag{2}$$

where M is the mining thickness, D is the width of the working face, α is the mean slope angle, H_0 is the mean mining depth under the slope, F is the coefficient of the soil layer, and λ is the lateral force coefficient of the soil layer.

$$\lambda = \frac{\mu}{1 - \mu} \tag{3}$$

where μ is the Poisson's ratio.

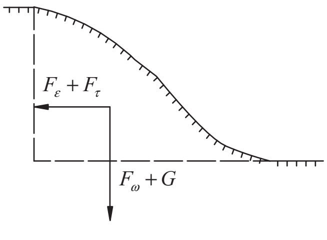

Fig. 1. Mechanical model of a mining slope.

$$G = A\gamma \tag{4}$$

where G is the gravity of the slope, A is the slope volume per thickness, γ is the volume weight, ε and i are the maximum static horizontal tensile deformation and the maximum static inclination deformation of slope surface in the inclination line, respectively. ε' and i' are the dynamic horizontal tensile deformation and the dynamic inclination deformation, respectively. C is the cohesion, L is the length of the sliding surface, and ξ is the ratio of slope height and mining depth.

$$\xi = h/H_0 \tag{5}$$

where h is the height of slope, H_0 the mean mining depth under slope, and η the deformation disturbance coefficient.

$$\eta = \frac{PW}{H_0 - h} \tag{6}$$

where W is the subsidence of the top of slope.

When calculating each additional stress by using Eq. (1), some precautions should be taken as follows:

(1) The coefficient, F, is characteristic of the stratum. The harder the stratum, the greater is the value of F. In general, the F value for a soil slope is 1.0–1.4.
(2) The value of ε is positive when the slope is located at the drawing zone; otherwise, it is negative. Although ε' is always positive, and is only considered when the top of the slope is located above the goaf and ε is negative, the value is about 60% of the static tensile deformation.
(3) The values of i and i' are positive when the inclination deformation is in the same direction with the inclination of slope; otherwise, they are negative.

3. Sliding mechanism of a mining slope

Mining slopes are classified into two types: rock slopes and soil slopes. In general, slopes in loess gully areas can be regarded as soil slopes because of the thick loose surface layer. Unlike rock slopes, a sliding face does not exist in soil slopes, similar to a fracture face. Therefore, a circular sliding face may exist after underground mining. The slope slides circularly when the down-sliding force is more than the anti-sliding force.

3.1. Circular sliding of soil slope

The circular sliding of a soil slope indicates the presence of a potential arc surface in the soil slope. The stability of a soil slope is usually analyzed by the circular sliding, slice, and finite element methods [16]. Generally, the circular sliding method is only applicable to a cohesive soil slope whose internal friction angle is 0. The finite element method is an intuitive simulation method using numerical calculation, which is disadvantaged by poor objectivity of discrete grids and low accuracy [17]. The slice method, however, is suitable for quantitative analysis of all kinds of soil slopes, with high precision. Generally, hilly loess areas in west China are covered with soil slopes of powder loess; among these the slice method was employed to study the sliding ground fissures of mining slopes.

In the slice method, the slope is divided into n slices in the vertical direction. All the stresses of each slice are projected into the sliding surface and divided as follows: (i) tangential force, T, along the sliding surface and (ii) normal force, N, perpendicular to the sliding surface, as shown in Fig. 2, where AB is the natural surface of the slope, AD is the circular sliding surface of the slope, α is the mean angle of the slope, and β_i is the sliding angle of the i-th slice of the slope.