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Landslides in Cold Regions in the Context of Climate Change

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Landslides in Cold Regions in the Context of Climate Change

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Foreword

During the past 100 years, the global climate is changing and the geological disasters caused by it are growing. In the high-altitude permafrost regions, the degradation rate of glacier is accelerating, such as Qinghai-Tibet Plateau in China, the Alps in Europe and high mountain in Central Asia South America. On the other hand, in the high-latitude permafrost regions, such as Northern Canada, Alaska in USA, higher and lesser Khingan in Northeast of China, Siberia in Russia and the Nordic, the Southern boundary of permafrost is moving Northward gradually. Even in Kilimanjaro Mount in Africa which is located near the equator, also has been reported on permafrost degradation.

Many new geological problems are emerging with phenomena of permafrost degradation and extreme weather. Because repeated freeze-thaw cycle and the melting of surface and shallow slope, the geological disasters such as mountain collapse, mud-rock flow, and landslide are growing. All of above not only drastically changed the local geological and environmental conditions, but also caused huge losses to human lives and property, and threatened the security of local infrastructure.

In order to promote landslide research, as well as to contribute for the development of international community, environmental protection and capacity-building. On 21 January 2002, the International Consortium on Landslides (ICL) was established in Kyoto, Japan. ICL is a nonprofit and nongovernmental organization consisting (in 2012) of 51 member institutions from 32 countries; its International Program on Landslides (IPL) was jointly established by the United Nations Educational, Scientific, and Cultural Organization (UNESCO), World Meteorological Organization (WMO), Food and Agricultural Organization of the United Nations (FAO), United Nations International Strategy for Disaster Reduction (UNISDR), United Nations University (UNU), International Council for Science (ICSU), International Union of Geological Sciences (IUGS), and the World Federation of Engineering Organizations (WFEO).

In the ICL 10th Anniversary Conference (19 January 2012 in Kyoto, Japan), ICL decided to set up ICL Cold Regions Landslides Network (ICL-CRLN). The goal of it is, through exchanging and cooperation of the scientists coming from different countries and regions, as well as different professional field such as geography, geology, meteorology and so on, such problems as landslide mechanism, landforms distinguish, early warning and forecasting, disaster Assessment were studied, which also could contribute to geological environment of the cold regions and safety of human life and property.

After legal procedures, ICL-CRLN announced its establishment in Harbin, China in July 2012. Currently, 15 scientists from Canada, Czech, China, Italy, Japan, Russia, and Switzerland joined ICL-CRLN. Wei Shan from Northeast Forestry University, China worked as the Network Coordinator, while Alexander Strom from Russia Geodynamic Research Center and Hideaki Marui from Niigata University, Japan served as the Deputy Coordinators.

At present, the study about landslides in cold region is not enough. However, this topic is likely to become concerns with the influence of climate changing on geological and environmental conditions in cold regions. This book we published now is a part of the study results of ICL-CRLN members, the content mainly is about landslides in cold region in the context of global climate changing. I appreciated their exploration spirit and their valuable research results, and also willing to recommend them to all the people interested in cold region landslide.

Paolo Canuti

Florence, Italy, 15 June 2013

Paolo Canuti
President of International Consortium
on Landslides

Preface

As Prof. Canuti said, this book presents up-to-date research results of landslides in cold region. We define the cold region as the place where the monthly average temperature is less than −10 °C in the coldest month. In cold mountainous and hilly areas, the characteristics of mechanism, movement, and damage to environment of landslides are different with the landslides in noncold region. Moreover, these characteristics are closely related to climate change.

In order to strengthen the international cooperation and exchanges of landslide research in cold region, I proposed to launch the network of landslide research in cold region during the 10th council of the International Consortium on Landslides (ICL) in Rome in October 2011. This proposal was gotten the approval and support from Prof. Paolo Canuti (the president of the ICL), Prof. Sassa (the executive chairperson of the ICL), and the delegates participating in the council. In January 2012, the establishment of the network of landslide research in cold region was obtained by official approval of the ICL on 10th anniversary of the ICL in Kyoto University. After 6 months of preparation, the establishment of the network of landslide research in cold region of the ICL was proclaimed in Harbin, China on July 23, 2012. During the first meeting, we discussed and adopted the regulation and action plan of this network, published the declaration, and held the academic exchange of landslide research in cold region. Prof. Paolo Canuti, the president of the ICL, participated and delivered the congratulation. Dr. Alexander Strom who is the Researcher of the Geodynamic Research Centre (the branch of the JSC "Hydro-project Institute", Russia), Prof. Hideaki Marui who is the Director of the Research Institute for Natural Hazards and Disaster Recovery of Niigata University in Japan, Dr. Ying Guo from the Institute of Engineering Consulting and Design of Northeast Forestry University in China and other colleagues did fruitful work of developing the network of landslide research in cold region of the ICL. I really appreciate their supports and contributions.

At present, the members of the network of landslide research in cold region of the ICL and other colleagues from different countries and regions are using different research approaches to conduct comprehensive study on the landslides in cold region under climate change. This book is the summary of interim research results of colleagues and also a commemoration for the first anniversary of the network of landslide research in cold region of the ICL and the 3rd World Landslide Forum which will be hold in Beijing in June 2014.

Due to the differences from the regions and technical requirements, the topics, methods, and contents of colleagues' research are different. Dr. Filippo Catani, Prof. Paolo Canuti, and Prof. Nicola Casagli who are from the Department of Earth Sciences, University of Florence in Italy, and Dr. Chunjiao Wang and Prof. Wei Shan who are from the Northeast Forestry University in China studied the distribution of permafrost and slope movement before landslide using remote sensing. Their research results provide a scientific basis for early warning and prediction. Dr. Alexander Strom who is from the Geodynamic Research Centre (the branch of JSC "Hydroproject Institute", Russia) studied the process of landslide caused by the glacier of high-elevation mountain area in Central Asia from geological history. Prof. Hideaki Marui who is from the Niigata University and Prof. Fawu Wang who is from the Shimane University in Japan analyzed two landslides triggered by snowmelt in the North Central of Japan. Dr. Marten Geertsema and Dr. Menno van Hees who are from the Ministry of Forests, Lands and Natural Resource Operations in Canada, and Prof. Marta Chiarle who is from the Consiglio Nazionale delle Ricerche (Istituto di Ricerca per la Protezione Idrogeologica U.O.S. Torino, Italy) studied the debris flow triggered by snowmelt in the British Columbia of Canada. Italian scholars A. M. Ferrero, A. Godio, M. R. Migliazza, L. Sambuelli, A. Segalini, and A. Théodule et al., and Dr. Zhaoguang Hu who is from the Northeast Forestry University in China studied the geophysical characteristics of landslides in cold region. Prof. Adam Emmer and Prof. Vít Vilímek who are from the Charles University in Prague, Dr. Jan Klimeš who is from the Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, Dr. Alejo Cochachin who is from the Unidad de Glaciologia y Recursos Hidricos in Peru, and Dr. Krivonogova and Dr. Stanislav Panov who are from the JSC Vedeneyev VNIIG in Russia studied the effect of landslides on reservoir safety in high-elevation mountain area in South America and the central Siberia permafrost in Russia. Marina Leibman who is the Chief Scientist of the Earth Cryosphere Institute SB RAS in Russia and her research team contributed four papers which presented the mechanism of permafrost landslides located in the northern Russia where is close to the Arctic Polar plains from geomorphology, vegetation and geochemistry. They also carried out the classification and risk assessment of landslides. Prof. Tonglu Li who is from Chang'an University in China and his team studied the mechanism of landslides in the permafrost of Qinghai-Tibet Plateau and the seasonal frozen region in the Northwest of China. Dr. Shiwei Shen and Prof. Lei Nie who are from the Jilin University presented a fast stability evaluation method of collapse in sliding type slopes. Prof. Wei Shan and Dr. Hua Jiang who are from the Northeast Forestry University studied the mechanism and movement characteristics of landslides located in the degraded areas of high-latitude permafrost in the Northeast China based on the data of climate change, geological survey, and monitoring. Dr. Ying Guo analyzed the effect of seasonal frozen-thaw process on the stability of soil slope according to the data of field monitoring and laboratory experiments.

In the occasion of completion of this edited book, I would like to thank all colleagues of the network of landslide research in cold region of the ICL.

Sincerely, I extend special thanks to my old friend, Prof. Fawu Wang who is one of the founders of the ICL. I appreciate his continued support and help for 10 years. Also, I would like to thank Agata Oelschläger, Kiruthika Poomalai, Fermine Shaly and Shine David of Springer. Without their excellent work, this book cannot be published on time and with high editing quality. Nonetheless, all errors and bias remain ours.

This book is the part of research results of my colleagues and me. Indeed, it is far from perfect. With the deepening of our research, more attention and more colleagues who plan to contribute to the landslide research in cold region, we will offer more high-quality research results, which will be the great contribution for global disaster mitigation.

Shan Wei

Harbin, China, 21 June 2013

Wei Shan
Coordinator of ICL Landslides
in Cold Regions Network,
Professor of Northeast Forestry University

Contents

Part I Landslides Related to Climate and Environment Changes

Part II Forming Mechanism of Landslide in Cold Region

Part III Impact of Landslide on Environment and Facilities

Part IV Research Methods for Landslide in Cold Region

Part V Case Study on Landlside in Cold Region

Part I
Landslides Related to Climate and Environment Changes

Catastrophic Slope Processes in Glaciated Zones of Mountainous Regions

Alexander Strom

Abstract Catastrophic slope failures that occur in glaciated zones of mountain ranges at high altitudes can be considered as landslides in cold regions, since ice plays an important role in their origination and emplacement. Case studies of the XX Century rock avalanche that fell onto the glacier and of the extraordinary prehistoric ice-rock avalanche are described briefly. They demonstrate that presence of large quantities of ice in the glaciated zones of high mountains results in significant masking of the origin of debris accumulations that could be found either on glaciers or at the feet of heavily glaciated slopes.

Keywords Glacier · Landslide · Rock avalanche · Ice-rock avalanche

1 Introduction

Cold regions include not only areas at high latitudes (Siberia, Far East of Russia, North-Eastern China, Northern Canada, Alaska, Southern Chile) but also high mountains and, especially, glaciated zones of mountainous regions regardless of latitude. The specific character of such processes in glaciated areas is predetermined by presence of permafrost and ice. The latter form large portion of the collapsing masses on the one hand and of the bed over which they move on the other hand.

Such phenomena as rock and ice-rock avalanches attract researchers' attention for many years (Evans and Clague 1988; Reznichenko 2012). Besides direct threat posed to local communities and infrastructure they play an important role in general evolution of glaciers and, thus, affect water balance of the rivers that

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originate from glaciers (Reznichenko et al. 2010). That is why study of various slope processes that take place in glaciated zones of mountainous ranges should be an important topic of the “Landslides in cold regions” ICL Network.

2 Catastrophic Slope Failures

Catastrophic slope failures that occur in the regions in question can be divided, at a large extent conventionally, in two main groups: (a) bedrock landslides that fell onto glaciers and move over them, and (b) slope failures that include large amount of ice.

The first group can be exemplified by 1964 Sherman Glacier rock avalanche (McSaveney 1975, 1978), 1986 Bualtar Glacier rock avalanche in Karakorum, Pakistan (Hewitt 1988), 1997 Mount Munday rock avalanche in British Columbia (Delaney and Evans 2008), rock avalanches that accompany the 2002 Denaly earthquake (Jubson et al. 2006; Schulz et al. 2008), and other historical case studies. Similar prehistoric event in Greenland was described by Kelly (1980). Comprehensive analysis of this type of rock avalanches was provided recently in the PhD thesis of Reznichenko (2012) and by Shugar and Clague (2011). Thorough review of slope stability in paraglacial environment was performed also by McColl (2012).

Second group can be exemplified by the catastrophic 1962 and 1970 Huaskaran ice-rock avalanches in Peru (Evans et al. 2009b) by the 2002 Kolka-Karmadon disaster in Northern Osetia (Petrakov et al. 2008; Evans et al. 2009a) and other less disastrous events (Huggel 2008).

Hereafter I present brief description of case studies related to both types of the phenomena—rock avalanche the caved onto glacier in northern Caucasus likely in 1959 or few years earlier and the extraordinary prehistoric ice-rock avalanche in the Alai valley (Kyrgyzstan).

2.1 *Rock Avalanche Over Glacier*

Looking over August 1959 aerial images of the glaciated zone of the Great Caucasus Range I found an impressive image of rock avalanche that fell on the glacier in the upper reaches of the Urukh river basin most likely same year or, may be, 1–2 years earlier (Fig. 1). This assumption is based on undisturbed shape of rock avalanche body without any evidence of reworking except some fractures at the upper and middle parts of the depositional zone that cross both ice and overlying debris. Rock avalanche debris with significant portion of large blocks up to several meters in size forms thin blanket that overlays minor irregularities of the underlying glacier relief (Fig. 2) in the same way as it was observed at the rock avalanches that accompanied the 2002 Denali earthquake (Jibson et al. 2006; Schulz et al. 2008).

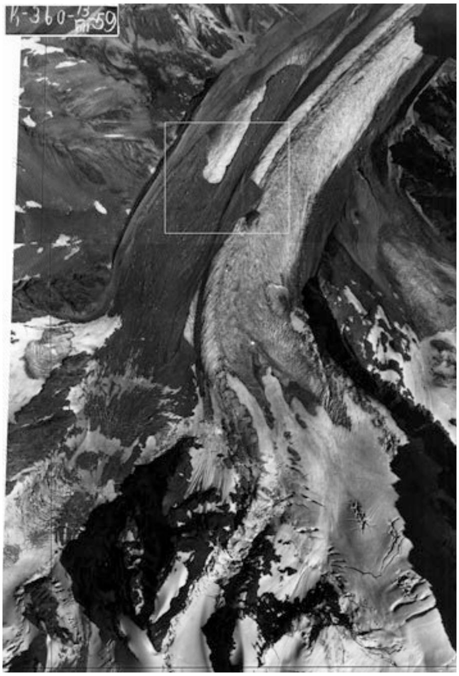

Fig. 1 Aerial photograph of rock avalanche deposits that form thin blanket of debris over glacier in the upper reaches of the Urukh River basin. Source zone of rock avalanche is in the *shadow*. Outlined fragment is shown on Fig. 2

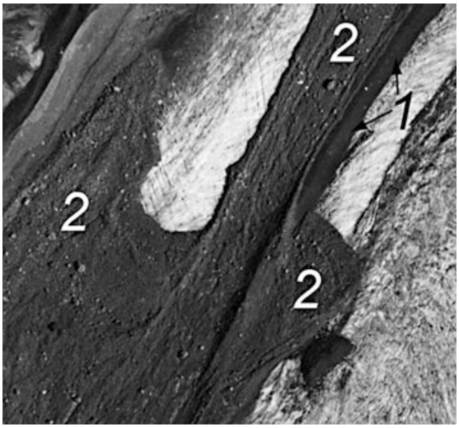

Fig. 2 Interaction of rock avalanche debris (2) with underlying glacier relief. 1—the moraine levee composed of much finer material. Note that diagonal fractures visible on ice in the *upper central* part of the image do not affect rock avalanche deposits

No historical records about this phenomenon were found in publications. However, fortunately, Goggle Earth provides high resolution space image of the same area obtained on November 23, 2004 (Fig. 3) allowing comparison of rock avalanche deposits shape and position after 45 years. If there would be no information about this rock avalanche, coarse deposits visible now on the surface of this glacier could be easily interpreted as "normal" moraine.

Fig. 3 Google Earth 2004 space image of the same area as shown on Fig. 1. Front of coarse rock avalanche material can be found on the glacier surface about 500 m downstream from its initial position, while the proximal part of rock avalanche almost disappeared being transformed into two levees very similar to lateral moraine

2.2 Prehistoric Extraordinary Ice-Rock Avalanche in the Alai Valley

Ice-rock avalanches carrying out large quantities of easily melting ice belong to the most hazardous natural phenomena in high mountains. They move very rapidly at an abnormally large distances (Petrakov et al. 2008; Evans et al. 2009a, b; Huggel 2008). However, the Komansu case study described briefly hereafter is extraordinary even among these outstanding events due to volume of material involved and runout distance (Fig. 4).

The site is located in the central part of the so called Alai valley—large intermountain depression between the Zaalay (Transalay) Range of the Northern Pamirs and the Alay Range of the Southern Tien Shan. The Zaalay Range, which was the source of this slope failure is up to 7 km a.s.l. high and rises up to 3.0–4.0 km above the depression bottom.

Zone of unusual irregular topography with hills and furrows (local term—“chukur”) about 14 km long across the Alay valley and up to 8 km along it (see Fig. 4) was first described in the middle of 20th Century by K.V. Kurdiukov who proposed that it is the eroded body of the gigantic rock avalanche about 4–5 km^3 in volume. Later on, Nikonov and his co-authors (1983) argued that his interpretation is wrong and that this feature, along with several other “chukur” fields typical of

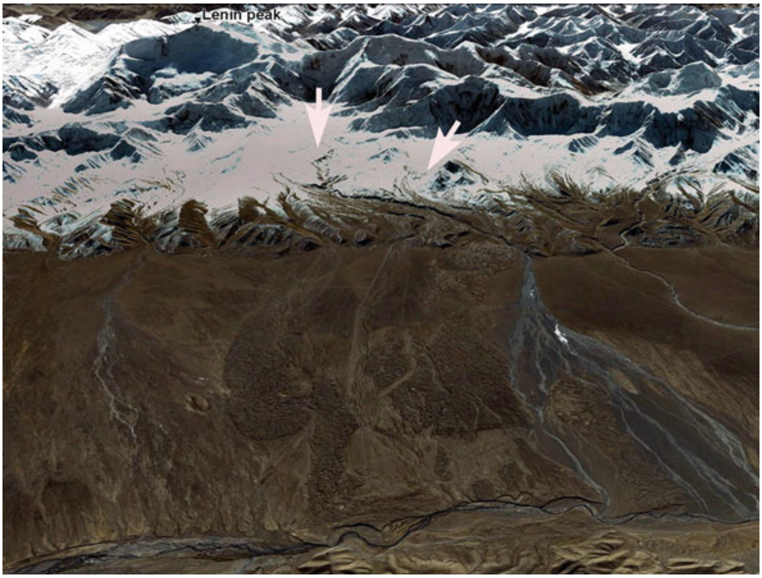

Fig. 4 The prehistoric Komansu ice-rock avalanche deposits in the central part of the Alai intermountain depression. 3D Google earth image. View from the north. *Arrows* indicate possible source zone of the slope failure. Distance from the watershed of the Zaalai range with the topmost summit—the Lenin Peak (7134 m a.s.l.) to the Kyzylsuu river at the foreground slightly exceeds 30 km. Traces of active faults pass along the foot of the range and at the frontal part of the avalanche body about 2.5 km south from the Kyzylsuu river

the Zaalay Range northern foothills have glacial origin. Indeed, microrelief of this feature is quite irregular, which is typical of moraines, rather then of rock avalanches. Some morphological and sedimentological peculiarities, however, contradict this interpretation.

First, the Komansu deposits front rises several tens of meters over the lowermost part of its base, indicating that it "climbed" on the opposite—northern slope of the valley, which is strange for the front of the glacier that had to move slowly being so far from its feeding zone. Second, material in some outcrops at this frontal part is completely unrounded, and represents breccia with sandy matrix typical of rock avalanches (Fig. 5). At some outcrops blocks of such material are mixed with moraine material but demonstrate jigsaw structure (Fig. 6). Third, at the outcrop along the right bank of Kyzylsuu River one can see at a distance of several hundreds meters that the Komansu body overlays two river terraces without any sign of their erosion by water (Fig. 7). Huge advancing glacier must produce large amount of melt water that would leave some signs of erosion at the terrace surface.

Besides, such overlaying, along with evidence of river damming visible at the north-eastern part of the Kumansu body where it is eroded by the Kyzylsuг river allows assumption that this feature is relatively young—Holocene. If so, it should occur later than maximal glaciation in this region took place.

Fig. 5 Crushed rock avalanche-style debris in the frontal part of the Komansu deposits

Fig. 6 The Jugsaw pazzle of breccia blocks in the moraine-like material. Outcrop at the left bank of the Kyzylsuu river

Most logical explanation of the totality of the observable features implies that the Kumansu body is the deposit of the gigantic extra-mobile ice-rock avalanche that originated on the glaciated northern slope of the Zaalay Range close to its watershed and travelled 27–33 km (depending on the location of its actual source) with elevation drop of about 3 km.

Large proportion of ice that was presented in the deposits, underwent intensive melting that led to formation of the chaotic moraine-like "chukur" relief. More recent glaciers degradation promoted significant erosion of the deposits of ice-rock avalanche. All these processes masked real origin of the studied feature producing relief more typical of glacial deposits rather then of those formed by purely gravitational processes.

Fig. 7 The Komansu body overlays two river terraces without any sign of water erosion

3 Conclusions

Case studies described herein briefly demonstrate that presence of large quantities of ice in the glaciated zones of high mountains results in significant masking of the origin of debris accumulations that could be found either directly on glaciers or at the feet of heavily glaciated slopes. Those that originated due to either bedrock or ice-bedrock slope failures often look like moraines even several decades after the event. It can explain the fact that source zones of most of large-scale bedrock landslides have been found not at the topmost parts of the ranges, but within the intermediate sections of their slopes (see, for example, Hewitt 2002).

Along with ongoing monitoring of slope failures in the remote hardly attainable glaciated areas that can be performed by use of the remote sensing data (Kaab et al. 2003) and seismological observations (McSaveney and Downes 2002) special studies focused on identification of significantly reworked slope failures in glaciated zones should be performed. They can provide important input data that will shed more light on interrelations between glaciers and rockslides.

Acknowledgments My study in the Alay valley was performed within the frames of the UNU PALM Project "Sustainable Land Management in the High Pamir and Pamir-Alai Mountains in Central Asia". During the 2009 field trip in this region I worked together with Mr. Alexander Meleshko, who passed away prematurely in 2010.

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Slope Instability Phenomenon in the Permafrost Region Along the Qinghai–Tibetan Highway, China

Hong Wang, Xianli Xing, Tonglu Li, Zhou Qin and Junhai Yang

Abstract The area of permafrost occupies 150 × 10^4 km^2 on the Tibetan Plateau. Slope stability in permafrost regions is one of serous geological problems in the construction of the Qinghai–Tibetan Highway, which has been claimed to be an environment harmony project. Based on the field investigation, it is found that the main types of slope failure in the permafrost regions include slope collapse, slope creeping, surface vegetation creeping, debris flow and thaw-slumping. Among which, the thaw-slumping is the most hazardous one to the environment, vegetation and the engineering. The slumping may attribute to engineering excavation, which can disturb the thermal balance of the slope soil and cause thawing. As the slope soil thawing, the strength decreases in a large extent or even lost mostly, then the slope may fail in a very low slope angle. The countermeasures for the thermal thawing slides should maintain the frozen state of the soil for keeping from thawing, using methods such as covering with coarse material which can prevent heat absorption and be good for heat release.

Keywords Slope stability · Permafrost · Tibetan Plateau · Failure mechanism · Embankment

1 Introduction

For construction of traffic lines and oil pipelines in high latitude permafrost region, research on permafrost was firstly performed in the developed countries such as Canada and United States. In 1974, McRoberts and Morgenstern (1974) divided

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slope instability of permafrost into three types: debris flow, landslide and collapse. For stability assessment of permafrost slope, three methods have been put forward at present, namely, the effective stress method proposed by Weeks (1969); the total stress method by Hutchinson (1974) and the method based on the effective stress and melting-consolidation theory by McRoberts and Morgenstern (1974). The three methods all established the calculation model on the shallow plane infinite slope and Mohr-Coulomb criterion, although their mechanisms are different. Another important feature of permafrost slope is creep deformation. With trees-rings, Wu (1984) estimated that one of the permafrost slopes in Alaska has been creeping in the past 80 years. Through laboratory tests, McRobert proved that creep of frozen soil can occur at very low stress levels (McRoberts 1978), and a long-term creep potential would cause a large-scale deformation and instability of the slope.

The area of permafrost occupies 150×10^4 km^2 on the Qinghai–Tibet Plateau (QTP). In the early time, human influence in this region is relatively weak. However, since the 1950s, with the sequential constructing of Qinghai–Tibet highway (QTH), Yunnan–Tibet highway (YTH), the Qinghai–Tibet railway (QTR), and South-to-North Water Transfer Project, disturbance of geological environment in the permafrost region inevitably lead to instability of the slopes. Slope stability is one of the key problems faced in the engineering construction. However, the research on slope stability of permafrost is still insufficient in China. The research is carried out combining with the construction of QTR and QTH. The permafrost on QTP, belongs to the plateau permafrost, is different from that on the other parts of the world which belongs to high altitude permafrost. Based on temperature environment, Lin et al. (2011) divided instable permafrost slope on QTP into the two types of frozen slope and thawing slope. The change in temperature will lead to deformation and instability of slopes, even though permafrost is general a solid material with higher strength. The frozen slope often has two types of failure modes. One is rock or soil falls, mainly occurs in rocky slopes with fractures and the soil slopes with rich ice, which may suffer from frequently frozen-heaving cycles. Since it is the most common failure type in natural and excavation slopes, passive or active protective measures have to be taken. Another type is creeping. The existence of ice in permafrost makes its creep character much more complex than that of normal soil and the creeping occurs even at very low stress levels, the creeping can happen both in steep-slope and moderate-slope, so it is widespread on QTP. Creeping changes with seasons, and the results of field test in the Fenghuo mountain region of QTP show that creep mainly occurs in winter and summer, creep strain decreases with the increase of the depth, but increases with ground temperature at the same depth (Wang and French 1995). The inverse displacement along the slope in winter implies the action of frost-heave. Failure of the frozen slopes generally occurs naturally and has less influence on the engineering. The thawing slope has three types of failure models: thaw slumping, mudflow terrace and vegetation creeping. In permafrost region, thaw slumping is widespread. Due to rise of air temperature, surface frozen soil thaws, soil with high content of ice changes into mixture of hard rock block and flowing slurry, which has quite low shear strength or even lose the strength. Thaw slumping has a very shallow sliding plane which roughly paralleling to the slope surface, and could occur on very gentle slopes. In the permafrost region of QTP, thaw slumping is likely to happen on the slopes with the gradient of higher than 3°. The failure has a retrogressive extension to backward and sideward and the failed land surface is hard to recover. Mudflow terrace is a ladder-like landform caused by sliding of thawed soil. A unique case was found in a wide valley with gradient of about 10° in the Fenghuo mountain. There are ten steps with width of 5–10 m each and well vegetation cover. Mud flow terrace is thought to be formed as the thawed soil slides down on the slope surface, the vegetation underneath may check the movement and company drainage and consolidation. At this period, the soil sliding down behind overlays on the former sliding mass to form a step with gentle surface. The same process may occur in a valley to form number of steps. Vegetation creep is an especial landform. The vegetation on the slope surface slides down in variety size of pieces to form the scale-like landscape. It occurs as the slope gradient higher than 15° and has less impact on the engineering, usually results in vegetation degradation and soil erosion, as well as the ecological crisis.

From the above mentioned, it is clear that thaw slumping is the worst of all the slope failures to engineering, but it is also induced by engineering.

2 Engineering Induced Thaw Slumping and the Forming Conditions

With construction of roads and railways on QTP since last century, the engineering disturbances caused thawing of frozen soil, and consequently thaw slumping and other slope failure occurred. The Qinghai–Tibet Highway (QTH) starts from Xining city, Qinghai province in the North–East, terminates to Lhasa city, Tibet in the South–West, with the total length of 1,936 km. QTH is a second degree road and mostly runs aside QTR line. QTH was started to construct in 1950 and put onto working in 1954. It was improved for times in the history. The last portion from Gelmud to Lhasa with the length of 1,140 km mostly lies on the permafrost region of high altitude over 4,500 m.

The thaw slumping caused by construction of QTH mainly locate in the Hohxil hill region (K3014–3019), Beiluhe Basin (K3030–3060), and southern slope of the Fenghuoshan mountain (K3070–3080) (Fig. 1). The total length is about 45 km.

The thaw slumping near the milepost K3035 was caused by an accidental removal of soil during road reconstruction in the years between 1990 and 1992. Outcropped ground surface formed after earth borrowing. In summer, thawing of ground ice on the pit wall led to collapse of the upper part of the soil, which caused slumping of the soil for the first time. Afterward, it started to develop outward year by year and now formed a slumping with the length of 103 m East–Westward, the width of about 72 m North–Southward, the thickness of 1.5–2.0 m and the size of

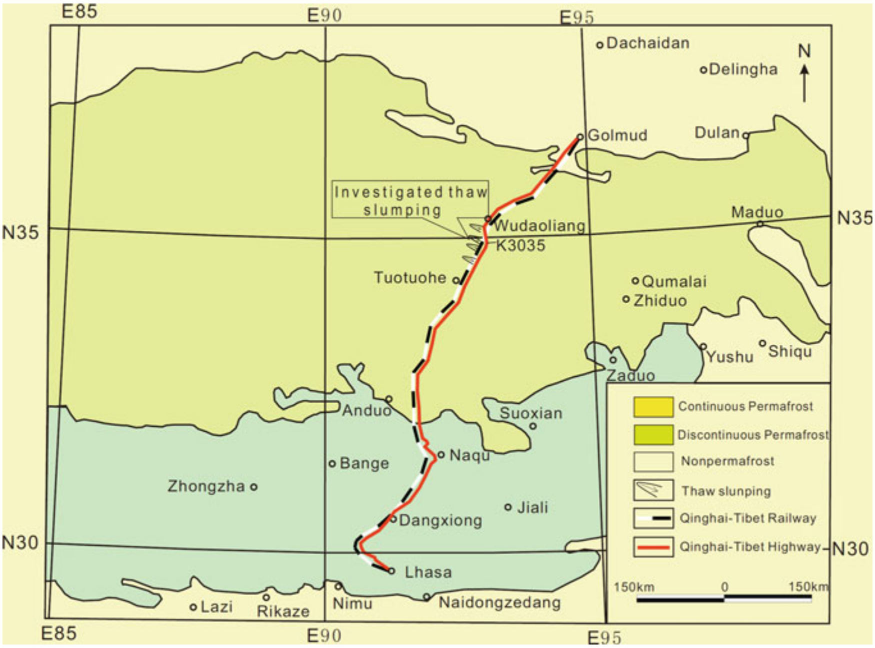

Fig. 1 Distribution of the permafrost and the thaw slumping on QTP

about 10,000 m^3 (Fig. 2). The slumping is located between Wudaoliang and the Tuotuo River, 40 km north of Fenghuo Mountain and at the altitude of 4,578 m. The slumping occurred on a gentle slope with the gradient of about 7°. We will take this case for further analysis on thaw slumping.

The area belongs to a dry-cold climate with thin air density and low air barometric. The four seasons here are not distinct and the annual freezing time lasts for seven to eight months. It freezes from September to next April,with the annual average temperature is −5.2 °C, extreme maximum temperature 23.2 °C and extreme minimum temperature −37.7 °C. It has the average annual rainfall of

Fig. 2 Thaw slumping near milepost K3035 of QTH

291 mm and the average evaporation of 1,317 mm. The annual mean ground temperature monitored is −1.75 °C, so it belongs to permafrost area of low temperature.

Boreholes and shafts revealed that the formations here are the upper Neocene lacustrine sediment and Holocene alluvial deposits. The strata from the surface is composed of 0.00 ~ 1.10 m reddish-brown sand, wet, loose, and locally intercalated with reddish-brown silty clay ($w_p = 11.4$–16.8 %, $w_L = 18.9$–26.9 %); 1.10–1.30 m, gray loose silt and fine sand; 1.30–2.00 m, red silty clay ($w_p = 14.6$ %, $w_L = 25.5$ %), with 20 cm ice block inclusions at the base; 2.00–4.00 m, thick ice bed with smooth surface; 4.00 ~ 11.80 m, highly weathered reddish-brown mudstone freezing all year; 11.8–13.3 m, gray sandstone, hard, with tiny fracture ice locally; under 13.3 m, argillaceous sandstone. According to the ice content and structure characteristics, the frozen soil from top to base is divided into the following three layers: 0.0–2.0 m, seasonal thawing layer; 2.0–4.0 m, soil containing ice; under 4.0 m, massive cryostructures. The upper boundary of the permafrost is about 2.0 m in depth, that is the upper surface of the thick ice bed.

3 Monitoring of the Thawed Soil Thickness

Two thermometer boreholes, A and B, were drilled on the K3035 slumping. Hole A is located behind the head scarp of the slumping, in which 5 temperature probes were installed in the distance of 0.5 m each other; Hole B is located in the upper of the slumping mass, also 5 probes set as Hole A. Positions of monitoring boreholes in plane and profile were shown in Figs. 3 and 4. Monitoring data applied here are from 16 August 2002 to 2005, which lasts for three climatic years.

Hole A represents the natural slope outside the K3035 slumping. Ground temperature at depth of 0.5, 1.0, 1.5, 2.0 and 2.5 m in the monitoring period is shown in Fig. 5 and the frozen depth in Fig. 6 respectively. First, it can be seen that soil temperature changes annually and there is a freezing period and a thawing period each year. The thawing period at the depth of 0.5 m lasts from early April to the beginning of December, and the freezing period lasts from early December to early April next year. With increase of the depth, the thawing period is shortened and delays in some extent. Figure 6 shows that the maximum thawing depth monitored is 2.2 m, generally appears in the mid-September and approximately the same in the three thawing periods. So, the upper boundary of the permafrost is 2.2 m.

The ground temperature at the depth of 0.5, 1.0, 1.5, 2.0 and 2.5 m monitored in Hole B is shown in Fig. 7 and the frozen depth in Fig. 6. Similar to Hole A, the soil temperature changes annually and the thawing period at the depth of 0.5 m is almost the same as that of Hole A. The thawing period is shortened with the increase of depth and also delays clearly. It can be seen from Fig. 6 that maximum thawing depth is relatively shallow, which is 1.5 m, and also the same in the three

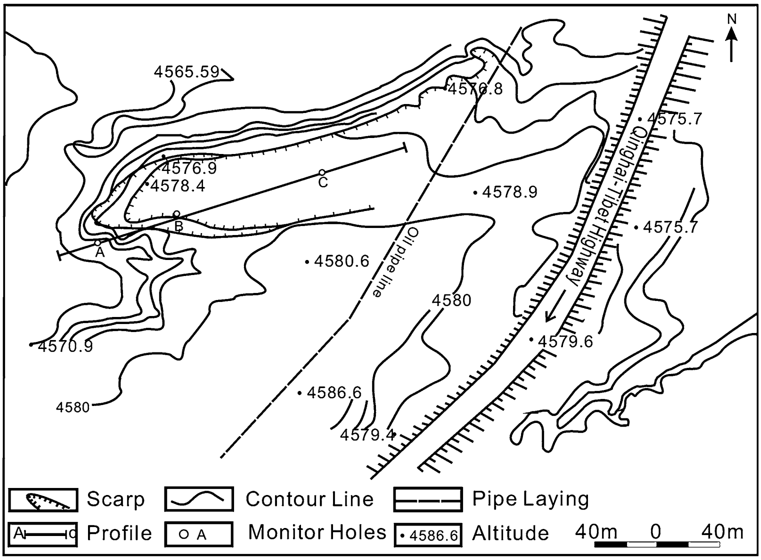

Fig. 3 Relief map and range of K3035 thaw slumping

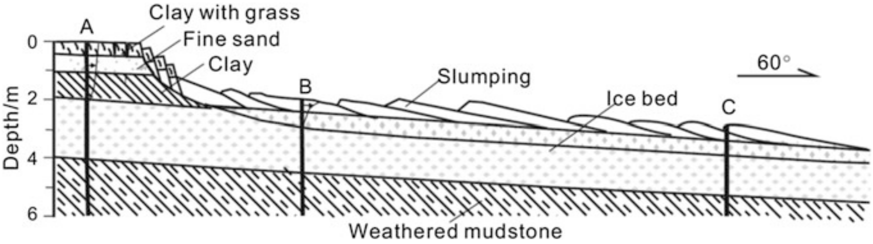

Fig. 4 Profile of the K3035 thaw slumping

is thawing periods. It shows that thaw slumping has changed the hydrothermal condition, and the annual maximum thawing depth is shallower than that in Hole A, so the upper boundary of the permafrost has redistributed in the slumping area.

In addition, Geokon-603 inclinometers were set in boreholes A, B and C. Of which, Hole C is located near the toe of the slumping mass as shown in Fig. 1. The monitoring started from 9 August 2002 to 16 April 2003, which had experienced a thawing period and a freezing one. Figure 8 shows the cumulative deformation of Holes A and C in the 250 days monitoring and that in Hole B in 15-day before 25 August, because the monitoring was stopped in Hole B at the date due to damage of the tube by extensive deformation. It can be seen that the maximum accumulative displacement at Hole A is 3.7 mm and that at Hole C is 10.9 mm. Even though Hole A is out of the boundary of the slumping, it still has slow displacement, but much smaller than that at Holes C, which indicates that the slumping

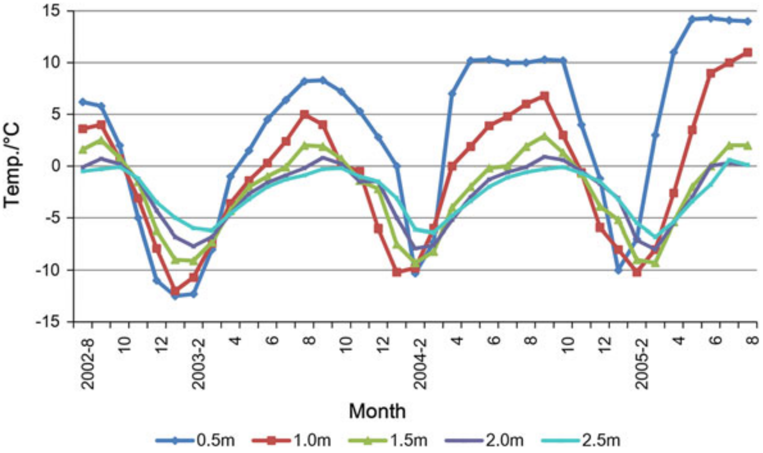

Fig. 5 Ground temperature changes at different depth versus time monitored in Hole *A*

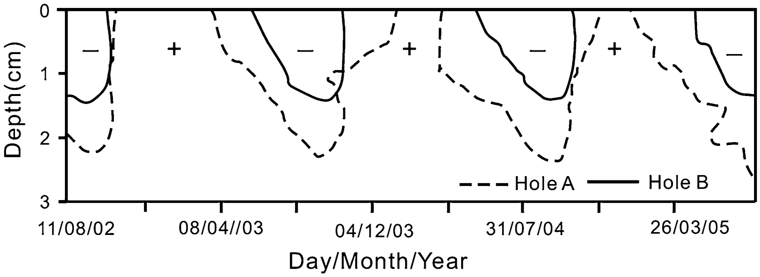

Fig. 6 The freezing depth monitored at Holes *A* and *B*

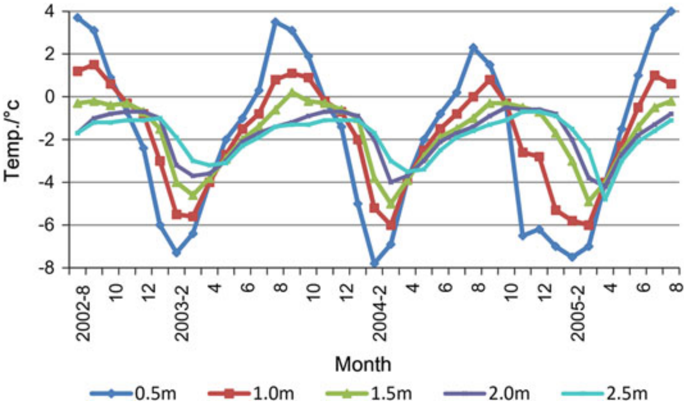

Fig. 7 Ground temperature changes at different depth versus time monitored in Hole *B*

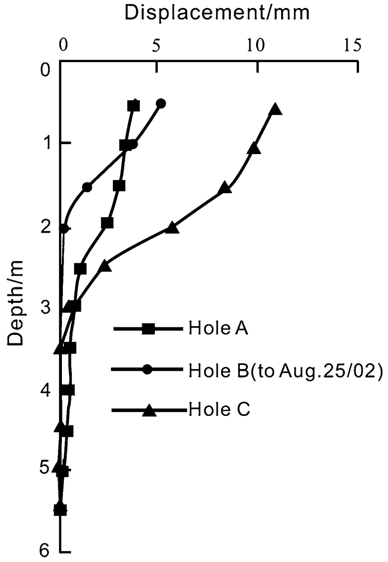

Fig. 8 Displacements versus depth monitored in the Holes *A*, *B* and *C* (8 Aug 2002 to 16 Apr 2003)

tends to develop backward. The maximum accumulative displacement at Hole B reached to 5 mm in 15 days reflects that displacement at the back of the slumping mass is larger than that in the front. Reclined fold and imbricate structure on the slope surface can also prove the movement feature.

Examining the displacement vertically, it is found that the deformation character of thaw slumping is different from that of general landslide. General landslide moves as blocks and has an obvious sliding surface. While the thaw slumping deforms transitionally, it means that, displacement changes from maximum to diminished from the surface to the bottom, which should be associated with the thermal gradient under the surface. With decreasing of temperature, viscous force of the sliding mass in plastic or flow state is enhanced and the strength of solid frozen bed is much higher, the displacement would be restricted in degrees with depth. There is no deformation under 2 m out of the slumping reflecting by the curve of Hole A, and the thickness of thawing soil observed at that point is 2.2 m, they basically agrees with each other. Obviously the deformation extended deeper on the slumping mass as seeing the curves of Holes B and C, but mainly concentrated in the depth of 0–2 m and diminished under 4.5 m. The ground temperature in Hole B shows that the thickness of the thawing soil is only 1.5 m, but the deformation zone extends below 1.5 m. It indicates that there is deformation in the frozen soil lying underneath the thawing layer. The curves of ground temperature at the depth of 1.5 m and 2.0 m in holes A and B are shown in Fig. 9. It can be seen that although the thickness of thawing soil at hole B is decreased, the ground temperature is increased. The lowest temperature of them has the difference over 4 °C. It indicates that the frozen soil in high temperature creeps too, so the effect on sliding mass has extended to the soil under the thawing layer. On the

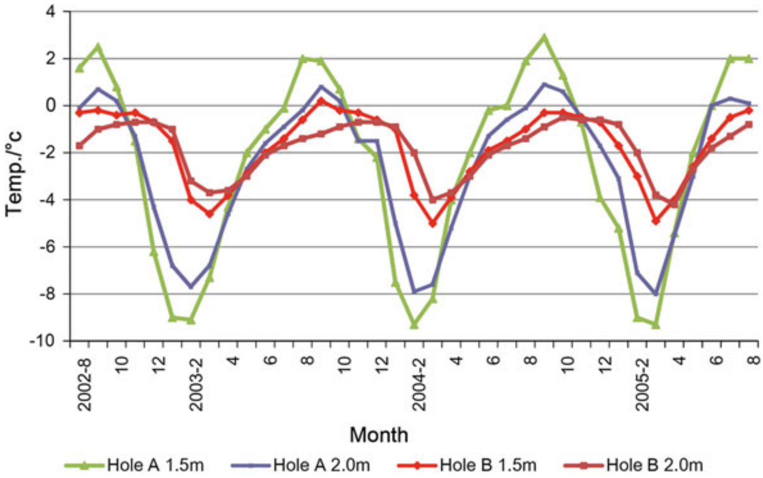

Fig. 9 Ground temperature versus month at depth of 1.5 and 2.0 m in Holes *A* and *B*

whole, deformation of the soil mainly occurred in the upper 2 m, above the surface of the thick ground ice, therefore, the thickness of thaw slumping is relatively less, but the influence area is large. It keeps on developing.

4 The Method for Thaw Slumping Stability Assessment

From the above analysis, thaw slumping has the features of thin thickness and broad area. The K3035 thaw slumping covers 7,200 m^2 of ground surface, but has the thickness of only 1.5–2.0 m, so the infinite slope model is suitable for its stability assessment as shown in Fig. 10. The model has the follow assumptions:

1. The sliding surface is a plane which parallels to the slope surface, so the thickness of the sliding mass is identical everywhere;
2. The thickness of the sliding mass is far more less than the length of the sliding mass;
3. The sides of the sliding mass extends infinitely, so the side effect is not considered;
4. The seepage flow direction is parallel downward to the sliding plane.

The shearing stress of the soil may be given by

$$\tau_f = c' + \sigma' \tan \phi' \tag{1}$$

To determine the factor of safety against failure along the plane *AB*, consider the slope element abcd. The forces that act on the vertical faces ab and cd are equal and opposite. The total weight of the slope element of unit length is