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Discussions

Interactive comment on "Temporary confined water responsible for triggering the landslide of a piedmont gentle slope in Ningzhen Area, China" *by* Shulan Guo et al.

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a certain period of time that has never been encountered before) in the middle layer of the slope was the most important factor in inducing the landslide. Through numerical simulation, we analyzed the formation process and influencing factors of the temporary confined water. Finally, we propose effective control measures for this kind of landslide. The research results can be used in the treatment of similar piedmont gentle slope landslides.

Keywords: piedmont gentle slope; temporary confined water; intermittent creeping landslide; numerical simulation; control measures

1. Introduction

According to the traditional view, a piedmont gentle slope is beneficial to the overall stability of a mountain (Zhou and Ou 1997; Pánek et al. 2014; Yan et al. 2019), which in turn has a counterpressure effect on the whole mountain. However, in recent years, landslides have increased significantly in piedmont gentle slopes in Jiangsu Province, China. For example, on July 3, 2016, a large-scale landslide occurred at Youzi Mountain, which is a typical piedmont gentle slope in Nanjing; on October 25, 2016, a landslide occurred on a piedmont gentle slope in the Fangshan scenic area of the Jiangning district, Nanjing, which led to the closure of the scenic area for several months. Some scholars believe that the occurrence of these landslides has a strong relationship with rainfall (Lo et al. 2010; Bai et al. 2013; Yu et al. 2020). Simultaneously, some studies have been published on the characteristics and sliding mechanisms of piedmont gentle slope landslides. Trandafir et al. (2013) employed numerical analysis to illustrate two major concepts that address the geomechanics of catastrophic landslides on gentle slopes in liquefiable soils due to earthquakes. Taking one landslide of Japan as an example, they believed that the gentle slope may experience large landslide movements due to earthquake-induced ground liquefaction as a result of void redistribution and formation of water films in liquefied deposits with continuous low-permeability interlayers. Adopting an early warning system called MoniFLaIR, Capparelli and Tiranti (2010) monitored and analyzed the influence of rainfall on landslides in the Piedmont area (Northern Italy) (Capparelli and Tiranti 2010; Trandafir et al. 2013).

Confined water is formed between two aquifuges and has confined properties. When the rain infiltrates into the lower part of the slope through the cracks in the upper part of the slope, if the surface of lower part of the slope is an impermeable layer and the middle is a permeable layer, high-intensity rainfall may not allow the converged

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Fig. 1.

groundwater to be discharged immediately along the interface, thus forming a "confined basin"(Huang et al. 2005; Jiao et al. 2005; Vennari et al. 2014). As shown in Fig. 1, the mountains in the Zhenjiang area show a special characteristic: The upper part of the mountain is mainly exposed bedrock with fracture development, with a steep slope, generally between 30° and 50°; the lower part of the mountain is composed of Quaternary gravelly soil and loose sediments with slope angles mostly between 8° and 15°, which we refer to as a piedmont gentle slope. The piedmont gentle slope in the Zhenjiang area has the topographic structure of a steep upward and gentle downward with a stratum structure: clay in the surface, coarse-grained soil or weathered rock in the middle and bedrock in the bottom, which forms a special "binary stratigraphic structure" (Yan et al. 2019). The permeability of the strata is weak-strong-weak from top to bottom. **Additionally, the upper part of the slope is usually rock with weathered fissures, which is convenient for rainfall infiltration.** This slope structure is conducive to the formation of confined water (Mikoš et al. 2004; Yan et al. 2010; Zeng 2010).

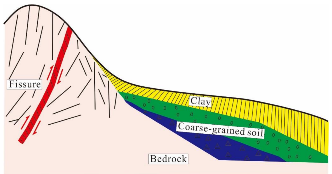


Fig. 1 Schematic diagram of Piedmont gentle slope in Zhenjiang area

In 2015, 7 landslides occurred on the western and northern sides of Paomashan Mountain (Fig. 2). Nearly 4 million yuan was spent for treatment, and the reinforcement measures of antislide piles and bolt lattice were set up in the upper part of the slope to control the sliding effectively. But the lower part of the slope was not treated because they believed that it is relatively gentle and no subsequent sliding would occur. Using inclinometer to monitor the displacement of silty clay layer and digital water level gauge to monitor the change of water pressure of gravel layer, they set up two monitoring holes in the lower part of the mountain just in case. In June 2016, the lower slope of P0 experienced downhill scarps and tension cracks at the rear edge of the slope, as shown in Fig. 3, causing the antislide pile in the upper part of the mountain to experience cracks and causing the soil of the slope to move

Fig. 2.

C3

(c) Downhill scarps and tension cracks at the rear edge of the slope

Fig. 3 Profile of the P0 slope

2. Background

Zhenjiang city is located in the south of Jiangsu Province, adjacent to Nanjing. There are many low mountains and residual hills in the city. It belongs to the subtropical monsoon climate zone, with a high temperature and rainy climate in the summer. The rainy season is concentrated in June, July and August. Paomashan Mountain is located in the center of Runzhou District, Zhenjiang City, Jiangsu Province (Fig. 2), which is a typical soil slope. According to the field survey data, the formation lithology in this slope is roughly divided into three layers, from top to bottom (Fig. 4): silty clay in the surface, gravel in the middle with relatively developed fissures, strongly weathered porphyry quartz diorite in the bottom, mainly composed of plagioclase, quartz, hornblende, etc. The physical and mechanical properties are shown in Table 1.

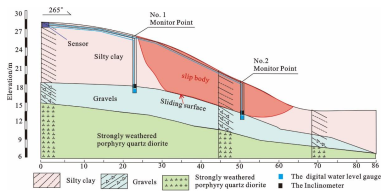


Fig. 4 The geological map of 1-1' section

2.1. Overview of the landslide

Since June 20, 2016, there has been continuous heavy rainfall in Zhenjiang city. At approximately 10 a.m. on June 24, confined water was detected. At 5:00 p.m. on June 25, the monitoring system began to receive displacement data of the layer of silty clay and the change of water pressure of the layer of gravels. On July 6, the landslide happened, which was a bedding slip (Fig. 4). The displacement data of the 12-day monitoring period are shown in Fig. 5. The change in water pressure is shown in Fig. 6.

According to the field survey, the slip body is located in the middle and lower part of the slope. With creep

Fig. 3.

C4

deformation of the slope, deeper and wider cracks were firstly formed at 0.2 m below No. 1. Under the condition of continuous heavy rainfall, the tension crack continued to extend, cut through and form a down bench, which provided an effective free surface for the soil above, and finally, the slope slides. The maximum displacement of No. 2 is 1337 mm, while the maximum displacement of No. 1 is 281 mm (Fig. 5). The sliding speed of No. 1 is obviously smaller than that of No. 2 (Table 2). The displacement-time relationship curve in the process of the landslide conforms to the characteristics of typical creeping landslides (Xu et al. 2008; Tang et al. 2014).

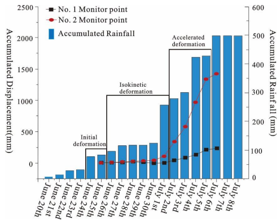


Fig. 5 Relative relationship between rainfall and displacement

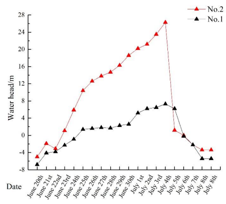


Fig. 6 Change in the water pressure

Fig. 4.

The landslide process can be divided into three stages: initial deformation, isokinetic deformation and accelerated deformation.

2.1.1. Initial deformation

From June 20 to 25, continuous rainfall occurred in Zhenjiang, during which the rainfall reached 45.2 mm on the 24th. According to the actual monitoring displacement data, the initial deformation of the slope occurred at 16:00 on the 25th and was 11 mm, the initial deformation speed was 2.1 mm/h, and the initial acceleration was 0.27 mm/h^2.

2.1.2. Isokinetic deformation

Continuous rainfall increased the water content in the slope, and the sliding force gradually increased. On June 26, the slope entered the isokinetic deformation stage, and the deformation gradually increased. The average deformation rate was 0.4 mm/h, and the acceleration range was -0.01~0.01 mm/h^2. According to the site investigation report, at this time, the number of subsequent deeper and wider cracks was obviously increased, and there are shear dislocation zones in the gullies on the northern side of the slope.

2.1.3. Accelerated deformation

From June 30 to July 1, there was continuous heavy rainfall, during which the maximum rainfall reached 88.8 mm/d, and the deformation of the slope increased significantly. At 8:00 on July 1, the slope entered the accelerated deformation stage. In this stage, the deformation rate of the slope accelerated which reached 11.3 mm/h. The range of acceleration fluctuated greatly (-0.40~0.52 mm/h^2). With the decrease in rainfall, the acceleration gradually decreased to 0, and the landslide returned to the stage of isokinetic deformation. However, at this time, the average deformation rate of the landslide was 13.9 mm/h, and the rainfall on the 4th increased to 122.2 mm. The landslide again enters the stage of accelerated deformation. The acceleration increased from 0 to 1.1 mm/h^2, and the deformation rate reached 22.3 mm/h. At this time, the sliding surface was completely connected, and the slope was damaged by sliding.

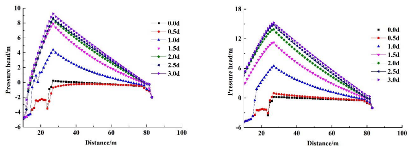
3. Influence of temporary confined water on landslide

Fig. 6 shows that under continuous heavy rainfall, confined water is formed in the gravel layer in the middle of the slope, with a maximum water head of 26.3 m. However, with the decrease in rainfall and the pressure release effect of slope deformation, the water head will gradually decrease, which we refer to as the "temporary confined aquifer". According to the traditional view, circular sliding generally occurs in the soil slope (Yan et al.

Fig. 5.

The change in the pressure head in the horizontal direction can be roughly divided into unconfined areas and confined areas. In the initial stage of rainfall (< 1 d), the variation in confined water level increases with the increase in rainfall intensity (except for the 75 mm/d rainfall). In the middle stage of rainfall (1 d~2 d), when the rainfall intensity is 150 mm/d instead of 175 mm/d, the confined water level reached a maximum of 13.5 m. In the later stage of rainfall (>2 d), the confined water level reached a maximum of 15 m. Therefore, 150 mm/d is the optimal rainfall intensity for the formation of confined water.

In addition, rainfall duration is also an important factor affecting the confined water level. Based on the rainfall data in the Zhenjiang area, taking the rainfall intensity of 125 mm/d and 150 mm/d as examples, the effects of rainfall duration on confined water level are studied (Fig. 9).



(a)125 mm/d (b) 150 mm/d

Fig. 9 Relationship between confined water level and rainfall duration

It can be seen from Fig. 9 that (1) When the rainfall intensity is 125 mm/d: in the early stage of rainfall (< 1.0 d), the water head decreases slightly because it is influenced by the stagnant water in the unsaturated zone, the supply of the middle and lower parts of the slope is reduced; in the middle stage of the rainfall (1.0 d ~ 2.0 d), the water head increases rapidly because the stagnant water in the unsaturated zone dissipates to the middle and lower parts of the slope; in the later stage of the rainfall (>2.0 d), the water head increases rapidly and gradually tends to be stable. (2) When the rainfall intensity is 125 mm/d: in the early stage of rainfall (< 1.0 d), the influence of the stagnant water in the unsaturated zone is weaker. The water head shows a rising trend and forms confined water rapidly; in the middle stage of rainfall (1.0 d ~ 2.0 d), it is the fastest stage of the confined water head increasing, and the increasing rate of confined water head decreases gradually; in the later stage of rainfall (> 2.0 d), the water

Fig. 6.

head tends to stabilize gradually. When the middle layer is completely filled with rainwater, the groundwater seepage will enter the stable seepage stage. According to the increasing rate of water head and head of confined water, when the rainfall duration is approximately 2.0 d, it is beneficial to form a higher confined water head.

3.2.2. Effect of the permeability coefficient of the middle layer

The permeability of the middle layer has a crucial influence on the formation of confined water (Finlay et al. 1997; Jiao et al. 2005; Rosone et al. 2018). Therefore, we studied the confined water level under the condition of different permeability coefficients of the middle layer when the rainfall intensity is 150 mm / d and the rainfall duration is 2 days.

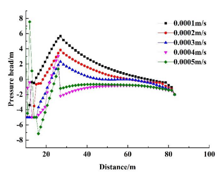


Fig. 10 Relationship between confined water level and permeability coefficient

Fig. 10 shows that when the permeability coefficient is 0.0001 m/s, 0.0002 m/s and 0.0003 m/s, confined water is formed in the middle and lower parts of the slope, and the confined water level decreases with the increase in the permeability coefficient. When the permeability coefficient is 0.0004 m/s and 0.0005 m/s, only partially confined water is formed in the upper part of the slope. Therefore, when the permeability coefficient of the middle layer is between 0.0001 m/s and 0.0003 m/s, it is beneficial to the formation of confined water.

3.3. Influence of temporary confined water on slope stability

In addition, setting the sliding surface in the interface between the layer of clay and gravel, we use the limit equilibrium theory to analyze the stability of the P0 slope, and the results are shown in Fig. 11. The factor of safety of the slope is far greater than 1 when there is no strong rainfall, and the slope is in a relatively stable state, and this indicates that strong rainfall is a necessary condition to induce such slope sliding. According to Fig. 6, the factor of safety of the slope is negatively related to the water pressure level in the slope. With the increase in rainfall duration

Fig. 7.

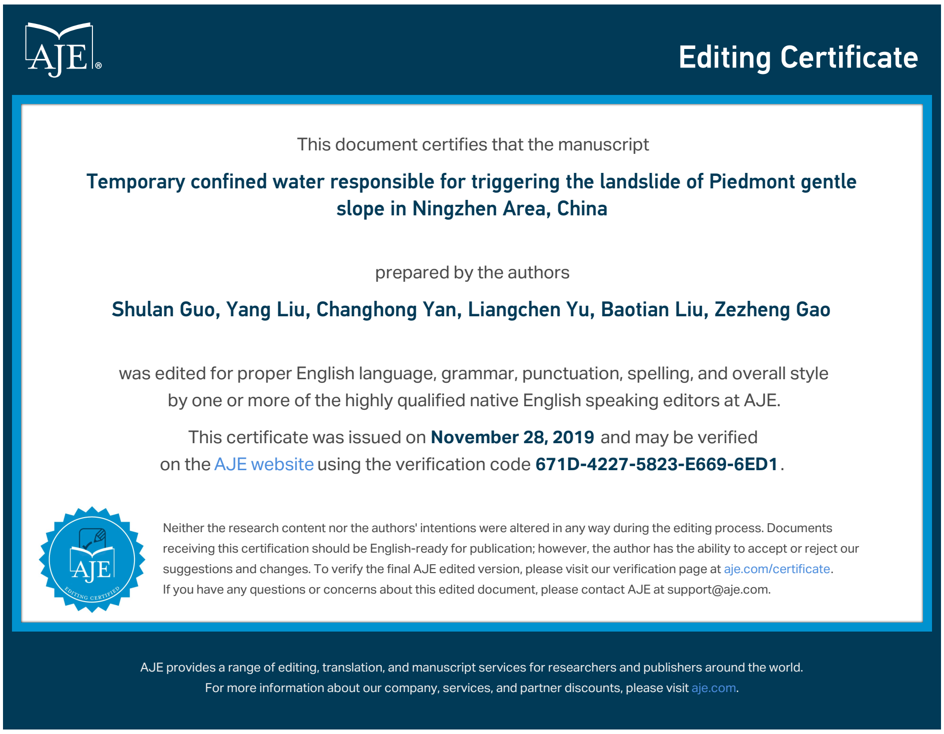

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Fig. 8.