The effect of slope orientation on the stability of cut slopes in swelling rocks and soils: case studies from Nanyang and Yanbian, China

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ABSTRACT

During the construction of the South-to-north water transfer middle line and Jilin-Hunchun high-speed railway line, a lot of excavations in swelling rock and soil were performed to achieve acceptable grades, eventually forming extensive swelling rock and soil slopes. Many of them slid after water storage and rainfall events. One interesting observation is that most of the landslides are south-facing. In this paper, the causes of this direction variation were thoroughly examined on the basis of the geological characteristics of project sites. It is concluded that the water storage and rainfall event are the direct external trigger of landslides while the intensive soil-atmosphere interaction is the main reason for the landslides in south-facing direction. Because of the influence of slope orientation, the solar radiation, temperature and humidity on south-facing and north-facing slopes are materially different. The unloading fissures caused by excavation unloading and the shrinkage fissures act as a main channel for the exchange of moisture and energy between soil and atmosphere. Owing to the intensive solar radiation and high temperature on the south-facing slopes, they are subjected to dramatic wetting-drying and freezing-thawing cycles, which can lead to a remarkable decrease in the strength of swelling rocks and soils. They are therefore more possible to slide.

Keywords: swelling rocks and soils, slope orientation, slope stability, wetting-drying cycles, freezing-thawing cycles

1 INTRODUCTION

Swelling rocks and soils are the typical problematic materials with a large amount of clay minerals (Shi et al. 2002). They swell and soften upon absorbing water, and they shrink and crack during dehydration. Moreover, swelling rocks and soils are susceptible to the atmospheric processes they are exposed to, including wetting-drying (W-D), freezing-thawing (F-T) and wetting-drying-freezing-thawing (W-D-F-T) cycles (Zeng et al. 2018a). These processes can pose undesirable changes to their mechanical properties and cause the instability of swelling rock and soil slopes (Kong et al. 2017; 2018). In China, where swelling rocks and soils have an extensive coverage, numerous swelling rock and soil landslides have been reported. Some researchers begin to notice that most of these landslides are south-facing (including south-facing, southwest-facing and southeast-facing) when they studied the swelling rock and soil landslides in the Nanning Basin (Zheng 2015), Nanyang Basin (Cheng et al. 2011), Hanzhong Basin (Ren 2014) and Yanji Basin (Zeng et al. 2018b). It is essential to understand the higher landslide incidence in south-facing slope and find ways to prevent the slope failure.

In terms of the direction variations in the slopes, a lot of researches have been documented. Even though located only a few dozens of meters apart, the microclimatic conditions on the south-facing and north-facing (including north-facing, northwest-facing and northeast-facing) slopes can be markedly different. The south-facing slopes in the north hemisphere receive more solar radiations and have a warmer, drier and more variable microclimate (Auslander et al. 2003). Chang et al. (1996) found that the south-facing slopes are subjected to more dramatic weathering owing to more solar radiations and tend to be frequently bald when they studied the mudstone slopes in the southwestern Taiwan. Chen et al. (2006) observed larger settlements in the south-facing embankment slope of the Qinghai-Tibet lines owing to the intense solar radiation. However, the effect of slope orientation on the stability of the swelling
rock and soils slopes has rarely been reported.
In this study, two cases from the Nanyang Basin and the Yanji Basin were described and the causes of higher landslide incidence in the south-facing slopes were thoroughly examined.

2 LANDSLIDE INVEATIGATIONS

2.1 Nanyang Basin
The Nanyang Basin is located in central China (Fig. 1). It is a fault-bounded basin formed during the Mesozoic-Cenozoic era, where expansive clays have an extensive coverage (Zhang et al. 2003). The Nanyang Basin has a mid-latitude continental climate with an average annual rainfall ranging from 705 to 1173 mm. About 60-70% of the annual rainfall occurs during flood season between June and August.

The South-to-north water transfer middle line traverses the Nanyang Basin from southwest to northeast. To find best way to protect expansive clay cut slopes, the Yangtze River Scientific Research Institute constructed a test channel in the Nanyang Basin, as shown in Fig. 2 (Cheng et al. 2011). The test channel was excavated in November 2008. The physical properties and mineralogical compositions of the excavated expansive clay were studied by Cheng et al. (2011) and Gong et al. (2014). The expansive clay is characterized by a large clay mineral content of 51% and a liquid limit ranging from 40.3% to 44.0%. In terms of the free swelling ratio (69%), the expansive clay has a medium-swell potential. As shown in Fig. 2, two cut slopes were formed after excavation: one facing NW(291°) and the other facing SE(111°). The channel is towards NE (21°) and 2.05 km long in total. The slope angle following excavation was 25.6° (slope ratio 1:2) and the width of channel bottom is 22 m. There was a 2.5 m wide berm at the mid-height of the slopes (Cheng et al. 2011; Gong et al. 2014). The channel was divided into six parts (I, II, III, IV, V and VI). Each part includes two face-to-face cut slopes. In parts I and III, the surface layer (1 m thick) was replaced by unexpansive soils and geotextile bags filled with expansive soil, respectively. In parts II and V, the surface layer was replaced by cement-treated soils. In parts IV and VI, the surface layer was reinforced by geogrids and composite geomembranes, respectively.

After the construction, water was injected to the test channel. During the 2-year operating period, large horizontal deformations were monitored on the south-facing slopes in parts I, II, III, IV and V while only slight deformations were observed on the north-facing ones (Fig. 3).

![Fig. 1. Location of the landslides in Nanyang.](image)

![Fig. 2. Typical cross-section of the test channel (after Cheng et al. (2011)).](image)
2.2 Yanji Basin

The Yanji Basin is located on the eastern foot of Changbai Mountain, northeast of China. It covers an area of about 980 km² and measures approximately 400 km from east to west and 35 km from north to south. The elevation in this region ranges from 155 to 1149 m. Rock type in the Yanji Basin mainly consist of silty mudstone and argillaceous siltstone in the Dalazi Formation of the Lower Cretaceous (K1d2), Longjing Formation of the Upper Cretaceous (K2) and Tertiary Hunchun Formation (E2.sh) (He et al. 2003). The Yanji Basin has a sub-humid continental monsoon climate with dry cold winters and wet hot summers the monthly mean temperature in Yanji Basin ranges from −13.2 °C in January to 21.7 °C in August. The temperature changes from being positive to negative approximately in December, and returns from being negative to positive in April of the next year with a maximum frozen depth of about 160 cm. The mean annual precipitation is 529.8 mm. More than 80% of annual rainfall occurs in the monsoon season during May and September.

The high-speed railway line from Jilin to Hunchun passes through the Yanji Basin from west to east. To achieve acceptable grades, numerous excavations were performed in the hillside, creating many cut slopes. Fig. 5 presents a typical cross-section of two cut slopes: one running south (180°) and the other running north (360°). The soil profile in the cut slopes mainly consists of four layers: planting soil, gravel soil, magenta mudstone and yellow-brown mudstone. The yellow-brown mudstone has a soft and friable layered and structure with joint fissures, while the magenta mudstone is fully weathered and has a loose structure. The minerals of the mudstones are mainly composed of montmorillonite, illite, feldspar and quartz. The clay minerals in the yellow-brown and magenta mudstones account for 28.2% and 34.1% of the total mineral components, respectively. The yellow-brown and magenta mudstones have free swelling ratios of 54% and 64%, respectively. The yellow-brown and magenta mudstones are characterized by a low-swell potential and a medium-swell potential, respectively (Zeng et al. 2018b).

During or following the construction, many south-facing slopes failed. Fig. 6 illustrates the failure of the south-facing slope between markers km 275+945 to km 276+205. The total volume of the released rock mass was estimated to be about 503000 m³. The elevation of
the front edge of the landslide was 248 m, and the elevation of the back edge was 274 m; thus, the relative elevation difference 26 m. The length of the slide was approximately 185 m and the width at the toe was around 260 m.

Fig. 6. K275 Typical landslide in the Yanji Basin.

3 DISCUSSIONS

As analyzed above, the swelling rock and soil landslides in the Nanyang and Yanji Basins are triggered by water storage and rainfall event, respectively. Upon absorbing water, the swelling rocks and soils can exhibit large swelling deformation and a significant decrease in shear strength. Moreover, the mechanical behavior of the swelling rocks and soils can be influenced by climatic processes. After excavation, the swelling rocks and soils on the cut slopes were exposed to atmosphere. Unloading cracks induced by excavation and drying-shrinking fissures caused by water loss propagated. These cracks and fissures served as water evaporation and infiltration paths for the exchange of moisture and energy between soil and atmosphere. As shown in Fig. 7, the cohesion decreases dramatically with increasing number of wetting-drying cycles while a slight decrease in the internal friction angle is observed. Apart from the wetting-drying cycles, the swelling mudstones in Yanji are affected by freezing-thawing process. Fig. 8 presents the variations in the shear strength parameters of the yellow-brown mudstone due to the wetting-drying-freezing-thawing cycles. As the number of wetting-drying-freezing-thawing cycles increases, the cohesion decreases greatly.

The stability of the cut slopes in the Nanyang and Yanji Basins are related to the slope orientation. Although the south-facing and north-facing slopes are located only a few hundred meters apart and share the same macroclimatic zone, the different microclimatic conditions on the south-facing and north-facing slopes are dramatically different (Auslander et al. 2003). The Nanyang and Yanji Basins are located in the middle latitudes of the Northern Hemisphere, and the sun rises in the southeast and sets in the southwest every day. The south-facing slopes receive more solar radiations than north-facing ones. The temperatures in south-facing slopes are higher than that in north-facing slopes. In summer, the swelling rocks and soils on south-facing slopes are drier and undergo more dramatic wetting-drying process (Segal et al. 1987; Auslander et al. 2003). In addition to the wetting-drying process, the mudstones in Yanji are subjected to freezing-thawing cycles in early spring when the temperature can be above 0 °C during the day but drop to below 0 °C at night. The freezing mudstones on the south-facing slopes with higher temperature are more likely to thaw during the day and subjected to more freezing-thawing cycles. Therefore, the mudstones in south-facing slopes undergo a more significant reduction in shear strength. The stability of south-facing slopes is distinctly lower than north-facing slopes and landslides always occur in south-facing slopes after rainfall events.

Fig. 7. Shear strength parameters of the Nanyang expansive clay with increasing wetting-drying cycles (after Cheng et al. (2011)).

Fig. 8. Shear strength parameters of the Yanji swelling mudstone with increasing wetting-drying-freezing-thawing cycles (after Kong et al. (2017)).

4 CONCLUSIONS

This study presents two swelling rock and soil
landslide from Nanyang and Yanbian, China. The slope orientation on the stability of cut slopes in swelling rocks and soils was examined. It was concluded that the water storage and rainfall event are the external trigger of the landslides. The interaction between swelling rocks and soils is the main internal factor. This process decreases significantly the shear strength of the swelling rocks and soils. The swelling rocks and soils on south-facing slopes are subjected to more wetting-drying and freezing-thawing cycles, and undergo a more significant reduction in the shear strength. The south-facing slopes are therefore more susceptible to failure.

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