Impacts of permafrost degradation on infrastructure

Hjort, Jan

2022-01

Hjort , J , Streletskiy , D , Dore , G , Wu , Q , Bjella , K & Luoto , M 2022 , ' Impacts of permafrost degradation on infrastructure ' , Nature Reviews Earth & Environment , vol. 3 , no. 1 , pp. 24-38 . https://doi.org/10.1038/s43017-021-00247-8

---

http://hdl.handle.net/10138/344541
https://doi.org/10.1038/s43017-021-00247-8

---

other
acceptedVersion

Impacts of permafrost degradation on infrastructure

Jan Hjort[1*], Dmitry Streletskiy[2,3], Guy Dore[4], Qingbai Wu[5], Kevin Bjella[6] and Miska Luoto[7]

[1]Geography Research Unit, University of Oulu, Finland.

[2]Department of Geography, The George Washington University, USA.

[3]Institute of the Earth's Cryosphere of Tyumen Scientific Centre of Siberian Branch of Russian Academy of Sciences, Russia.

[4]Department of Civil Engineering and Water Engineering, Laval University, Canada.

[5]State key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, China.

[6]Cold Regions Research and Engineering Laboratory, Fairbanks Alaska, USA.

[7]Department of Geosciences and Geography, University of Helsinki, Finland.

*email: jan.hjort@oulu.fi

Abstract

Degradation of permafrost damages infrastructure and can jeopardize the sustainable development of polar and high-altitude regions. Warming and thawing of ice-rich permafrost is related to several natural hazards, which can pose a serious threat to the integrity of constructions and the economy. In this Review, we explore the extent and costs of observed and predicted infrastructure damages, and methods to mitigate adverse consequences of permafrost degradation. We also present the diversity of permafrost hazards and problems associated with construction and development in permafrost areas. Finally, we highlight seven topics to support sustainable infrastructure in the future. The observed damages are substantial and cumulative problems of infrastructure can be exacerbated owing to the increasing human activity in permafrost areas and climate change. It has been estimated that from one-third to more than half of critical circumpolar infrastructure could be at risk by mid-century. Permafrost degradation-related infrastructure costs could rise to tens of billion US dollars by the second half of the century. To successfully manage with climate change effects in permafrost areas a better understanding is needed about which constructions are likely to be affected by permafrost degradation. Especially, mitigation measures are needed to secure existing infrastructure and future development projects.

Key points

- Operational infrastructure is critical for sustainable development of Arctic and high-altitude communities, but the integrity of constructions is jeopardized by degrading permafrost.

- The extent of observed damages is substantial (up to tens of percentages of infrastructure elements) and is likely to increase with climate warming.

- From one-third to more than 50% of fundamental circumpolar infrastructure is at risk by mid-century.

- Engineering solutions to mitigate the effects of degrading permafrost exist but their economic cost is high at regional scales.

- There is a need to quantify the economic impacts of climate change on infrastructure and occurrence of permafrost-related infrastructure failure across the permafrost areas.

- Future development projects should conduct local-scale infrastructure risk assessments and apply mitigation measures to avoid detrimental effects on constructions, socio-economic activities, and ecosystems in permafrost areas under rapidly changing climatic conditions.

Introduction

Polar and high-altitude regions have received increased attention in research, media and political discussion owing to the observed unprecedentedly rapid and substantial changes in the environment[1,2]. While there have been numerous reports on shrinking glaciers and ecosystems changes[3,4], less attention has been devoted to permafrost degradation (warming and thawing of permafrost)[5,6] and its implications[7-12]. As more than one-fifth of the Northern Hemisphere's exposed land surface is classified as permafrost region[13], the lack of documentation and guidance is clearly a shortage.

In addition to the potential adverse effects on climate, ecosystems and earth surface processes, permafrost degradation will damage infrastructure, the backbone of human activities in remote regions[2,14-16] (FIG. 1). Especially, degradation of ice-rich permafrost increases the risk of various gradual and abrupt natural hazards, which can impair roads, buildings, pipelines, airports and other types of infrastructure[6,17-19]. At least 120,000 buildings, 40,000 km of roads and 9,500 km of pipelines were estimated to be located in permafrost areas of the Northern Hemisphere[20]. Negative effects of permafrost degradation on infrastructure are already evident[6,21]. In the near future, cumulative problems of infrastructure damage can be exacerbated, if recent projections of infrastructure risks are materialised[20,22,23]. Up to 70% of fundamental circumpolar infrastructure could be at risk by mid-century[20].

Beyond the permafrost research community, permafrost-infrastructure interaction has received relatively little consideration in focusing on the impacts of climate warming. This lack of attention is a significant shortage as the Arctic and high-altitude regions are undergoing significant changes in community patterns and economic activities, creating challenges for decision-makers, planners, and engineers[8,24]. Despite a general desire to meet the climate targets of the Paris Agreement, the extraction of oil and other natural resources can, in addition to other human activities, increase in the permafrost regions[8-10]. Thus, operational infrastructure is critical to the development and economy of permafrost regions and the environment[2,15,19,20,23,25,26]. In response to the experienced and projected impacts, communities and decision makers are identifying opportunities for adaptation to manage the impacts of permafrost degradation on infrastructure[27-30].

In this Review, we provide a stand-alone forward-looking assessment focused first on the fundamental problems associated with construction in permafrost areas, second on permafrost degradation-related hazards affecting infrastructure, third on the extent and costs of observed and predicted infrastructure damages, and fourth on methods to mitigate adverse consequences of permafrost degradation. In the end, we highlight seven topics that should be considered to support operational infrastructure in permafrost areas in the future. Owing to the increasing economic and environmental relevance of the permafrost areas[8,19,23,24,31], such a review is of a vital importance for sustainable development of Arctic and high-altitude cold regions.

Building on permafrost

Infrastructure construction faces many challenging problems in permafrost areas[27-29]. As a special foundation soil beneath infrastructure in cold regions, the major difference between permafrost and non-permafrost is the presence of ground ice of variable types and thickness[32]. Variable ice content and thermal state makes permafrost sensitive to environmental factors, engineering activities and changing properties during the process of freezing and thawing[33]. Therefore, infrastructure stability must consider and predict the impact of climatic and environment factors and engineering activities on permafrost[21,27,28,34].

Permafrost soil exhibits vastly changeable properties of engineering from thawed to frozen state due to the phase change of water to ice, and vice versa[32]. Soils, especially fine-grained soils, can show heaving (from less than one cm to 40 cm/a) during the freezing process of the wet soils within the active layer[32]. Under the action of frost heaving, significant forces (up to 300 kPa) can be generated leading to infrastructure deformation and failure[32,33]. Conversely, frozen soil with high ice content will show significant strength and volume changes during the thawing process resulting in potential infrastructure deformation and damage[33]. In general, frozen soil has higher strength increasing with decreasing temperature due to the ice cement role within the frozen soils. But as the soil temperature increases the strength rapidly decreases[35]. As the soil temperature rises, the un-frozen water in the ice matrix can exhibit compression and increasing creep rate properties. When the soil temperature surpasses the freezing point, the bearing capacity is greatly reduced due to increases in excess water and volume displacement, and the soil can no longer satisfy the engineering stability, leading to differential settlement and infrastructure failure[36].

Spatial distribution and thickness (up to 1500 m in Russia, 500 m in Canada and 700 m in Alaska) of permafrost varies substantially[11,13,32]. Additionally, permafrost temperatures (from 0 to about -20 °C) are variable due to climate and local factors such as topography, soil properties, vegetation, snow, and hydrology[6,11,37]. Local features are highly influential in discontinuous and sporadic permafrost areas, increasing the difficulty of site surveys and engineering solutions. Therefore, engineering geological conditions are required to be accurately explored and spatially predicted to guide engineering design and construction in permafrost areas, to include evaluation of thaw settlement and frost heaving potential as well as changing bearing capacity[34,38]. Generally additional cost is required for adequate survey in engineering geological conditions[39].

Infrastructure in permafrost areas with different types of foundations and architecture leads to highly variable thermal impacts, with potentially large differences for the effects on the underlying permafrost[33,40]. Deep foundations rely on adfreeze of ground ice and soil with a pile or pier, and rising ground ice temperature decreases the adfreeze bond, therefore design needs to account for permafrost conditions during entire life span of the structure based on heat source of infrastructure types. Consideration of change in adfreeze bond can alter the design principle of engineering and choice of expected engineering measures of preventing freezing-thawing damage. Structures with high loads can require slab-on-grade design, imparting high heat flux to the frozen ground, while lighter load structures can utilize an elevated design to decouple the structure from the terrain and maintain the frozen condition[21,34].

While thermal disturbance caused by construction or operation of any particular structure can contribute to the degradation of the underlying permafrost, rapidly changing climatic conditions and associated permafrost warming and increase in active layer thickness may exacerbate the problem further leading to reduced strength of frozen soils[41]. Thus, climate warming must be properly accounted for during engineering design in permafrost areas[42]. However, choosing the right climatic input to estimate changes in permafrost geotechnical properties is not a trivial task as it requires understanding of biases and uncertainties in climate models[9,10]. While engineering design can account for the worst case projected climatic scenario (such as Representative Concentration Pathway (RCP) 8.5) such design is not always economically feasible as it requires additional capital expenditures. At the same time, downplaying role of climate change (for example use of RCP 2.6 or not accounting for climate warming) can translate to higher operational expenses during the lifespan of the structure. Meanwhile, protection of the environment also needs to be considered for engineering design and construction because permafrost degradation alters environmental conditions (for example hydrology)[32]. For some particularly sensitive areas, the additional cost of environmental protection can increase significantly in engineering construction of permafrost areas[39]. Moreover, climate warming increases the vulnerability of the infrastructure in permafrost areas to resist and/or adjust with the environment changes[43]. Thus, future infrastructure design and construction practices need to consider the issue of permafrost stability, have the ability to adjust to changing conditions but at the same time evaluate in the context of other factors such as increase in extreme events (such as flooding) and slope instability[44]. Failure to account for other environmental variables can increase the susceptibility of infrastructure built on permafrost, and increase maintenance and replacement costs[15,23].

Permafrost degradation-related hazards

Proactive planning in permafrost area requires knowledge of ground and climate conditions[32,34]. Moreover, it is important to consider permafrost degradation-related natural hazards (hereafter permafrost hazards) that can jeopardize the integrity of infrastructure under projected warmer and wetter climates[11,45-48]. Mutually related permafrost hazards include warming of permafrost, thickening of active layer, development of taliks (thawed layers), and thaw-related hazards (thermokarst, mass-wasting processes on slopes, and water-related thermal erosion) (FIG. 2).

Warming of permafrost. It is evident that permafrost warming is a global phenomenon[49,50]. For example, ground temperatures have increased by 0.29 °C across the permafrost area between 2007 and 2016 (REF[11]). Increasing ground temperatures are likely to increase the unfrozen water content of the active layer and decrease the ice bonding (cohesion) of soil particles, resulting in a gradual loss of bearing strength[33] (FIG. 2). Moreover, warming of near-surface ice-rich permafrost increases creep rates of common types of foundations and eventual loss of adfreeze bond support for pilings[41,51]. These changes can greatly reduce permafrost's capacity to carry structural loads imposed by buildings and structures for the longer term (FIG. 2). In some of the Russian Arctic cities, bearing capacity has decreased by even more than 40% between 1960s and 2000s (REF[41]).

Owing to higher rates of warming in the Arctic and high-altitude regions and the thermal properties of frozen ground (for example latent heat associated with phase change) the rise of ground temperatures has been more pronounced in areas characterized by cold permafrost (< -5 °C) when compared to areas with relatively warm permafrost (> -3 °C)[11]. The rise of temperature in cold permafrost is not as critical as the rise in warm permafrost because ground temperatures close to the melting point are the most detrimental for infrastructure[51]. For example, adfreeze bond strength can decrease less than 10% when the temperature rises from -6 to -4 °C, whereas the decrease is ca. 50% when the temperature rises from -3 to -1 °C (REF[51]). Because of the projected warming of permafrost[46,52], there will be increasing number of engineered structures in hazardous regions with ground temperatures close to 0 °C in the future[11].

Thickening of active layer. Along with the higher ground temperatures thicker active layers have been observed across the permafrost areas[49], although the relationship between permafrost degradation and active layer thickness is not straightforward[53]. Reported regionally variable but dominantly increasing active layer thicknesses across the circumpolar area during 1990–2015 (REF[54]). The highest observed rates were over 10 cm per year in Central Asian mountains[54]. Thickness of active layer could increase from 0.8 to 6.5 cm per decade by the end of this century, when averaged over all permafrost areas (REF[55]). At the highest, the total increase in active layer thickness could be 120–200 cm on the Qinghai–Tibetan Plateau by 2100 REF[55]. Thickening of active layer could result in increased thaw settlement during summer and frost heave during winter, and lead to frost-jacking of piles[56]. Moreover, higher active layer thickness could lead to a decrease in frozen-ground adfreeze strength, resulting in an increase in the creep settlement rate of existing piles and footings[57]. The thickened active layer can expose critical foundation elements designed for direct frozen ground bearing or adfreeze, to newly thawed low bearing strength and poorly consolidated soils. However, high variability of active layer response to climate warming limits our understanding of the potential effects of active layer dynamics on infrastructure.

Development of thawed layers. Extreme weather conditions, for example heatwaves and heavy rainfall during the thaw season, are more likely under climate change[45]. An abnormally warm summer can lead to the development of taliks in the top of the permafrost, which decreases the load-bearing strength of the ground and systems supporting infrastructure[57] (FIG. 2). These residual thaw layers can lead to progressive surface settlement and slope movements. Moreover, current climate models depict an increase in high-latitude precipitation[45]. Therefore, potentially broad and long-lasting impacts of increased precipitation on hydrology and ground thermal conditions should be taken into consideration when estimating infrastructure hazard potential in different regions[37,48].

Permafrost thaw hazards. Thaw of frozen ground is critical for engineered constructions because the strength of soil drops substantially as the temperature rises above the melting point and ground ice melts[58] (FIG. 2). The amount of thaw settlement is mostly related to the soil moisture content (especially ground-ice) and bulk density[58]. If permafrost is ice-rich, the melt of ice can result in thermokarst (and uneven terrain) that threatens the existing infrastructure but also complicates new construction projects[59]. Based on climate change projections an substantial amount (>30–60%) of near-surface permafrost can be lost by the end of this century[46,52,60,61]. It is evident that the most pronounced changes in permafrost distribution will occur in warmer permafrost areas. These areas are often the most densely built and populated stressing the high infrastructure risk potential in the near-future[62].

Periglacial slope processes are common factors affecting constructions with shallow foundations, especially transportation infrastructure[47] (FIG. 2). Slope processes range from slow mass-movements such as permafrost creep and solifluction to more rapid ones like landslides and earthflows (retrogressive thaw slumps and active-layer detachment slides). Potential hotspots of landslides are sites with abrupt permafrost thaw (that can cover up to 20% of the circumpolar permafrost area)[63], particularly close to sea-, lake- and riverbanks where water-induced thermal erosion and abrasion is effective[64] (FIG. 2). For example, a 60-fold increase in retrogressive thaw slumps was observed in the Canadian Arctic in a 30-year period, mainly owing to particularly warm summer conditions (REF[65]). Thus, the projected increase in summer temperatures and precipitation can increase thermal erosion and mass-wasting related infrastructure hazards, especially in coastal[66] and topographically complex regions[47,65]. Under projected hydrological changes the existing water pathways cannot be adequately designed resulting in overflow and damages to infrastructure[29,67].

Observed infrastructure damages

Although several reports have linked widespread damage to infrastructure with climate change, the infrastructure damages on permafrost can easily misattributed to climate change[68]. For example, the majority of damage to structures in the Russian permafrost areas in the period 1980 to 2000 resulted mainly from poor maintenance rather than climatic change[69]. Consequently, building on permafrost and maintaining operational infrastructure is a highly challenging task even without climate change, but climate warming induced permafrost degradation can exacerbate engineering challenges beyond feasible solutions[18,70]. While indigenous peoples for centuries had developed intimate knowledge of living and building structures on permafrost, rapidly changing climatic conditions, accelerating rates of costal erosion, permafrost warming and ground subsidence have recently threatened traditional lifestyles, subsistence economies, food security and accessibility among others[71,72].

Russia, North America, and Qinghai–Tibet Plateau are central permafrost areas with varying infrastructure features. Russian permafrost regions contain substantial population concentrated mainly in large industrial centres with dense multi-storey buildings whereas other regions on permafrost have less concentrated population residing in one-two storey residential houses. While having smaller housing stock on permafrost, North America and Qinghai–Tibet Plateau are characterized by higher proportion of transportation infrastructure[27,29]. Trans-Alaska pipeline system, Qinghai–Tibet engineering corridor and Canada's Arctic airports and airstrips are examples of transportation infrastructure that are central for the operation of communities in these permafrost areas[8,27-29]. Owing to the main infrastructure and socio-economic differences between the regions Russia is characterized by damage of various engineered structures whereas damages of linear infrastructure dominate North America and Qinghai–Tibet Plateau.

Russia and Europe. Almost 65% of land areas of Russia is underlain by permafrost[73]. More than 60% of settlements and vast majority of population (nearly 90%) in the Arctic permafrost areas are located in Russia[62]. Greenland and Svalbard have a few notable settlements and other infrastructure on permafrost whereas other parts of Europe have relatively little infrastructure in the permafrost area[62,74]. Russian expansion to the eastern and northern regions have led to permafrost encounters documented as early as 16th century. Centuries of error and trial allowed to gain knowledge and experience of construction on permafrost, which was summarized in the textbooks, construction manuals and regulations as early as the beginning of 20th century[32,34]. To this date, the Russian permafrost area is unique in unparalleled degree of industrialization and urbanization and host several large cities, such as Vorkuta, Yakutsk, and Norilsk among others[75]. Unlike other parts of permafrost area, that generally characterized by small individual houses and light-weight administrative and industrial facilities that have only few floors, Russia is characterized by large apartment buildings, and heavy-built industrial facilities. It also characterized by focal areas with high population density, and centralized network of heating and utilities all of which makes impacts of human activities on permafrost more concentrated and damages more pronounced. Historically, the ability of foundations to support structures on permafrost was estimated using the climatological data available prior to construction. However, rapidly changing climatic conditions and increasing technogenesis challenged the paradigm[76,77].

The development of geographic information system (GIS) -based approach to geotechnical modelling allowed to bridge the gap between climate change and permafrost geotechnical environment. Using various types of climate input in combination with permafrost modelling it became possible to provide regional assessments of changes in permafrost bearing capacity under various climatic condition[41]. Using gridded-climate input and detailed parameterization of soil conditions in Northwest Siberia REF[78] found that ability of foundations to support structures have already decreased by 17 % on average with some locations experienced up to 45% decrease relative to 1960-1990 period due to the increasing permafrost temperatures and active layer thickness. Further analysis focused on the Russian cities found that foundation stability has decreased by more than 15–20% in several towns (for example in Salekhard, Noviy Urengoy, and Nadym)[79].

Climatically-induced permafrost degradation exacerbated by socio-economic transformations leading to dismantling of adequate permafrost monitoring after collapse of the Soviet Union resulted in neglect of the infrastructure in Russian permafrost areas. By the beginning of 21st century majority of buildings on permafrost had deformations, from ca. 10% in Yakutsk and Noril'sk up to 80 % in Vorkuta[69], with later studies revealing even higher numbers of structures affected by permafrost degradation[21,76] (Supplementary Table 1; FIG. 3a–c). In Greenland, Svalbard and European mountains, thaw damages are clearly less extensive and common, this owing to the terrain inherently reduced ground ice content, differences in type and size of engineered structures and higher investments to construction and maintenance[80-84]. For example, of the ca. 1000 infrastructure elements located on permafrost in the French Alps, less than 3% were identified to be damaged owing to permafrost degradation[84].

North America. More than half of Canadian and 80% of Alaskan's land surfaces are characterized by the presence of permafrost. With sparse population (only ca. 7% of the

Arctic permafrost areas[62]) and abundant natural resources, the social and economic development of these vast territories depends heavily on a reliable transportation infrastructure[85], although coastal erosion and relocation of settlements are also issues[66,71,72]. North America does not have the large industrial centres with densely arranged vertical structures like Russia. Therefore, most of the infrastructure problems are related to horizontal or linear infrastructure. For example, there exist ca. 6800 kms of road and 270 airstrips on permafrost[20]. Construction of roads, airstrips, railways or other linear infrastructure where snow is removed leads to local ground cooling and formation of artificial dams affecting the surface hydrology, at the same time snow accumulation along the linear types of infrastructure leads to waterlogging and permafrost degradation[29]. These consequences are naturally common across permafrost areas with various types of linear infrastructure.

Signs of degradation of structures and adjacent land are becoming increasingly evident in Northern Canada and Alaska (FIG. 3). In the North-West Territories, the estimated value of infrastructure at risk due to climate warming is equivalent to 25% of the value of the assets[86]. Surface distortions, depressions and cracks at the edge of embankments, sinkholes, longitudinal cracks, lateral embankment spreading and water ponding along roadside and drainage ditches are the most common problems observed along embankments built on thaw-sensitive permafrost (FIG. 3 d–f; synthesis of several publications in REFs[87,88]. Several types of degradations are also observed in areas adjacent to linear structures. Amongst others, retrogressive thaws slumps, active layer detachment slides, thermal erosion gullies, and newly developed icing (‘aufeis’) zones are increasingly threatening the integrity of linear infrastructures. More circumscribed problems such as differential settlement caused by creeping of ice-rich warm and/or saline permafrost under thick embankments[89]; sudden collapse due to the erosion or melting of ice-wedge[90] have also been documented recently.

There has been an increase in the frequency and severity of issues related to permafrost degradation and slope stability along the Alaska Highway (Yukon) (FIG. 3 d and e) as well as the Dempster highway (Yukon and Northwest Territories)[91-93]. Most of these highways are on permafrost and several sensitive areas have been documented and are monitored by both highway administrations. For example, The Alaska Transportation and Public Facilities, estimated that the state spends 11 million US dollars ($) annually on permafrost related problems with roads. Several issues, including thermal erosion, ice-wedge degradation and thaw slumps related to permafrost degradation have also been documented on the newly constructed Inuvik to Tuktoyaktuk Highway (Northwest Territories)[94], on roads and airstrips in Nunavik (Quebec)[95], and on the Iqaluit airstrip (Nunavut) (FIG. 3 f). In the North-West Territories, thawing permafrost is causing approximately $41 million (ca. 51 million Canadian dollars) worth of damage to public infrastructure every year[86].

Qinghai–Tibet Plateau. About 40% of Qinghai–Tibet Plateau is characterized by the presence of permafrost[96]. In Qinghai-Tibet Plateau, including Qinghai Province and Tibet Autonomous Region, the total length of roads and railways is more than 200,000 kms and 3,900 kms, respectively[97]. Climate warming along with thermal influences from engineering construction foster permafrost degradation, seriously threatening the stability of infrastructure on Qinghai-Tibet Plateau[98,99] (FIG. 3 g–i). In the past years, many economically and societally important transportation infrastructure were constructed, the Qinghai-Tibet Highway (QTH), the Qinghai-Kangding Highway, the Gong-Yu Express Highway, the Qinghai-

Tibet Railway (QTR), and the Qinghai-Tibet DC power transmission line. These infrastructures experienced different extent of distresses and even failure due to rapid degradation of underlying permafrost[40].

The QTH underwent major repairs between 1991 and 2011 to stabilize the underlying permafrost, for a total cost of nearly $0.7 billion (4.5 billion Yuan), about six times of the total costs for building and paving the QTH during 1950-1954 and 1979-1985, respectively. The costs for mitigating damages associated with permafrost have significantly increased the QTH operation cost, up to ca. $64 million (420 million Yuan) between 1986 and 2007, 1.5 times of total maintenance costs from 1955 to 1985. Although QTH has been maintained and reconstructed several times in the last decades, embankment damages due to the underlying permafrost degradation are evident at 30% of total road length in permafrost areas[100] (FIG. 3 h and i). Majority (85%) of the road damages were produced by thaw settlement and less (15%) by frost heave[100,101]. For example, QTH was reconstructed from 1991 to 1999 by increasing the thickness of the embankments, which resulted in new damages (longitudinal and road shoulder cracks)[100-102]. These damages were mainly caused by thaw consolidation within roadbed soil under embankments. Meanwhile, QTR opened to traffic in 2006, embankment experienced deformations ranging from 25 mm/a to 75 mm/a[99,103] due to thawing of underlying permafrost. Also transition sections between bridges and embankments experienced substantial (10–160 cm) deformations from 2006 to 2014 owing to degradation of permafrost[104].

Projected impacts

Spatial information of permafrost and infrastructure hazards are of importance to enable planners and policy-makers to identify both high- and low-risk areas when planning future infrastructure at settlement and transport route scales. For example, investments and developments in industry and extraction of natural resources requires extensive maps of permafrost hazards. Moreover, sustainable regional planning and infrastructure management require information on the costs of maintaining current and planning new constructions under climate change[105,106].

Since early 2000's the number of geographical hazard assessments has increased along with the development of climate projections[8,27,28]. The existing circumpolar infrastructure could be affected by degrading permafrost under global warming was first presented geographically by REF[17] (see also REF[107]). Comparable regional and national-scale infrastructure hazard mappings with developed data and methodologies have been presented for Russia[41,51,108,109], Greenland[110], Qinghai–Tibet[44,111,112] and Alaska[113]. For example, REF[114] estimated substantial reduction in stability of infrastructure on permafrost in Russia by the mid-21st century. The cities of Salekhard, Norilsk, Yakutsk, and Anadyr were estimated to lose on average 20, 30, 26, 20% of bearing capacity respectively by 2050 under RCP 8.5 scenario. Most of the studies have considered hazard areas by mid or late 21st century acknowledging the relatively short lifespan (often 20–50 years) of infrastructure in the permafrost areas[27,39].

Many of the seminal geographical hazard assessments were based on the exploration of changes in active layer thickness in combination with ground ice content[17,107,108,111]. More recently, other environmental factors such as surficial geology, temperature and thaw of permafrost, and slope gradient have been included into the explorations[44,110,112,113]. In coastal environments, coastline erosion rates can be used in hazard assessments[66]. Recent circumpolar hazard explorations were presented in REFs[20,23,115]. The circumpolar distribution of high-hazard areas depend on the considered environmental factors. On one hand, if we consider thickening of active layer and thaw settlement, the high-hazard areas occur in the mid and northern parts of the circumpolar permafrost area with abundant ground ice and pronounced climate warming[20,22,23,115] (FIG. 4a and d). On the other hand, if we emphasize the thaw of near-surface permafrost and loss of structure bearing capacity, the high-hazard areas form a 'hazard belt' close to the southern margin of polar permafrost[20,22,23] (FIG. 4b, c, and e). Considering permafrost degradation, ground ice conditions, and surficial geology the most critical areas with high hazard potential for infrastructure damage are the Pechora region, the northwestern parts of the Ural Mountains, northwest and central Siberia, northwest Canada as well as the yedoma areas of Alaska where regional and local scale infrastructure risk assessments are important when planning new infrastructure in future decades[20,22,23,115] (FIG. 4 and 5b). For example, the Yamal-Nenets region in northwestern Siberia is essential because of the extensive oil and natural gas production fields and high level of industrialization[22].

Despite the seminal nature of the permafrost thaw risk assessments presented in REFs[17,107] they did not include quantitative estimates of the amount infrastructure in high hazard areas or at risk of damage. Recently, REF[20] quantified the detailed amount of infrastructure elements potentially at risk across the circumpolar permafrost area under climate change. The results showed that 69% of the residential, transportation, and industrial infrastructure is located in areas with high potential for near-surface permafrost thaw by the mid-century (FIG. 5a; Supplementary FIG. 1). Considering ground properties (such as ground ice and frost susceptibility of ground material) in addition to permafrost thaw one-third of the pan-Arctic infrastructures and 45% of the hydrocarbon extraction fields in the Russian Arctic were located in areas where permafrost hazards could jeopardize current infrastructure and future developments[20] (FIG. 5b; Supplementary FIG. 2). Owing to the uncertainty in circumpolar geospatial datasets and statistically-based modelling methods, and the fact that the effect of engineered structures on ground thermal regime was not considered, local errors in the determination of hazard potential are likely[20,115]. In a population study, 42% of the 1162 permanent settlements will become permafrost-free due to thawing by 2050 (REF[62]). Among the settlements remaining on permafrost, ca. 40% are in high hazard areas[62].

The replacement costs and damages due to projected changes, including permafrost degradation are available for Alaska[15,39], Canada[116] and Russia[117-119]. Maintaining stable and safe transportation infrastructure in Alaska and Northern Canada is an important engineering challenge. For example, the costs of permafrost damage to Alaska's publicly owned infrastructure are expected to grow by an estimated 10 to 20 percent, or $3.6 billion to $6.1 billion, by 2030[87]. REF[15] estimate the cost due to near surface permafrost thaw for the period 2015–2099 at $2.1 billion for RCP 8.5 and $1.6 billion for RCP 4.5.

In the Yukon, nearly 50% of the North Alaska Highway is considered to be highly vulnerable to permafrost thaw and is showing important signs of degradation[91]. The cost to maintain these sections of road is estimated to be eight times more expensive than equivalent sections on stable ground[120]. In Russia, the total cost of support and maintenance of road infrastructure due to permafrost degradation from 2020 to 2050 was estimated at ca. $7.0 billion (422 billion RUB) for the existing network (no additional development), and ca. $14.4 billion (865 billion RUB) for the modernization scenario based on the additional cost of the construction of new roads and engineering facilities according to development goals outlined in the Transport Strategy of Russian Federation, which is about 0.2 to 0.5 billion per year[118]. Another study estimated the cost of residential housing replacement due to permafrost degradation and decrease of foundation bearing capacity about $0.5-0.6 billion per year (30–36 billion RUB) between 2020–2050[121].

The only pan-Arctic study to estimate the costs of permafrost degradation is focused on critical infrastructure such as roads, railways, pipelines, ports, airports and buildings[23]. The estimated lifecycle replacement costs to maintain infrastructure on permafrost will require $15.5 billion by 2059 under RCP 8.5 scenario[23]. Linear infrastructure (roads, railways, and pipelines) is expected to be the most affected with pipelines being the most vulnerable type of infrastructure. In addition, damages associated with thaw subsidence and decrease of permafrost bearing capacity were estimated to add additional $21.6 billion[23]. However, the presented estimate was largely constrained by the availability of infrastructure data, especially in the case of Russia. The sustainable development of the permafrost regions urgently requires more detailed assessments of infrastructure costs and risks associated with permafrost degradation and their impacts on communities and the economy.

Mitigation methods

Methods to stabilize infrastructure constructed on permafrost have been used in Russia since well before World War II, and since the 1940's in North America[35]. The type of permafrost terrain, either *thaw-stable* or *thaw-unstable*, can be determined by the inherent ground ice content and by the soil type. Soils are considered 'thaw-unstable' when volumetric ice content is in excess of the natural porosity of the unfrozen soil and when hydraulic conductivity of the soil does not allow for effective dissipation of excess pore pressures during the thawing process. This information on ice content and hydraulic conductivity is critical to determine the type of foundation and the type of adaptation to be used. A common classification of adaptation methods used in North America is 'active' and 'passive' protection systems[35]. Active systems involve the use of an external source of power to refrigerate permafrost, while passive systems use natural phenomena such as convection, evaporation and/or condensation to cool the ground.

Two main approaches are used in Russia for construction design in permafrost-affected environments[34,41]. According to 'Principle I' permafrost is used as the foundation and is protected from degradation during the construction and during the life of the structure which is accomplished by decoupling structures from permafrost, such as creating of crawl spaces under the buildings, using passive and active cooling methods. Principle I can be used and developed further for considering climate warming in engineering design in areas with warm permafrost[122]. For example, in Qinghai-Tibet Plateau, 36% of permafrost is considered to be especially warm and extra-unstable (ground temperature > -0.5 °C)[123]. Under these conditions, engineering must cool permafrost to ensure stability under climate warming. Alternatively, ‘Principle II’ can be used, involving thawing the permafrost before or during the construction and protecting the ground from permafrost aggradation during the life of the structure.

There exist several mitigation methods (see below and FIG. 6 for different examples)[29,38,124,125] that can be classified into three main categories: methods based on preventing heat intake to permafrost; methods enhancing ground heat extraction; and embankment reinforcement or ground improvement to help the structure resist permafrost degradation[29]. The methods can also be classified based on heat transfer mode: methods based on adjusting and controlling heat conduction; methods based on adjusting and controlling heat convection; methods based on heat radiation; and comprehensive methods[124]. In areas of warm-discontinuous permafrost with variable ground ice characteristics alternatives routs either with complete avoidance and/or minimalized encounter of high ice content and warm permafrost soils can be developed. Alternatives are being developed providing methods for full-scale ground ice and permafrost temperature characterization across the project areas[38,125], via combined geophysical surveys and prescribed geotechnical drilling. In some cases, proper characterization can prescribe full removal of the ice-rich material when depth of excess ground ice and structural fill material availability are favorable to the project budget and timeline.

Transportation infrastructure. Considering the impact of climate warming, transportation infrastructure built on thaw sensitive permafrost should be protected, either by cooling the underlying permafrost or by considering pre-thawing to adapt and mitigate the impact of climate warming[40,124,126-128] (FIG. 6). Several techniques have been experimented and have proven to be effective in cooling permafrost under transportation embankments. Some of these techniques are now used for large scale applications across the circumpolar high-altitude areas (Supplementary FIG. 3).

Heat removal techniques have been widely tested and used. Different types and shapes of air convection embankments (ACEs) have been used in Alaska (Thompson Drive[129]), Canada (Alaska Highway[130]; Puvirnituk airstrip[131]), and China[29,132]. For QTR observations showed that embankments with crushed rock structure can adapt to a climate warming of 1.0°C[40,133]. Thermosyphons have been used within transportation infrastructures in Russia[134], Alaska[135], Canada[136], and China[123,137]. Other techniques such as the heat drain[131] have also been successfully used to enhance ground heat extraction (FIG. 6). In most cases, the heat extraction systems have successfully cooled the ground during winter, improving thus significantly the heat budget at the ground surface. Recent monitoring results show that beneath a U-shaped ACE, the ground temperature of the permafrost from 4 to 10 m in depth was lowered by 0.5 °C[138]. Based on the experimental work at Beaver Creek in Canada, the presence of a 3 m thick ACE layer across the highway embankment has reduced winter temperatures at the contact between the embankment and natural ground by approximately 5 °C[29]. Under a heat drain at the Tasiujaq test section in Canada, the mean annual temperature at the contact of the embankment and the natural ground was reduced by 2.2 °C, and, at the end of the monitoring period, the permafrost table had risen more than 2 m compared with the reference section[29]. It should be noted that the cost of these systems is high and their application is generally restricted to limited areas of highly sensitive soils.

Methods based on the reduction of heat intake during summer have been used to protect permafrost underneath transportation infrastructure, of which can adapt the impact of climate warming and stabilize permafrost (FIG. 6). The most common method is embankment insulation used successfully at several locations in permafrost areas, of which can only mitigate permafrost thawing due to climate warming[139-140]. The use of sunsheds to protect embankment slopes[126,130,141], and high albedo surfaces to protect paved embankments[140,142.143] have also proved to be very effective to impede heat intake during summer. Reduction in the annual average surface temperature by approximately 1 °C and to permafrost aggradation of between 0.5 and 1.0 m under pavements with high-albedo surfaces have been reported by different authors[29]. For sunsheds, temperatures at the surface of embankment slopes were observed to be 4 to 5 °C lower in summer and 3 °C lower in winter when compared with an unprotected slope. In QTP, the difference was from 8 to 15 °C[29,144]. Special techniques such as the use of gentle slopes to reduce the adverse effect of snow accumulatio on slopes and the replacement of embankments by a ‘dry bridge’ widely used on the QTR to minimize disturbance and protect permafrost[40] can also be considered in special conditions.

Some new mitigation techniques have been applied in the Gongyu express highway construction in China, for example the combination technique of oriented heat-transfer asphalt pavement and crushed-rock structure[123]. The first three years of monitoring show that these new techniques prevented rapid permafrost thaw. A field experiment showed that embankment with hollow concrete bricks and ventilation ducts can effectively decrease permafrost temperature at deeper than 15 m depth[145]. Moreover, numerical model shows that embankment with crushed-rock interlayer and perforated ventilation ducts can effectively prevent permafrost thawing for an area where the mean annual air temperature is -4.0 °C and air temperature increases by 0.052 °C/year[146]. Although these approaches increase the engineering cost, they can well adapt the underlying permafrost degradation driven by long-term warming of climate.

Pipeline stability depends on its construction mode, elevated or buried, in permafrost areas. Thaw settlement and subsequent frost heave often lead to pipeline deformation, even lose pipeline service function[147,148]. Heat removal techniques, for example, thermosyphons, different air ventilated duct systems, and energy storage systems, are tested and used to adjust and control the thermal regime of permafrost under the pipelines[149].

Buildings and other vertical structures. Proper characterization of ground ice content and extent through rigorous geotechnical studies provides great advantages for the planning and the design of foundations for vertical infrastructure, whether it is a house, industrial facility, or an elevated road. Selection of construction site in areas of low thaw sensitivity permafrost reduces risk of poor structure performance in a context of warming climate. A good knowledge of permafrost characteristics and conditions is essential to reduce the risk of foundation failure due to permafrost degradation[27,38,150]. Complete understanding of the subsurface conditions allows the selection of the appropriate foundation techniques[38,140,151].

During the Soviet time, rapid urbanization and industrialization of Russian permafrost areas revolutionized permafrost research and engineering[152]. One of the most significant developments was introduction of piling foundations (buildings are constructed on elevated piles that are anchored in permafrost) in Norilsk in mid-1950s[109]. Piling foundations allowed to minimize the disturbance of permafrost due to construction and allowed to maintain the permafrost temperature under the buildings as buildings provide shade in the summer and have no snow accumulation in the crawl spaces in the winter therefore protecting the permafrost[153]. Natural ventilation of crawl spaces can be enhanced by various types of passive or active cooling devises, such as thermosyphons. In QTP, pile foundation is usually used by considering permafrost temperature, ground ice and sites conditions[154]. Thermosyphons are used to stabilize permafrost surrounding the piles, if required due to impacts of climate warming or human activities leading to permafrost degradation[154].

Summary and future perspectives

Functional infrastructure is critical for sustainable development of Arctic and high-altitude regions, but the integrity of constructions is jeopardized by degrading permafrost[2,8,17,28]. The extent of observed damages is considerable and is likely to increase under projected climate change. It should be noted that a substantial proportion of permafrost degradation around infrastructure is caused by the modification of the landscape and disturbance of thermal equilibrium caused by the construction and maintenance of the structure, and not as a result of climate change. In future, cumulative problems of infrastructure damage in permafrost areas can be exacerbated owing to the increasing utilization of natural resources, construction, and climate change. It has been estimated that from one-third to more than half of fundamental circumpolar and high-altitude infrastructure could be at risk by 2050 REF[20]. Permafrost degradation-related infrastructure costs could rise to some tens of billion US dollars by the mid and late century[15,22,23,118,121].

To effectively cope with climate change effects and support sustainable development in permafrost areas, it is critical to firstly develop relevant data resources such as permafrost characteristic, temperature and geotechnical monitoring with proper data archival and exchange, secondly improve permafrost and geotechnical modelling across space and time, thirdly comprehensively map permafrost hazards, fourthly evaluate the economic value of constructions and natural resources at risk across the permafrost area, fifthly improve infrastructure risk assessment approaches, sixthly develop new mitigation measures as well as design and construction practices, and seventhly improve communication and distribution of information among scientists and stakeholders (FIG. 7).

First, it is important to produce high-resolution geospatial data on climate (air temperature) and ground conditions (ground ice content). Different datasets are currently collected by a wide variety of scientists, governmental agencies, and other groups, but coordination and harmonization of data products and accessible (open) publication of datasets need improvements. Moreover, spatial resolution of climate, ground ice, surficial geology and vegetation data are commonly too coarse or observations too scattered for high-resolution modelling of permafrost. Forecasting the changes in environmental conditions for infrastructure in permafrost area is particularly difficult due to the lack of long-term monitoring data (for example ground temperatures in human-disturbed environments). Thus, approaches that enable accurate mapping, monitoring, and prediction of fine-scale climate and ground conditions across large spatio-temporal scales urgently require development and subsequent integration into planning and construction methods on permafrost.

Second, the forthcoming construction projects and infrastructure risk assessments would significantly benefit from high-resolution process-based models of ground thermal regime and of ground ice distribution applicable for large areas. Moreover, there is a practical need for bridging the spatial gap between computationally expensive, short timescale geotechnical models and coarse scaled land surface models. Results of REF[155] suggest that current model-based approaches which do not explicitly consider engineered structures in their designs are likely to underestimate the timing of future damage. Thus, further improved models would be essential in assessing potential infrastructure damages under climate change.

Third, engineering solutions to mitigate the effects of degrading permafrost exist but their economic cost is high at regional scales. Consequently, high-resolution maps of permafrost hazards are of importance to identify risk areas and make provision for mitigation techniques, but detailed engineering solutions need to be based on detailed geotechnical investigation. To identify areas of permafrost hazards process-based methods could be applied at local and regional scales and geospatial data-based methodologies (remote sensing and statistical modelling) at circumpolar scale. For example, detailed hazard maps are needed in land use planning and could be used to identify risks related to the storage of toxic substances (fuels, chemicals, and industrial waste products) to avoid environmental pollution comparable to the diesel spill near the Norilsk City in the Taimyr region in May 2020 REF[156]. Moreover, hazard maps are required in economic assessments.

Fourth, there is an urgent need for more detailed calculations of the costs associated with permafrost degradation and its impacts on communities and infrastructure. However, lack of comprehensive and readily available data on infrastructure attributes and location as well as costs of construction and repair limit the development of such assessments. Further complications arise from the general lack of long-term socio-economic and demographic projections targeting permafrost regions. Improved permafrost projections, detailed hazard maps and verified infrastructure databases with construction costs, will enable to assess the economic impacts of permafrost degradation on infrastructure at a circumpolar scale and to justify the cost of mitigation measures.

Fifth, future construction projects should be based on infrastructure risk assessment and management approaches to minimize the risk of failure or poor infrastructure performance under climate stress. Risk assessment can be used to determine the suitability of a project, the appropriate design as well as appropriate maintenance practices. All decisions of this nature are dependent upon the risk tolerance of the project stakeholders. The risk can be reduced either by reducing the probability of occurrence of a hazard or by mitigating its consequences. Mitigation methods reduce the probability of occurrence of permafrost related hazards, compared to traditional design methods, by decreasing the likelihood of permafrost degradation and its associated problems. Alternatively, intensive maintenance can be a good management strategy to minimize the consequences of poor infrastructure performance.

Sixth, new mitigation measures as well as design and construction concepts are needed to control the thermal impacts of climate warming and engineering construction, especially for discontinuous ice-rich warm-permafrost. It is also important to monitor the effects of mitigation measures on ground thermal regime in different environmental and construction settings. At the same time, new designs are considered to accommodate movements as the permafrost destabilizes, especially for critical infrastructures, for example bridges, tunnels, and large buildings. These creative ideas are critical important for high-speed railway and express highway in permafrost areas under the impact of climate warming.

Finally, more collaboration and better communication between scientists, local people and authorities, industry, and governments are needed for promoting sustainable and resource-efficient infrastructure in the future. Especially, scientists need to be more active in distributing data and study results for engineers and decision-makers. A better dialog between scientists and engineers would help to create design criteria that offer the best alternatives for construction choices and maintenance options. Standardizing best practices for planning, designing, and constructing infrastructure for permafrost conditions, now and in the future, will help balance sustainable growth and development for local community and wider stakeholder needs.

In conclusion, to successfully manage climate change impacts in Arctic and high-altitude, a better understanding is needed about which constructions are likely to be affected by permafrost degradation, where they are located, and how to implement adaptive management, considering the changing environmental conditions. Appropriate mitigation measures are needed to secure existing infrastructure and future development projects, and to protect the nature and societies from environmental disasters.

Figure legends

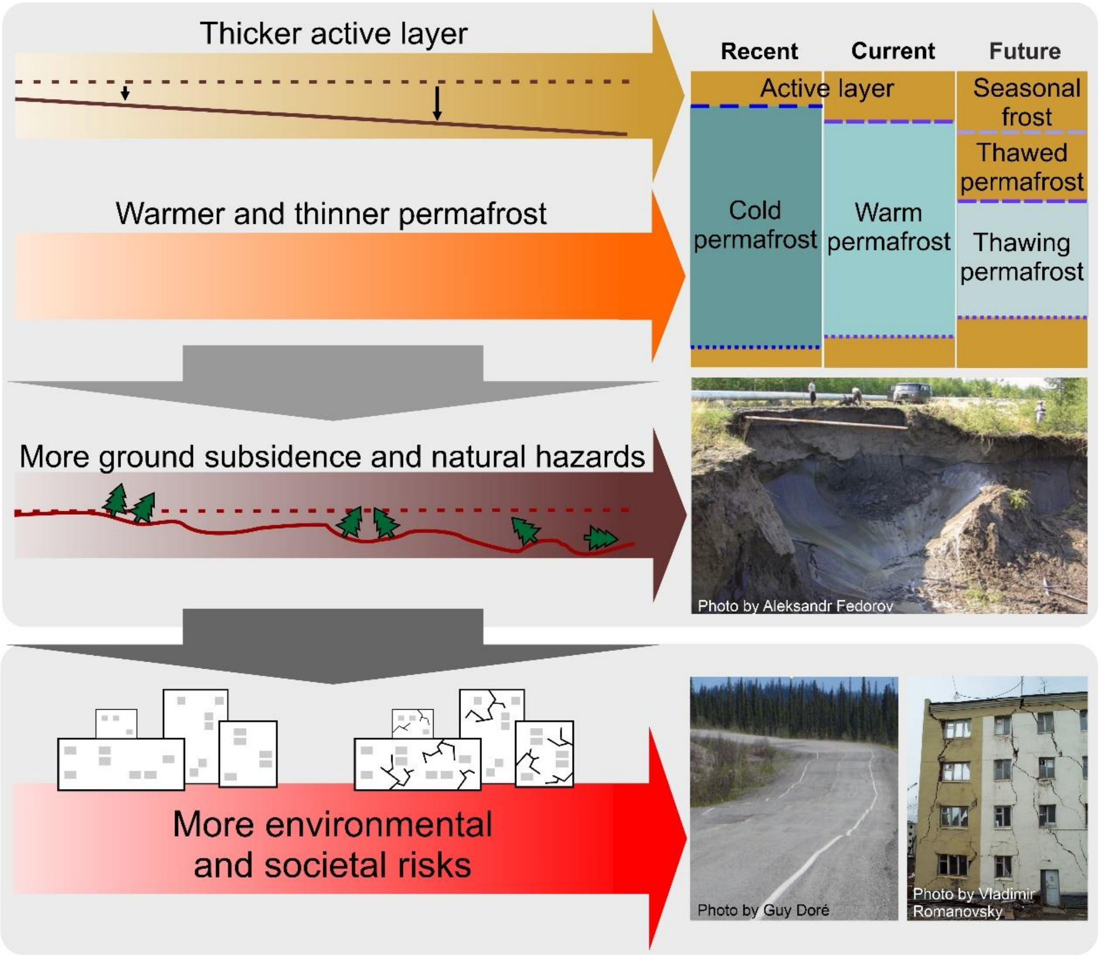

Fig. 1. **Degrading permafrost threatens environment and societies by damaging infrastructure.** A schematic presentation of degrading permafrost (thickening of active layer and warming and thawing of permafrost) causing natural hazards and environmental and societal risks such as damage of critical infrastructure in polar and high-altitude regions.

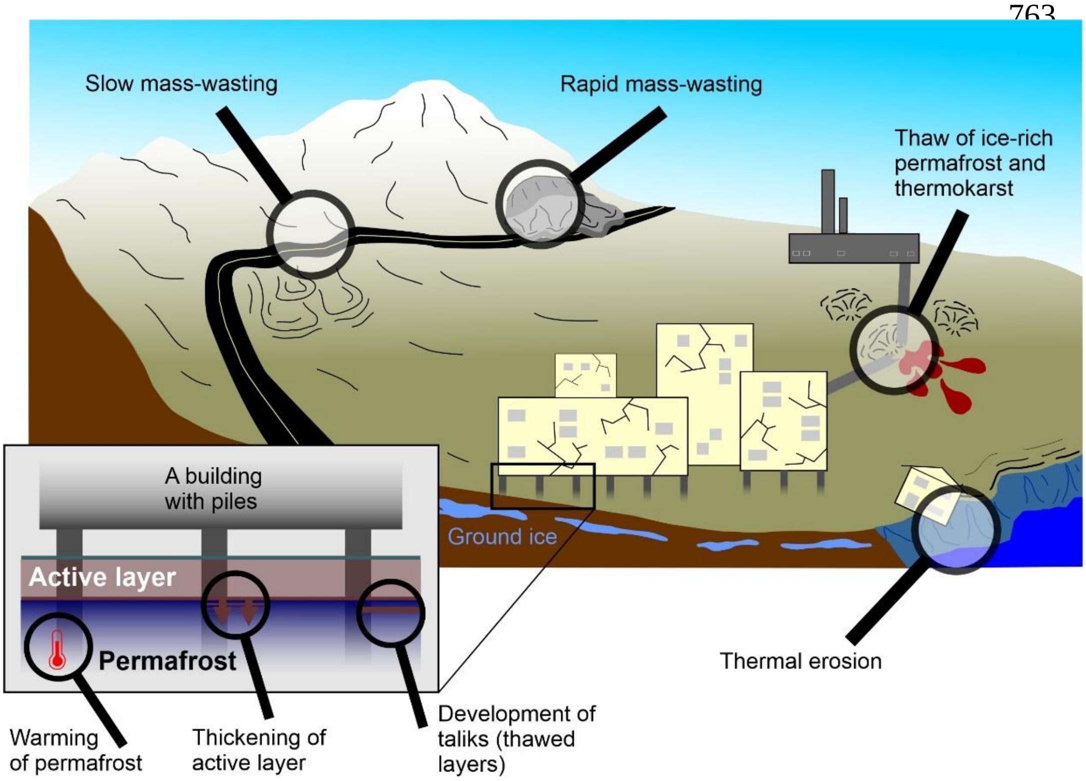

Fig. 2. **Permafrost hazards damaging infrastructure**. A schematic presentation of permafrost degradation related natural hazards that threatens the integrity of critical infrastructure (roads, pipelines, buildings, and industrial facilities) in permafrost areas (see text for further details on permafrost hazards).

Fig. 3. **Infrastructure damages owing to degradation of permafrost. a** and **b** Damaged buildings due to permafrost degradation in Yakutia, Russia (Photos by Ivan Khristoforov). **c** Below-ground pipeline in crossing an area with ice-rich permafrost and thermokarst development in Yamal-Nenets, Russia. **d** Longitudinal cracking due to shoulder rotation along the Alaska Highway in Yukon, Canada. **e** Thermokarst affecting partly the embankment of the Alaska Highway in the Yukon, Canada (Photo by Eva Stephani). **f** Sinkhole in the Iqaluit runway (Nunavut, Canada). **g** Embankment deformation of the Gongyu express highway, China (Photo by Chen Ji). **h** Collapsed bridge of Qinghai-Tibet Highway, China. **i** Longitudinal cracks of Qinghai-Tibet Highway, China.

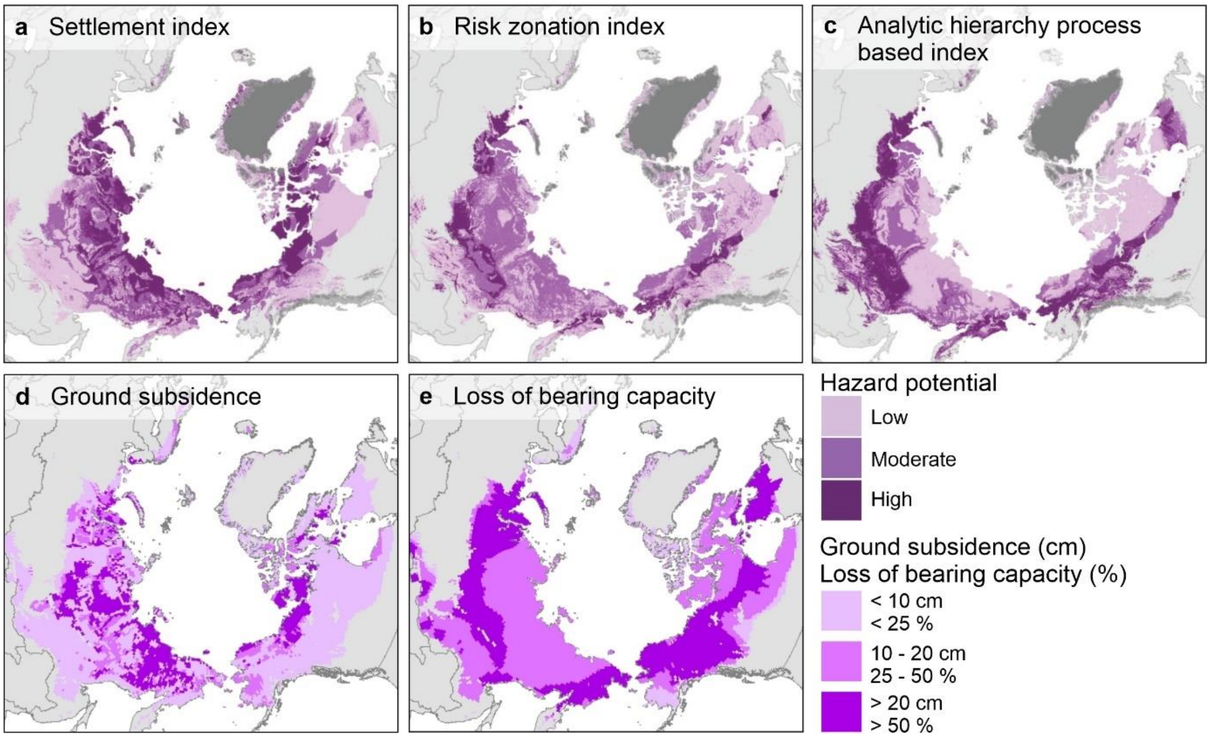

Fig. 4. **Geography of permafrost hazards across the circumpolar area.** Distribution of high-hazard areas depend on the considered indices and environmental factors. Maps depict **a** settlement index[115], **b** risk zonation index[115], **c** analytic hierarchy process (AHP) based index[115], **d** ground subsidence[23], and **e** loss of structure bearing capacity[23]. Geohazard indices (**a**–**c**) show near-surface permafrost degradation related risks to infrastructure under Representative Concentration Pathway (RCP) 4.5 scenario by the middle of the century (2041–2060)[20,115]. Settlement index (**a**) is computed based on the relative increase of active layer thickness and ground ice content, risk zonation index (**b**) considers type of surface geology (sediment or bedrock), frost susceptibility of ground material, ground ice content and permafrost thaw potential, and AHP based index (**c**) is based on different factors with varying weights. The factors considered in AHP are ground temperature, ground ice content, relative increase of active layer thickness, fine-grained sediment content and slope gradient (see REF[20,115] for further details). Modelled ground subsidence (**d**) and change in bearing capacity (**e**) are shown between 2005–2010 and 2050–2059, under RCP8.5 scenario (for further details, see REF[23]). World Borders dataset is distributed under CC BY-SA 3.0 license (https://creativecommons.org/licenses/by-sa/3.0/) on http://thematicmapping.org/downloads/world_borders.php.

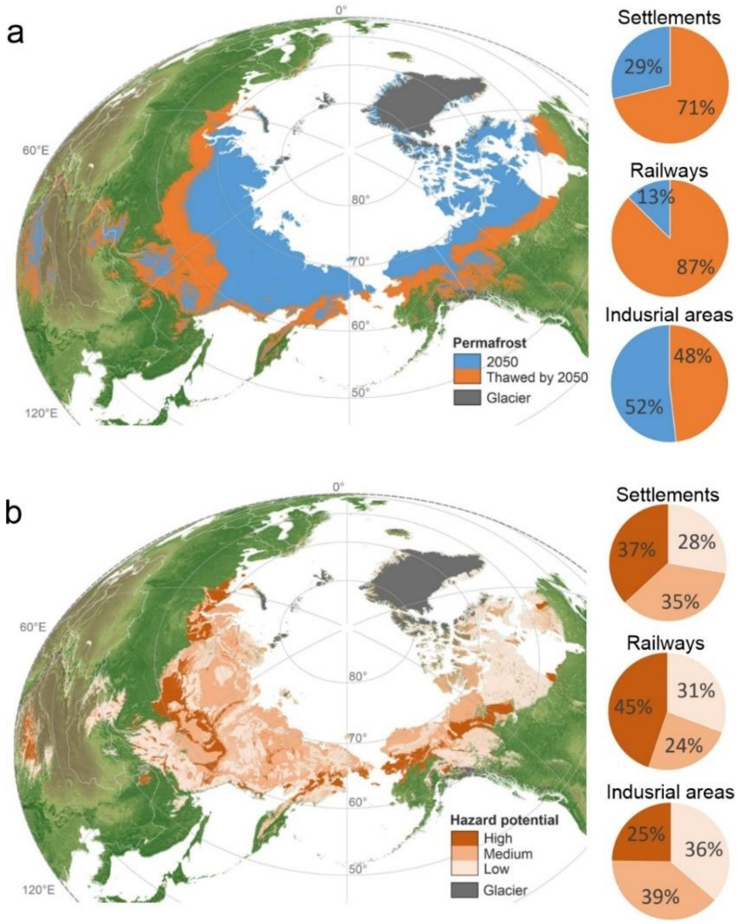

Fig. 5. **Circumpolar infrastructure at risk by 2050**[20]. **a** Proportion of settlements, railways, and industrial infrastructure in areas of near-surface permafrost thaw (orange) and **b** hazard zones (shades of brown; high-medium-low) based on Representative Concentration Pathway 4.5 scenario by the middle of the century (2041–2060). In **b**, the hazard potential depicts permafrost degradation related risks of infrastructure damage and the zones were determined based on a consensus of three different geohazard indices (see FIG. 4a–c). Factors considered in the determination of hazard potential were relative increase of active layer thickness, ground ice content, permafrost temperature and thaw, surficial ground materials, and slope gradient (see REF[20,115] for further details). Owing to the fact that the effect of engineered structures on ground thermal regime and potential abrupt thaw of permafrost were not considered in the infrastructure risk computations in REF[20] the presented risk estimates can be conservative.

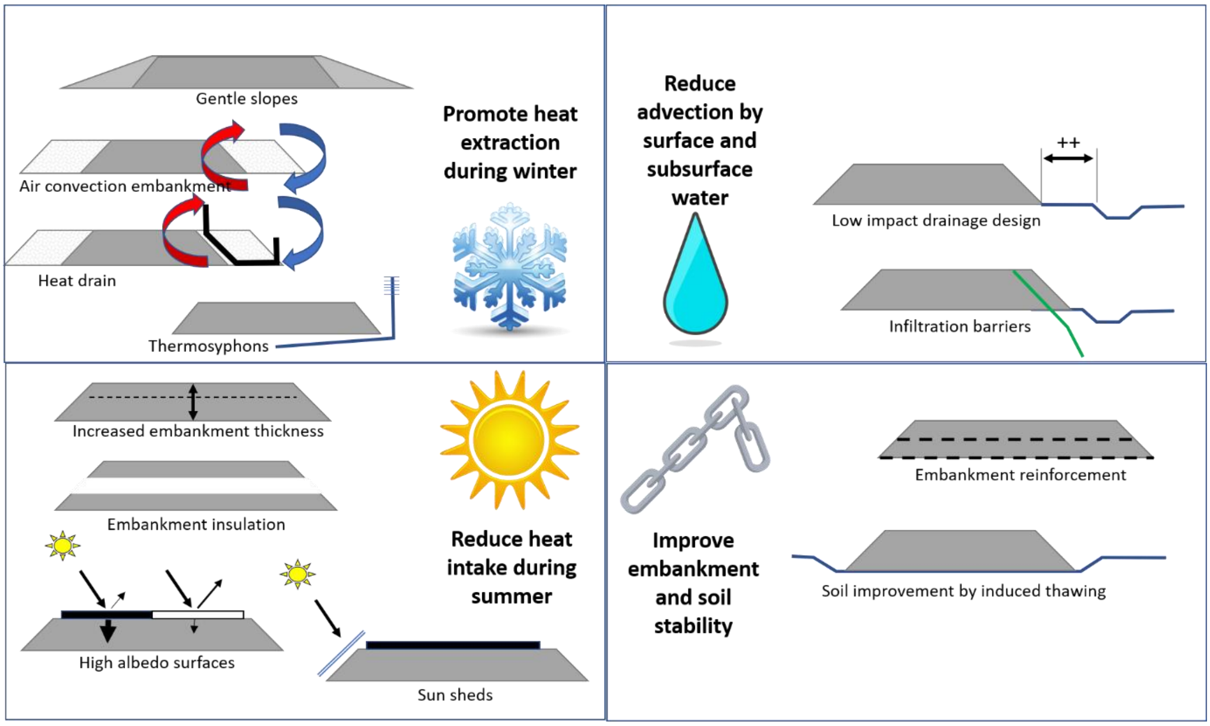

Fig. 6. **Schematic illustration summarizing different mitigation methods for transportation infrastructure**. Heat extraction in the winter can be promoted by preventing snow accumulation and its insulative effect (gentle slopes) or by enhancing heat transfer by using mechanisms such as convection (air convection embankment, heat drain or air ducts) or phase change (thermosyphons). Heat intake in soils during summer can be reduced by reducing heat transfer by solar radiation (modified surface albedo or sun sheds), or by impeding heat flux to permafrost using thick gravel layers or insulation boards. Advection from surface or subsurface water flow van be reduced by intercepting water at some distance from the embankment or by using impervious membranes. Finally, mechanical performance of embankments can be improved by using reinforcement layers or by using induced thawing to improve soil conditions. (Modified from REF[157])

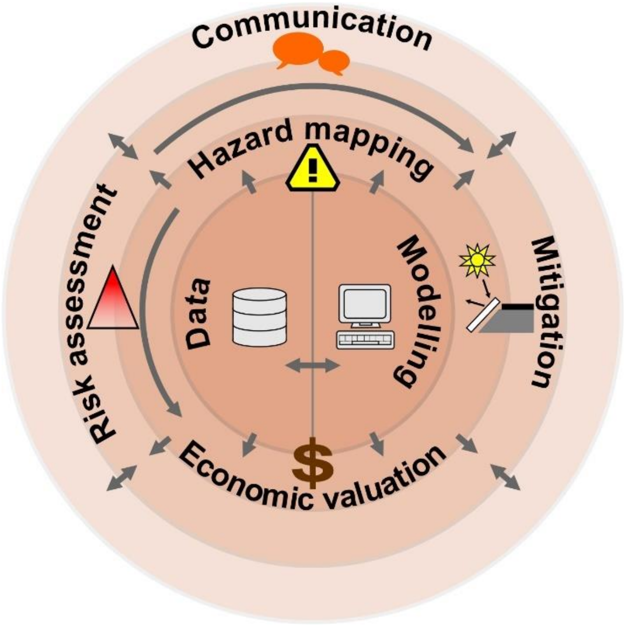

Fig. 7. **Potential topics to support sustainable infrastructure in permafrost areas in the future**. A schematic presentation with simplified connections between issues that should be considered to secure existing and future infrastructure under climate change (see text for further details). For example, spatially and temporally high-resolution data of permafrost characteristics, including temperature and ground ice content are needed for mapping, planning, and construction purposes. Developed permafrost models could be used to assess infrastructure hazards and economic consequences of climate warming. Moreover, geotechnical models could be used in infrastructure risk assessments and when developing new mitigation methods for construction.

References

1
Box, J. E. et al. Key indicators of Arctic climate change: 1971–2017*. Environ. Res. Lett*. **14**, 045010 (2019).

2
Vincent, W. F. in *The Palgrave Handbook of Arctic Policy and Politics* (ed. Coates, K. S. & Holroyd, C.) 507–526 (Palgrave Macmillan, Cham, 2020).

3
Zemp, M., et al. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* **568**, 382-386 (2019).

4
Myers-Smith, I. H. et al. Complexity revealed in the greening of the Arctic. *Nat. Clim. Chang*. **10**, 106–117 (2020).

5
Dobinski, W. Permafrost. *Earth Sci. Rev.* **108**, 158–169 (2011).

6
Streletskiy, D. in *Snow and Ice-Related Hazards, Risks, and Disasters* (ed. Haeberli W. & Whiteman C.) 297–322 (Elsevier, Oxford, 2021).

7
Stocker, T. F. et al. IPCC Climate Change 2013. Fifth Assessment Report. *Intergovernmental Panel on Climate Change (IPCC)* https://www.ipcc.ch/report/ar5/wg1/ (2014). (accessed March 2021)

8
AMAP. *Snow, Water, Ice and Permafrost in the Arctic (SWIPA)* (ed. Symon, C.) (Arctic Monitoring and Assessment Programme (AMAP), Oslo, 2017).

9
Abram, N. et al. IPCC special report on the ocean and cryosphere in a changing climate. *Intergovernmental Panel on Climate Change (IPCC)* https://www.ipcc.ch/srocc/home/ (2019). (accessed March 2021).

10
Arneth, A. et al. IPCC special report on climate change and land. *Intergovernmental Panel on Climate Change (IPCC)* https://www.ipcc.ch/report/srccl/ (2019). (accessed March 2021).

11
Biskaborn, B. K. et al. Permafrost is warming at a global scale. *Nat. Commun.* **10**, 264 (2019).

12
Lenton, T. M. et al. Climate tipping points—too risky to bet against. *Nature* **575**, 592–595 (2019).

13
Obu, J. How much of the Earth's surface is underlain by permafrost? J. Geophys. Res. Earth Surf. e2021JF006123 (2021).

14
Whiteman, G., Hope, C. & Wadhams, P. Climate science: Vast costs of Arctic change. *Nature* **499**, 401–403 (2013).

15
Melvin, A. M. et al. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *PNAS* **114**, E122-E131 (2017).

16
Alvarez, J., Yumashev, D. & Whiteman, G. A framework for assessing the economic impacts of Arctic change. *Ambio* **49**, 407–418 (2020).

17
Nelson, F. E., Anisimov O. A. & Shiklomanov N. I. Subsidence risk from thawing permafrost. *Nature* **410**, 889–890 (2001).

18
Nelson F.E. Unforzen in Time. *Science* **299**, 1673-1675 (2003).

19
Instanes, A. et al. Changes to freshwater systems affecting Arctic infrastructure and natural resources. *J. Geophys. Res. Biogeo.* **121**, 567–585 (2016).

20
Hjort, J. et al. Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nat. Commum*. **9**, 5147 (2018).

21
Grebenets, V., Streletskiy, D. & Shiklomanov, N. Geotechnical safety issues in the cities of Polar Regions. *Geog., Environ. Sustain*. **5**, 104–119 (2012).

22
Streletskiy, D. A. et al. Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. *Environ. Res. Lett*. **14**, 025003 (2019).

23
Suter, L., Streletskiy, D. & Shiklomanov N. Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic. *Polar Geogr*. **42**, 267–286 (2019).

24
Gautier, D. L. et al. Assessment of undiscovered oil and gas in the Arctic. *Science* **324**, 1175–1179 (2009).

25
Cheng, G. D. & Zhao, L. The problems associated with permafrost in the development of the Qinghai-Xizang Plateau. *Quat. Sci.* **20**, 521–531 (2000).

26
Larsen, J. N. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (ed. Barros V. J. et al.) 1567–1612 (Cambridge University Press, New York, 2014).

27
Instanes, A. et al. in: *Arctic climate impact assessment* (ed. Symon, C., Arris, L. & Heal B.) 908–944 (Cambridge University Press, New York, 2005).

28
Callaghan, T. V. et al. in *Snow, water, ice and permafrost in the Arctic (SWIPA)*. (ed. Symon, C.) 5-1–5-62 (Arctic Monitoring and Assessment Programme (AMAP), Oslo, 2012).

29
Doré, G., Niu, F. & Brooks, H. Adaptation Methods for Transportation Infrastructure Built on Degrading Permafrost. *Permafr. Periglac. Process*. **27**, 352–354 (2016).

30
Ford, J. D. et al. Evaluating climate change vulnerability assessments: a case study of research focusing on the built environment in northern Canada. *Mitig. Adapt. Strat. Glob. Chang*. **20**, 1267–1288 (2015).

31
Bordignon, F. A scientometric review of permafrost research based on textual analysis (1948–2020). *Scientometrics* **126**, 417–436 (2021).

32
Harris, S.A., Brouchkov, A., & Cheng, G. Geocryology: Characteristics and Use of Frozen Ground and Permafrost Landforms. (CRC Press, Boca Raton, 2017).

33
Andersland, O. B. & Ladanyi, B. *An introduction to frozen ground engineering*. (Springer Science & Business Media, 2013).

34
Khrustalev, L. N. Geotechnical fundamentals for permafrost regions. (Moscow State University, Moscow, 2005) (in Russian).

35
Shur, Y. L. & Goering, D. J. in *Permafrost Soils* (ed. Margesin, R.) 251-260 (Springer, Berlin, 2009).

36
Dumais, S. & Konrad, J. M. Large-strain nonlinear thaw consolidation analysis of the inuvik warm-oil experimental pipeline buried in permafrost. *J. Cold Reg. Eng.* **33**, 04018014 (2019).

37
Chen, L., Fortier, D., McKenzie, J. & Sliger, M. Impact of heat advection on the thermal regime of roads built on permafrost. *Hydrol. Process.* **34**, 1647–1664 (2020).

38
Bjella, K. L. et al. Improving design methodologies and assessment tools for building on permafrost in a warming climate. https://hdl.handle.net/11681/38879 (2020).

39
Larsen, P. H. et al. Estimating future costs for Alaska public infrastructure at risk from climate change. *Glob. Environ. Change* **18**, 442–457 (2008).

40
Wu, B., Sheng, Y., Yu, Q., Chen, J. & Ma, W. Engineering in the rugged permafrost terrain on the roof of the world under a warming climate. *Permafr. Periglac. Process* **31**, 417–428 (2020).

41
Streletskiy, D. A., Shiklomanov, N. I. & Nelson, F. E. Permafrost, infrastructure, and climate change: a GIS-based landscape approach to geotechnical modeling. *Arct. Antarct. Alp. Res.* **44**, 368–380 (2012).

42
Instanes, A. Incorporating climate warming scenarios in coastal permafrost engineering design–Case studies from Svalbard and northwest Russia. *Cold Reg. Sci. Tech.* **131**, 76-87 (2016).

43
Kanevski, M., Connor, B., Schnabel, W. & Bjella, K. in *Cold Regions Engineering 2019* (eds. Bilodeau, J.-P, Nadeau, D. F., Fortier, D. & Conciatori, D.) 588–596 (American Society of Civil Engineers (ASCE), Reston, 2019).

44
Niu, F., Luo, J., Lin Z., Liu, M., Yin, G. Thaw-induced slope failures and susceptibility mapping in permafrost regions of the Qinghai–Tibet Engineering Corridor, China. *Nat. Haz.* **74**, 1667–1682 (2014).

45
Bintanja, R. & Andry, O. Towards a rain-dominated Arctic. *Nat. Clim. Chang*. **7**, 263–267 (2017).

46
Burke, E. J., Zhang, Y. & Krinner, G. Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change. *The Cryosphere* **14**, 3155–3174 (2020).

47
Deline, P. et al. in *Snow and Ice-Related Hazards, Risks, and Disasters* (ed. Haeberli, W. & Whiteman, C.) 501–540 (Elsevier, 2021).

48
Mekonnen, Z. A., Riley, W. J., Grant, R. F. & Romanovsky, V. E. Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate. *Environ. Res. Lett.* **16**, 024008 (2021).

49
Romanovsky, V. E. et al. Terrestrial Permafrost. *Bull. Amer. Meteor. Soc.*, **101,** S153–S156 (2020).

50
Smith, S. L. et al. The changing thermal state of permafrost [tentative title]. *Nat. Rev. Earth Environ*. **XX**, XXX–XXX (2021).

51
Instanes, A. & Anisimov, O. in *Proceedings Ninth International Conference on Permafrost* (ed. Kane, D. & Hinkel, K. M.) 779–784 (University of Alaska Fairbanks, Fairbanks, 2008).

52
Yokohata, T. et al. Model improvement and future projection of permafrost processes in a global land surface model. *PEPS* **7**, 69 (2020).

53
Dobiński, W. Permafrost active layer. *Earth Sci. Rev.* **208**, 103301 (2020).

54
Luo, D. et al. Recent changes in the active layer thickness across the northern hemisphere. *Environ. Earth Sci.* **75**, 555 (2016).

55
Peng, X. et al. Spatiotemporal changes in active layer thickness under contemporary and projected climate in the Northern Hemisphere. *J. Clim*. **31** 251–266 (2018).

56
Liu, J., Wang, T., Tai, B. & Lv, P. A method for frost jacking prediction of single pile in permafrost. *Acta Geotech.* **15**, 455–470 (2020).

57
Yu, W. et al. Engineering risk analysis in cold regions: State of the art and perspectives. *Cold Reg. Sci. Tech.* **171**, 102963 (2020).

58
Ma, W, & Wang, D.Y. *Frozen soil mechanics*. (Science Press, Beijing, 2014).

59
Luo, J., Niu, F., Lin, Z., Liu, M., & Yin, G. Thermokarst lake changes between 1969 and 2010 in the Beilu river basin, Qinghai–Tibet Plateau, China. *Sci. Bull.* **60**, 556–564 (2015).

60
Koven, C. D., Riley, W. J. & Stern, A. Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth System Models. *J. Clim*. **26**, 1877–1900 (2013).

61
McGuire, A. D. et al. Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *PNAS* **115**, 3882–3887 (2018).

62
Ramage, J. et al. Population living on permafrost in the Arctic. *Popul. Environ.* (2021). https://doi.org/10.1007/s11111-020-00370-6

63
Turetsky, M. R. et al. Permafrost collapse is accelerating carbon release. *Nature* **569**, 32–34 (2019).

64
Niu, F., Luo, J., Lin, Z., Fang, J. & Liu, M. Thaw-induced slope failures and stability analyses in permafrost regions of the Qinghai-Tibet Plateau, China. *Landslides* **13**, 55–65 (2016).

65
Lewkowicz, A. G., & Way, R. G. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. *Nat. Commun.* **10**, 1329 (2019).

66
Irrgang, A. M. et al. Permafrost coastal dynamics in the twenty-first Century Arctic [tentative title]. *Nat. Rev. Earth Environ.* **XX**, XXX–XXX (2021).

67
Douglas, T. A., Turetsky, M. R. & Koven, C. D. Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. *npj Clim. Atmos. Sci*. **3**, 28 (2020).

68
Anisimov, et al. in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson C. E.) 653–685 (Cambridge University Press, Cambridge, 2007).

69
Kronik, Y. A. in *Proceedings of the Second Conference of Russian Geocryologists* (ed. Melnikov, V.) 138–146 (Moscow State University, Moscow, 2001).

70
Wu, Q. B., Dong, X. F., Liu, Y. Z. & Jin, H. J. Responses of Permafrost on the Qinghai-Tibet Plateau, China, to Climate Change and Engineering Construction. *Arct. Antarct. Alp. Res.* **39**, 682-687 (2007).

71
Gibson, C. M., Brinkman, T., Cold, H., Brown, D., & Turetsky, M. Identifying increasing risks of hazards for northern land-users caused by permafrost thaw: integrating scientific and community-based research approaches. *Environ. Res. Lett.* **16**, 064047 (2021).

72
Nyland, K. E. et al. Traditional Iñupiat ice cellars (SIĠḶUAQ) in Barrow, Alaska: characteristics, temperature monitoring, and distribution. *Geogr. Rev.* **107**, 143-158 (2017).

73
Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. A. & Brown, J. Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geogr*. **31**, 47-68 (2008).

74
Harris, C., et al. Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth Sci. Rev.* **92**, 117-171 (2009).

75
Streletskiy, D. & Shiklomanov, N. in *Sustaining Russia's Arctic Cities: Resource Politics, Migration, and Climate Change* (ed. Orttung, R. W.) 201–220 (Berghahn Press, New York, 2016).

76
Khrustalev, L. N., Parmuzin, S.Y. & Emelyanova, L.V. Reliability of northern infrastructure in conditions of changing climate. (University Book Press, Moscow, 2011).

77
Khrustalev, L. N. & Davidova, I. V. Forecast of climate warming and account of it at estimation of foundation reliability for buildings in permafrost zone. *Earth Cryos*. **11**, 68–75 (2007).

78
Streletskiy, D., Shiklomanov, N. & Grebenets, V. Changes of foundation bearing capacity due to climate warming in Northwest Siberia. *Earth Cryos*. **16**, 22–32 (2012).

79
Streletskiy, D. A., Shiklomanov, N. I. & Hatleberg, E. in *Proceedings of the 10th International Conference on Permafrost* (ed. Hinkel, K. M.) 407–412 (The Northern Publisher, Salekhard, 2012).

80
Humlum, O., Instanes, A. & Sollid, J. L. Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. *Polar Res.* **22**, 191-215 (2003).

81
Instanes, A. in *Proceedings of 8th International Permafrost Conference* (ed. Arenson, L. U., Phillips, M. & Springman, S. M.) 461–466 (CRC Press, Zürich, 2003).

82
Phillips, M. et al. Monitoring and reconstruction of a chairlift midway station in creeping permafrost terrain, Grächen, Swiss Alps. *Cold. Reg. Sci. Technol*. **47**, 32–42 (2007).

83
Jaskólski, M. W., Pawłowski, Ł. & Strzelecki, M. C. High Arctic coasts at risk—the case study of coastal zone development and degradation associated with climate changes and multidirectional human impacts in Longyearbyen (Adventfjorden, Svalbard). *Land Degrad. Dev*. **29**, 2514–2524 (2018).

84
Duvillard, P. A., Ravanel, L., Marcer, M. & Schoeneich, P. Recent evolution of damage to infrastructure on permafrost in the French Alps. *Reg. Environ. Change* **19**, 1281–1293 (2019).

85
Doré, G. & Zubeck, H. *Cold Region Pavement Engineering*. 425 (McGraw-Hill Professional & American Society of Civil Engineers (ASCE) Press, Reston, 2009).

86
Levitt, M. Nation-Building at Home, Vigilance Beyond: Preparing for the Coming Decades in the Arctic. (House of Commons, Ottawa, 2019).

87
Connor, B. & Harper, J. How vulnerable is Alaska’s transportation to climate change? *Trans. Res. News* **284**, 23–29 (2013).

88
Brooks, H. *Quantitative Risk Analysis for Linear Infrastructure Supported by Permafrost: Methodology and Computer Program*. (Doctoral dissertation, Université Laval, Québec, Canada 2018).

89
McHattie, R.L. & Esch, D.C. in *Proceedings of the 5th International Conference on Permafrost* (ed. Senneset, K.) 1292-1297 (Tapis Publishers, Trondheim, 1988).

90
Tetra Tech EBA Inc. *Inuvik Airport Runway Settlement Field Report*. (Government of Northwest Territories, Department of Transportation, Airport Division, 2014).

91
Calmels, F. et al*. Vulnerability of the North Alaska Highway to Permafrost Thaw: A Field Guide and Data Synthesis* (ed. Halladay, P.) (Yukon Research Center, Whitehorse, 2015).

92
Calmels, F., Roy, L.-P., Grandmont, K., Pugh R. *Summary of climate- and geohazard-related vulnerabilities for the Dempster Highway corridor*. (Yukon Research Centre, Whitehorse, 2018).

93
Burn, C. et al. Permafrost characterization of the Dempster Highway, Yukon and Northwest Territories. In *GEOQuébec2015: 68th Canadian Geotechnical Conference & 7th Canadian Permafrost Conference* 21-23 (Canadian Geotechnical Society, Québec, 2015).

94
De Guzman, E. M. B., Alfaro, M., Doré, G. & Arenson, L. U. Performance of highway embankments in the Arctic corridor constructed under winter conditions. *Can. Geotech. J.* (2020). https://doi.org/10.1139/cgj-2019-0121kong

95
L'Hérault, E., Allard, M., Barrette, C., Doré, G. & Sarrazin, D. *Investigations géotechniques, caractérisation du pergélisol et stratégie d'adaptation dans un contexte de changements climatiques pour les aéroports d'Umiujaq, Inukjuak, Puvirnituq, Akulivik, Salluit, Quaqtaq, Kangirsuk et Tasiujaq, Nunavik. Rapport final.* (Center for Nordic Studies, Laval University, Québec, 2012).

96
Zou, D. et al. A new map of permafrost distribution on the Tibetan plateau. *The Cryosphere* **11**, 2527–2542 (2017).

97
Huang, Y. Z., Zhang, F. L. & Yang, X. Economic growth contribution and spatial effect of Tibet highway based on cryosphere service function accounting. *J. Glaciol. Geocryo.* **41**, 719–729 (2019).

98

Cheng, G. D. Influences of local factors on permafrost occurrence and their implications for Qinghai-Xizang Railway design*, Sci. China Earth Sci.* **47**, 704–709 (2004).

99

Ma, W., Mu, Y., Wu, Q., Sun, Z. & Liu, Y. Characteristics and mechanisms of embankment deformation along the Qinghai–Tibet Railway in permafrost regions. *Cold Reg. Sci. Technol*. **67**, 178–186 (2011).

100

Chai M. et al. Characteristics of asphalt pavement damage in degradation permafrost regions: Case study of the Qinghai-Tibet Highway, China*. J. Cold Reg. Eng*. **32**, 05018003 (2018).

101

Wang, S., Chen, J., Zhang, J. & Li, Z. Development of highway constructing technology in the permafrost region on the Qinghai-Tibet plateau. *Sci. China Technol. Sci*. **52**, 497–506 (2009).

102

Zhang, J., Huo, M. & Chen, J. Stability Technical Problems and Countermeasures of Highway Roadbed. (China Communication Press, Beijing, 2008).

103

Ma, W., Qi, J. L. & Wu, Q. B. Analysis of the Deformation of Embankments on the Qinghai-Tibet Railway. *J. Geotechn. Geoenviron. Engin.* **134**, 1645–1654 (2008).

104

Wang, J. & Wu, Q. Settlement analysis of embankment-bridge transition section in the permafrost regions of Qinghai-Tibet railway. *J. Glaciol. Geocryol*. **39**, 79–85 (2017).

105

Schweikert, A., Chinowsky, P., Kwiatkowski, K. & Espinet, X. The infrastructure planning support system: Analyzing the impact of climate change on road infrastructure and development. *Transp. Policy* **35**, 146-153 (2014).

106

Chappin, E.J.L. & van der Lei, T. Adaptation of interconnected infrastructures to climate change: A socio-technical systems perspective. *Util. Policy* **31**, 10-17 (2014).

107

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. Climate change and hazard zonation in the circum-Arctic permafrost regions. *Nat. Haz.* **26**, 203–225 (2002).

108

Anisimov, O. & Reneva, S. Permafrost and changing climate: the Russian perspective. *Ambio* **35**, 169–175 (2006).

109
Shiklomanov, N. I., Streletskiy, D. A., Grebenets, V. I. & Suter, L. Conquering the permafrost: urban infrastructure development in Norilsk, Russia. *Polar Geogr*. **40**, 273–290 (2017).

110
Daanen, R. P. et al. Permafrost degradation risk zone assessment using simulation models. *The Cryosphere* **5**, 1043–1056 (2011).

111
Zhang, Z. & Wu, Q. Freeze-thaw hazard zonation and climate change in Qinghai-Tibet Plateau permafrost, *Nat. Haz.* **61**, 403–423 (2012).

112
Ni, J. et al. Risk assessment of potential thaw settlement hazard in the permafrost regions of Qinghai-Tibet Plateau. *Sci. Total Environ.* **776**, 145855 (2021).

113
Hong, E., Perkins, R. & Trainor, S. Thaw settlement hazard of permafrost related to climate warming in Alaska. *Arctic* **67**, 93–103 (2014).

114
Shiklomanov, N. I., Streletskiy, D. A., Swales, T. B. & Kokorev, V. A. Climate change and stability of urban infrastructure in Russian permafrost regions: prognostic assessment based on GCM climate projections. *Geogr. Rev*. **107**, 125–142 (2017).

115
Karjalainen, O. et al. Circumpolar permafrost maps and geohazard indices for near-future infrastructure risk assessments. *Sci. Data* **6**, 190037 (2019).

116
Dore, M. & Burton, I. *Costs of adaptation to climate change in Canada: A stratified estimate by sectors and regions: Social infrastructure* (ed. Dore, M.) (Brock University, St. Catharines, 2001).

117
Porfiriev, B. N. et al. Climate change impact on economic growth and specific sectors' development of the Russian Arctic*. Arctic: Ecol. Econ*. **4**, 4–17 (2017).

118
Porfiriev, B., Eliseev, D. & Streletskiy, D. Economic Assessment of Permafrost Degradation Effects on Road Infrastructure Sustainability under Climate Change in the Russian Arctic. *Her.Russ. Acad. Sci.* **89**, 567–576 (2019).

119
Badina, S. V. Prediction of Socioeconomic Risks in the Cryolithic Zone of the Russian Arctic in the Context of Upcoming Climate Changes. *Stud. Russ. Econ. Dev*. **31**, 396–403 (2020).

120
Reimchein, D., Doré, G., Fortier, D., Stanley, B. & Walsh, R. Cost and Constructability of Permafrost Test Sections Along the Alaska Highway, Yukon, in *Proceedings of the 2009 Annual Conference Transportation Association of Canada*, 1-20 (Transportation Association of Canada, Vancouver, 2009).

121
Porfiriev, B. N., Elisseev, D. O. & Streletskiy, D. A. Economic Assessment of Permafrost Degradation Effects on the Housing Sector in the Russian Arctic. *Her.Russ. Acad. Sci.* **91**, 17–25 (2021).

122
Wu, Q. B. & Ma, W. in *Research Monograph of Cold and Arid Regions Engineering and Environment* (ed. Ma, W. & Niu, F. J.) 155–161 (Lanzhou University Press, Lanzhou, 2012).

123
Wang, S., Niu, F., Chen, J. & Dong, Y. Permafrost research in China related to express highway construction. *Permafr. Periglac. Process.* **31,** 406–416 (2020).

124
Cheng, G. A roadbed cooling approach for the construction of Qinghai-Tibet Railway. *Cold. Reg. Sci. Technol.* **42**, 169–176 (2005).

125
Bjella, K. L. *Dalton Highway 9 to 11 Mile expedient resistivity permafrost investigation.* (Alaska Department of Transportation and Public Facilities, Fairbanks, 2014).

126
Ma, W., Cheng, G. & Wu, Q. Construction on permafrost foundations: Lessons learned from the Qinghai-Tibet railroad. *Cold Reg. Sci. Technol*. **59**, 3–11 (2009).

127
Kondratiev, V. G. in *ISCORD 2013: Planning for Sustainable Cold Regions* (ed. Zufelt, J. E.) 541–548 (American Society of Civil Engineers (ASCE), Anchorage, 2013).

128
Hu, T., Liu, J., Chang, J. & Hao, Z. Development of a novel vapor compression refrigeration system (VCRS) for permafrost cooling. *Cold. Reg. Sci. Technol.* **181**, 103173 (2021).

129
Goering, D. J. & Kumar, P. Winter-time convection in open-graded embankments. *Cold. Reg. Sci. Technol.* **24**, 57–74 (1996).

130
Malenfant-Lepage, J., Doré, G., Fortier, F. & Murchison, P. in *Proceedings of the 10th International Conference on Permafrost* (ed. Hinkel, K. M.) 261–267 (The Northern Publisher, Salekhard, 2012).

131
Kong, X., Doré, G., Calmels, F. & Lemieux, C. Modeling the thermal response of air convection embankment in permafrost regions. *Cold Reg. Sci. Technol*. **182**, 103169 (2020).

132
Cheng, G., Wu, Q. & Ma, W. Engineering Effect of Proactive Roadbed- Cooling for the Qinghai-Tibet Railway, *Sci. China* **52**, 530–538 (2009).

133
Wu, Q., Zhao, H., Zhang, Z., Chen, J. & Liu, Y. Long-term role of cooling the underlying permafrost of the crushed rock structure embankment along the Qinghai–Xizang railway, *Permafr. Periglac. Process.* **31**, 172–183 (2020).

134
Kuznetsov, G. et al. Heat transfer in a two-phase closed thermosyphon working in Polar Regions. *Therm. Sci. Eng. Prog.* **22**, 100846 (2021).

135
Forsström, A., Long, E., Zarling, J. & Knutsson, S. in *Proceedings of the 11th International Conference on Cold Regions Engineering* (ed. Merrill, K. S.) 645–655 (American Society of Civil Engineers, Anchorage, 2002).

136
Hayley D. W., Roggensack, W. D., Jubien, W. E. & Johnson, P. V. in *Proceedings of the 4th International Conference on Permafrost* (ed. Embleton, C.) 468–473 (National Academy Press, Washington D.C., 1983).

137
Chen, L., Yu, W., Lu, Y. & Liu, W. Numerical simulation on the performance of thermosyphon adopted to mitigate thaw settlement of embankment in sandy permafrost zone. *Appl. Therm. Eng.* **128**, 1624–1633 (2018).

138
Niu, F. et al. Long-term thermal regimes of the Qinghai-Tibet Railway embankments in plateau permafrost regions. *Sci. China Earth Sci.* **58**, 1669-1676 (2015).

139
Cheng, G., Zhang, J., Sheng, Y. & Chen, J. Principle of thermal insulation for permafrost protection, *Cold Reg. Sci. Technol.* **40**, 71–79 (2004).

140
Bjella, K. in *ISCORD 2013: Planning for Sustainable Cold Regions* (ed. Zufelt, J. E.) 565–575 (American Society of Civil Engineers (ASCE), Anchorage, 2013).

141
Esch, D. in *Proceedings of the 5th International Conference on Permafrost* (ed. Senneset, K.) 1223–1228 (Tapis Publishers, Trondheim, 1988).

142
Richard, C., Doré, G., Lemieux, C., Bilodeau, J. P. & Haure-Touzé, J. in *Cold Regions Engineering 2015: Developing and Maintaining Resilient Infrastructure* (ed. Guthrie, W. S.) 181–192 (American Society of Civil Engineers (ASCE), Reston, 2015).

143
Dumais, S. & Doré, G. An albedo based model for the calculation of pavement surface temperatures in permafrost regions. *Cold Reg. Sci. Technol.* ***123**, 44–52* (2015).

144
Feng, W. J., Ma, W., Li, D. Q. & Zhang L. Application investigation of awning to roadway engineering on the Qinghai-Tibet Plateau. *Cold Reg. Sci. Technol.* **45**, 51–58 (2006).

145
Yu, Q. H., Mu, Y. H., Yuan, C., Ma, W. & Pan, X. C. The cold accumulative effect of expressway embankment with a combined cooling measure in permafrost zones. *Cold Reg. Sci. Technol.* **163**, 59–67 (2019).

146
Zhang, M, Y, et al. Evaluating the cooling performance of crushed-rock interlayer embankments with unperforated and perforated ventilation ducts in permafrost regions. *Energy* **93**, 874–881 (2015).

147
Nixon, J. F. & Burgess, M. Norman Wells pipeline settlement and uplift movements. *Can. Geotech. J.* **36**, 119-135 (1999).

148
Jin, H. et al. Zonation and assessment of frozen-ground conditions for engineering geology along the China–Russia crude oil pipeline route from Mo'he to Daqing, Northeastern China. *Cold Reg. Sci. Technol.* **64**, 213–225 (2010).

149
Li, G. et al. Permafrost Engineering Problem Along China-Russia Crude Oil Pipeline and Mitigative Measure (In Chinese with English abstract). *Bull. Chin. Acad. Sci.* **36**, 150-159 (2021).

150
Stephani, E., Fortier, D., Shur, Y., Fortier, R. & Doré G. A geosystems approach to permafrost investigations for engineering applications, an example from a road stabilization experiment, Beaver Creek, Yukon, Canada, *Cold Reg. Sci. Tech.* **100**, 20–35 (2014).

151
Bjella, K. L. in *GeoCalgary2010 Proceedings of the 63rd Canadian Geotechnical Conference and the 6th Canadian Permafrost Conference*, (ed. Kwok, C., Moorman, B., Armstrong, R. & Henderson, J.) 970–977 (Canadian Geotechnical Society, Calgary, 2010).

152
Shiklomanov, N. From Exploration to Systematic Investigation: Development of Geocryology in 19th-and Early—20th-Century Russia. *Phys. Geogr*. **26**, 249–263 (2005).

153
Streletskiy, D., Anisimov, O. & Vasiliev, A. in *Snow and Ice-Related Hazards, Risks, and Disasters* (ed. Haeberli, W. & Whiteman, C.) 303–344 (Elsevier, Amsterdam, 2014).

154
Yu, Q.H., Ji, Y., Zhang, Z., Wen, Z. & Feng, C. Design and research of high voltage transmission lines on the Qinghai–Tibet plateau—a special issue on the permafrost power lines. *Cold Reg. Sci. Technol.* **121**, 179-186 (2016).

155
Schneider von Deimling, T. et al. Consequences of permafrost degradation for Arctic infrastructure – bridging the model gap between regional and engineering scales. *The Cryosphere* **15**, 2451–2471 (2021).

156
Rajendran, S. et al. Monitoring oil spill in Norilsk, Russia using satellite data. *Sci. Rep*. **11**, 3817 (2021).

157
L'Hérault, E. et al. Adapter la conception et développer des outils de gestion intégrés pour soutenir l'adaptation aux changements climatiques des infrastructures de transport du Ministère des Transports du Québec en région de pergélisol au Nunavik. (Université Laval, Québec, 2019).

Acknowledgements

J.H. acknowledges funding from the Academy of Finland (Grant 315519), Q.W. from the National Natural Science Foundation of China (Grant 41690144), and D.S. from the National Science Foundation (Grants 1545913, 2019691, 2022504, and 1558389). Olli Karjalainen helped with the figures and Oona Könönen with the management of references.

Author contributions

J.H. and M.L. developed the content of the manuscript with contributions from D.S., G.D., and Q.W. J.H. led the preparation of the manuscript with contribution from D.S., G.D., Q.W., K.B. and M.L.

Competing interests

The authors declare no competing financial interests.

Supplementary information

Supplementary information is available for this paper at…

Glossary

Permafrost: Ground with a temperature remaining at or below 0 °C for at least two consecutive years.

Warming of permafrost: An increase of permafrost temperature (ground temperature remains at or below 0 °C also after the warming).

Thaw of permafrost: Increase of permafrost temperature accompanied by melting of ground ice.

Infrastructure: Facilities with permanent foundations on ice-free land.

Natural hazard: A natural phenomenon that can have a negative effect on humans or the environment.

Ground ice: A general term referring to all types of ice contained in freezing and frozen ground.

Active layer: The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

Bearing capacity: The maximum load a soil or rock, frozen or unfrozen, can support from an applied load, within a defined measure of accepted strain (movement due to loading).

Bearing strength: The ability of a soil, sediment, or rock to support the direct application of a load or stress, either concentrated or diffused, and is measured in force.

Near-surface permafrost: Permafrost in the topmost ground layers (<10–15 m depth).

Mass-wasting: Downslope movement of soil or rock on, or near, the earth's surface under the influence of gravity.

Adfreeze: The process by which two objects are bonded together by ice formed between them.

Frost-jacking: Cumulative upward displacement of objects embedded in the ground, caused by frost action.

Permafrost creep: The slow deformation that results from long-term application of a stress too small to produce failure in the permanently frozen material.

Solifluction: Slow downslope flow of saturated unfrozen earth materials.

Retrogressive thaw slump: A slope failure resulting from thawing of ice-rich permafrost.

Active-layer detachment slide: A slope failure in which the thawed or thawing portion of the active layer detaches from the underlying frozen material.

Thermal erosion: The erosion of ice-bearing permafrost by the combined thermal and mechanical action of moving water.

Thermokarst: The process by which characteristic landforms result from the thawing of ice-rich permafrost or the melting of massive ice.

Bulk density: The weight of soil in a given volume.

Critical infrastructure: A general term for engineered structures (residential, transportation, and industrial) important for Arctic and high-altitude communities and the economy.

Sinkhole in permafrost: A small depression in the ground caused by collapse of the surface layer due to thaw of ice-rich permafrost.

Ice-wedge: A massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded ice.

Talik: A layer or body of unfrozen ground occurring in a permafrost area due to a local anomaly in thermal, hydrological, hydrogeological, or hydrochemical conditions.

Yedoma: An organic-rich permafrost with high ground ice content.

Excess ice: The volume of ice in the ground which exceeds the total pore volume that the ground would have under natural unfrozen conditions

Permafrost table: The upper boundary surface of permafrost.