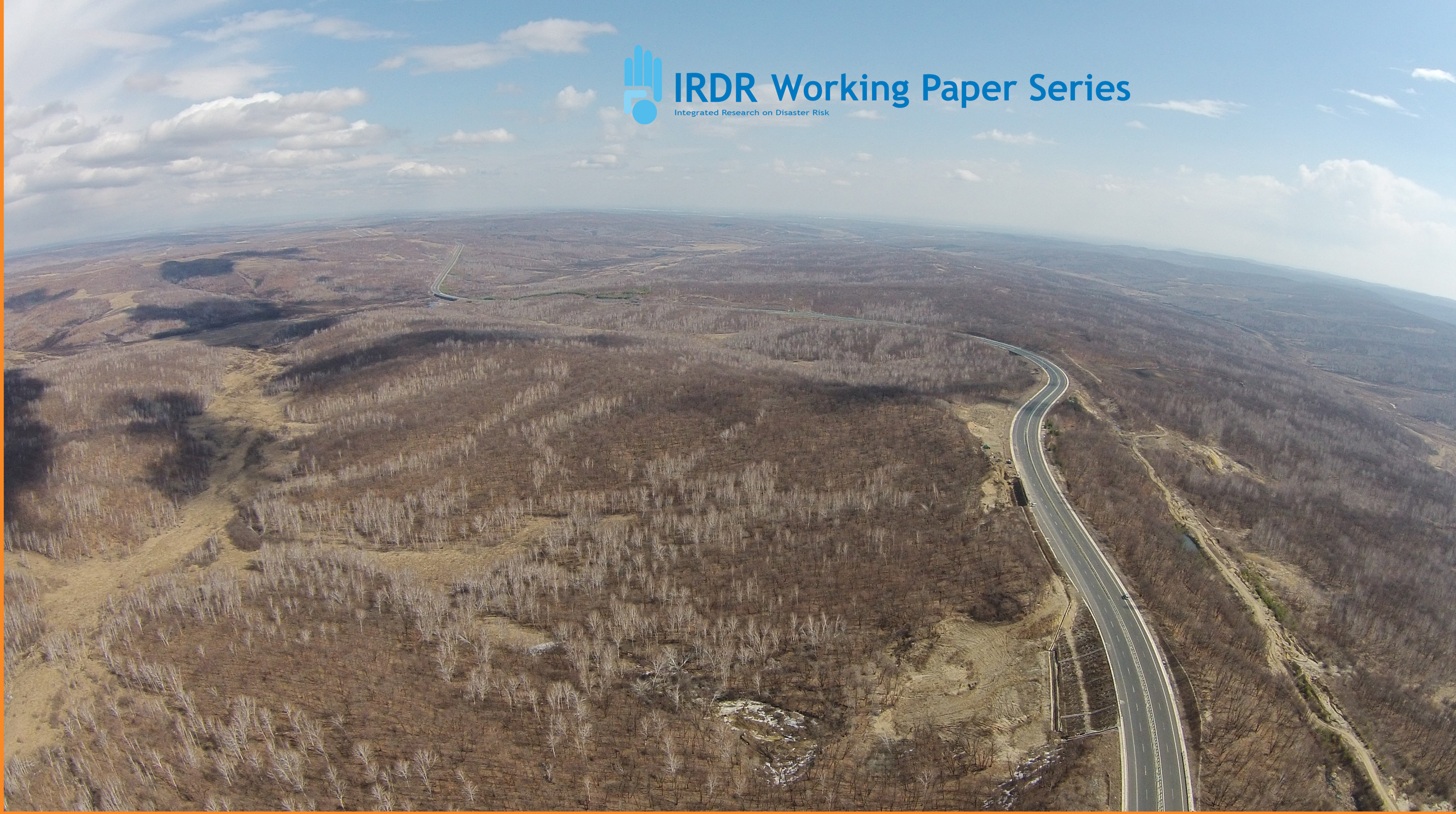

IRDR Working Paper Series

Integrated Research on Disaster Risk

Understanding the Geological Environmental Risks of Permafrost Degradation

Environmental and engineering geology in permafrost areas in Northeast China

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IRDR
Integrated Research on Disaster Risk

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About the Series

This Working Paper Series is a new publication of Integrated Research on Disaster Risk (IRDR), following the decision of the IRDR Scientific Committee in April 2019 to act to 'Expand IRDR Network and Scientific Output' (No. 5 of the IRDR Action Plan 2018-2020).

IRDR is an international scientific programme under co-sponsorship of the International Science Council (ISC) and United Nations Office for Disaster Risk Reduction (UNISDR) and with support from China Association for Science and Technology (CAST) and Chinese Academy of Sciences (CAS). Started in 2010, the Programme has been pioneering in the promoting international and interdisciplinary studies on DRR and has made its contributions through scientific publication and policy papers as well as dialogue toward shaping international agenda in the understanding disaster risks, bridging science and policy gaps and promoting knowledge for actions, all required in the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR) and its top priorities. Over time, the scientific agenda of IRDR has attracted many international renowned expertise and institutions. IRDR community is now, institutionally speaking, characterized by its strong Scientific Committee and six thematic working groups, thirteen IRDR national committees (IRDR NCs) and one regional committee (IRDR RC), sixteen international centres of excellence (IRDR ICoEs), a group of some one hundred fifty Young Scientists (IRDR YS) and a broad partnership with national, regional and international institutions working for SFDRR.

This Working Paper Series is thus specially made to facilitate the dissemination of the work of IRDR NCs, ICoEs, YS and institutions and individual experts that IRDR considers relevant to its mission and research agenda, and of important values for much broader range of audience working in DRR domains. As one will notice, all working papers in this series has anchored their relevance and contributions of their work toward SFDRR, IRDR, SDGs and Paris Agreement on climate change. It is the hope of the authors of the working papers and IRDR that this working paper series will not only bring new knowledge, experience and information toward disaster risk reduction, but also helped build better coherence of DRR with the mainstream agenda of UN today toward inclusive, resilient and sustainable human societies.

Team of IRDR-IPO

Understanding the Geological Environmental Risks of Permafrost Degradation

Environmental and engineering geology in permafrost areas in Northeast China

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Content

Abstract of this Working Paper

Permafrost is one of the elements of the cryosphere. Changes in thermodynamic stability of permafrost can directly affect the changes of Hydrosphere, Biosphere and Lithosphere, which could then have a significant impact on land hydrology, ecological environment, surface processes and the stability of major engineering in the permafrost distribution area. Under the trend of global warming, the frequency and intensity of environmental and engineering geological disasters caused by permafrost degradation are steadily increasing. For countries with permafrost distribution, important issues such as poverty eradication, climate change mitigation and adaptation, and sustainable economic and social development will face serious challenges. Therefore, there is an urgent need to share the knowledge and experience of disaster risk reduction (DRR) and to strengthen international cooperation for disaster risk reduction in response to priority actions under the Sendai Framework.

With the support of the Chinese government, the Field scientific observation and research station of the Ministry of Education - Geological environment system of permafrost area in Northeast China (FSSE-PFNEC) and the Provincial Collaborative Innovation Centre - Environment and road construction &maintenance in permafrost area of Northeast China (PCIC-PFER) were established. In addition, the Geological environment risk research plan for permafrost degraded areas in Northeast China (GERRP) was launched. Through cooperation with IRDR (Integrated Research on Disaster Risk), as well as IPL-WCoE ICL-CRLN (International Consortium on Landslides – Cold Regions Landslide Network), ICGdR (International Consortium on Geo-disaster Reduction) academic activities and the regular academic symposium, shared a case study on geological and environmental changes in the permafrost region of Northeast China. The main goal of establishing a platform for researchers and decision makers is to work together to find actionable policies to promote research on disaster risk and mitigation in permafrost areas in the context of climate change. This working paper introduces the results of a study on geological and environmental changes in the permafrost area of Northeast China.

Keywords

Disaster risk reduction, Climate Change, Permafrost, Sendai Framework

Indications of contributions to IRDR Science Plan and UN Agendas

IRDR Sub-objectives	1.1; 2.3; 3.1
SFDRR targets	SFDRR Target D and G
SDGs and/or Climate Goals	SDG Target 9; 11; 13; 15
S/T Roadmap actions	1.1.2; 1.1.6; 2.1.3; 2.2.1

1. How does this study contribute to IRDR research objectives?

Geological environment risk research plan for permafrost degraded areas in Northeast China (GERRP) is highly relevant to IRDR research objectives, in particular toward IRDR (Integrated Research on Disaster Risk) sub-objective 1.1: Identifying hazards and vulnerabilities leading to risks. GERRP provides new data and insights on the occurrence and distribution of permafrost degradation areas in Northeast China, as well as the key factors contributing to the degradation and impacts. In addition, GERRP research results are used by local governments and construction companies to support decision making in this large terrestrial area in relation to road infrastructure development as well as environmental management, thus contributing to IRDR sub-objective 2.3: Improving the quality of decision-making practices. Further, GERRP through its systematic field surveys and mapping provides comprehensive vulnerability assessment of permafrost degradation, a critical knowledge both for local development and national development, therefore has contributions toward IRDR sub-objective 3.1: Vulnerability assessments.

2. How does this study contribute to SFDRR targets?

The main contributions from GERRP to SFDRR are around Priority 1: Understanding disaster risk and Priority 2: Strengthening disaster risk governance to manage disaster risk. GERRP identified and analysed the key factors and causes of permafrost degradations in Northeast China, which are interlinked to both climate change processes and local development contexts. The data and knowledge obtained through surveys and studies help to address the SFDRR Target D: Substantially reduce disaster damage to critical infrastructure and disruption of basic services and Target G: Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.

3. How does this study contribute to SDGs and the Climate Goal?

Goal 9. Industry, innovation and infrastructure: To establish a unified permafrost disaster assessment criteria and technical standards for infrastructure construction, so that developing countries can more easily receive technical assistance to support the development of "sustainable industrial infrastructure" in the countries having permafrost.

Goal 11. Sustainable cities and communities: To establish a unified monitoring indicator for environmental system, that can comprehensively evaluate the impact of climate and permafrost changes on ecological environment, hydrology and water resources, surface process changes, food security, and habitat security, and to support the coordinated development of human beings, cities and communities.

Goal 13. Climate action: To establish a global monitoring network of climate and environmental change, share the results of monitoring data, timely release early warnings of disasters, and support the countries concerned to take joint and urgent action to address climate change and its impacts.

Goal 15. Life on land: Through sky-to-earth observation and ground monitoring systems to achieve the whole process monitoring of river basin hydrology and ecosystems, to strengthen water resources protection, to achieve the goal of protecting terrestrial ecosystems, preventing desertification, curbing soil degradation and protecting biodiversity.

4. How does this study contribute to Science & Technology Roadmap Actions?

Permafrost is sensitive to climate and environmental changes: climate warming especially has a greater impact on permafrost conditions. At the same time, as part of the cryosphere, the permafrost temperature and phase changes directly affect the changes of other layers (hydrosphere, biosphere and lithosphere). Therefore, early understanding of the Earth Critical Zone (ECZ) changes in permafrost area is fundamental to understand the geological environment risks in permafrost areas. One of the highlights of GERRP is the exchange of case studies of environmental and engineering geological research in cold areas, which provide a wide range of research results for relevant researchers and decision makers.

Due to the complexity of geological and environmental issues arising from permafrost degradation, a wide range of disciplines and fields are involved, requiring multidisciplinary cooperation in research and collaborative action in many sectors to enhance disaster risk management. GERRP through IRDR, IPL-WCoE, ICL-CRLN, ICGdR platform, organized relevant academic conferences to support and promote the relevant research exchange and cooperation among the organizations and researchers.

Main Text

1. Climate Change and Cryosphere Response

Climate change refers to a change in the climate average state or a climate change that lasts for a long period of time (typically 30 years or more). The cause of climate change may be natural processes within the climate system, or external forcing, sustained changes to atmospheric composition and land use by human activities. The Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) notes that greenhouse gases, aerosols, particulates, chemicals and other impurities emitted by human activities, as well as changes in land use, have contributed to global warming effects since the industrial revolution of the 1850s. Studies have shown that since the 1950s, more than 50% of global warming has been caused by human activity (more than 95% confidence)(Stocker T F, Qin D.H., et al. 2013).

The cryosphere is a zone with negative temperature in which the earth's surface is distributed continuously with a certain thickness and the water element is frozen. It is one of the five components of the climate system, and is the most sensitive to changes. The cryosphere has important impacts on the atmosphere, water resources and cycles, ecosystems, land and marine environments, and sustainable socio-economic development. The hydrothermal and dynamic mechanisms, change processes, and influence and adaptation of the cryosphere elements are not only the main research focus of cryosphere science, but are also key to understand cryosphere hazards (Qin D. H., Ding Y. J.,et al. 2018).

Climate warming causes cryosphere elements to change significantly, mainly in the form of scale reduction and temperature increase (Qin D.H., Yao T.D., et al.2020). The frequency and intensity of the occurrence of cryosphere disasters is increasing markedly. The regional characteristics of the cryosphere determine that its changes will first affect countries and economies of high latitudes, and gradually transmit to the mid-latitudes. Coupled with the impact of these changes on the oceans, impacts on low latitudes and small island countries are also inevitable, resulting in global effects (IPCC.2013). Efforts to address poverty eradication, climate change mitigation and adaptation, and sustainable socio-economic development in affected cryosphere areas will face serious challenges.

Global warming leads to profound changes in the Earth's climate system, significantly affecting and disturbing existing inter-adaptive relationships between humans and ecological systems. Climate change and its impact on terrestrial cryosphere systems has become a leading hot topic of global concern. In 2019-2020 alone, *Nature* and its sub-journals published 17 research papers on the effects of climate change (Lenton TM, et al.2019; Wake, B.,et al. 2019; Hall, A., et al. 2019), including topics such as effects of summer warming and changes on Arctic permafrost and cryosphere factors(Porter, T.J., et al.2019; Yumashev, D., et al. 2019), climate change and permafrost changes (Wang,C.,et al.2019; Pohl, B.,et al.2019) , climate change and greenhouse gas emissions in permafrost areas (Wadham JL, et al.2019; Merritt R Turetsky, et al.2019; Zhang, L.,et al.2020; Ruebsam, W.,et al.2020; Zeke Hausfatheret al.2020), climate change and the geographical distribution of natural disasters in high-cold mountain areas (Schlögel, R., et al.2020),climate change and hydrologic and water resources in permafrost areas (Shakoor, A., et al. 2019; St. Pierre, K.A., et al. 2019; Liu B.J., et al. 2019; Gao J., et al. 2019.)and other multidisciplinary issues .

Permafrost comprises about 20% of the earth's land area, mainly in Europe, northern Asia, North America, and the Arctic Ocean shallow continental shelf, as well as low-to-medium-latitude mountains, plateaus and other inaccessible, economically underdeveloped areas (Figure 1). As one of the elements of the cryosphere, changes in thermodynamic stability of permafrost will directly affect changes in the terrestrial hydrosphere, biosphere and lithosphere. These thermodynamic changes will also have a significant impact on changes in land hydrology, ecological environment, surface process and major engineering stability.

This paper combines direction from the *Sendai Framework for Disaster Risk Reduction 2015-2030*, *The Sustainable Development Goals*, and *The Science and Technology Roadmap to Support the Implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030* with our researches on the impact of climate change on permafrost in Northeast China.

Figure 1. Permafrost distribution in the northern hemisphere

2. Climate Change and Permafrost in Northeast China

Permafrost in Northeast China is located on the southern edge of the Eurasian permafrost zone and is an important part of this zone. Permafrost is affected by latitude, elevation, solar radiation, surface cover, climate and other complex factors. Its regional geographical distribution in Northeast China corresponds to the air average annual temperature of 0℃ as its southern boundary, like a W-shaped spread, mainly distributed in the Great and Lesser Khingan Mountains., The Changbai Mountains also have sporadic permafrost distribution (Figure 2).

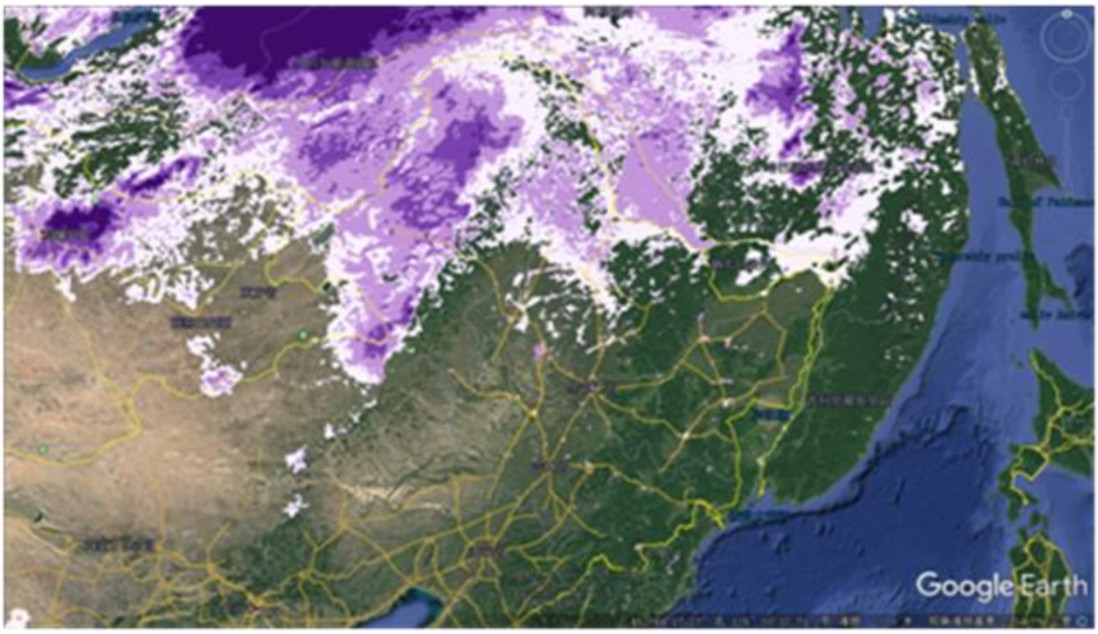

Figure 2. Permafrost in Northeast China

The climate in Northeast China is dry and cold in winter(affected by Siberian high pressure), humid and warm in summer(affected by the Pacific subtropical high pressure control); the difference in air annual temperature is 40-50℃. The surface temperature is relatively low in the lower elevations and shady slopes, which are affected by solar radiation, surface swamps, moss, humus layer and winter snow. Temperature inversion here forms a unique permafrost deposit condition. Permafrost is mostly distributed in the northwest shady slopes and relatively lower terrain. The degradation process is first on sunny slopes then on shady slopes, first in higher elevations then in lower elevations. This unique permafrost distribution and degradation phenomenon is similar to the permafrost in Siberia Russia, known as the "Khingan Baikal" permafrost.

Since the 1990s, permafrost in Northeast China has been severely degraded, due to global warming. Experts have defined that the area of ground with "ground surface freezing number" greater than 0.5 is permafrost area. Using the meteorological data of the National Meteorological Station, the curve of mean ground surface freezing number in the permafrost area of Northeast China from 1979 to 2018was drawn and showed a high consistency with the variation of Arctic sea ice area. Figure 3 shows the results.

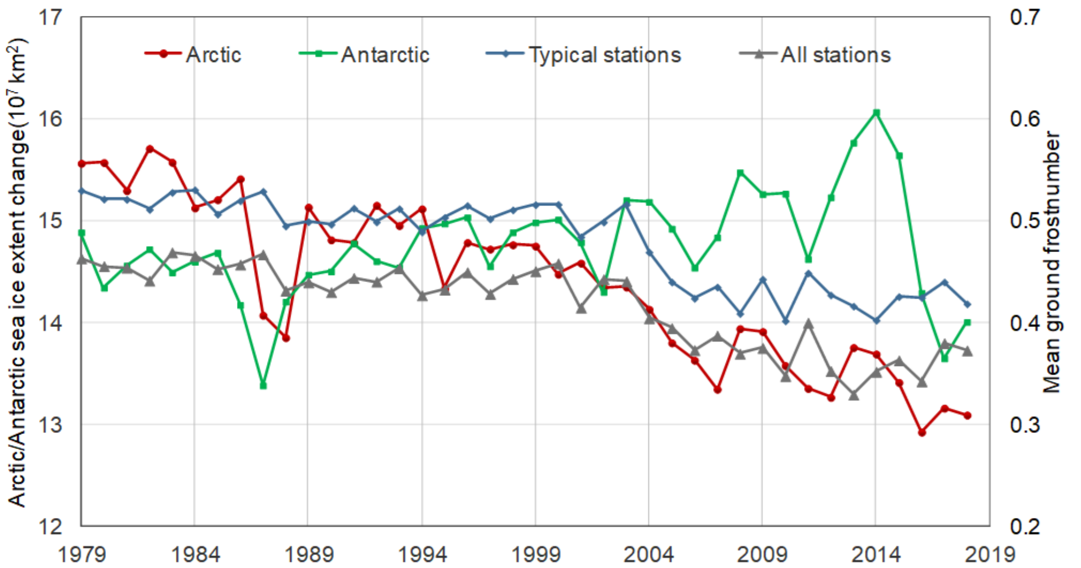

Figure 3. Ground surface freezing number（data from meteorological station）in Northeast China and Arctic sea ice area

Using the average annual air temperature data of several meteorological stations in Northeast China, combined with DEM, the distribution of permafrost in Northeast China at different times (Figure 4) was mapped, where seasonal frozen soil depth is more than 1.8 meters. Figures 4a and 4b are permafrost (including sporadic permafrost, discontinuous permafrost and continuous permafrost)maps in Northeast China between 1971-1975 and 2011-2015, respectively. In the past 40 years, the total area of frozen soiled creased by 18.6%from 1.18×10^6km²to 9.61×10^5km², and the permafrost area decreased by 28.3% from 4.12×10^5km² to 2.95×10^5km².

a. 1971-1975 b. 2011-2015

Figure 4. Permafrost distribution maps in Northeast China

3. Environmental and Engineering Geological Problems in the Permafrost Area of Northeast China

Climate warming and permafrost degradation have led to an increasing number of environmental and engineering geological problems in permafrost degradation areas, which pose challenges to local environments and the stability of engineering structures.

Along K149-K183 section of the Bei'an-Heihe Expressway (BH Expressway) in the southern boundary of the permafrost zone in Northeast China, disasters such as ground subsidence, slope icing, landslides and other events caused by permafrost melting have seriously threatened the stability and safety of road operations since 1999.At the same time, melting permafrost also leads to seasonally high concentrations of greenhouse gases, triggering wildfires that may further accelerate permafrost degradation and environmental changes of terrestrial ecosystems and road areas.

3.1 Permafrost distribution, surface deformation and topographic factors

Three Landsat 7 ETM + image data covering the K149-K183 road area of BH Expressway in Sunwu County, China in March, May and September, 2009 were obtained. The infrared surface temperature of the satellite at the transit time was calculated using the radiation transfer equation method. The inversion results were classified using natural breakpoint classification. By analysing the surface temperature variation and manually interpreting it, intersection calculation was performed on the low-temperature area, and the permafrost distribution map for 2009 was obtained (Figure 5).

A total of 18 L-band ALOS/PALSAR SAR (Advanced Land Observing Satellite-1/Phased Array type L-band Synthetic Aperture Radar) images over the study area from July 2007 to December 2010 were used as data sources to retrieve information on the surface deformation caused by permafrost degradation. The annual average deformation rate map along the line of sight direction from 2007 to 2010 was obtained, as shown in Figure 5. Combined with the SRTM DEM (Shuttle Radar Topography Mission Digital Elevation Model) (with a resolution of 30m), further quantitative analysis of the relationship between the permafrost distribution characteristics and the surface deformation data from slope, aspect and elevation was conducted.

The deformation points were further divided into 8 grades of surface deformation. The accumulated deformation values for the grades are respectively ＜-100mm, -100~-50mm, -50~-25mm, -25~-0mm, 0~25mm, 25~50mm, 50~100mm and ≥100mm.The three factors i.e. elevation values, slope and aspect of permafrost area, and point targets with different grades of deformation are extracted respectively, so as to further analyse the relationship between permafrost distribution, surface deformation and topographic factors. Based on the study area data, the statistical results are converted into the percentages of the different factors of permafrost area and surface deformation in the study area. The results are shown in Figure 6-8.According to the elevation distribution of different deformation grades represented by different colour curves, we can see that, firstly, the point targets with the accumulated deformation values within ± 25 mm account for about 78% of the total point targets., This deformation grade is widely distributed in the area, which also means most of the surface in the study area is relatively stable, and deformation values are small. Secondly, permafrost area accounts for about 14% of the total study area, the elevation values of permafrost distribution are between 230m and 400m, and the main distribution range is between 230m and 320m, which corresponds to the relatively low terrain in the area. Moreover, the distribution curve of permafrost has three peaks at the elevation values of 240m, 310m and 360m, which indicates the permafrost distribution is the same as the topography of the study area with stepped distribution, and the terrain is higher in the west and lower in the east. The accumulated deformation variables within the range of < 100mm and > 100mm were lower, indicating that areas with larger deformation variables are less common in the area. All the deformation values with positively skewed distribution were below the elevation value of 300m, indicating the deformation distribution is at lower elevations. According to the analysis of Figure 7, permafrost and deformation are mainly distributed in the gently sloped areas with a gradient of 0-6 °.

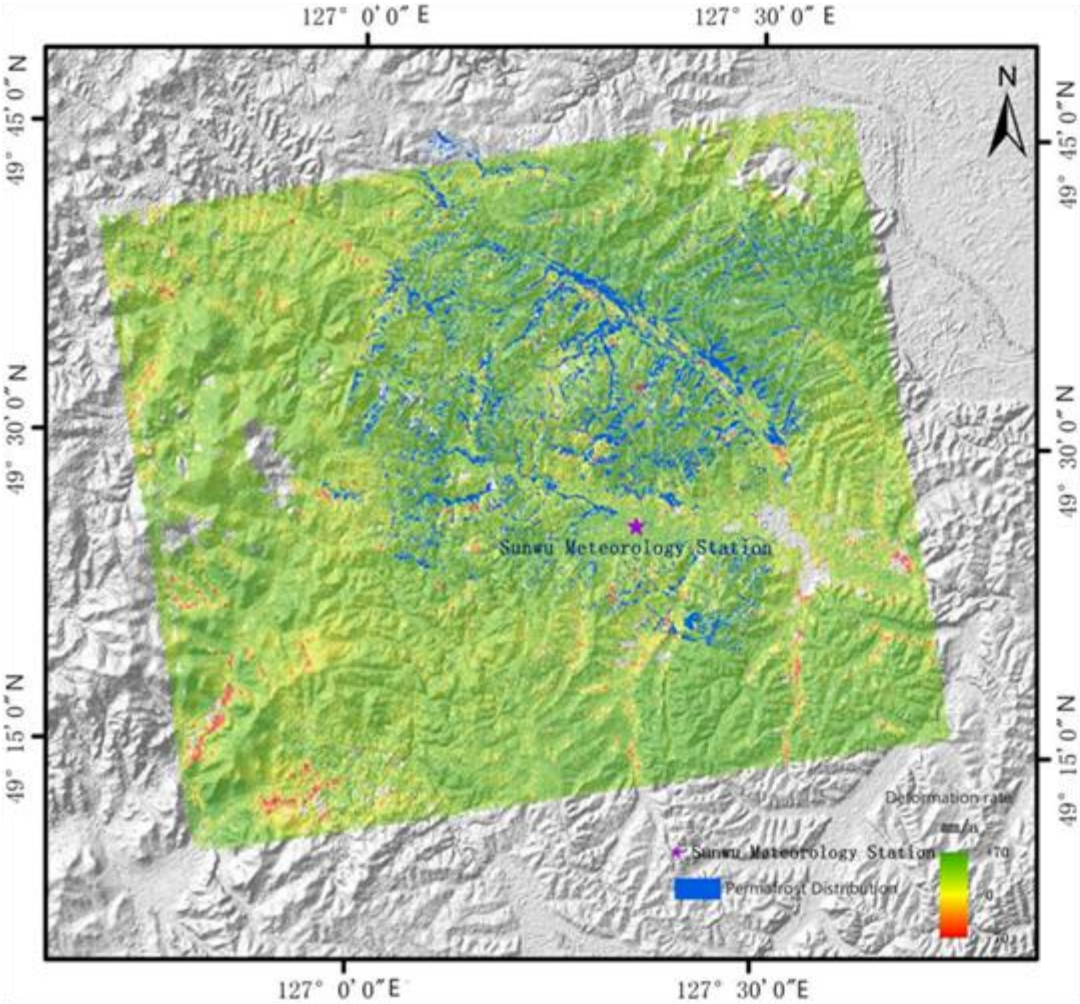

Figure 5. Permafrost distribution map and average annual deformation rate along the line of sight direction in the K149-K183 road area of BH Expressway

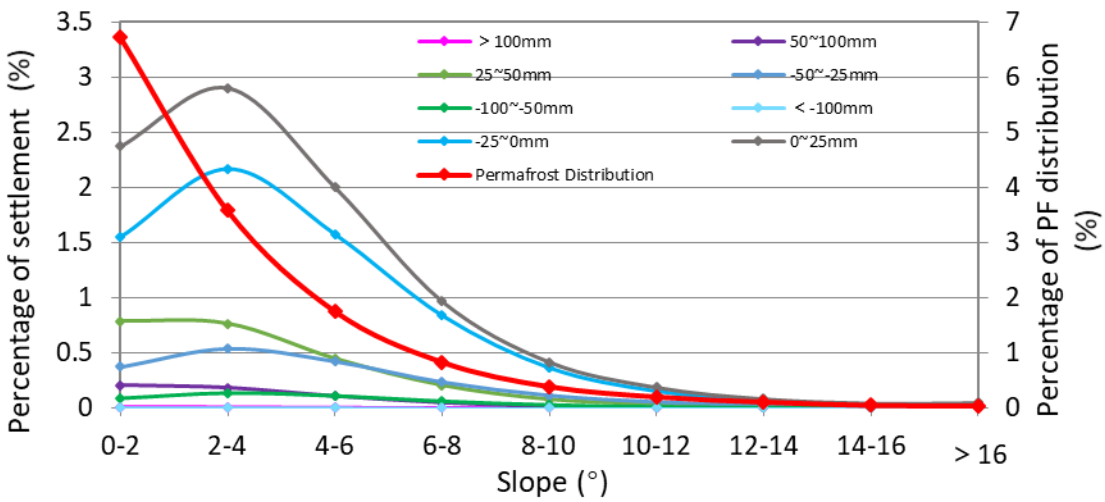

Figure.7. Slope distribution of permafrost and point targets with different deformation

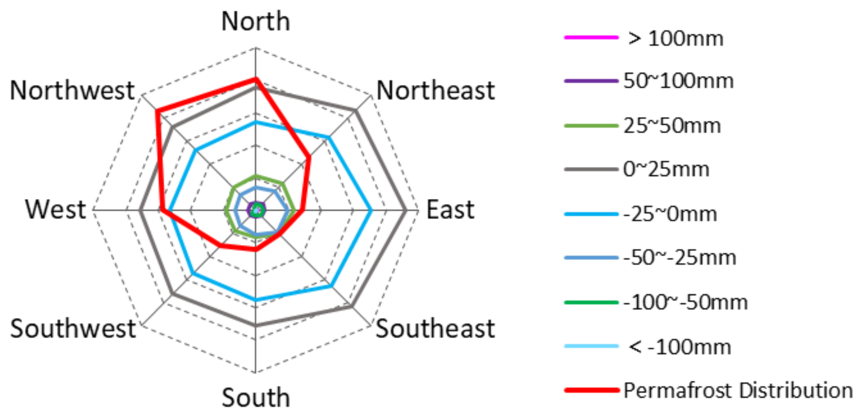

Figure 8. Aspect distribution of permafrost and point targets with different deformation

We can see from Figure8 that permafrost distribution is significantly different, with most on the shaded slope facing north and northwest, followed by northeast and west. The deformation distribution is mainly distributed on the slope facing east and southeast, followed by northeast and north. According to the elevation and slope distribution and the law of permafrost degradation, permafrost is mainly distributed on the shaded slope in the gentle and low-lying position, particularly in the slope range of 0-2°. These results indicate that the deformation is mainly caused by melting of already degraded permafrost located at higher elevations and sunny slopes. There are a large number of deformation points on the shaded slope, which proves that the permafrost that still exists is also in the process of degradation.

The results show the average annual deformation rate of the road area is 70mm/yr, and the obvious deformation areas are mainly located in the relatively low-lying areas such as ditches and depressions. The distribution characteristics of the deformation points with the average annual deformation rate greater than -35mm/yr and the "Khingan Baikal" permafrost are especially consistent.

This pattern of distribution in low-lying areas can also be proved by the distribution map of cumulative deformation variables. The superposition map of the surface distribution and accumulated deformation values with 25mm ~ 50mm and - 50mm ~ - 25mm is shown in Figure9. Through comparison, it can be seen that the surface deformation in the gentle valleys of permafrost areas is mainly realized as uplift, while in the boundary of permafrost area deformations are mainly realized as subsidence. In combination with the above mentioned, the comparative analysis of distribution situations of slope, aspect and elevation prove that the permafrost degradation is characterized by a decrease from higher to lower, from sunny slopes to shaded slopes. The soils on the slope fall and slide following the first degraded permafrost melting, and accumulate in low-lying valleys.

3.2 Permafrost degradation and landslides

The melting of permafrost on hillsides leads to landslides, which seriously threaten the stability of roadbeds. One section of BH Expressway was built on a hillside and was destabilised by landslides caused by melting permafrost (Figures 10 A, B, C)in August 1998, requiring this section to be rerouted to its current position. This road was widened into an expressway from April 2009 to September 2011. During the survey before construction, it was found that there were landslides in four places within 3m range along the left side of K177 - K180 section, with a slide volume of more than 20000m^3.In addition, many landslides can be found within 2km range of the road area(Figure 10 A). The landslide location is basically in line with the distribution of permafrost, and it is guessed that these landslides are caused by permafrost melting.

In June 2010, a survey of the K178+530 landslide (Figure 11) found the landslide movement had a low angle, intermittent characteristics of sliding (Wang C.J., et al. 2015), and the distribution of permafrost in Figure 10A was consistent with the geological survey results. The occurrence time and rate of sliding have a relationship with the slope soil pore water pressure. The landslide movement gradually stagnated with the soil pore water pressure gradually decreasing. At the same time the permafrost melt water seeped into the landslide body, forming icing on the slope in winter. The ice increased the weight of the shallow soil on the slope, reduced the soil body anti-shear strength, and became the main cause of the movement. Due to the lack of survey and monitoring data prior to 2009, the initial sliding time of this landslide could not be determined. From the satellite photos of 15 June 2004 and the satellite photos of 12 September 2010, the distance from the landslide front edge to its end edge (marked in red straight line) grew from 101.26m to 145.05m, and the front edge moved 43.79m forward. The position of the end edge of the landslide remained basically unchanged (Figure 10F, G, H). As seen in Figure 10, the end edge of landslide is near the left side of the roadbed, and forms an arc-shaped step during the sliding process. The slope of the landslide body is between 8°-15°.As icing builds up in winter, the leading edge pushes the original surface soil to slide forward together and form a bulge (Figure 12-14).

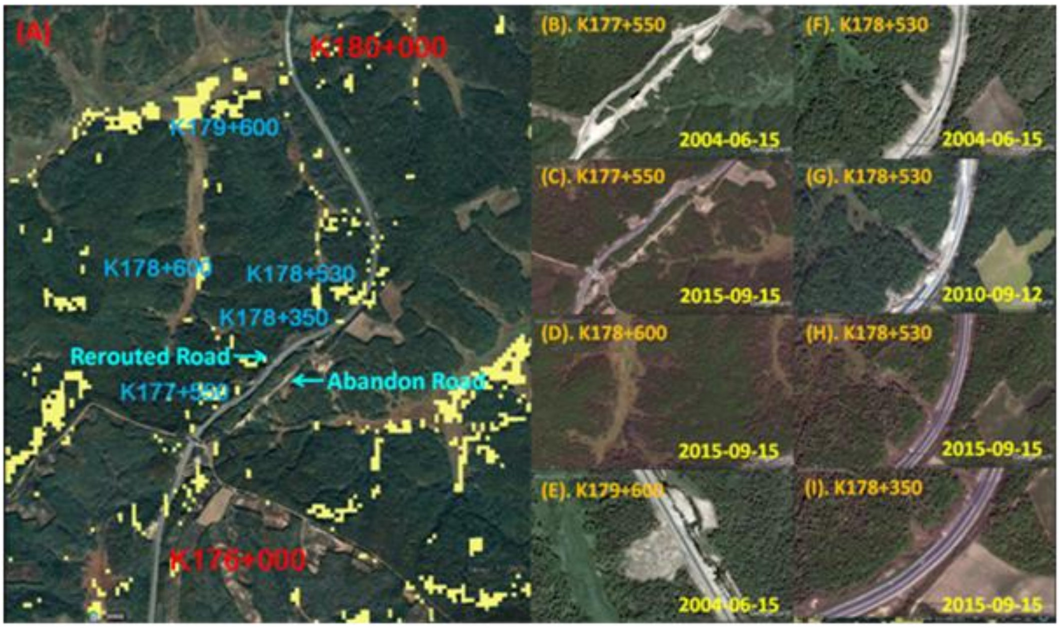

Figure 10. Permafrost and landslide distribution map in K176-K180 section

Figure 11. View of K178+530 landslide

Figure 12. View of the K179+600 landslide

Figure 13. View of K178+350 landslide

Figure 14. View of the K177+550 landslide

3.3 Permafrost degradation and subgrade thawing and settlement

Swamp wetlands and permafrost are mostly distributed in relatively low-lying areas. Permafrost degradation led to the subgrade thawing and settlement of many sections of the BH Expressway. Using the regional permafrost distribution map and geological survey results, in July 2009, during the construction of the widening and expansion of BH Expressway, the K161+440 section was selected as the monitoring section. The soil temperature and deformation observation equipment were installed to monitor soil body temperature and subsidence at the left foot of the subgrade（LFS） and the central separation zone (CSZ) of the road, respectively. The surface vegetation of this section is mostly *Carex*, moss and other wetland species. The surface soil layer is humus, which is suitable for permafrost occurrence., Road construction and other external disturbance factors resulted in the melting of permafrost in this section, causing the roadbed to produce a larger deformation during the construction and operation period, and seriously threatening the safety of the road (Figure 15A).

Using the ground temperature monitoring data, a contour map of the ground temperature change at CSZ and LFS of the K161-440 section was drawn (Figure 15 B and C). The results show the temperature of the permafrost in CSZ and LFS is higher than -1˚C, indicating high temperature permafrost. This temperature range puts the permafrost in a severe phase transition zone, and its physical and mechanical properties are very likely to change greatly under the influence of temperature changes. The natural permafrost table (PFT) is particularly sensitive to air temperature changes and its pattern significantly correlates with the seasonal air temperature. Therefore, the PFT in CSZ and LFS has obvious seasonal variation and fluctuates frequently. Overall, there is a clear degradation trend, mainly showing a going down of the permafrost table, a going up of the permafrost base, and thinning of the permafrost layer. The thickness of the permafrost at LFS was about 9.7m and at CSZ was about 5.3m when monitoring began in September 2009. After 7 years, the thickness of the permafrost at LFS was about 6.7m (reduced by 3m) and at CSZ was about 1.4m (reduced by 3.9m). Permafrost at CSZ is more obviously affected by construction disturbance.

The subgrade settlement is extremely sensitive to changes in permafrost temperature underground. The settlement curve at CSZ of K161+440 section is shown in Figure 16D.Asroad filling progressed from 2009 to August 2011, there was a significant acceleration in vertical displacement of each monitoring point during the filling of the roadbed. The maximum vertical deformation was 27.8cm. From August 2011 to October 2016, the vertical displacement gradually decreased although at a reduced rate over time. The vertical displacement showed a corresponding relationship with soil temperature. This relationship exists mainly because of the continuous degradation of permafrost under the roadbed, and the fact that the roadbed takes longer to reach stability with the melting of permafrost. During the road operation, the vertical deformation of the monitoring point in May-October 2014 was larger than that of other years. The deformation at CSZ amounted to 7.9cm. Comparing the soil temperature monitoring data, it can be seen that the warming of the permafrost underground is greater in the corresponding period, indicating the faster the permafrost degradation, the greater the vertical deformation.

Climate change and engineering activities are the main factors in permafrost degradation. For high-temperature permafrost, the impact of construction disturbances on permafrost degradation is higher than that of climate change.

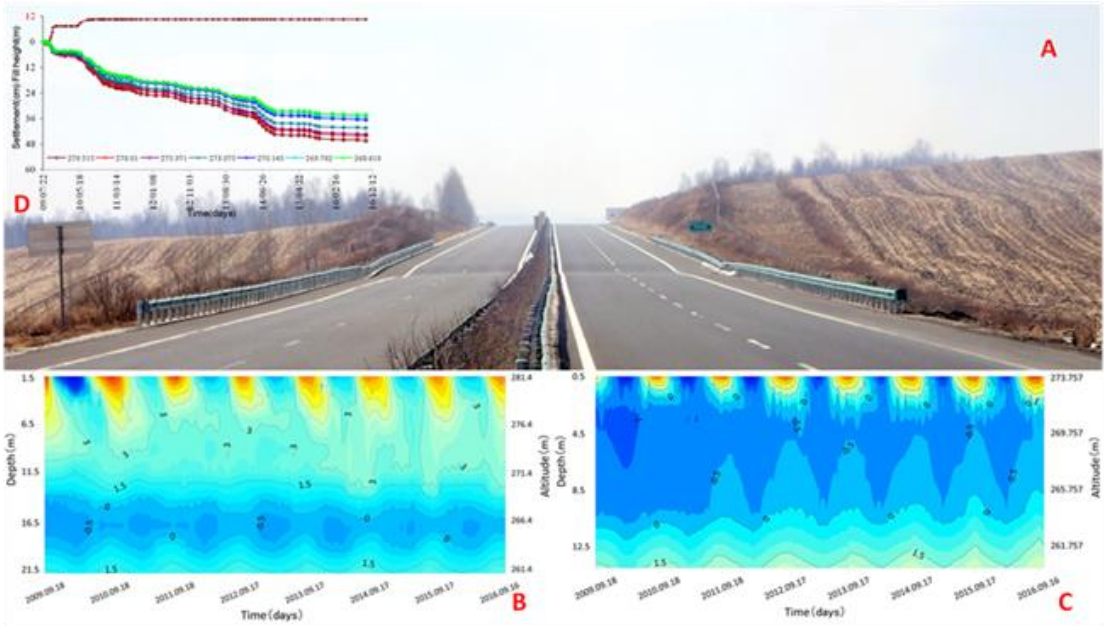

Figure 15.1. Monitoring results of Ground temperature and uneven settlement of the subgrade in K161+440～K161+450 section during road operation

Figure 15.2. Measuring point position of Ground temperature and uneven settlement of the subgrade in K161+440～K161+450 section during road operation

3.4 Greenhouse gas emissions and wildfires in permafrost wetlands

With global warming, the increase of greenhouse gas emissions and the frequency of wildfires in permafrost areas has gradually attracted attention. In Northeast China, the distribution of wildfires has a clear correspondence with the distribution of permafrost. Figure 16A is a three-dimensional image of the burned area of road K156-K166 of BH Expressway on March 31, 2018. Figure 16B shows the distribution map of permafrost in the road area. Figure 16C is an image of a wildfire burning on the road area taken by the Sentinel Satellite on 2018.03.25.

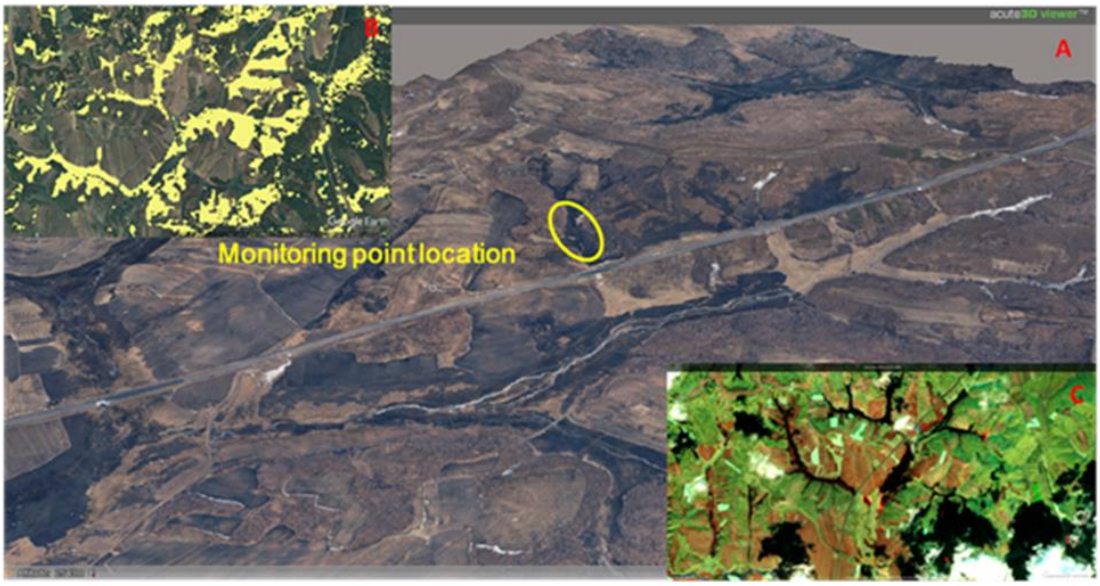

Figure 16. Image of the burned area of K156-K166 section of BH Expressway (2018.03)

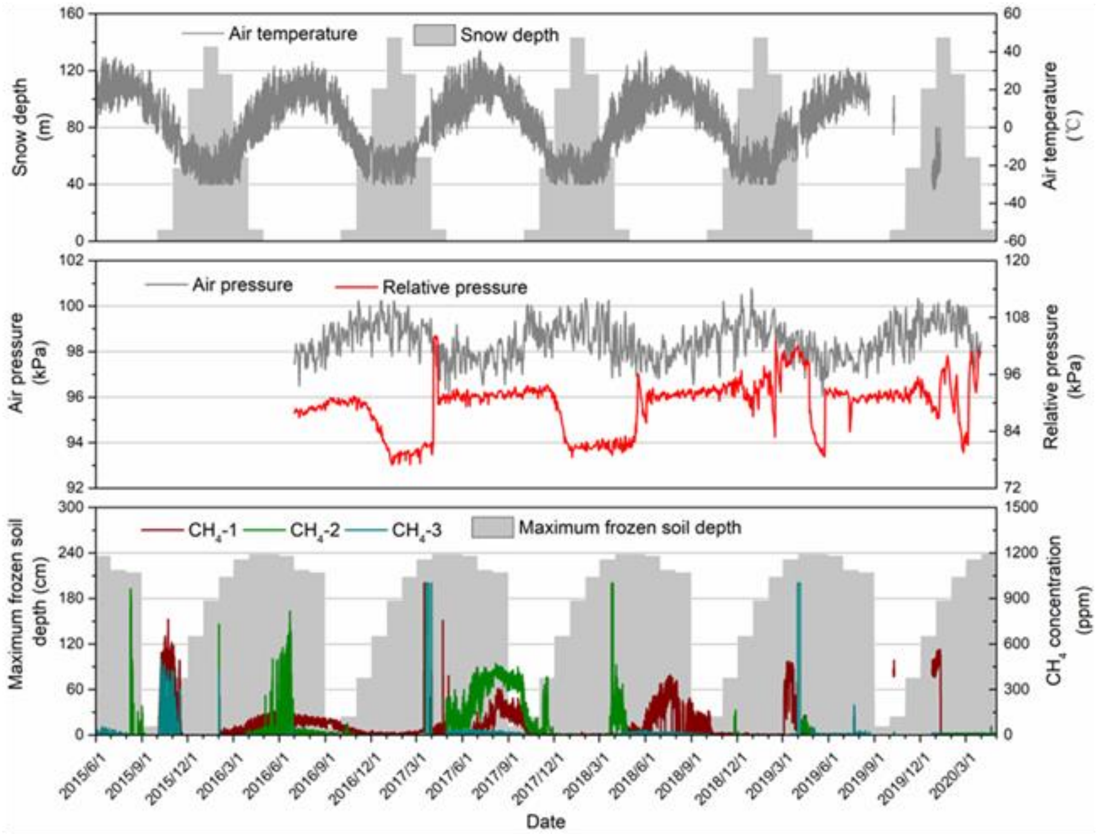

Figure 17. Monitoring factors in K161+200-K161+900 section of BH Expressway

In the permafrost degradation area north of Lesser Khingan Mountain in Northeast China, in late March each year, just as surface snow melts completely, the concentration of surface methane increases suddenly and continuously for a short time. Meanwhile, there are many wildfires in the distribution range of permafrost in the valley. This phenomenon is confirmed by field investigation, UAV (unmanned aerial vehicle) and satellite images (as shown in Figure 16C). In April 2016, drilling was carried out on the left side of the

K161+200-K161+900 section of the BH Expressway, which is 50-100m away from the subgrade slope toe. Combustible ice samples were obtained 11 meters below the ground. The monitoring found the surface methane concentration at the measuring point showed an obvious annual seasonal cycle change, and had a corresponding relationship with the algebraic sum of the pore water pressure and air pressure at one meter below the ground (Figure 17). At present, the mechanism of regional wildfire ignition during this time period is unclear.

3.5 Degradation of permafrost and species change of old landslide trees

During the slow degradation process of the island-shaped permafrost on the hillside, the moisture content of the shallow soil on the slope surface showed obvious differences, which weakened the shear strength of the slope body and led to the slow movement of the landslide. The movement of the slope body stopped after reaching the stress balance (Figure 10A, D). However, the degradation of permafrost continues, the local high water content persists, and the soil temperature will also change, resulting in changes in the species of trees and other plants growing on the hillside (Figure 18).

The survey at a straight line distance of 1,000 meters from the BH Expressway found there are multiple birch trees growing along the cracks in the boundary of the old landslide. The vegetation is obviously different from the growth of Mongolian oak in and out of the landslide. The main difference between the growth conditions required for the two species is that birch trees are more likely to grow in soil with higher water content and lower temperature. Landslides caused by water saturation during the melting and phase transformation of permafrost have such soil conditions. The high-density resistivity method was used to probe the K178+600 landslide along the sliding direction and vertical sliding direction, and the accuracy of the above inference is verified by the distribution position of permafrost in Figure 10A. The core samples of birch and Mongolian oak were drilled respectively, and the analysis results are shown in Figure19. Evidence shows the permafrost in the vicinity of K178 + 600 landslide began to degenerate 70 years ago. With regional permafrost degradation, the local tree and plant species populations are also succeeding in the growth competition process.

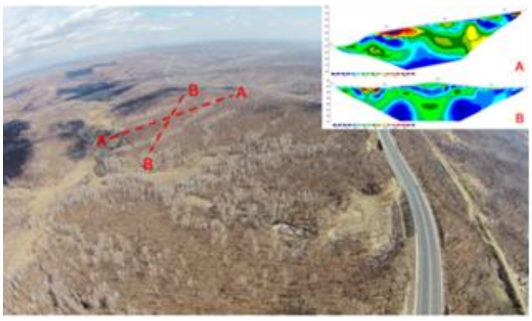

Figure 18. Landslide body measuring line and resistivity map(K178 + 600)

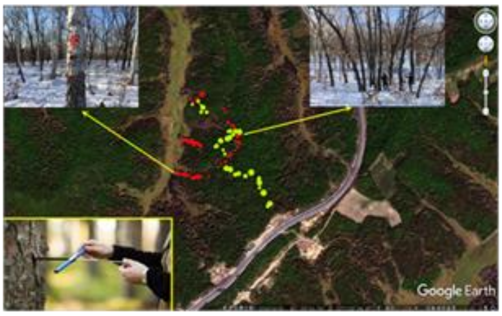

Figure 19. Tree species and age differences on the Landslide body (K178 + 600)

4. The Implications and Main Work of ICRSE in Addressing Permafrost Hazards in Northeast China

With the development of the economy and manufacturing industry and the improvement of living standards (such as commodity circulation and sightseeing tourism travel), the demand for land transportation has increased rapidly. Therefore, the problem of permafrost risk and its impact on the engineering corridor cannot be avoided and must be solved as a matter of priority in the construction of highways and high-speed railways in Eurasia (Figure 20). At the same time, adaptation to the environmental changes in permafrost areas against the background of global warming has become an important area of global development. However, due to the complexity of permafrost and climate change issues and the limitations of understanding, there are not many research findings in related fields.

The research work on permafrost in Northeast China began in the 1950s, mainly in the field of forestry production and site selection of construction and road projects in forested areas. In 1973, a scientific survey of the permafrost area in Northeast China was organized, and the southern boundary of the permafrost area with an average annual air temperature of 0˚C was determined. The distribution range and distribution characteristics of different types of permafrost were initially known. In the following 20 years, there were few researches. In the late 1990s, with the acceleration of transportation infrastructure construction in Northeast China, the engineering and environmental problems caused by the degradation of permafrost have received more attention.

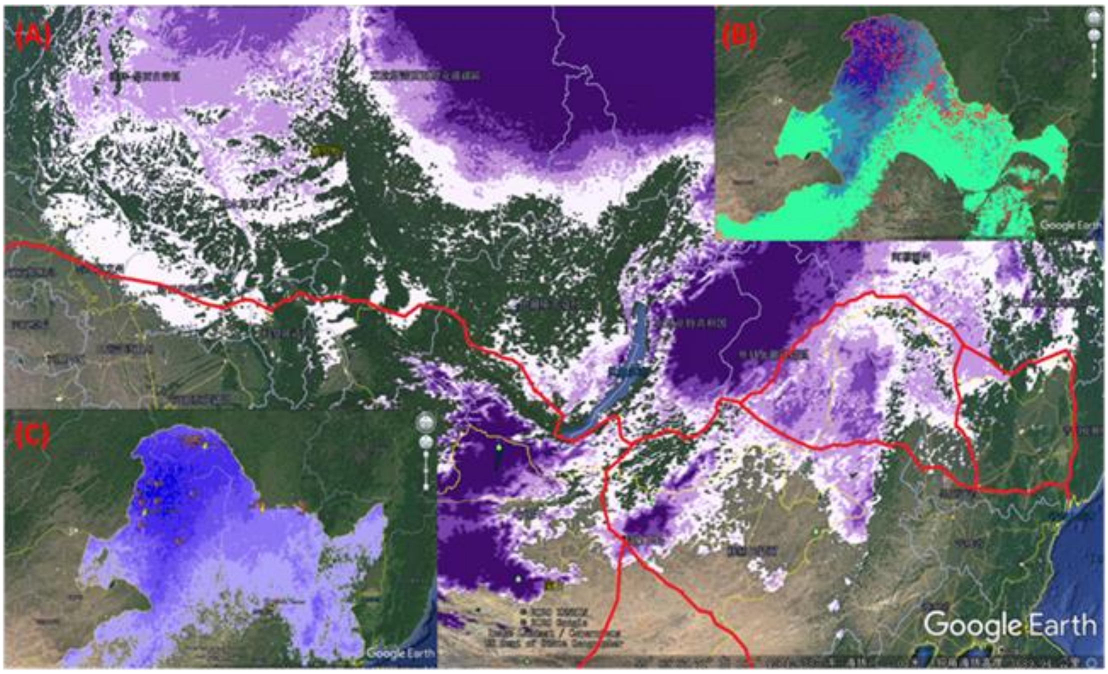

Figure 20. Permafrost engineering corridor in Eurasian land
A. Siberian Railway and Land Passage of the China-Mongolia.
B. Distribution of wildfires in the permafrost area of Northeast China since 2000.
C. The layout of FSSE-PFNEC

Northeast Forestry University has been carrying out research work on environmental change and engineering problems in the permafrost area of Northeast China. The University set up the Institute of Cold Region Science and Engineering of Northeast Forestry University (ICRSE) and shared the research results by organizing and participating in relevant academic conferences, publishing academic papers and editing academic publications. The *Geological environment risk research plan for permafrost degraded areas in Northeast China* (GERRP) was proposed in conjunction with the United Nations Hyogo Framework for Action (HFA) 2005-2015and Sendai Framework for Disaster Risk Reduction2015 - 2030(SFDRR). Extensive cooperation was carried out with many universities and research institutions at home and abroad, focusing on the following issues:

- Changes in the exposure and conservation status of permafrost in Eurasia;
- The impact of climate change and human activities on changes in permafrost in Eurasia;
- Effects of permafrost changes in Eurasia on regional hydrology and water resources;
- The feedback relationship between greenhouse gas emissions from permafrost degradation and climate change;
- Mechanism of wildfires in the permafrost areas of Eurasia and their impact on the environment and northern forests;
- Environmental geological disasters, secondary disasters and disaster chains caused by permafrost degradation;
- The impact of permafrost degradation on water resources, food, forest resources, homeland security and structural stability;
- The international mechanism for the risk management of permafrost disasters.

ICRSE attaches great importance to basic and applied research, and actively serves the development of local construction. In order to accumulate long-term field observation data, support related research continued. With the approval of the Ministry of Education of China, ICRSE established the "Field scientific observation and research station of the Ministry of Education - Geological environment system of permafrost area in Northeast China (FSSE-PFNEC) ", and adopted the "one centre, multi-site" construction model. The observation site covers various types of permafrost area in Northeast China, monitoring parameters to meet the research needs of the Earth Critical Zone (ECZ) in the permafrost area (Figure 20C). At the same time, in cooperation with the National Key Laboratory of Permafrost Engineering of the Northwest Institute of Eco-Environment and Resource, CAS (China), the Quality Supervision Bureau of the Transportation Project construction of Inner Mongolia Autonomous Region, the Heilongjiang Highway Science Research Institute and Heilongjiang Transportation Investment Group Co., Ltd., the Provincial Collaborative Innovation Centre of Environment of permafrost area, road construction and maintenance in Northeast China (PCIC-PFER) was established in cooperation with the research and development of technology related permafrost area.

ICRSE highly values the training of specialized personnel of cold region science and permafrost engineering, and has a master's degree in "Cold Region Traffic Infrastructure

Engineering", a doctoral degree "Prevention and Mitigation of Cold Region Traffic Disaster" and a post-doctoral research station. ICRSE cooperates with relevant disciplines and institutions inside and outside the university to carry out the training of specialized personnel in relevant disciplines.

Under the active advocacy of Northeast Forestry University and other institutions, the International Consortium on Landslides (ICL) established the Cold Region Landslide Research Network(ICL-CRLN) in 2012 and held its founding conference and its first academic seminar in Harbin (China), from July 23-27, 2012. The outcome of the meeting was published in Springer (Figure 21).At the 3rd World Landslide Forum, held in Beijing from May 27 to June 3, 2014, the results were recognized and awarded by UNESCO (Figure 22). ICRSE is the International Coordinator of ICL-CRLN, the convenor of the session (Landslides in Cold Regions) of every World Landslide Forum (WLF), and the location of ICL-IPL Global Landslide Research Excellence Centre(WCoE)(Figure 23).

Figure 21. Academic Seminar and Publications of ICL-CRLN(2012.07.23 Harbin)

Figure22.UNESCO Director-General Ms. Irina Bokova presents awards for Prof.Shan Wei (2014.06.03 Beijing)

Figure23.UNESCO official, ICL chairman presented the certificate of WCoE and IPL-203 (2017.06.02 Lubljana)

ICRSE actively organized and participated in international academic exchanges, and successfully presided over the session "The environmental geology and engineering geology of cold regions" at the12th IAEG (International Association for Engineering Geology and the Environment) Academic Conference in Turin (Italy) on September 15-19, 2014.The results of the conference exchange were published in Springer. From October 22 to 25, 2014, at the invitation of Prof. Stephan Gruber of Carleton University

(Canada), ICRSE participated in a seminar on *Impacts of permafrost thaw in mountainous areas of Canada and beyond* in Whistler (Canada), organized by the Natural Science and Engineering Research Council of Canada (NSERC), and made an academic presentation.

ICRSE maintains long-term, stable academic exchange relations with the Institute of Disaster Prevention of Kyoto University (Japan), the Seismic Engineering Laboratory of Kanazawa University (Japan), the Department of Geosciences of Shimane University (Japan), the Siberian Branch of Sciences Academy Russian, the Department of Geosciences of Florence University (Italy), the Department of Geography and Environmental Sciences of Carleton University (Canada), the University of Alaska Fairbanks (USA), the Northwest Institute of Eco-Environment and Resource, CAS (China), Tongji University, Shanghai Jiaotong University, Huazhong University of Science and Technology, South China University of Technology, Harbin University of Technology and other domestic and foreign university and research institutions..

At the invitation of IRDR, Prof. Shan Wei and Dr. Guo Ying participated in "The Second Asian Conference on Science and Technology Disaster Reduction" in Beijing from April 17-18, 2018, and made relevant academic reports and interactive exchanges (Figure 24).

Figure 24. Exchange at *The Second Asian Conference on Science and Technology Disaster Reduction*(2018.04.17Beijing)

With the support of IRDR, ICL-IPL, ICGdR (International Consortium on Geo-disaster Reduction), NSFC (National Natural Science Foundation of China) and others, the event " Academic Seminar on Engineering Geology and Environmental Geology in the Permafrost Along the Sino-Russian-Mongolian Economic Corridor under the Background of Climate Change" and the "Annual Academic Conference of 2018 on Cold Region Landslides Research Network of International Landslide Association and Global Centre of Excellence in Cold Region Landslide Research" were successfully held at Northeast Forestry University, Harbin China from Nov. 16-19, 2018 (Figure 25). Scholars and officials from IRDR, ICL and China, Russia, Canada, Italy and the Czech Republic have conducted extensive exchanges and discussions on many problems of permafrost areas against the background of climate change, including geological hazard risk, disaster process, disaster resistance technology, and risk management, and have achieved academic cooperation and research intentions in a wide range of fields.

ICRSE places a high priority on fulfilling its international obligations and supporting and promoting education and knowledge about geological disasters and disaster reduction. As Distinguished Professor of UNESCO Chair on Geo-environmental Disaster, Prof. Shan and Dr.Guo participated in the "UNESCO Chair 2019 Field School on Geo-environmental Disaster Reduction in Shimane University, Japan" education and training at Shimane University from 14 to 19 March 2019, and taught at the International Academy. During participation in “Third UN World Conference on Disaster Risk Reduction” held in Sendai, Japan, March 14-18, 2015, Shan and Guo signed “ISDR-ICL Sendai Partnerships 2015-2025 for global promotion of understanding and reducing landslide disaster risk”with relevant academic organizations and research institutions., The relevant research results were edited in the book *Landslide Dynamics: ISDR-ICL Landslide Interactive Teaching Tool*, which was available for free download on the Springer website for relevant researchers. During the meeting of the “19th Session of the Board of Representatives of the ICL (BOR/ICL)” at UNESCO Head, Paris, September 16-19, 2019, ICRSE signed “The Kyoto Landslide Commitment 2020” with other international counterparts (Figure 26), and assumed the organization and editorial publishing of the Session of WLF5: Landslides in Cold Regions.

Figure 25. Group Photo of the Conference (2018.11.16 Harbin)

Figure 26. The first group of signatories of the Kyoto Landslide Commitment 2020 (2019.09.18, UNESCO, Paris)

5. GERRP Deliverables

5.1 Engineering treatment of permafrost degradation

Northeast China is located in the southern boundary of Eurasia permafrost. As mentioned above, climate change and engineering activities are the main factors influencing permafrost degradation, and the trend of permafrost degradation in this region is irreversible. Therefore, in regarding the residual permafrost, we adhere to the concept of removal, using manual excavation, active thermal thawing and other means to minimize the impact of permafrost degradation on engineering construction. The following takes the typical section of BH Highway as the example to introduce the specific engineering treatment measures and post- construction situation.

5.1.1 Foundation treatment in permafrost area

In K161 + 400 section of BH Highway, a certain number of hot gravel piles were driven underground in 2009 summer (Figure 27A). The heated gravel helps to melt permafrost quickly, and the melted water is discharged through the gravel piles. This engineering treatment accelerates the process of thawing, settlement and consolidation of residual permafrost. After the construction of that year, the subgrade settlement was about 2 meters (Figure 27B); there has been no significant settlement in this section in recent years. In addition to this treatment, the residual permafrost also can be removed by digging and replacing during the winter.

Figure 27.Using hot gravel piles for Permafrost Foundation treatment

5.1.2 Stability treatment of landslide slope

The landslides along the BH Highway are caused by the degradation of permafrost. When the water from permafrost thawing and infiltration rainwater converge along the geological structure layer, and there is an impermeable layer (mudstone or frozen layer) on the underlying surface, a sliding surface will be formed and low angle creep of the soil body will occur. This kind of relatively shallow sliding can be controlled by some engineering measures. For example, in K178 + 530 section, the back edge of the landslide has entered the scope of widening subgrade, and the landslide is still in the process of slow movement. We adopt the engineering measures of replacing this road section with bridges (Figure 28). On the one hand, the underground pile foundation of the bridge plays the role of anti-slide pile, locking the location of the landslide back edge, supporting the subgrade of the old road and ensuring the stability of the old road subgrade. On the other hand, the bridge helps avoid loading on the back edge of the landslide and slows down the landslide sliding. The engineering practice shows that this measure achieves the expected effect, and the subgrade of this section has been kept stable for 10 years. The prevention and treatment measures for landslide sections should also include in the design of the road route the location where permafrost degradation is complete, such as sunny slopes and slope tops, which should be selected first. The unstable area caused by permafrost degradation should be avoided as much as possible. When it is inevitable to cross the sliding area of permafrost thermal melting, deep anti-slide pile or bridge can be used to cross the unstable area. According to the characteristics of regional water catchment, necessary drainage facilities such as buried gravel ditches should be built around the structure to discharge the melt water in time and eliminate the sliding surface as soon as possible.

Figure 28. Replacing the road section with bridge

5.2 Main research publications

One of the highlights of GERRP is cooperation with international academic organizations and relevant researchers to edit and publish geological and environmental disaster research cases in permafrost regions in Northeast China (Figure 29, 30). The research results GERRP shared contributed to the understanding of disasters, the management of disaster risks, and the development of DRR (disaster risk reduction). The publications *Landslides in Cold Regions in the Context of Climate Change* (Figure 21), *Engineering Geology for Society and Territory-Volume1*, and *Climate Change and Engineering Geology* were representative results.

Figure 29.Participation in ICL-related publications (ICL-Landslide Forum essay collection and Landslide Teaching Tool book)

Figure 30.Participation in relevant professional books

5.3 Training, research platform building and disaster prevention technology output

GERRP emphasizes the training of specialized personnel and scientific research, and has established professional personnel training at all levels of undergraduate, master, doctor, and postdoctoral. In addition to the relevant laboratories on campus, GERRP established the FSSE-PFNEC research station to provide data support and conditional support for practical teaching and scientific research. GERRP also established PCIC-PFER, which provides guaranteed conditions and application platforms for multidisciplinary cross-disaster research and development.

Over the past 20 years, a group of young scientists were trained through GERRP, enriching the organization’s research achievements. Some research results have been transformed into engineering applications and have been valued and rewarded by the academic community. Many aspects are in the process of continuous in-depth research (Figure 31).

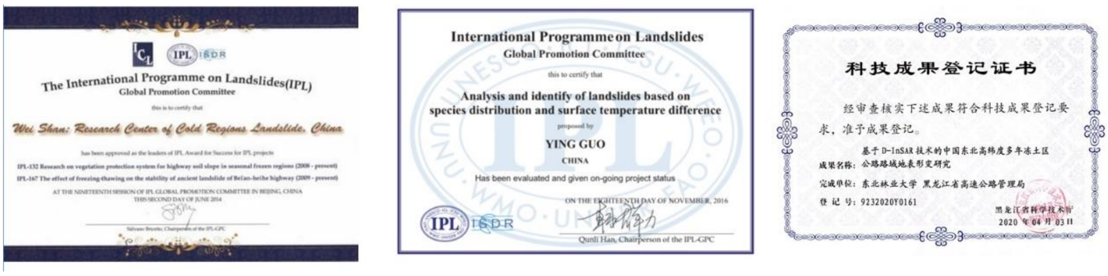

Figure 31.Relevant project certificates and reward certificates

6. The Way Forward

GERRP has worked closely with Integrated Research on Disaster Risk (IRDR) for a long time. IRDR is a decade-long research project by the International Science Council (ISC) and the United Nations Office for Disaster Risk Reduction (UNDRR). IRDR takes a global, multidisciplinary approach that addresses the challenges posed by disasters, mitigates their impact, and improves relevant decision-making mechanisms. With the common interest and vision of the DRR field, GERRP has received the attention and support of IRDR.IRDR greatly facilitated GERRP in creating its network and platform for scientists and practitioners in countries along the China-Mongolia-Russia economic corridor to address issues related to natural disasters in 2018. Looking ahead, GERRP will shift its focus from natural disaster mechanisms in permafrost areas under climate change and risk assessment of individual disasters, to studies on the knock-on effects of natural disasters in the Earth Critical Zone (ECZ) in permafrost and on cross-border disaster management. The new focus calls for interdisciplinary research into different types of natural hazards and for thresholds for their evolution from one hazard to another. At the same time, responding to cross-border disasters and establishing business management mechanisms requires a more specific platform, not only involving decision makers, but also practitioners at the community level to create effective and reliable channels of communication among countries at risk of transboundary disasters. With the efforts of GERRP, a safer and more proactive future of disaster reduction in the cryosphere can be imagined.

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