

Slope instability phenomena in permafrost regions of Qinghai-Tibet Plateau, China

Abstract Permafrost covers a significant area of the Qinghai-Tibet Plateau. Slope instability problem in the region was often neglected, though it plays important roles in engineering construction and landform processes. In this paper, the slope instability phenomena in the permafrost regions on the plateau are discussed. The slope failures often occur in the forms of thaw-induced landslides and gelifluction. Thaw-induced landslides are closely related to active layer detachment and changes of permafrost conditions. Such landslides include retrogressive flow and thaw slump and are hazardous to engineering constructions. Gelifluction includes deep-seated movement and surface movement. It is an important factor in landform planation because it may spread over a large area and remain active for a long period of time.

Keywords Slope instability · Permafrost · Qinghai-Tibet plateau

Introduction

On the Qinghai-Tibet Plateau, permafrost underlies 1,500,000 km², 75% of the permafrost region in China (Fig. 1). The permafrost on the plateau is featured by high-ground temperature (warm permafrost) and rich ground ice. In the past, despite engineering activities in the region, slope instability problems have been neglected and there were few reported case histories of slope failure in the permafrost on the plateau. Now, with the construction of the Qinghai-Tibet Railway, four repairs of the Qinghai-Tibet Highway, and the planned transfer of water from the Yangtze River to the Yellow River, problems related to permafrost slopes, are attracting much more attention than before. On the other hand, because of inadequate understanding of the slope instability in permafrost regions and lack of experience, some cut slopes have failed just 1 year after construction.

The existence of permafrost is closely related to the local climate of the Qinghai-Tibet Plateau. It was predicted that the mean annual air temperature would increase from 2.2 to 2.6°C on the plateau in 100 years (Qin 2002). If this climate prediction is correct, the area of the permafrost would decrease by 8.8–13.5% in the coming 50 years (Nan et al. 2004). In fact, the monitored data of the ground temperature have shown that, on the plateau, there is an obvious trend of permafrost degradation or ground temperature rising (Cheng and Dramis 1992; Wang 1993; Wu and Tong 1995; Tong and Wu 1996; Ding 1998). During the past 30 years, the north boundary of the permafrost has retreated about 0.5 to 1 km southwards, and the southern boundary has retreated about 1.2 km northwards under natural climate changing conditions (Tong and Wu 1996). Under such conditions, deepening of the active layer and melting of the ground ice are presumably reducing the stability of slopes (Harris et al. 2001).

In permafrost regions, landslides can develop on very gentle slopes. Active layer failures in North America were well reported (Johnston 1981). Starting in the 1970s, these features have been studied in Mackenzie Valley (Mackay and Matthews 1973; McRoberts and Morgenstern 1974). There are also reported cases in other Arctic regions (Anderson et al. 1969; Carter and Galloway 1981; Mathewson and Mayer-Cole 1984) and Siberian region (Leibman 1995; Leibman and Egorov 1996; Leibman et al. 2003). On the Qinghai-Tibet Plateau, a number of cases have also been reported (Du and Xie 1965; Wang 1990; Niu et al. 2002). Landslides that occurred in the permafrost regions on the plateau are mainly involved in the active layer, meaning that the failures are limited to the permafrost table.

In this paper, some slope instability phenomena occurred on natural slopes are reported. Their failure or deformation occurrences and influencing factors are analyzed based on in situ investigation. The surveyed sites are shown in Fig. 1.

Thaw-induced landslides in permafrost regions of Qinghai-Tibet plateau

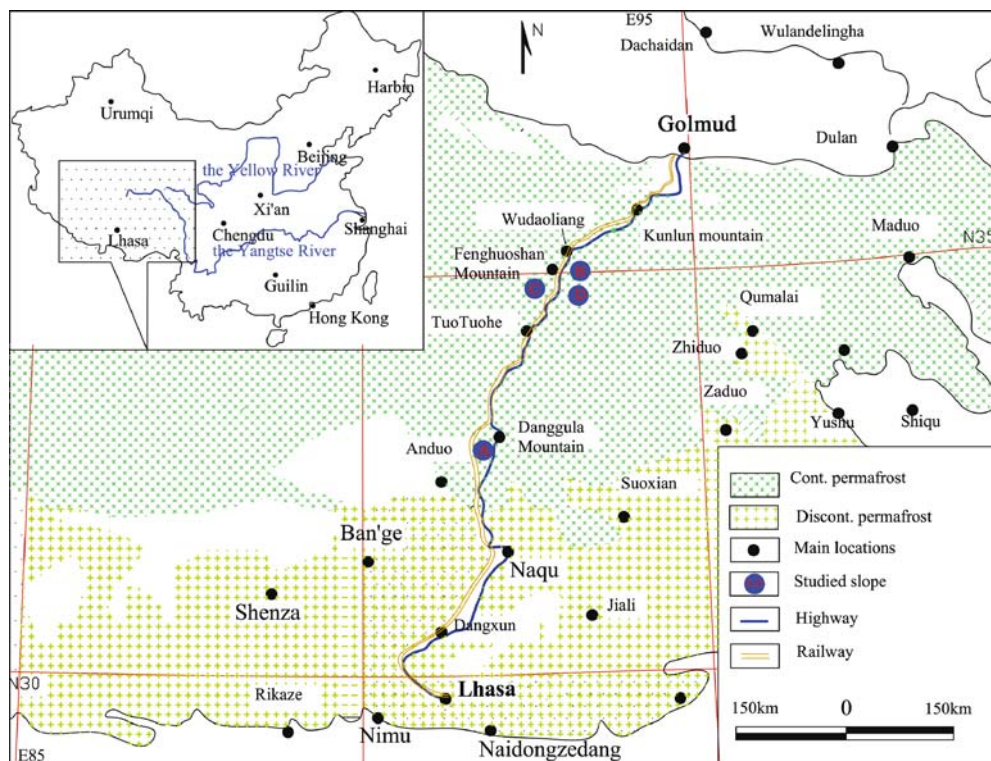
Ground in permafrost regions consists of perennially frozen ground and the active layer. Seasonal thawing of the active layer, especially the soil near the permafrost table, is normally associated with slow movement. When the slope toe is cut or disturbed by other forces, the slope movement may become significant.

Retrogressive flow on the Danggula Mountain slopes

Retrogressive flows in the permafrost regions in the Arctic zone have been widely reported. Figure 2 shows a serious flow developed near the Arctic Ocean. In the permafrost regions on the Qinghai-Tibet Plateau, similar flow phenomenon also occurs widely. Figure 3 shows a typical case of this kind of retrogressive flow, which is located in a Danggula Mountain slope (location a in Fig. 1) in the southern part of the continuous permafrost zone. The flow is on a south-facing slope. Its gradient is some 10°. The mean annual air temperature around the area is -6.5~-5.5°C. The strata in the Danggula Mountain area consist of highly weathered limestone covered by alluvial gravels and coarse sands with a thickness of 2–10 m. The permafrost there is rich in ice, and its thickness on the mountain is 40–120 m. The permafrost table is 1.5–3.2 m below the ground surface. In the gentle flanking slopes of the mountain, ground water above the permafrost table is commonly rich, which is favorable for debris flow to occur.

The retrogressive flow at the Danggula Mountain Pass (Fig. 3) is about 120 m long in the slope direction and 100 m wide. The landslide shows a lobate shape and has left a scarp at the backedge with a height of about 1.5 m. This kind of landslide is characterized by a mixture of debris from the active layer soils and melted water.

Fig. 1 Permafrost distribution and the surveyed sites in the Qinghai-Tibet Plateau



The debris flows along the slope and forces the soil mass in front of it to move and form a concave shape. Normally, gentle slopes in permafrost are stable when there is no thermal disturbance or other force. This retrogressive flow was initiated by the toe cutting where local Tibetan herd men removed blocks to construct a temporary sheep pen. When the ice-rich permafrost was uncovered, it melted and led the active layer to lose its support and then fall off. This process had repeated year after year and the failed area had been extending backwards. This cycle would not stop until the ice-rich permafrost stops from being exposed. The starting time of the slide was not known exactly, but it had continued for over 10 years. And there was no evidence indicating that the slide would stop.

Thaw slumps near the Fenghuoshan Mountain

Thaw slumps are quite common in permafrost regions. Such landslides are dominated by active-layer detachments and can develop on very gentle slopes. Their morphology can be classified

into compact forms and elongated forms. Along the Qinghai-Tibet Highway, compact thaw slumps are common in mountainous or hilly terrain. A detailed study has been carried out on such a kind of landslide at milestone K3035 of the Qinghai-Tibet Highway.

The studied thaw slump is at an elevation of 4,600 m above sea level. The mean annual air temperature here is -5.2°C . The slope at K3035 is on the northwest side of the Qinghai-Tibet Highway and faces nearly south. About 15~20% of the ground surface is covered with vegetation and the slope is $6\sim 7^{\circ}$. The subsurface soil stratigraphy on the slope was explored with trenches and boreholes and is described from the ground surface down as follows: 0.0~1.0 m, reddish brown and moist fine sand; 1.0~1.3 m, gray and moist fine sand with interbeds of reddish brown clay; 1.3~2.0 m, red and saturated clay, hard when it is frozen and soft-plastic when thawed; 2.0~4.0 m, massive ground ice (Fig. 4), volumetric ice content is higher than 85%; 4.0~15.0 m, highly-weathered



Fig. 2 Retrogressive flow in permafrost region near the Arctic Ocean



Fig. 3 Retrogressive flow on the slope of Danggula Mountain of the Qinghai-Tibet Plateau



Fig. 4 Massive ground-ice in Fenghuoshan Mountain region of the Qinghai-Tibet Plateau

mudstone with interlayers of sand stone. The permafrost table is 2.0 m according to the borehole and ground temperature monitoring.

The thaw slumping area at K3035 milestone is arc-shaped (Fig. 5, location b in Fig. 1). By 2003, the size of the slide was 75 m wide and 103 m long, and the total volume of the failure mass was about 10,000 m³. The failure area was composed of a series of arcuate blocks, concaving toward the toe of the slope. The head-scarp consisted of a series of collapsed blocks (Fig. 6). Behind the head-scarp of the slide, there was a series of fissures. A significant feature of the landslide was that the fallen blocks did not slide in unison. From the front edge to the back, blocks moved successively and formed a kind of imbricate structure (Fig. 7). The original sliding was caused by excavation of the slope toe in 1990 during the repairing of the Qinghai-Tibet Highway. After that, the excavation began to collapse in warm seasons and leave the ground ice exposed to the air (Fig. 8 shows another thaw slump in its initial stage when the ground-ice was exposed and began to thaw). As the collapsed soil masses accumulate on the gentler slope surface of the ground ice, the melted water concentrated on the surface resulting in additional losses in strength. The whole sliding process was a continuous repetition of the original sliding. In past studies, thaw slumping was regarded to have a life of 3–5 years (Du and Xie 1965). However, according to our recent survey and monitoring, the thaw

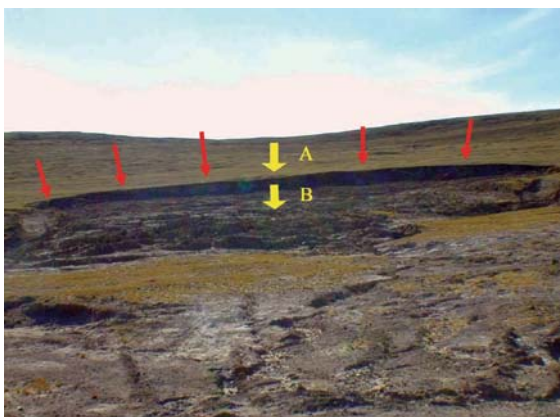


Fig. 5 Thaw slump at milestone K3035 of the Qinghai-Tibet Highway (the monitoring boreholes: a in undisturbed area; b in failed area)



Fig. 6 The head-scarp of the thaw slump at K3035 of the Qinghai-Tibet Highway

slump at K3035 has been active for more than 10 years. That means that, similar to retrogressive flow, thaw slumping will not stop until the ice-rich permafrost disappears.

To identify the sliding surface and measure the movement of the slope at milestone K3035, boreholes were drilled and inclinometers were installed. Figure 9 showed the measured displacements at different locations on the slope. Two holes were drilled on the undisturbed slope (without crack) and the front part of the sliding mass, respectively (marked a and b in Fig. 5). The results indicated that the collapsed soils on the ground-ice surface moved much more quickly than the undisturbed natural ground did. The figure also clearly showed that the inflexion points of the two curves were close to 2.0 m in depth, coinciding with the ground-ice surface. This indicates that the buried surface of the ground-ice at 2.0 m depth was the sliding surface.

Thaw slumps have damaged local engineering structures. For example, the slump at milestone K3035 of the highway has blocked a culvert several times. Also, it raises geohazard problems to the Qinghai-Tibet Railway because the railway crosses many ice-rich permafrost slopes where thaw slump hazards should be carefully evaluated.

Gelifluction

Gelifluction is used to identify slow downslope flow of unfrozen earth materials on a frozen substrate. Such landslide is quite



Fig. 7 The imbricate structure caused by inconsistent movement of fallen blocks in the thaw slump at K3035 of the Qinghai-Tibet Highway



Fig. 8 Thaw slump in the initial stage (ground-ice was exposed and landslide process began)



Fig. 10 Deep-seated gelifluction in Fenghuoshan Mountain region of the Qinghai-Tibet Plateau

common on the plateau, and plays an important role in landform process. According to the past field investigation (Du and Xie 1965), gelifluction on the plateau can be classified into two types. The first one is deep-seated flow, mainly developed on north-facing slopes. Such kind of flow means that the whole active layer soils slowly flow or slide on the ground-ice surface or the permafrost table. The other one is surface gelifluction formed by debris flow, mainly developed on south-facing slopes. Both of the two types can be found easily on the plateau.

Deep-seated gelifluction on Fenghuoshan Mountain slope

A deep-seated gelifluction developed in wide grooves in a north-facing slope of the Fenghuoshan Mountain on the plateau. Its landform looks like a low river terrace (Fig. 10, location c in Fig. 1). This landform is more than 100 m long and 35–50 m wide with a gradient of 10–15°, and it consisted of 10 steps of terraces with well-developed vegetation on the surface. Based on field investigation and groove prospecting, Du and Xie (1965) considered that the flow was identified by deforming zone near the permafrost table. Therefore, such gelifluction was called deep-seated one. A possible explanation of the landform was that, during freeze-thaw cycles, the strength of the soil near the ground-ice surface was weakened

by the melting water from the ground ice. Then the soils slowly flow along the ground-ice surface and formed the terrace landform. This process is controlled by seasonal climate changes and it is difficult to predict how long it would last, though the landform scale is wide and its characteristics are significant.

Surface gelifluction on Fenghuoshan Mountain slope

The surface gelifluction on the plateau mainly shows as fish scale turfs on slopes (Fig. 11, location d in Fig. 1). Such movement of the vegetation layer occurred on the south-facing slopes with a gradient over 15°. The turfs were cut into small scales by frost fissures in freezing periods and gradually slid along the slope surface in thaw periods.

Although gelifluction has little influence on engineering structures, it is of great importance to the landform planation because of its wide spreading and long-time activity. It is also hazardous to the natural environment because the vegetations on the plateau are weak in recovery under the atrocious climate conditions. On some steep slopes, vegetation degradation is serious, particularly in some places where local residents use turfs as the wall material.

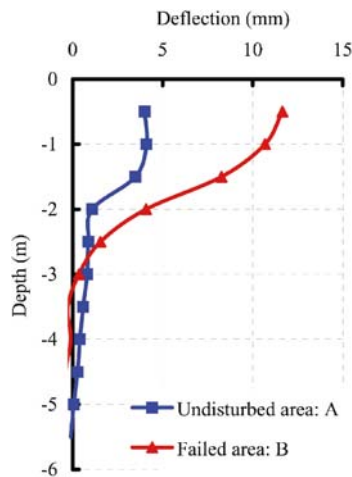


Fig. 9 Deformations in borehole **a** and **b** on slope at K3035 of the Qinghai-Tibet Highway (from June to October 2002)



Fig. 11 Surface gelifluction in Fenghuoshan Mountain region of the Qinghai-Tibet Plateau

Concluding summary

- (1) Thaw-induced landslides in permafrost regions on the Qinghai-Tibet Plateau mainly include retrogressive flow and thaw slump. They are active during thawing period and will not stop until the ice-rich permafrost stops from being exposed. Such landslides are hazardous to local engineering projects.
- (2) Gelifluction, including deep-seated type and surface type, is very common on the plateau. Such landslide is an important factor in landform planation because of its wide spreading and long-time activities

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