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Formation Mechanism and Stability Analysis Method for Wedge Loess Collapse

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Abstract Wedge loess collapse is one of the important forms of loess collapses. Wedge collapse is mainly controlled by two structural planes whose tendencies are opposite. In the process of slope excavation, the unloading effect on the slope surface results in the compressive stress in the slope body to be readjusted, stress difference of slope body increases gradually from inside to outside, and the free surface in the slope body becomes slack and deformed. The original joint fissure of slope expands gradually. When the wedge is in a state of criticality, a sliding trend emerges on a sliding surface. If the shearing strength of the cement on this sliding surface could not resist the sliding force, the load gradually and rapidly moves to another slide surface, and a wedge collapse will arise. According to the destruction mechanism of wedge collapses, the model of geomechanics is proposed. Formulas are established to calculate the coefficient of stability of wedge and various structural planes by combining the limit equilibrium equation with Mohr-Coulomb strength criterion. The stability analysis method of wedge loess collapse is put forward. The research results provide the theoretical basis for the quantitative evaluation of the stability of loess collapse and they have important reference value for the design and construction of loess collapse control.

Keywords Loess collapse, Wedge collapse, Formation mechanism, Stability Analysis

1. Forewords

Loess collapse is the most common geological disaster in the loess area. According to the statistics [1-2], 354 people were killed and 227 were wounded due to pore cave destruction in the Loess collapse disasters from 2001 to 2005 in YanAn. In recent years, the frequency of the collapse disasters in loess area is unabated, which directly threaten the safety of people's lives and property. Wedge loess collapse is the most common loess collapse disaster in the loess area, especially in the loess plateau of Northern Shaanxi province in China. Loess plateau of Northern Shaanxi is located in the southeast of Shaan-gan-ning basin. The stratigraphic units with the regional joints in Shaan-gan-ning basin district of the northern China are in good development. Loess is the unconsolidated sediments produced in quaternary and the original joint, secondary joint and tectonic joint are within it; however, those joints are one of the main reasons resulting in the landslides. Wedge loess collapse happens when the joints within the loess slope and the different combinations of the slope surface divide the slope soil into the different blocks with free face.

People pay attention to the wedge collapse early as it is the most common disaster type of collapse. Hu and Lei et al [2-3] gave the definition of wedge collapse following investigation; Xu and Wang et al [5] also have also carried out the study on the development by stage of wedge collapse; Xing et al [6] have carried out the centrifugal model test for rock slope, which explains some rules for the deformation and destruction caused by wedge collapse; Zhan [7] has compiled the analysis calculation program for plane polar projection and obtained the analysis method for the stability of wedge collapse based on the plane projection; Zuo et al [8] have carried out the secondary development for ANSYS software on the basis of three dimensional rigid body limit equilibrium theory, and compiled the "wedge slope stability analysis system", which implements the fast evaluation for the stability of wedge slope; Lu et al [9] have utilized the limit equilibrium principle to analyze the equilibrium condition of rock wedge under bearing force and derive the safety factor of the wedge tetrahedron. Qu et al [10] have studied the relationship between the loess clay content and development degree of the loess collapse (slip) disasters from microscopic perspective. Wang [11] has studied the failure modes of the loess collapse wedge based on discrete element numerical value in simulation. Currently, research is mainly focused on the collapse wedge in rock wedge collapse, and research on the loess collapse is scare, and the research on loess wedge collapse is rare. At present, the analysis on the stability of loess collapse is mainly qualitative evaluation [12]. Some experts and scholars also put forward the simple calculation formulas for stability [13-14]. All these theoretical calculations only consider the

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mechanical balance after the collapse body has disconnected from all, but very little consideration has been taken into the structure characteristics of rock and soil. Furthermore, the Mohr coulomb criterion of soil has not been considered. Therefore, the results obtained by using the theory formula still claim further verification. In addition, whether the stability analysis for loess collapse is suitable for wedge collapse is also debatable.

In this paper, the geological mode of loess collapse wedge is set up according to the geological characteristics of the wedge collapse, which reveals the formation mechanism of wedge loess collapse and generalizes the geological mechanical model. The calculation formula for the whole stability coefficient of loess collapse wedge and stability coefficient of each structural plane are established by combining the limit equilibrium equation with the Mohr coulomb criterion. The analysis method for the stability of wedge loess collapse is proposed. The results provide theoretical basis for quantitative evaluation of the stability of loess collapse.

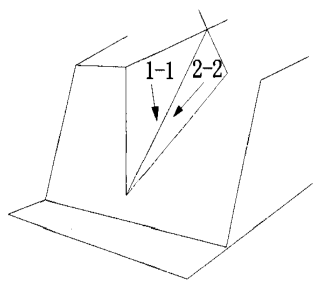
2. Formation Mechanism of Wedge Collapse

2.1. The Formation Process of the Toppling Collapse

Wedge loess collapse is an important form of the loess collapse, which usually refers to the destruction of tetrahedral wedge. In fact, due to the vertical joint, the original joint, tectonic joint and such multiple sets of structure planes are within the loess. The wedge formed by being cut is in three dimensional space state, including wedge pentahedron, hexahedron, and other types. The stability analysis method is basically similar to the wedge tetrahedron. Wedge tetrahedron is only the simplest situation in general wedge destruction. The destruction of the wedge tetrahedron collapse is mainly controlled by the two groups of the structure planes whose tendencies are opposite. The collapse body moves along the direction of the combination of intersecting line of the two structure planes, and the angle of the intersecting line which is exposed out of the slope surface is less than the angle of slope. Because the collapse body moves along the two structural planes at the same time, its mechanical mechanism is more complex. In the process of slope excavation, the unloading effect on the slope surface results in the compressive stress in the slope body to be readjusted. The stress difference of slope body increases gradually from the inside to the outside. The soil becomes flabby, intensity is reduced, and the free surface in the slope body becomes slack and deformed. With the continuous development of unloading deformation, the fissures of the original joints in slope body are constantly widening. Under the influence of the external load, the function of water and under creep deformation, the wedge is in the critical sliding state. A sliding trend emerges on the sliding surface.

When the shearing strength properties of cement on the sliding surface can not resist the sliding force, the load will gradually or quickly transfer to another sliding surface. If the shearing strength properties of cement on the other sliding surface can resist the sliding force, the side slope remains stable; otherwise, the side slope will be destroyed, and the soil will frequently have collapses in the form of wedge destruction (Fig. 1).

(a) Wedge collapse at Lian dagou Village of Ansai County



(b) Sliding deformation figure of wedge

Figure 1. A case of wedge collapse

3. Stability Analysis of the Wedge Collapse

3.1. Analysis Method for the Stability of the Wedge Loess Collapse

Suppose wedge loess collapse occurs at the side slope surface with the slope angle of i and slope height of H (figure 2), and suppose it moves along the two intersecting line OZ of two structural planes, the trend and slope angle of two structural planes KP_1Q and KP_2Q are respectively ω_a, δ_a, ω_b and δ_b; the slope angle of the two intersecting lines is α, the dip angle α can be calculated by the following formula:

$$\tan\alpha = \frac{\tan\delta_a \cos\omega_a - \tan\delta_b \cos\omega_b}{\tan\delta_b \sin\omega_b - \tan\delta_a \sin\omega_a} \tag{1}$$

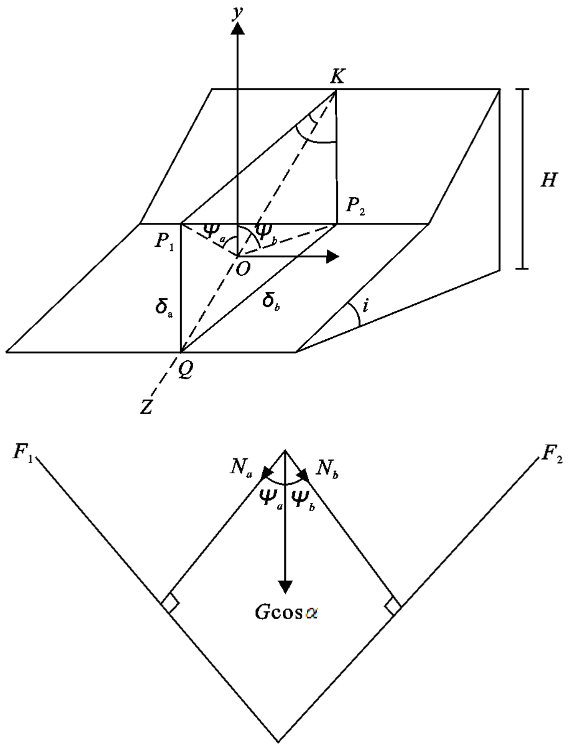


Figure 2. The force diagram of the wedge–tetrahedron

According to the static equilibrium conditions, the following can be obtained:

$$N_a\omega_a - N_b\sin\omega_b = 0 \quad (2)$$

$$N_a\cos\omega_a + N_b\cos\omega_b - G\cos\alpha = 0 \quad (3)$$

$$F_S\sin\alpha - [N_a\tan\varphi_a + c_aA_a + N_b\tan\varphi_b + c_bA_b] = 0 \quad (4)$$

In the formula:

A_a—— area of sliding plane KP_1Q

A_b——area of sliding plane KP_2Q

N_a , N_b—— the pressure of sliding planes KP_1Q , KP_2Q

G—self-weight of wedge, $G = \frac{1}{6}\gamma H^3(\cot\alpha - \cot i)^2 \bullet (\cot\omega_b + \cot\omega_a)\sin\alpha$; the rest is the same as the former calculation.

The following can be obtained by combining above formulas:

$$N_a = \frac{G\cos\alpha\cos\omega_b}{\sin(\omega_a+\omega_b)} \quad (5)$$

$$N_b = \frac{G\cos\alpha\cos\omega_a}{\sin(\omega_a+\omega_b)} \quad (6)$$

Every parameter of the slider of wedge tetrahedron is put into the formula. Suppose the cohesion and internal friction angle of the same kind of collapse body are the same, then the safety factor Fs of the wedge tetrahedron can be obtained by the following formula:

$$F_s = \frac{\tan\varphi(N_a+N_b) + c(A_a+A_b)}{G\sin\alpha} \quad (7)$$

In the formula: c , φ ——cohesive force and internal friction angle of sliding plane

This Research indicates that the internal friction angle of loess is not sensitive to the soil moisture content, and that the intensity of cohesive force decreases in the wet. The cohesive force and the soil moisture content follow the following formula: $c(w) = B_1w^{-B_2}$. B1, B2 are the test parameters which are greater than 0, w is the soil moisture content.

F_s , the formula of overall stability coefficient of wedge collapse is as follows:

$$F_s = \frac{\tan\varphi(\cos\omega_a+\cos\omega_b)}{\tan\alpha\sin(\omega_a+\omega_b)} + \frac{B_1w^{-B_2}(A_a+A_b)}{G\sin\alpha} \quad (8)$$

Stability coefficient on each sliding surface can be obtained by the limit equilibrium condition:

$$F_a = \frac{c_aA_a + N_a\tan\varphi_a}{N_a\tan\psi_a} \quad (9)$$

$$F_b = \frac{c_bA_b + N_b\tan\varphi_b}{N_b\tan\psi_b} \quad (10)$$

If the two-dimensional surface is the only consideration, then Stability coefficient of KP_1Q , KP_2Q surfaces is as follows:

$$F'_a = \frac{B_1w_a^{-B_2}A_a + G\cos\alpha\tan\varphi_a}{G\sin\alpha} \quad (11)$$

$$F'_b = \frac{B_1w_b^{-B_2}A_b + G\cos\alpha\tan\varphi_b}{G\sin\alpha} \quad (12)$$

Actually, F'_a and F'_b in the two formulas above are used to verify bearing capacity of the other sliding surface.

If $F_a < 1$, $F_s = F'_b > 1$ or $F_b < 1$, $F_s = F'_a > 1$, it shows that the sliding resistance of one sliding surface of the wedge collapse body is greater than the sliding force, and the sliding resistance of the other sliding surface of the wedge collapse body is greater than the sliding force，and then the stability coefficient of collapse body can take the average value of stability coefficient of two surfaces of wedge collapse, $F_s = (F'_a + F'_b)/2$, if $F_s \geq 1$, the collapse body is stable , if $F_s < 1$, then the collapse is formed.

If $F_a < 1$, $F'_b < 1$ or $F_b < 1$, $F'_a < 1$, it follows that two surfaces of wedge collapse can not bear the sliding force, and the collapse body will separate from the parent body and the collapse results.

3.2. Case Study

Table 1. Geometric elements and characteristics of wedge

Classification of structural plane	Dip angle/(°)	Area/m^2	Cohesion /kPa	Internal fraction angle/(°)	Testing constant B1	Testing constant B2
Plane KP_1Q	43.5	1.25	22.7	20.0	42.2	0.042
Plane KP_2Q	68.0	1.37	43.5	22.6	43.3	0.049
Top place of side slope	12.0	0.96	–	–	–	–
The slope plane of side slope	65.0	1.75	–	–	–	–
Fissure of trailing edge	70	0.53	–	–	–	–

Table 2. Analysis and calculation results of wedge

Conditions of calculation	F'_a	F'_b	$\frac{F'_a + F'_b}{2}$	stability coefficient F_s	stability	Remark
Natural state	1.22	1.18	1.20	1.18	stable	–
hydrostatic pressure	1.17	1.10	1.14	1.10	Better stable	1//3 of structural surface is soaked with water
	1.09	1.03	1.06	1.03	under stable	2//3 of structural surface is soaked with water
	1.01	0.95	0.98	0.98	instability	Structural plane is totally soaked with water

The wedge collapse at the Lian dagou Village of Ansai County is located at the Lian dagou Village of Ansai County of Yan'an. The tawny collapse body is made up of Q2 loess which characterizes of the rigidity of hard plastics. The slope height is 23m; the slope angle is 65°; the moisture content is 17.8%; the natural gravity is 17.3kN/m^3 and the collapse is in the shape of wedge, which can be simplified as the mode of fig. 2; the slope angle of plane KP_1Q is 43.5°; the tendency is 103°; the cohesion is 22.7kPa, internal fraction angle is 22.6°; the slope top of side slope is 12° and tendency is 195°. The geometric elements and characteristics of wedge are displayed in Table 1.

The wedge-shaped collapse is first divided into two operating modes: natural mode and hydrostatic pressure mode. Then these two modes are calculated. When the 1/3 of the surface structure is soaked with water, the moisture content of the 1/3 lower part of the structure is assumed to be 100% water-soaked while the 2/3 upper part of the structure is assumed to be in the natural moisture content. The same principle is followed hereinafter. The results of the calculation show that wedge will not cause sliding collapse destruction in a natural state under all the above conditions; under the mode of hydrostatic pressure and with the fissures in the trailing edge, the water-soaked structural surface will be softened and will cause the wedge to be in the critical state.

As it shown in Table 2, in the natural state, the stability coefficient of wedge collapse at Lian dagou village is 1.18. Under the state of hydrostatic pressure, when 1/3 of structural surface of trailing edge is soaked with water , the stability coefficient of wedge collapse is 1.10, which is in the stable state; when 2/3 of structural surface of trailing edge is soaked with water, the stability coefficient of wedge collapse is 1.03; when the structural surface of trailing edge is totally soaked with water, the stability coefficient of wedge collapse is 0.98, which shows that the wedge is in the state of destruction. In other words, collapse disaster strikes. In fact, after the collapse has formed, it is in the stable state all the time; July 1, 2013 witnessed a heavy rainfall in Yan'an of Northern Shaanxi and the highest daily rainfall was 114mm. The structural surface of collapse was soaked with water gradually; the stable state of collapse gradually turned into the state of instability; 1/3 of structural surface is soaked with water. On July 15, the rain stopped and weather turned to be fine, so the collapse remained stable. It started to rain on July 16 again. The structural surface had been totally soaked with water on July 20, and the wedge body was completely destroyed and collapse disaster happened. The results of the calculation match well with the actual situation.

4. Conclusions and Suggestions

(1) Due to the vertical joint , the original joint and tectonic joint and such multiple sets of structure planes exist within

the loess, the wedge formed by being cut is in three dimensional space state, and the collapse destruction of the wedge tetrahedron is mainly controlled by two groups of structural planes whose tendencies are opposite .

(2) In the process of slope excavation, the unloading effect on the slope surface results in the compressive stress in the slope body to be readjusted, stress difference of slope body increases gradually from inside to outside. The soil becomes flabby; the intensity is reduced; the free face in the slope body becomes slack and then deforms. With the continuous development of unloading deformation, the fissures of the original joints in slope body is constantly widening; with the external load and the function of water or under the influence of creep deformation, the wedge is in the critical sliding state and a sliding trend arise first on the sliding surface. When the shearing strength properties of cement on the sliding surface can not resist the slide force, the load will gradually or quickly move to another sliding surface. If the shearing strength properties of cement on the other slip surface can resist the sliding force, the side slope remains stable; otherwise, the side slope will be destroyed.

(3) By the destruction mechanism of wedge collapses, the geomechanics model is obtained. Formulas are established to calculate the general coefficient of stability of wedge and various structural planes by combining the limit equilibrium equation with Mohr-Coulomb strength criterion. The stability analysis method of loess collapse with wedge is proposed. The research results will provide the theoretical basis for the investigation and design of loess collapse.

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