Impacts of permafrost degradation on infrastructure

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Abstract | The warming and thawing of ice-rich permafrost pose considerable threat to the integrity of polar and high-altitude infrastructure, in turn jeopardizing sustainable development. In this Review, we explore the extent and costs of observed and predicted infrastructure damage associated with permafrost degradation, and the methods available to mitigate such adverse consequences. Permafrost change imposes various threats to infrastructure, namely through warming, active layer thickening and thaw-related hazards such as thermokarst and mass wasting. These impacts, often linked to anthropogenic warming, are exacerbated through increased human activity. Observed infrastructure damage is substantial, with up to 80% of buildings in some Russian cities and ~30% of some road surfaces in the Qinghai–Tibet Plateau reporting damage. Under anthropogenic warming, infrastructure damage is projected to continue, with 30–50% of critical circumpolar infrastructure thought to be at high risk by 2050. Accordingly, permafrost degradation-related infrastructure costs could rise to tens of billions of US dollars by the second half of the century. Several mitigation techniques exist to alleviate these impacts, including convection embankments, thermosyphons and piling foundations, with proven success at preserving and cooling permafrost and stabilizing infrastructure. To be effective, however, better understanding is needed on the regions at high risk.

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

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

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

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

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Polar and high-altitude regions have received increased attention owing to the unprecedented and rapid environmental changes they have exhibited[1,2]. One type of major change are those associated with permafrost, which covers approximately one-fifth of the northern hemisphere's exposed land surface[3]. For example, permafrost has undergone rapid warming, with temperatures typically increasing by 0.3–1.0 °C per decade since the 1980s, and corresponding increases in active layer depths[4]. As such, permafrost has exhibited extensive degradation (warming and thaw), with resulting impacts on ecosystem functioning[5], greenhouse gas emissions (including CO_2, CH_4 and N_2O)[6,7] and geomorphological characteristics[8].

In addition to these potential adverse environmental effects, permafrost degradation also poses threats to society via impacts on infrastructure, the backbone of human activities in remote regions[2,9–11] (FIG. 1). At least 120,000 buildings, 40,000 km of roads and 9,500 km of pipelines, for instance, are located in permafrost areas of the northern hemisphere[12]. An increase in the risk of gradual and abrupt natural hazards (such as thermokarst and thermal erosion) arising from degradation of ice-rich permafrost can, therefore, impair this infrastructure[13–16]. Indeed, these negative effects are already evident[13], as evidenced by damage to numerous buildings[17] and the diesel spill near Norilsk City, Russia in 2020 (REF.[18]). Moreover, with projections indicating continued warming of permafrost, the cumulative problems of infrastructure damage can be exacerbated[19,20], with up to 70% of fundamental circumpolar infrastructure at risk by mid-century[12]. These impacts create challenges for decision makers, planners and engineers[21,22], particularly given that operational infrastructure is critical to the sustainable development and economy of Arctic and high-altitude cold regions[2,10,12,16,19,20,22–25]. In response, communities and decision makers must identify opportunities for adaptation[26–29].

In this Review, we bring together knowledge of permafrost degradation impacts on infrastructure. We first outline the fundamental problems associated with construction in permafrost areas, and next discuss permafrost degradation-related hazards that affect infrastructure. The extent and costs of observed and predicted infrastructure damage are subsequently reported, alongside the methods to mitigate such adverse consequences. We end with seven topics that should be considered to support operational infrastructure in permafrost areas in the future.

Key points

- Operational infrastructure is critical for sustainable development of Arctic and high-altitude communities, but their integrity is jeopardized by degrading permafrost.
- The extent of observed infrastructure damage is substantial (up to 60–80% of infrastructure elements) and is likely to increase with climate warming.
- Nearly 70% of current infrastructure in the permafrost domain is in areas with high potential for thaw of near-surface permafrost by 2050.
- Engineering solutions are able to mitigate the effects of degrading permafrost, but their economic cost is often high.
- Greater efforts are needed to quantify the economic impacts and occurrence of permafrost-related infrastructure failure.
- Future development projects should conduct local-scale infrastructure risk assessments and apply mitigation measures to avoid detrimental impacts.

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

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

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).

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

Building on permafrost

Infrastructure construction faces many challenges in permafrost areas, including the impact of climatic, environmental and engineering influences[17,26–33]. These factors, coupled with high spatial variability in permafrost properties[3,13,30,34,35] (such as distribution, mechanical properties, thickness and temperature), necessitate accurate exploration and spatial prediction of permafrost properties to guide engineering design and construction[32,36], all of which increase the difficulty of site surveys and engineering solutions, and thus come at additional cost[37].

The thermal state of permafrost and the presence of ground ice of variable type and thickness[30] strongly influence infrastructure stability[31]. Permafrost soil exhibits vastly changeable properties from thawed to frozen state owing to the phase change of water[32]. Soils, especially fine-grained soils, can heave 1–40 cm per year during the freezing process of the wet soils within the active layer[30], generating forces up to 300 kPa that can lead to infrastructure deformation and failure[30,31]. During the thawing process, frozen soil with a high ice content also exhibits substantial strength and volume changes comparable to the ground ice content, similarly resulting in potential infrastructure deformation and damage[31].

In general, frozen soil has higher strength, increasing with decreasing temperature owing to ice cementation within frozen soils. As soil temperatures increase, however, strength rapidly decreases[33] from compression and increasing creep rate of the unfrozen water in the ice matrix. When the soil temperature surpasses the freezing point, the bearing capacity is greatly reduced; excess water and volume displacement mean the soil can no longer satisfy engineering stability, leading to differential settlement and infrastructure failure[30,32,38].

Interactions between infrastructure and permafrost can also influence construction. Different foundations and architecture lead to highly variable thermal impacts, with potentially contrasting effects[31,39]. For example, deep foundations rely on adfreeze of ground ice and soil with a pile or pier, the bond of which decreases as ground ice temperatures rise. Design therefore needs to account for permafrost conditions during the entire lifespan of the structure based on the heat source of infrastructure types, with consideration of change in the adfreeze bond often altering the design principle of engineering and choice of expected engineering measures to prevent freeze–thaw damage. Moreover, structures with high loads require slab-on-grade design, imparting high heat flux to the frozen ground. Lighter load structures, in contrast, can utilize an elevated design to decouple the structure from the terrain and maintain the frozen condition[17,32,36].

Although such construction and/or operation-related thermal disturbances can contribute to permafrost degradation, and thus reduce soil strength, they are exacerbated by rapidly changing climatic conditions and associated permafrost warming[40]. Climate warming must therefore be properly accounted for during engineering design in permafrost areas[41]. However, choosing the right climatic input to estimate changes in permafrost geotechnical properties is non-trivial, requiring understanding of biases and uncertainties in climate models[42,43]. For instance, basing designs on worst-case climate scenarios could require additional (perhaps unnecessary) capital expenditure, whereas a lesser scenario could translate to higher operational expenses should warming be worse than projected.

As permafrost degradation, in turn, alters environmental conditions, environmental protection must also be considered for engineering design and construction. Permafrost thaw, for example, modifies hydrology, which can accelerate the thaw[30]. As such, in particularly sensitive areas with ice-rich fine-grained soil material, environmental protection can substantially increase the costs of engineering construction[37].

Climate warming further increases the vulnerability of infrastructure to resist and/or adjust to the environmental changes[44] because the adverse effects of warming were not previously considered at the time of construction[40]. Thus, future infrastructure design and construction practices need to consider the issue of permafrost stability and have the ability to adjust to changing conditions, but at the same time to evaluate in the context of other factors such as an increase in extreme events and slope instability[45]. Failure to account for other environmental variables can increase the susceptibility of infrastructure built on permafrost, and increase maintenance and replacement costs[10,20].

Permafrost degradation-related hazards

Permafrost degradation can lead to subsequent hazards (hereafter permafrost hazards) that jeopardize the integrity of infrastructure[34,46–49]. These permafrost hazards include warming of permafrost and thickening

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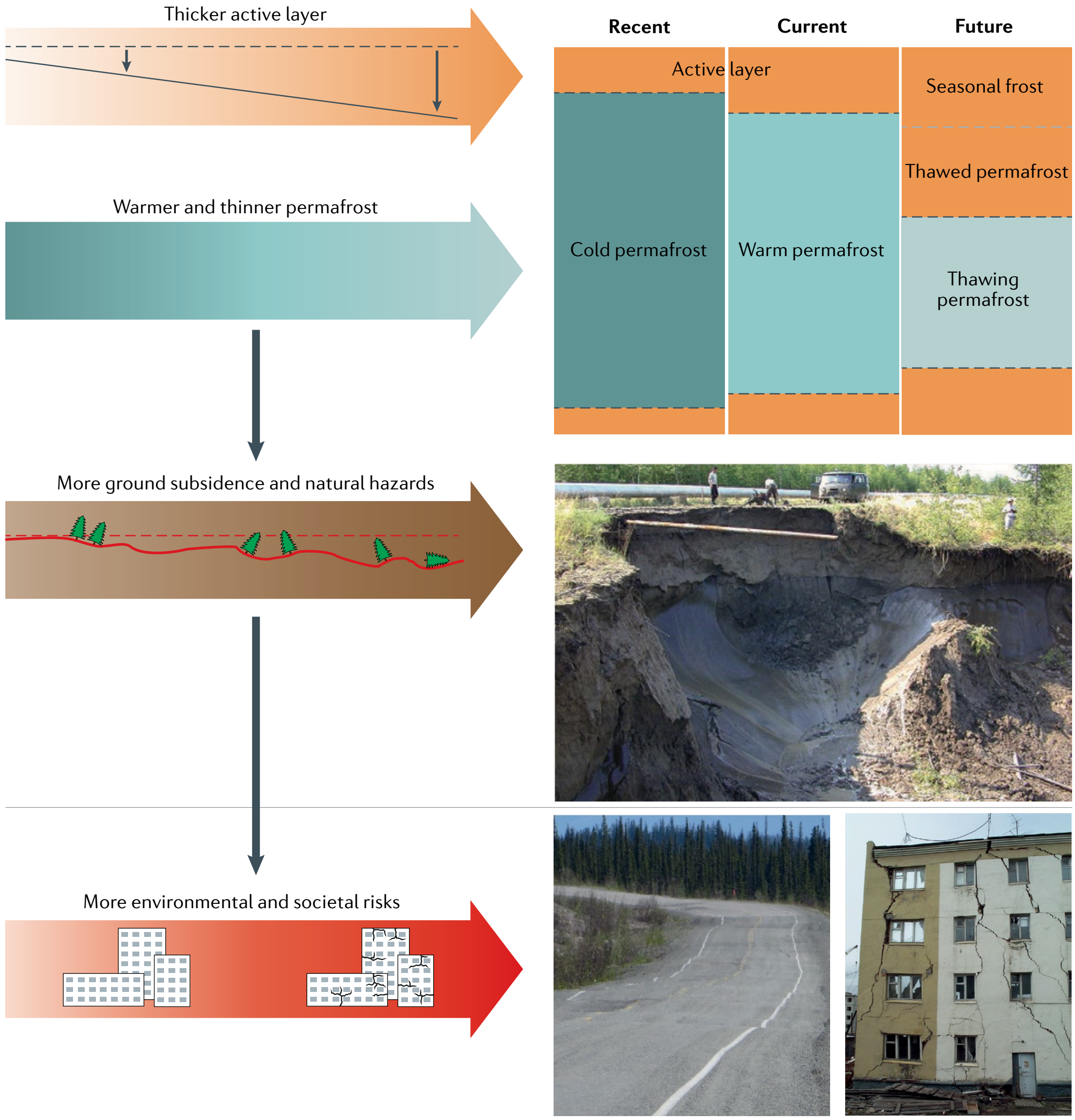


Fig. 1 | **Degrading permafrost threatens the environment and societies through infrastructure damage.** Schematic presentation of degrading permafrost (thickening of active layer and warming and thawing of permafrost) causing natural hazards and environmental and societal risks. Schematic on the left adapted with permission from REF.[12], under a Creative Commons license CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/). Top photograph is reprinted with permission from REF.[13], Elsevier. Bottom-left photograph is courtesy of Vladimir Romanovsky and bottom-right photograph is courtesy of Aleksandr Fedorov.

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

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

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

of the active layer, as well as thaw-related hazards such as the development of taliks, ground subsidence and thermokarst in low-lying areas, mass wasting on slopes, and thermal erosion and abrasion along riverbanks and coasts (FIG. 2).

Warming and active layer thickening

Permafrost temperature and active layer thickness are two critical variables required for design and construction on permafrost[30]. Permafrost warming is a widespread phenomenon[4,50], with globally averaged permafrost ground temperatures having increased by 0.29 °C from 2007 to 2016 (REF.[34]), and areas characterized by continuous permafrost warming at faster rates compared with discontinuous permafrost. These increased ground temperatures enhance the unfrozen water content of the active layer and decrease ice bonding (cohesion) of soil particles, resulting in a gradual loss of bearing strength[31] (FIG. 2). Near-surface warming in ice-rich permafrost further increases creep rates of common foundations and causes eventual loss of adfreeze bond support for pilings[40,51]. These perturbations are dependent on the thermal properties of the frozen ground, with changes in warm permafrost regions (above −3 °C) being most critical for infrastructure given the proximity to the melting point[51]. For example, adfreeze bond strength decreases by <10% when the temperature rises from −6 to −4 °C, but decreases by ~50% when the temperature rises from −3 to −1 °C[51].

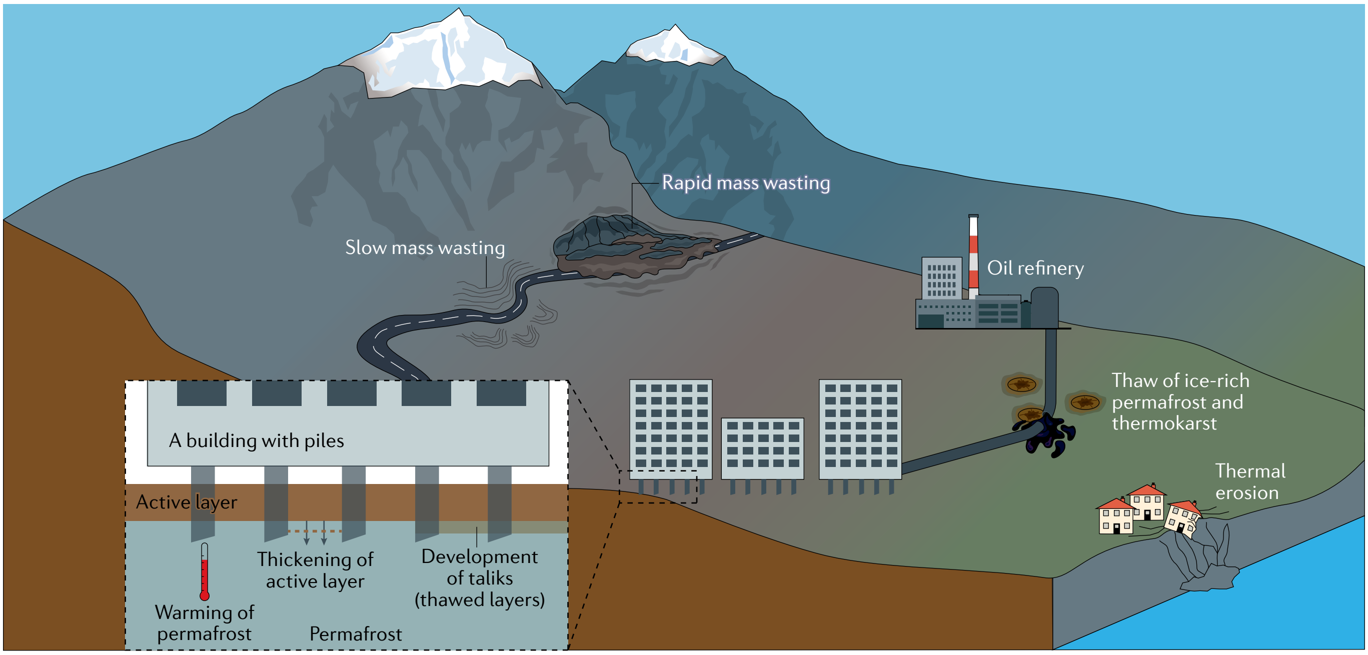


Fig. 2 | **Permafrost hazards damaging infrastructure.** Schematic presentation of permafrost degradation-related natural hazards that threaten the integrity of critical infrastructure (roads, pipelines, buildings and industrial facilities) in permafrost areas.

Collectively, these impacts of warming reduce permafrost's capacity to carry loads imposed by infrastructure, particularly in the long term. Indeed, in some Russian Arctic cities, bearing capacity has decreased by more than 40% between the 1960s and 2000s[40]. Moreover, with permafrost warming projected to continue[47,52], an increasing number of engineered structures will be located in regions with ground temperatures close to 0 °C[34], enhancing hazard potential.

Coincident with higher ground temperatures have been observations of active layer deepening[4,50] (although the relationship between permafrost degradation and active layer thickness is not straightforward[53]). Although regionally variable, active layer thickness changes have predominantly increased from ~1990 (REF.[54]). The largest changes have been in the Central Asian mountains, where thickening of >10 cm per year is observed[54]. As with permafrost temperature, these changes are projected to continue with anthropogenic warming. On the Qinghai–Tibetan Plateau, for instance, the total increase in active layer thickness could exceed 120–200 cm by 2100. However, globally averaged rates are lower at 0.8–6.5 cm per decade over the same time period[55].

This thickening of the active layer can have multiple effects relevant to infrastructure, including thaw settlement during summer, frost heave during winter and frost jacking of piles[56]. Greater active layer thicknesses can also lead to a decrease in frozen-ground adfreeze strength, enhancing creep settlement of existing piles and footings and exposing foundations to cryogenic weathering[17,57]. In addition, 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.

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

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

Permafrost thaw hazards

The thaw of frozen ground is critical for engineered construction; the strength of soil drops substantially as temperatures rise above the melting point and ground ice melts[30,58] (FIG. 2), threatening infrastructure through multiple processes. Given that permafrost thaw is most pronounced in regions of warm permafrost — where the population and infrastructure are most dense — these hazards represent considerable risk potential in the near future[59], particularly given that 30–60% of near-surface permafrost might be lost by the end of this century[47,52,60,61].

Weather conditions including heatwaves and heavy rainfall are more likely to occur with anthropogenic warming, particularly during the thaw season[46]. Such events (or, more broadly, the impacts of precipitation on hydrology) can lead to the development of supra-permafrost taliks[62]. Taliks decrease the load-bearing strength of the ground and systems supporting infrastructure[57] (FIG. 2), and initiate progressive surface settlement and slope movements. In addition to naturally developed taliks, thawed layers are common under buildings, road embankments and pipeline systems[17,62], amplifying infrastructure damage as in Norilsk, Russia[63].

The amount of thaw settlement is primarily related to soil moisture content (especially ground ice)[58]. If permafrost is ice-rich, melt can result in thermokarst and uneven terrain[8]. Thermokarst involves penetration of thaw into ice-rich layers of permafrost. It can cause localized, but also widespread, instability of the ground surface and ground subsidence[64]. As such, thermokarst threatens existing infrastructure and complicates new construction projects as fragmentation of the landscape increases distances, limits accessibility and increase economic costs of operation on permafrost[64,65].

Periglacial slope processes are additional factors that affect constructions with shallow foundations, especially transportation infrastructure[48] (FIG. 2). Slope processes range from slow mass movements such as permafrost creep and solifluction, to those that are more rapid such as landslides and earthflows (retrogressive thaw slumps and active layer detachment slides). Potential hotspots of landslides are sites with abrupt permafrost thaw (which can cover up to 20% of the circumpolar permafrost area)[66], particularly close to sea banks, lake banks and riverbanks where water-induced thermal erosion and abrasion is effective[67] (FIG. 2). For example, a 60-fold increase in retrogressive thaw slumps was observed in the Canadian Arctic between 1984 and 2015, mainly owing to warm summer conditions[68]. Thus, the projected increase in summer temperatures and precipitation could increase thermal erosion and mass wasting-related infrastructure hazards, especially in coastal[69] and topographically complex[48,68] regions. Under projected hydrological changes, the existing water pathways cannot be adequately designed, resulting in overflow and damage to infrastructure[28,70].

Observed infrastructure damage

Collectively, the aforementioned permafrost risks — warming and thickening of the active layer, and permafrost thaw-related hazards — represent a substantial threat to existing and future infrastructure in permafrost regions. Indeed, several reports of widespread infrastructure damage have emerged, commonly linked to climatic change. However, infrastructure damage on permafrost can easily be misattributed to such factors[71]. The majority of damage to structures in Russian permafrost areas from 1980 to 2000, for example, largely resulted from poor maintenance[72]. Nevertheless, rapidly changing climatic conditions and resulting permafrost degradation can exacerbate such maintenance issues, pushing engineering challenges beyond feasible solutions[15,73]. Technological advances have bridged connections between climate change and the permafrost geotechnical environment, facilitating assessments and projections of infrastructure degradation[74,75]. For instance, regional assessments of changes in permafrost bearing capacity under various climatic conditions are now possible using climate input in combination with permafrost modelling[40]. Observed infrastructure impacts in Russia (and Europe), North America and the Qinghai–Tibet Plateau are now discussed, which collectively threaten traditional lifestyles, subsistence economies, food security and accessibility[76,77].

Russia and Europe

Almost 65% of Russian land area is underlain by permafrost[78]. Accordingly, these regions contain a large number of settlements and, thus, comparatively high population density; more than 60% of settlements and nearly 90% of the population in Arctic permafrost areas are located in Russia[59]. Indeed, the Russian permafrost area is unparalleled in the degree of industrialization and urbanization, hosting several large cities such as Vorkuta, Yakutsk and Norilsk[79]. Unlike other permafrost areas that are generally characterized by small individual houses and lightweight administrative or industrial facilities, Russia is therefore characterized by large apartment buildings and heavy-built industrial facilities. Moreover, owing to a high population density and a related centralized network of heating and utilities, the impacts of human activities on permafrost are particularly pronounced, affecting various engineered structures.

Climatically induced permafrost degradation, exacerbated by socio-economic transformations that dismantled adequate permafrost monitoring, resulted in neglect of the infrastructure in Russian permafrost areas. Indeed, by the beginning of the twenty-first century, many buildings on permafrost had deformations, ranging from ~10% of structures in Yakutsk and Norilsk to 80% of those in Vorkuta[17,72,74] (FIG. 3a–c; Supplementary Table 1). Substantial reductions in foundation stability have also been observed. For example, in north-west Siberia, increasing permafrost temperatures and active layer thicknesses have reduced foundation support by 17%, on average, over 1990–2010 relative to 1960–1990, reaching up to 45% reductions in some locations[80]. Consistently, foundation stability reductions of 15–20% have also been reported in Salekhard, Noviy Urengoy and Nadym[81].

Outside Russia, a few notable settlements and other infrastructure are found in Greenland, Svalbard and European mountains[59,82]. In these locations, thaw damage is less extensive and common owing to reduced ground ice content, differences in type and size of engineered structures, and higher investment in construction and maintenance[83–88]. For example, of the ~1,000 infrastructure elements located on permafrost in the French Alps, fewer than 3% were identified to be damaged by permafrost degradation[87].

North America

More than 50% of Canadian and 80% of Alaskan land surfaces are characterized by the presence of permafrost. In contrast to Russia, North America does not have large industrial centres with densely arranged vertical structures. Instead, its sparse population (representing 7% of the entire Arctic permafrost area population[59]) and abundant resources depend on horizontal or linear transportation infrastructure[89]. These include ~6,800 km of road, 270 airstrips[12] as well as infrastructure such as the Trans-Alaska Pipeline System.

The construction of such linear infrastructure has multiple impacts, including local ground cooling where snow is removed; modified surface hydrology where artificial dams are built; and waterlogging and permafrost degradation where snow accumulates along the linear infrastructure[28]. These effects lead to surface distortions, depressions and cracks at the edge of embankments, as well as sinkholes, longitudinal cracks, lateral embankment spreading and water ponding along roadside and drainage ditches[90,91] (FIG. 3d–f). Degradation is also observed in areas adjacent to linear structures, including retrogressive thaw slumps, active layer detachment slides, thermal erosion gullies and newly developed icing ('aufeis') zones[91]. More circumscribed problems such as differential settlement caused by creeping of ice-rich warm and/or saline permafrost

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 slumps
Slope failure resulting from thawing of ice-rich permafrost.

Active layer detachment slides
Slope failure in which the thawed or thawing portions of the active layer detach from the underlying frozen material.

Fig. 3 | **Infrastructure damage owing to degradation of permafrost. a–c** | Infrastructure damage in Russia, including damaged buildings in Yakutia (panels **a** and **b**) and a below-ground pipeline crossing an area with ice-rich permafrost and thermokarst development in Yamal-Nenets (panel **c**). **d–f** | Infrastructure damage in North America, including longitudinal cracking due to shoulder rotation along the Alaska Highway in Yukon, Canada (panel **d**), thermokarst affecting the embankment of the Alaska Highway in Yukon, Canada (panel **e**) and a sinkhole in the Iqaluit runway (Nunavut, Canada) (panel **f**). **g–i** | Infrastructure damage in the Qinghai–Tibet Plateau, including embankment deformation of Gong–Yu Express Highway (panel **g**), a collapsed bridge of Qinghai–Tibet Highway (QTH) (panel **h**) and longitudinal cracks of QTH (panel **i**). Panels **a** and **b** courtesy of Ivan Khristoforov, panel **e** courtesy of Eva Stephani and panel **g** courtesy of Chen Ji.

under thick embankments[92], and sudden collapse due to the erosion or melting of ice wedge[93], have also been documented.

Such structural degradation is becoming increasingly evident in northern Canada and Alaska. Indeed, there has been an increased frequency and severity of issues related to permafrost degradation and slope stability along the Alaska Highway (Yukon) (FIG. 3d,e), as well as the Dempster Highway (Yukon and Northwest Territories)[94–96]. 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)[97], on roads and airstrips in Nunavik (Quebec)[98] and on the Iqaluit airstrip (Nunavut) (FIG. 3f). As a result, in the Northwest Territories, the estimated value of infrastructure at risk owing to climate warming is equivalent to 25% of the value of the assets, with thawing permafrost causing approximately US $41 million (ca. Canadian $51 million) of damage to public infrastructure every year[99]. Similarly, Alaska Transportation and Public Facilities estimate that the state spends US $11 million annually on permafrost-related problems with roads.

Qinghai–Tibet Plateau

About 40% of the Qinghai–Tibet Plateau (incorporating Qinghai Province and Tibet Autonomous Region) is characterized by the presence of permafrost[100]. As in North America, the region is typified by linear infrastructure, including 200,000 km of roads and 3,900 km of railways[101]. For example, much economically and societally important transportation infrastructure has been constructed, including 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.

Climate warming, along with thermal influences from engineering construction, have fostered permafrost degradation, threatening the stability of such infrastructure[39,102,103] (FIG. 3g–i). Embankment damage on the QTH, for instance, is evident on 30% of the total road

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

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

length in permafrost areas[104]. Roughly 85% of road damage is produced by thaw settlement, with the remaining 15% by frost heave[104,105]. Although the QTH has been reconstructed and maintained several times, these actions sometimes result in further damage. For example, the thickness of the embankments was increased between 1991 and 1999, resulting in longitudinal and road shoulder cracks associated with thaw consolidation within roadbed soil under embankments[104–106]. The costs of permafrost-related QTH repairs have been substantial. Between 1991 and 2011, costs totalled ~US $0.7 billion (4.5 billion Chinese yuan), roughly six times the costs for building and paving the QTH during 1950–1954 and 1979–1985, respectively (Q.W., unpublished work). Accordingly, mitigating damage associated with permafrost has substantially increased QTH operation costs, up to ~US $64 million (420 million Chinese yuan) between 1986 and 2007, 1.5 times the total maintenance costs from 1955 to 1985 (Q.W., unpublished work).

On the QTR, which opened to traffic in 2006, embankments have also experienced deformations ranging from 25 to 75 mm per year[103,107] and deformations of 10–160 cm in transition sections between bridges and embankments owing to permafrost thaw and degradation[108].

Projected impacts

To effectively plan and manage future growth in permafrost regions, contributing to sustainable development, both hazard maps (to identify high-risk and low-risk areas for future infrastructure) and economic information (for both maintenance and planning new constructions under warming) are required[109,110]. Hazard maps can be utilized to identify hazardous and thaw risk areas[111–113], or related to infrastructure data to assess infrastructure risks[12] and economic consequences[10,19].

Permafrost thaw risk assessments

The number of geographical hazard assessments in permafrost regions has increased substantially, coincident with an expansion of climate projections[21,26,27]. Most assessments consider hazard areas by the mid or late twenty-first century, acknowledging the relatively short lifespan (often 20–50 years) of infrastructure in the permafrost areas[26,37]. Many of the seminal geographical hazard assessments were based on the exploration of changes in active layer thickness in combination with ground ice content[14,111,112,114]. More recently, however, other environmental factors such as surficial geology, temperature and thaw of permafrost, slope gradient and coastal erosion have been included[45,69,113,115,116].

Permafrost thaw risk assessments exist at circumpolar[12,14,20,114,117] and regional[19,40,45,51,63,111–113,115,116] scales. The circumpolar distribution of high-hazard areas depends on the included environmental factors. If thickening of the active layer and thaw settlement is considered, high-hazard areas occur in the mid and northern regions of the circumpolar permafrost area with abundant ground ice and pronounced climate warming[12,19,20,117] (FIG. 4a,d). If the thaw of near-surface permafrost and loss of structure-bearing capacity is emphasized, high-hazard areas form a 'hazard belt' close to the southern margin of polar permafrost[12,19,20] (FIG. 4b,c,e).

At the regional scale, several regions have been highlighted as having high hazard potential, which must therefore be considered in future infrastructure planning[19,40,111,113,117]. These areas include the Pechora area, the north-western parts of the Ural Mountains, north-west and central Siberia, north-west Canada and yedoma areas of Alaska (FIGS 4 and 5). In Russia, for example, a substantial reduction in the stability of infrastructure on permafrost is expected by approximately 2050, with the cities of Salekhard, Norilsk, Yakutsk and Anadyr estimated to lose, on average, 20%, 30%, 26% and 20% of bearing capacity, respectively, under Representative Concentration Pathway (RCP) 8.5 (REF.[118]). The at-risk Yamal-Nenets region in north-western Siberia is essential owing to its extensive oil and natural gas production fields and high level of industrialization[19].

Infrastructure at risk

Under anthropogenic warming, it is estimated that 69% of residential, transportation and industrial infrastructure is located in areas with high potential for near-surface permafrost thaw by mid-century[12] (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 pan-Arctic infrastructure and 45% of hydrocarbon extraction fields in the Russian Arctic are located in areas where permafrost hazards could jeopardize current infrastructure and future developments[12] (FIG. 5b; Supplementary Fig. 2). Owing to the uncertainties in circumpolar geospatial data sets and statistically based modelling methods, and the fact that the effect of engineered structures on the ground thermal regime was not considered, local errors in the determination of hazard potential are likely[12,117]. Forty-two per cent of the 1,162 permanent settlements will become permafrost-free owing to thawing by 2050 (REF.[59]). Among the settlements remaining on permafrost, approximately 40% are in high-hazard areas[59].

In region-specific risk assessments, the Central Asian mountains (including the Qinghai–Tibet Plateau) had more infrastructure in areas prone to permafrost thaw by 2050 (FIG. 5a), when compared with North America and the other parts of Eurasia (mostly Russia)[12]. For example, more than 90% of the buildings, roads and railways in the Central Asian mountains occurred in areas with high potential for permafrost thaw by mid-century. When considering high-hazard areas (FIG. 5b), Eurasia had, on average, the highest amount of infrastructure elements such as buildings, roads, airports and industrial areas at risk. However, North America and the Central Asian mountains had a clearly higher proportion of railways (more than 60%) in high-hazard areas when compared with the other parts of Eurasia (around 40%)[12].

Economic costs

The sustainable development of permafrost regions urgently requires more detailed assessments of infrastructure costs and risks associated with permafrost

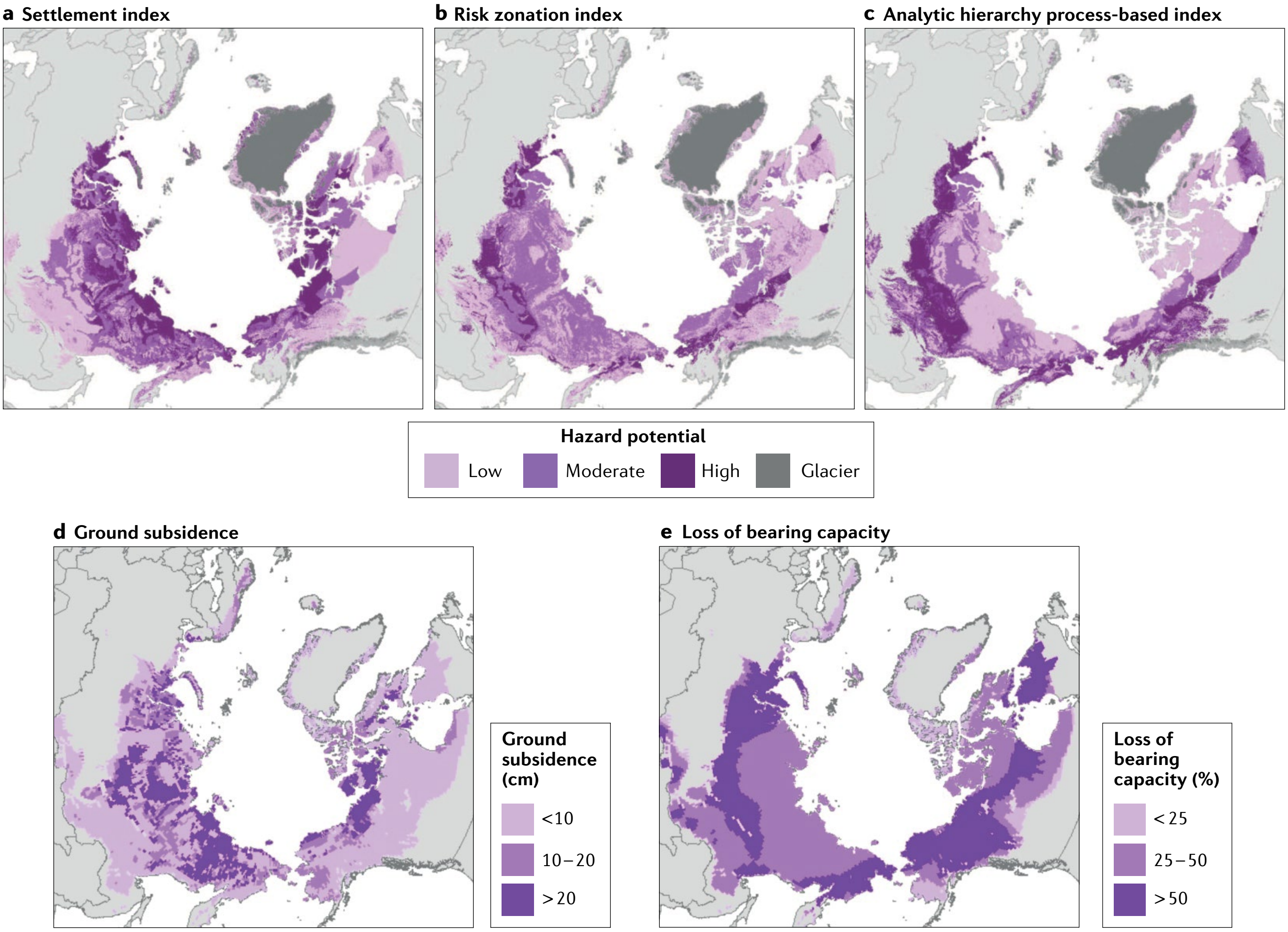


Fig. 4 | **Geography of permafrost hazards across the circumpolar area. a** | Settlement index[117] (relative increase of active layer thickness and ground ice content) for the circumpolar region by the middle of the century (2041–2060)[12,117] under Representative Concentration Pathway (RCP) 4.5. **b** | Risk zonation index[117], as in panel **a**, considering type of surface geology (sediment or bedrock), frost susceptibility of ground material, ground ice content and permafrost thaw potential. **c** | Analytic hierarchy process-based index[117], as in panel **a**, considering ground temperature, ground ice content, relative increase of active layer thickness, fine-grained sediment content and slope gradient[12,117]. **d** | Difference in modelled ground subsidence[20] between 2005–2010 and 2050–2059 under RCP8.5. **e** | Loss of structure-bearing capacity[20], as in part **d**. High-hazard areas occur in mid and northern parts of circumpolar permafrost area or close to the southern margin of polar permafrost depending on the index used. Parts **a**–**b** are adapted from REF.[117], CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

degradation and their impacts on communities and the economy. The only pan-Arctic estimation of the costs of permafrost degradation is focused on critical infrastructure such as roads, railways, pipelines, ports, airports and buildings[20]. The estimated lifecycle replacement costs to maintain infrastructure on permafrost will require US $15.5 billion by 2059 under RCP8.5 (REF.[20]). Linear infrastructure (roads, railways and pipelines) is expected to be the most affected, with pipelines being the most vulnerable. In addition, damage associated with thaw subsidence and a decrease in permafrost bearing capacity is estimated to add an additional US $21.6 billion to those associated with maintenance costs[20]. However, this value is largely constrained by the availability of infrastructure data, especially in the case of Russia.

These costs are further demonstrated with regional analyses[10,37,90,119–124]. For example, in Russia, the total cost of support and maintenance of road infrastructure owing to permafrost degradation from 2020 to 2050 is estimated to reach ~US $7.0 billion (422 billion RUB) for the existing network (no additional development), and ~US $14.4 billion (865 billion RUB) for a modernization scenario incorporating the development goals outlined in the Transport Strategy of Russian Federation, accounting for ~US $0.2–0.5 billion of new infrastructure per year[121]. However, much larger costs of residential housing replacement have also been expressed, totalling US $0.5–0.6 billion per year (30–36 billion RUB) over 2020–2050 (REF.[124]).

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 10–20%, or US $3.6–6.1 billion, by 2030 (REF.[90]). The costs of near-surface permafrost thaw alone reach US $2.1 billion under RCP8.5 and US $1.6 billion for RCP4.5 over 2015–2099 (REF.[10]). In Yukon, nearly 50% of the North Alaska Highway is considered to be highly vulnerable to permafrost thaw and is showing important signs of degradation[94]. The cost to maintain these sections of road is estimated to be eight times higher-than for equivalent sections on stable ground[123].

Mitigation methods

Given the impacts of permafrost degradation on infrastructure, efforts are needed to minimize their effects, many of which have been used in Russia and North America for decades[33]. Considering the impact of climatic warming, several mitigation methods exist to combat infrastructure damage[28,36,125,126]. Different classifications are proposed, such as the North American 'active and passive' classification[33] and the Russian 'Principle 1, 2 and 3' classification[32,40]. Here, the methods will be classified into three main categories: methods that prevent heat intake to permafrost; methods enhancing ground heat extraction; and embankment reinforcement or ground improvement to enhance structural resistance to permafrost degradation[28]. With transportation infrastructure, for example, protection is required by either cooling the underlying permafrost or considering pre-thawing[39,125,127–129]. As will now be discussed, several of these techniques (TABLE 1) have been experimented with, proved to be effective and, in some instances, are now used for large-scale applications across the circumpolar permafrost region for infrastructure mitigation (Supplementary Fig. 3).

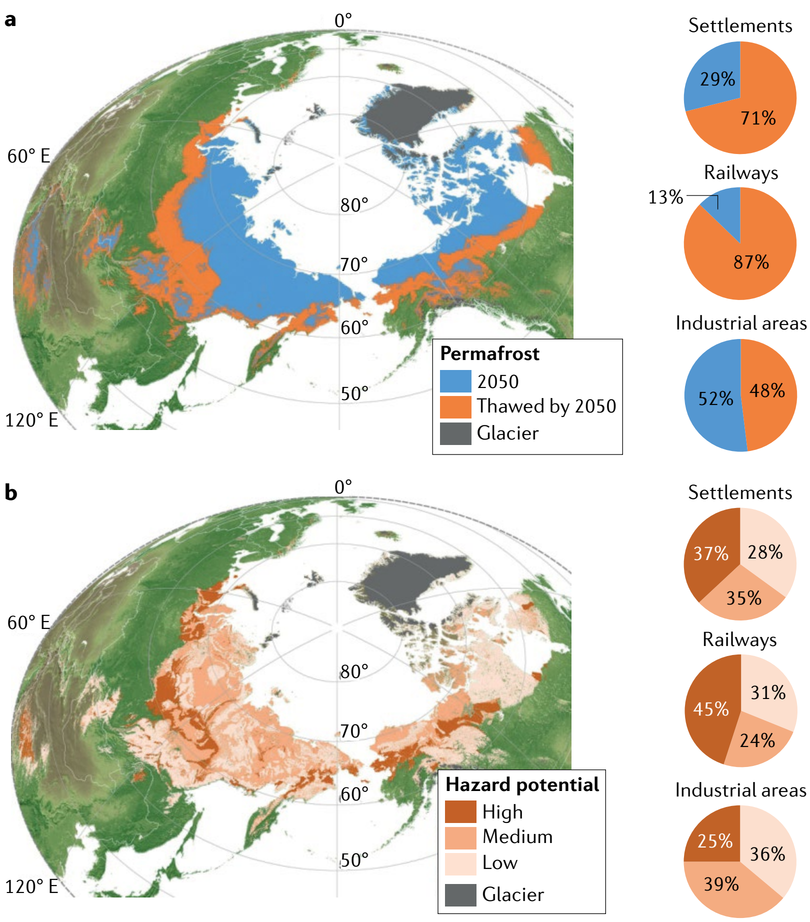


Fig. 5 | **Circumpolar infrastructure at risk by 2050. a** | Map of near-surface permafrost expected to exist (blue) or have thawed (orange) by 2050 based on Representative Concentration Pathway (RCP) 4.5, and proportion of settlements, railway and industrial infrastructure that exist in those domains. **b** | Permafrost degradation-related infrastructure hazard risk, as in panel **a**, as derived from consensus of three different geohazard indices (FIG. 4a–c). Factors considered in determination of hazard potential were relative increase of active layer thickness, ground ice content, permafrost temperature and thaw, surficial ground materials and slope gradient[12,117]. As the effect of engineered structures on ground thermal regime and potential abrupt thaw of permafrost were not considered[12], the presented risk estimates can be conservative. A substantial portion of circumpolar infrastructure is at risk, but the amount depends on the considered hazard factors and infrastructure types (railways at higher risk and industrial areas at lower risk). Adapted from REF.[12], Springer Nature Limited.

Enhancing ground heat extraction

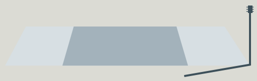
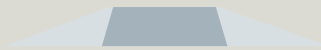
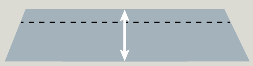
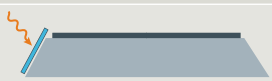
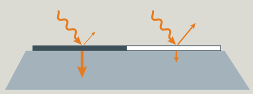
Heat removal techniques have been widely tested, taking advantage of favourable thermal gradients during winter to enhance ground heat extraction[28]. Various techniques exist, including convection embankments, thermosyphons, heat drains and gentle slopes (TABLE 1), which, in most cases, successfully cool the ground during winter.

Air convection embankments. Air convection embankments (ACEs) use a porous stone layer to generate convection within the embankment[28]: upper layers become colder than lower layers, encouraging the creation of convective cells that cause outflow of warmer air. As convection is much more efficient than conduction in earth structures[130], ACEs substantially improve heat extraction during winter. During summer, warm air stays at the top of the layer and cold air at the bottom, and the system becomes dormant. It thus acts as an insulation layer in the embankment. Various forms of ACE layer have been tested and used, including ACE layers across the full width of the embankment[28,131,132], ACE layers applied in the shoulders of the embankments[28,131,132] and a combination of both, referred to as 'U-shape' ACEs[106,125,133–135].

ACEs are used in various regions, including Thomson Drive, Alaska[131], the Alaska Highway[132] and the Puvirnituk airstrip[136], Canada, as well as on the QTR[125,133,134] and the QTH[106] in China[28,133]. Such techniques have proved successful. For instance, on the QTR, embankments with a crushed rock structure can adapt to warming of 1.0 °C[39,134]. In the same location, a U-shaped ACE also successfully lowered the permafrost ground temperature (at 4–10 m depth) by 0.5 °C[137]. Moreover, at Beaver Creek, Canada, an ACE layer 3 m thick across the highway embankment reduced winter temperatures at the contact between the embankment and natural ground by approximately 5 °C[28].

Thermosyphons. Thermosyphons consist of a pipe, divided into two sections, the evaporator and condenser, and pressurized with a working fluid, often carbon dioxide, present in both liquid and gaseous forms[30]. When the condenser section is exposed to low temperatures, changes in pressure cause evaporation of the working fluid along the length of the embedded evaporator section. Heat is extracted from the ground to evaporate the

Table 1 | **Mitigation methods for transportation infrastructure**

Mitigation technique	Schematic	Key mechanism	Impact	Cost[a]
Promote heat extraction during winter				
Air convection embankment (ACE)		Allow convection cells to form naturally in porous embankment materials	Enhance heat extraction in winter	$$$
Thermosyphons		Use evaporation to absorb heat and condensation to release heat in the radiator of a sealed pressurized pipe	Enhance heat extraction in winter	$$$
Heat drain		Allow convective flow in porous drainage blanket inserted in the embankment shoulder	Enhance heat extraction in winter	$$
Gentle slopes		Enhance the laminar flow of wind across the embankment and reduce snow accumulation on slopes	Facilitate heat extraction by reducing snow accumulation on the downwind side of the embankment	$$
Reduce heat intake during summer				
Embankment insulation		Increase thermal resistance within the embankment	Reduce heat intake in summer and heat extraction in winter	$$
Increase embankment thickness		Increase thermal resistance within the embankment	Reduce heat intake in summer but also reduce heat extraction in winter	$
Sunsheds		Reflect solar radiation and prevent snow accumulation on the slope surface	Reduce surface temperature in summer and in winter	$$
High albedo surfaces		Reflect solar radiation	Reduce surface temperature, mostly in summer	$
Improve embankment and soil stability				
Embankment reinforcement		Add horizontal tensile strength to embankments	Reduce lateral spreading and the risk of shear failure in embankments	$$
Induced thaw		Improve soil bearing capacity by controlled thawing and consolidation of a layer of ice-rich permafrost	Strongly reduce thaw sensitivity of embankment soil foundations	$$ – $$$

[a]$, $$ and $$$ indicate low, medium and high cost, respectively.

fluid. The working vapour flows up to the condenser section, where the latent heat is released as it condenses. Heat transfer continues throughout winter, whereas in summer the surface conditions effectively 'turn off' the thermosyphon.

Themosyphons have been used within transportation infrastructures in Russia[138], Alaska[139], Canada[140] and China[141,142]. At the Cheena Hot Spring Road in Alaska[143], three test sections have been monitored, in each case revealing permafrost temperature decreases of up to 3 °C compared with a reference section, and up to 6 m reductions in maximum thaw depth. At a test site along the QTH, vertical thermosyphons have raised the permafrost table by nearly 5 m underneath the embankment slope and by approximately 3 m under the centreline of the embankment[144].

Heat drains. Other techniques such as the heat drain[136] have also been successfully used to enhance ground heat extraction. Heat drains use a highly permeable geocomposite drainage blanket 25 mm thick made of a corrugated plastic core covered on both sides by geotextile, to promote convective heat flow in the embankment shoulder[28]. Natural convection is generated by the density instability caused by air in the drain warmed by ground heat. Warm air tends to flow upwards in the drain and is evacuated by the system outlet. The resulting air movement in the drain sucks cold air through the inlet, which then flows through the geocomposite layer and cools the soil. A slope of approximately 2% in the 'flat' section of the heat drain is required to facilitate convective flow in the drain, whereas a 45° slope in the steep section allows air movement inside the drain while maintaining reasonable construction conditions[28]. The drain is connected at both ends to a chimney system, allowing cold air intake and warm air outflow.

Under a heat drain at the Tasiujaq test section, Canada, the mean annual temperature at the contact of the embankment and the natural ground was reduced by 2.2 °C. Furthermore, at the end of the monitoring period, the permafrost table had risen more than 2 m compared with the reference section[28].

Gentle slopes. Building embankments with gentle slopes can also be considered a technique enhancing heat extraction. In crosswind conditions, slopes constructed

Permafrost table
The upper boundary surface of permafrost.

with an inclination between 4H:1V and 6H:1V will considerably reduce turbulence on the downwind side of the embankment, and thus strongly reduce snow accumulation on the embankment slopes and adjacent ground[28]. Snow accumulation along embankments being a major factor of ground heat retention, gentle slopes effectively enhance heat extraction during winter. A test section with a 7H:1V slope has been constructed and monitored at the Tasiujaq airstrip in Canada[28]. The gentle slope has proved to be the most effective system to cool permafrost and raise the permafrost table by up to 3 m during winter[145]. Indeed, bare gravel could be observed all across the gentle slope whereas the slope of the reference section was covered by 1.2 m of snow. The gentle slope has thus cooled effectively the embankment by approximately 4 °C, 1 m above natural ground compared with the reference section[145].

Other special techniques such as the replacement of embankments by a 'dry bridge' widely used on the QTR to minimize disturbance and protect permafrost[39] can also be considered in special conditions.

Preventing heat intake to permafrost

Methods based on the reduction of heat intake during summer have also been used to protect permafrost underneath transportation infrastructure (TABLE 1).

Embankment insulation. The most common method to reduce summertime heat intake is embankment insulation[146,147]. Placing a polystyrene insulation layer within the embankment structure increases thermal resistance and reduces heat flow to the permafrost in summer. However, the insulation layer also impedes heat loss from the underlying permafrost in winter. The key to successful insulation is thus to place the insulation layer at the end of winter to preserve cold soil conditions.

Embankment insulation is used successfully at several locations in North America, Europe and Asia[146,147], in all cases providing good permafrost protection. For example, at the Inuvik airstrip, Canada[148], long-term monitoring indicates a 1–1.5 m rise in the permafrost table compared with the reference section for insulation thicknesses of 50–115 mm. However, under a warming climate, it is expected that embankment insulation will delay permafrost degradation but will not stop it. Field measurements along the QTH and QTR[146] showed that, with insulation, degradation of the underlying permafrost occurs irrespective of embankment height.

Sunsheds and high albedo surfaces. Sunsheds to protect embankment slopes[127,132,149] and high albedo surfaces to protect paved embankments[147,150,151] have also been used to impede heat intake during summer by intercepting and reflecting solar radiation. High albedo surfaces are used mainly on paved surfaces and sunsheds on embankment slopes. Both techniques have proved to be very effective, as indicated by test sections in Alaska and Yukon (Canada) and on the Qinghai–Tibet Plateau in China. For instance, at the Beaver Creek test site in Yukon, Canada, the summer temperature under the sunshed remained lower than the reference section, with the peak temperature being about 5 °C cooler[152]. In the Qinghai–Tibet plateau, these sunshed effects were more substantial at 8–15 °C[28,153]. When designed properly, sunsheds can also prevent snow accumulation in contact with the embankment slope surface, allowing heat extraction in winter. For example, the winter temperature of the surface under the Beaver Creek sunsheds was approximately 7 °C cooler than the surface temperature of the slopes at the reference section[152], in general providing 311% more cooling in winter and 38% less warming in summer at the ground surface[152]. For pavements with high albedo surfaces, surface temperature reductions typically reach ~1 °C, with permafrost aggradation between 0.5 and 1.0 m[28].

Structural resistance to degradation

In this category (TABLE 1), the intent is to improve soil conditions to mitigate the effect of permafrost thawing or to adapt the embankment structure to improve its capacity to resist the effect of permafrost degradation[28]. Embankments can be reinforced by removing a layer of ice-rich permafrost and replacing it with granular materials with low frost susceptibility, or by including controlled thawing prior to embankment construction. Geotextiles or geogrids are usually used to improve the structural capacity, with the reinforcement layers typically placed between or wrapped around embankment layers to resist embankment spreading or shear failure due to permafrost degradation[28].

Ground improvement by excavation and replacement or induced thawing is often used in permafrost regions but is rarely documented. Passive and active thaw techniques have been effectively implemented at trial plots to thaw permafrost soils in Alaska[154]. Differences between thaw depths achieved with the different treatments have been as much as 40%. Embankment reinforcement has been tested and used to a limited extent in Alaska, Canada and Russia[155–157]. In the case of a reinforced test section on the Inuvik to Toktoyaktuk Highway in Canada, using a combination of field observations and mechanical modelling, a 31% reduction in displacement was obtained when using a wicking geotextile whereas a 15% reduction is obtained using a regular reinforcement geotextile[158].

Combined approaches

Several new techniques have also emerged, specifically the combination of multiple approaches. In the Gong–Yu Express Highway construction in China, for example, an oriented heat-transfer asphalt pavement and a crushed rock structure[142] have been combined, preventing rapid permafrost thaw. Embankments with hollow concrete bricks and ventilation ducts can further effectively decrease permafrost temperature at depths up to 15 m. For example, the permafrost temperatures at 4–10 m depths decreased about −0.7 °C between 2009 and 2011 (REF.[159]). Moreover, numerical models indicate that embankments with a 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 per year[135]. Although these approaches increase the engineering cost, they can well adapt the underlying permafrost degradation driven by long-term warming of climate.

Buildings and other vertical structures

Proper characterization of ground ice content and extent through rigorous geotechnical methods provides great advantages for the planning and the design of foundations for vertical infrastructure. Indeed, good knowledge of permafrost characteristics and conditions is essential to reduce the risk of foundation failure due to permafrost degradation[26,36,160], and allow the selection of the appropriate foundation techniques[36,147,161].

Rapid urbanization and industrialization of Russian permafrost areas revolutionized permafrost research and engineering[162]. One of the most substantial developments was introducing piling foundations (buildings are constructed on elevated piles that are anchored in permafrost) in Norilsk in the mid-1950s[63]. Piling foundations minimize the disturbance of permafrost due to construction and maintain the permafrost temperature through shade provision and snow accumulation protection[163]. Natural ventilation of crawl spaces can be enhanced through passive or active cooling devices, such as thermosyphons. In the Qinghai–Tibet Plateau, a pile foundation is usually used by considering permafrost temperature, ground ice and site conditions[164]. Thermosyphons are used to stabilize permafrost surrounding the piles, if required because of the impacts of climate warming or human activities leading to permafrost degradation[164].

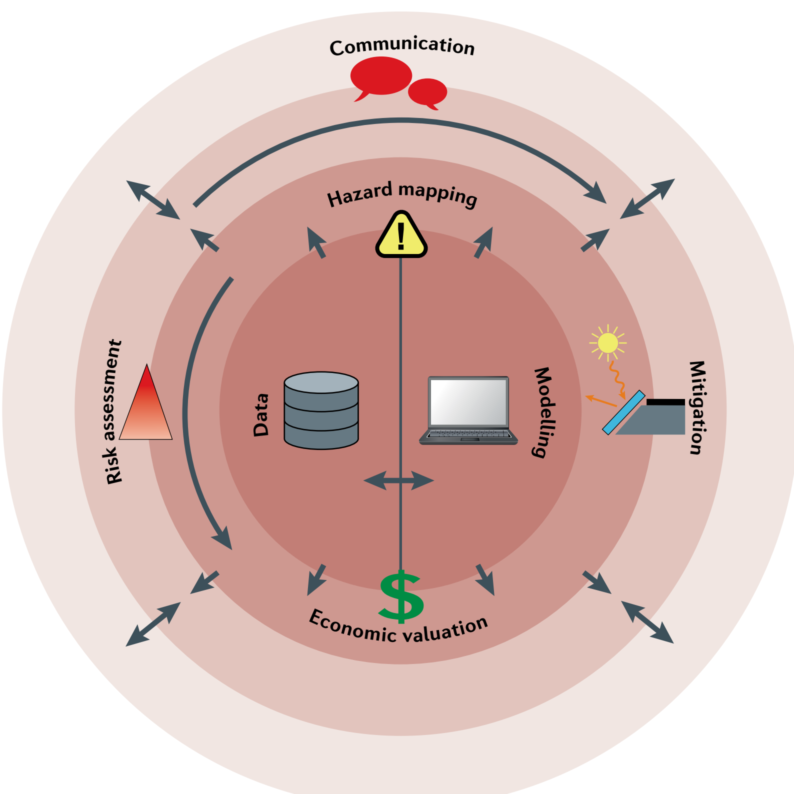


Fig. 6 | **Topics to support sustainable infrastructure in permafrost areas in the future.** Connections between issues that should be considered to secure existing and future infrastructure under climate change.

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[2,14,21,27]. The extent of observed damage is considerable: 10–80% of buildings have deformations in Russian permafrost areas[17,72,74] and up to 30% of road embankments have damage in the Qinghai–Tibet Plateau[104]. This damage is further likely to increase under continued anthropogenic warming, with an estimated 30–50% of fundamental circumpolar and high-altitude infrastructure at high risk by 2050 (REF.[12]). Increasing utilization of natural resources, construction and climate change will also likely compound infrastructure damage. Accordingly, permafrost degradation-related infrastructure costs could rise to tens of billion of US dollars by the mid and late century[10,19,20,121,124]. To effectively cope with and mitigate these effects, several critical developments are required (FIG. 6).

It is important to produce high-resolution geospatial data on climate (air and near-surface temperatures) and ground conditions (ice content). Different data sets 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 data sets need improvements. For example, circumpolar data sets on observed ground ice content and spatial predictions of ground ice would advance permafrost hazard mapping. The spatial resolution of climate, ground ice, surficial geology and vegetation data are also commonly too coarse, or observations too scattered, for high-resolution modelling of permafrost. For local, regional and circumpolar analyses, spatial resolution of ground data should be 1–10 m, <100 m and ~1 km, respectively. Forecasting changes in environmental conditions relevant to permafrost infrastructure is particularly difficult owing to the lack of long-term monitoring data (for example, ground temperatures in human-disturbed environments). Thus, geospatial data-based approaches that enable accurate mapping, monitoring and prediction of fine-scale climate and ground conditions across large spatio-temporal scales require development and subsequent integration into planning and construction methods on permafrost.

Forthcoming construction projects and infrastructure risk assessments would substantially benefit from using high-resolution process-based models of ground thermal regime[165,166]. There is a practical need for bridging the spatial gap between computationally expensive, short-timescale geotechnical models and coarse-scale land surface models. Current model-based approaches that do not explicitly consider engineered structures in their designs are likely to underestimate the timing of future damage. Thus, models that consider the thermal effect of engineered structures would be essential in assessing potential infrastructure damage under climate change[167].

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, make provision for mitigation techniques and perform economic assessments. 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 scales. 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 Norilsk diesel spill[18].

There is also an urgent need for more detailed calculations of the costs associated with permafrost degradation and its impacts on communities and infrastructure. However, the 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 assessments of the economic impacts of permafrost degradation on infrastructure at a circumpolar scale and to justify the cost of mitigation measures.

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 with 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.

More efficient mitigation measures, as well as new design and construction concepts, are further needed to control the thermal impacts of climate warming and engineering construction, especially for discontinuous ice-rich warm permafrost. It is also important to routinely monitor the effects of mitigation measures on the ground thermal regime in different environmental and construction settings. At the same time, new designs are considered to accommodate movement as the permafrost destabilizes, especially for critical infrastructures, for example, bridges, tunnels and large buildings. These creative ideas are critically important for high-speed railways and express highways 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. In particular, scientists need to be more active in distributing data and results for engineers and decision makers. A better dialogue 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.

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