A numerical simulation study of landslides induced by irrigation in Heifangtai loess area—A case study of Huangci

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Abstract. In order to investigate the mechanism underlying the formation of landslides induced by irrigation in Heifangtai loess area, the Phase2 software was used for numerical simulation of the typical profile of Huangci landslide, and conditions of the landslide in natural and saturated states were respectively simulated. The following findings have been obtained through analysis and calculation: In natural state, the maximum shear strain increment is 0.072, and the maximum horizontal displacement is 0.096m, observed on the slope surface; the slope is stable at this point. In saturated state, the maximum shear strain increment is 0.084, and the horizontal displacement on the potential slip surface is especially large, which is 0.168m; the slope is unstable at this point. The Huangci landslide is a typical landslide in the Heifangtai landslide group containing landslides with similar characteristics. It can be preliminarily concluded that Heifangtai landslides are also induced by the increase of moisture content resulting from long-term irrigation.

1. Introduction

The loess coverage area in China is about $63.1 \times 104 km^2$, accounting for 6.6% of the national territory area (Liu, 1985). Loess areas are distributed in the hinterland of Mainland China, featuring arid climate and low rainfall, and the rainy days are mainly concentrated in summer when the evaporation is intensive; farmland irrigation is necessary to guarantee normal agricultural production (Wang et al, 1992,1999). However, landslide disasters induced by irrigation take place frequently, and areas with irrigation-induced landslides have experienced the most frequent and serious geological disasters in the loess plateau region of Northwest China, or even in China. In recent years, this issue has received extensive attention from China's engineering geology and loessology circles.

Irrigation-induced landslides have caused huge losses to local people's production, living and property, hampering the regional economic and social development to some extent. Derbyshire (2002), Xu (2008,2012) and other scholars have probed into irrigation-induced landslides at Heifangtai, Lanzhou (Zhang et al, 2010), but landslide prevention and control is still an international challenge due to the complexity of sliding mechanism (Li et al, 2015; Peng et al, 2017).

The Huangci landslide in the Heifangtai landslide group was taken as a case study. Phase2, a numerical simulation software, was used to establish a calculation model for the Huangci landslide; the stress and displacement conditions of the landslide were simulated in natural and saturated states to investigate the mechanism underlying the formation of Huangci landslide induced by irrigation.

2. Organization of the Text

2.1. Section Headings

3. Engineering overview

3.1. Location and landslide overview
Located in Yanguoxia Town, Yongjing Town, Gansu (see Fig. 1-a), Heifangtai has an altitude of about 1,700m, a length of over 10km from east to west, and a total terrace area of 13.44km². Slide has occurred in this area more than 120 times, averagely 3~4 times per year, forming a large landslide group (see Fig. 1-b).
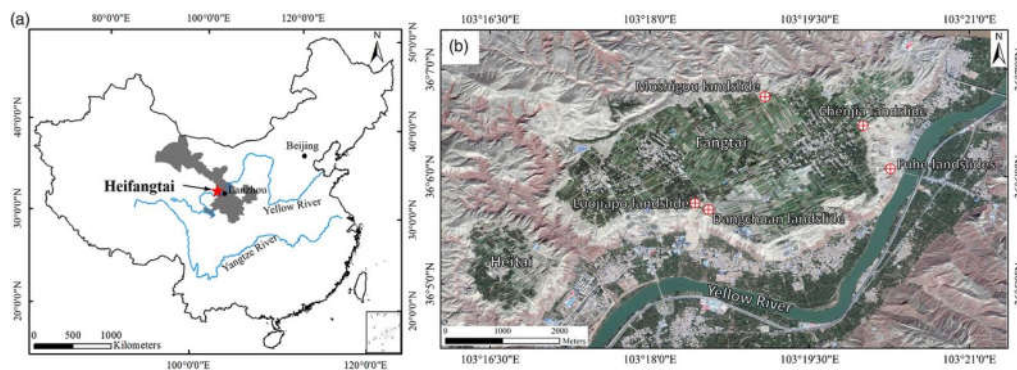

Fig. 1 (a) Location of Heifangtai; (b) Heifangtai landslide group. (Peng et al, 2017)

3.2. Overview of Huangci landslide
At two o'clock on the morning of January 30, 1995, a large-scale landslide took place in Huangci Village, forming two benches with the front one being the old slip mass and the rear one being the new slip mass. At 13 o'clock on May 14, 2006, another massive landslide occurred in Huangci Village. The Huangci landslide is a loess-bedrock landslide, the profile of which is shown in Fig. 3. As can be seen from Fig. 2 , a third bench was formed behind the previous first and second slip masses, which resulted in great losses. Owing to early monitoring and forecasting in the local area, the disaster did not cause any casualties. The two slides led to three benches having an imbricate structure. The Huangci landslide was formed by level-by-level traction and advancement of the slip masses from front to back. Currently each part of the landslide basically keeps its original look, but numerous tensile and shear fractures have been developed on the slope. The slip mass strata from the top down are landslide deposit, river alluvial clay and gravel formations, slip-mass-disturbing sandstone and mudstone, and Cretaceous sandstone-mudstone interbed. Although the Huangci landslide has slid several times, it is highly possible that a landslide disaster is induced again due to the property of local soil mass and the infiltration of irrigation water. Therefore, it is still worthy of study.
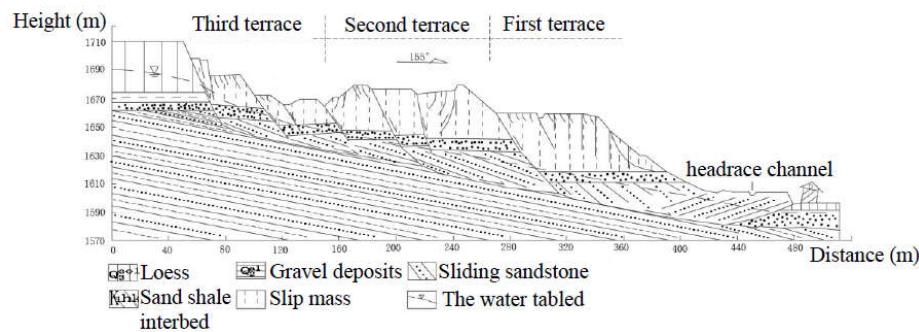
Fig. 2 Profile of Huangci landslide

4. Phase2-based investigation of the sliding mechanism of Huangci landslide

A major cause of the occurrence of Huangci landslide is the infiltration of irrigation water which changes the soil parameters; the soft interlayer between bedrock and loess also creates a condition for the occurrence of landslide. Phase2 was used in this study to simulate behaviors of Huangci geologic bodies in natural and saturated states, respectively, and analyze the changes in displacement and stress of rock and soil mass. It is hoped to investigate its sliding mechanism through software simulation.

4.1. Modeling

The profile of Huangci landslide (as shown in Fig. 3) in CAD format was imported to Phase2 to establish a two-dimensional finite element model which was subject to meshing. The model established is 510m long and 140m wide. The Mohr-Coulomb criterion was applied for selection of physical and mechanical parameters of rock and soil mass in the model.

4.2. Determination of physical and mechanical parameters for model calculation

The profile of Huangci landslide contains six materials: Malan loess, landslide deposit, clay formation, gravel formation, slip-mass-disturbing sandstone and mudstone, and Cretaceous sandstone and mudstone. The numerical simulation model, considering the conditions in natural and saturated states, was used for calculation and analysis of these materials. According to the findings of previous laboratory experiments, the values of physical and mechanical parameters of the six materials in natural and saturated states are listed in Table 1.

Table 1. List of physical and mechanical parameters of the rock and soil mass of Huangci landslide in natural and saturated states

Parameter name	Unit weight γ (KN/m³)	Cohesion C (Mpa)	Internal friction angle φ (°)	Young's modulus E (MPa)	Poisson's ratio μ
Malan loess	15.9/18.5	24.2/17.1	25.7/23.2	9.3/4.6	0.31/0.33
Landslide deposit	14.5/20.0	23.7/16.7	23.6/15.2	8.0/3.8	0.25/0.27
Clay formation	17.8/19.1	21.2/18.6	25.2/23.6	7.0/3.3	0.29/0.31
Gravel formation	22.0/24.2	3.0/1.1	28.8/26.1	13300/6400	0.30/0.32
Slip-mass-disturbing sandstone and mudstone	19.0/21.6	30.2/22.6	31.7/27.5	15000/7200	0.33/0.35
Cretaceous sandstone and mudstone	20.6/23.7	35.1/24.9	34.3/30.2	19300/9500	0.38/0.40

4.3. Calculated results and analysis

4.3.1. Stability calculation and analysis in natural state. The calculation model established in Phase2 can be used to observe the changes in stress and displacement at each point under different moisture contents. Fig. 3 shows the slope condition in natural state.
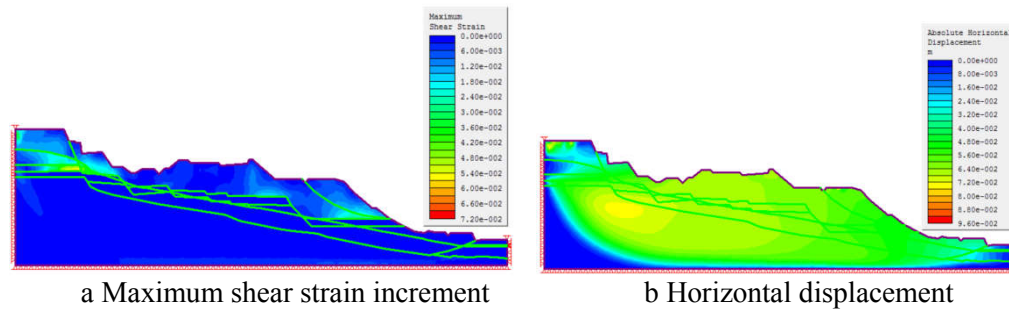

a Maximum shear strain increment   b Horizontal displacement

Fig. 3 Calculated results of slope stability in natural state

Under natural conditions, as can be seen from Fig. 3-a, the shear strain increment on the slope occurs only on the surface of contact between loess and gravel formation at the rear edge of slip mass, and the overall increment is small; the maximum shear strain increment is 0.072%. According to Fig. 3-b, the deformation of primal slope shows a trend of progressive decrease from the surface to the inside of slope; the maximum horizontal displacement is 0.096m, observed on the slope surface. On the whole, the slope is stable under natural conditions.

4.3.2. Stability calculation and analysis in saturated state. In saturated state, both the cohesion and the internal friction angle of each soil stratum exhibit a decrease compared with those in natural state, which has triggered the occurrence of Huangci landslide. Fig. 4 shows the results of stability analysis in saturated state through Phase2-based simulation.
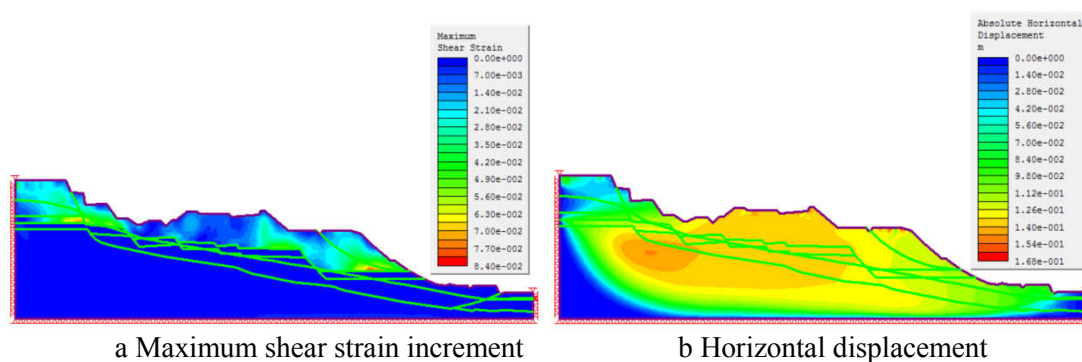

a Maximum shear strain increment   b Horizontal displacement

Fig. 4 Calculated results of slope stability in saturated state

In saturated state, as can be seen from Fig. 6-a, the shear strain increment on the slope occurs on the surface of contact between loess and gravel formation at the rear edge of slip mass and also on the potential slip surface at the front edge of slip mass, and the overall increment is larger compared with that in natural state; the maximum shear strain increment is 0.084%. According to Fig. 6-b, the deformation shows a trend of progressive decrease from the surface to the inside of slope; the maximum displacement is observed on the potential slip surface at the front and rear edges of slip mass; the horizontal displacement on the potential slip surface is especially large, which is 0.168m. On the whole, the slope is unstable in saturated state; large deformation occurs on the potential slip

surface at both the front and rear edges of slip mass; it is possible that another landslide disaster takes place.

5. Conclusion

The Huangci landslide was studied by means of numerical simulation to investigate the sliding mechanism of Huangci landslide and calculate its maximum shear strain increment and horizontal displacement in natural and saturated states. The following conclusions have been drawn through the study:

(1). The Phase2 software was used to investigate the sliding mechanism of Huangci landslide. The following findings have been obtained through analysis and calculation: In natural state, the maximum shear strain increment is 0.072, and the maximum horizontal displacement is 0.096m, observed on the slope surface; the slope is stable at this point. In saturated state, the maximum shear strain increment is 0.084, and the horizontal displacement on the potential slip surface is especially large, which is 0.168m; the slope is unstable at this point.

(2). The Huangci landslide is a typical landslide in the Heifangtai landslide group containing landslides with similar characteristics. It can be preliminarily concluded that Heifangtai landslides are also induced by the increase of moisture content resulting from long-term irrigation.

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