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Permafrost and Climate Change: Geotechnical Implications [and Discussion]

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Permafrost and climate change: geotechnical implications

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The behaviour of the ground in the cold regions of the world is characterized by freezing and thawing. The porous and particulate nature of soils presents conditions for phase change which lead to their unique properties and behaviour in cold climates. Accordingly, the periodic and unstable nature of atmospheric climate and of surface microclimate produces characteristic disturbances in the near-surface layers of the ground in the cold regions. These include the consequences of melting such as subsidence (thermokarst topography) and instability of slopes (landslides, mudflows), as well as the thermodynamic and mechanical effects of freezing, especially frost heave. Frozen soils show temperature-dependent creep (some forms of solifluction and deformation of foundations) and continuing heave (expansion of ground over long periods of time). These effects have important geotechnical implications for the design of highways, airports, buildings and, notably, pipelines. The complexity of the design problems for major structures, especially pipelines, has not been widely understood.

If there is global warming due to anthropogenic emissions of gases this will influence the direction and intensity of the ground disturbances, the nature of which has been recognized over the last three or four decades. However the effects of such warming due to atmospheric climate change will only become apparent over many decades. In the short term they will be masked by other ground temperature changes due to microclimatic effects and to inter-annual variability of climate and weather. Over a period of a century or more, if warming trends continue, there will be important modifications of terrain and physiography.

1. Introduction

Transitions between the solid and liquid phases of water are responsible for most of the properties and behaviour of earth materials which are particular to the cold regions (Williams & Smith 1991). This is of fundamental importance in understanding the consequences of thermal disturbance such as climate change. The transitions do not occur only at the normal freezing point but to several degrees below that temperature. Particle surface forces and capillarity cause the freezing point of the water in the soil to fall as ice forms. The water remaining has a thermodynamic potential such that water moves along temperature gradients both within the frozen soil and in adjacent unfrozen material. Ice accumulates as a result, in the form of segregations in the frozen soil.

These segregations are excess ice, so-called because, when thawed, the water will be in excess of that which the void space of the soil can accomodate. The formation of

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the excess ice gives frost heave. This causes stresses and deformations which disrupt foundations for constructions of all types (see e.g. Johnston 1981, Phukan 1985). Thawing of the ground containing excess ice leads to break-up of roads, slope failures and disturbance by subsidence, of foundations for buildings, pipelines and other constructions. Current research is largely geotechnical in application (Burn & Smith 1993).

Corresponding effects occur under natural conditions giving rise to various forms of slope instability and the development of numerous features of surface relief including small hillocks and mounds and various forms of so-called patterned ground (Washburn 1978).

The creep properties of frozen soil are less well-known than the strength loss associated with thaw but are important particularly where complex structures may be harmed by deformation of frozen ground. The creep properties relate to the ice in the frozen soil. The nature of the bonds between ice and particles and between ice and the unfrozen, adsorbed water are also important (Ershov 1996). As the amounts of unfrozen water change in response to temperature changes or applied stresses, gradients of potential cause migrations of water and associated translocation of ice. The creep properties are highly dependent on temperature, especially in the range from freezing point to −2 °C or −3 °C.

2. Relation of ground temperatures to atmospheric climate

The implications of climate change in the Arctic for constructed foundations of all types, centre on temperatures within the ground and their importance in relation to the characteristic behaviour described above.

Temperatures in the near-surface ground depend broadly on the atmospheric climate but are modified by the complex processes of energy exchange that operate continuously between atmosphere and subsurface. Thus the strictly local surface conditions: vegetation or other cover, topographic form and aspect, and the thermal properties of the soils themselves (Williams & Smith 1991) are responsible for the ubiquitous local variations in ground temperature and, notably, in the mean annual ground temperature.

Once the temperatures for the soil surface have been established, the precise temperature values with depth and time depend essentially on the thermal diffusivity of the earth materials in question. The seasonal (annual) temperature wave moves down into the ground but it weakens with depth, is delayed and reaches only to 15 to 20 m depth or much less if there is a latent heat exchange due to freezing and thawing. Longer-term variations in the atmospheric climate, over decades, centuries, millenia and longer, are transmitted to greater depths, the depth usually being roughly proportional to the square root of time from onset. Permafrost (figure 1) is the condition where ground remains frozen year in year out. It is not, of course, ‘permanently’ frozen – indeed it is the formation (aggradation) and disappearance (degradation) of permafrost that are geotechnically the most important consequences of temperature change. In addition to the excess ice formed by moisture migration, large bodies of excess ice of various origins occur frequently in permafrost. Mean annual ground temperatures (a value less than 0 °C defines the presence of permafrost), commonly differ from mean annual air temperatures by several degrees but the amount varies. Where the ground temperatures generally are around 0 °C permafrost occurs in a discontinuous or patchy fashion.

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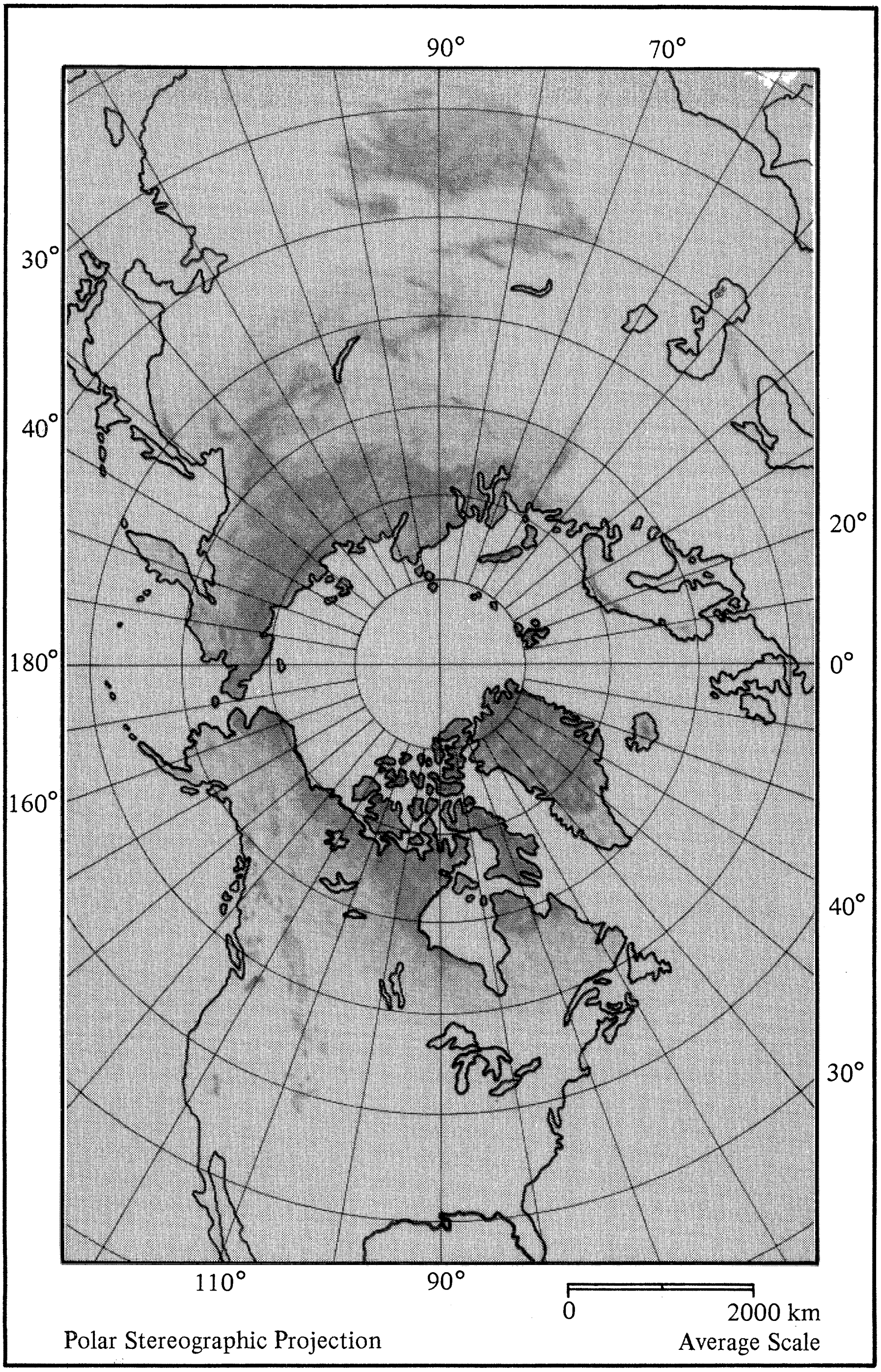

Figure 1. Permafrost in the Northern Hemisphere. The intensity of shading indicates the degree of continuity, the lightest indicating occasional permafrost which underlies only limited, discrete areas in the terrain (from Williams & Smith 1991).

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Summer thawing extends to a depth depending on the mean annual temperature and amplitude of the annual temperature wave in the ground surface. In the absence of permafrost, winter freezing, which extends deeper under colder conditions but rarely to more than a metre or two, is an important geotechnical consideration.

3. Role of microclimatic disturbance

Modifications of the ground surface and its cover, the causes of which may be natural or anthropogenic, disturb the energy balance and lead to compensating changes in ground temperatures. The effects of damaging or removing vegetation, for example, in the permafrost regions, are usually to allow the arrival of more heat to the surface and deeper summer thawing. If there is as a result, sufficient subsidence (consolidation) that standing water occurs, then the thaw process is accelerated still further by the heat-absorbing properties of the water and the increased thermal conductivity of the more saturated materials. When the mean annual temperature of the ground surface rises above 0 °C the permafrost starts to thaw from the surface down and given time, all of the permafrost will disappear. Destruction of the natural vegetation by passage of vehicles is perhaps the classic example of environmental damage in the Arctic. The subsidence and standing water that mark sometimes a single vehicle pass continue to enlarge.

Changes of atmospheric climate inevitably lead to changes in microclimate. For example, heavier snow fall will give a deeper, insulating snow cover and thus higher winter (and thus mean annual) ground temperatures. In areas where the permafrost is discontinuous and relatively warm (within a degree or two of 0 °C) it can be absent where winter snow cover is deeper than elsewhere. Further examples are climate-induced changes to the vegetation cover, modification to wind patterns or to soil moisture conditions, any of which affect the energy balance and thus the temperature of the ground. Conceivably a change of atmospheric climate might lead only to a compensating change of ground temperature (to re-establish the energy balance at the ground surface) but so complex is the ground surface energy exchange, modification of other components as well is to be expected. Koster *et al.* (1994) and Brown (1994) review the extensive literature on climate change in relation to permafrost.

4. Evidence for ground warming

The effects of warming of the ground are easily recognized in the cold regions. The consequences of human activity disturbing the microclimate serve as analogues for natural effects which modify ground thermal conditions and illustrate the nature, extent and rapidity of terrain disturbance. In the absence of surface disturbance by human activity, the origins of obvious warming, whether microclimatic or climatic, are often unclear.

If there are large bodies of ice in the permafrost their melting leads to subsidence and if this is widespread the terrain is referred to as thermokarst. Such wet, irregular and (during its formation at least) unstable terrain covers tens of thousands of square kilometres particularly in the Arctic regions of the former Soviet Union and (although to a lesser extent) Arctic and sub-Arctic Canada. It is reasonable to assume much of this warming was due to a changing atmospheric climate, rather than to local, microclimatic effects.

There are also areas of thermokarst too large to ascribe to purely local microclimatic effects yet which are not so widespread or uniform to attribute them with certainty to global atmospheric effects. They may be the result of climate changes which are less than global in extent and microclimatic effects can also be extensive, as for example, the long-term effects of destruction of vegetation by forest fires (an increased incidence of forest fires may itself reflect climate change).

Mean annual air temperatures have commonly shown increases of 1–2 °C in this century. Temperatures in the ground reflect such changes of atmospheric climate and Lachenbruch *et al.* (1988), for example, describe temperature profiles for Alaska which indicate a 2–4 °C warming at the permafrost surface in this century. Some profiles however indicated that cooling had occurred during the past decade. Meteorological observations on the other hand show that cooling occurred between 1940 and 1960 over much of the State (Osterkamp & Lachenbruch 1990). The somewhat confusing details are similar to what is reported for other locations: attempts to correlate climate history with ground temperature profiles have had only limited success (particularly as depth increases). Furthermore, the irregular distribution of inferred temperature changes suggests that whatever the connection may be with anthropogenic atmospheric pollution, it is not a simple one. Changes in precipitation or other components of the soil moisture regime have various complicating effects considered further below (§ 6).

General circulation models predict larger changes of atmospheric climate in the future although there is considerable uncertainty; Karlén *et al.* (1993) for example, stress the inherent variability of climate through historical time. Relatively conservative prognoses are that global temperatures will increase by 2 °C over the next 100 years with possibly several times that figure for the polar regions (IPPC 1990). If such occurs, similar temperature increases can be expected to follow generally, although not necessarily uniformly, within the ground. There will also continue to be, simultaneously, occurrences of warming of the ground and thaw, due to strictly microclimatic effects, and in fact, microclimatic effects will continue to produce cooling and new freezing in particular situations.

5. Geotechnical consequences of environmental change

In the cold regions, the geotechnical properties and behaviour of earth materials are extremely sensitive to changes in the environment, whether natural or anthropogenic, in a manner without counterpart elsewhere on the Earth's surface. The cold regions extend further than the polar regions, with extensive permafrost at much lower latitudes in interior continental, high altitude situations, e.g. northern China (figure 1). As a whole, the geotechnical problems are amongst the economically most significant aspects of cold climates. In the absence of freezing, temperature changes of earth materials usually have little effect on their geotechnical properties. But at freezing temperatures, especially those close to 0 °C, temperature effects become the dominant design consideration. The effects of freezing or thawing have long been reasonably successfully overcome for most structures by relatively simple but costly engineering procedures (Johnston 1981; Phukan 1985). The worst situations in the terrain will if possible be avoided by relocation of the structure. Replacement of soils at risk from frost heave is widely used, for example in highway and airport construction. A design procedure of using permafrost as a foundation material involves insulation to prevent thawing and the use of piles extending below the depth of any expected thaw. In the last two decades however, new demands have arisen, most notably (both geotechnically and in terms of cost) in engineering for oil and gas extraction and particularly for pipelines (Williams 1989).

Where permafrost is absent, then foundations for buildings, highways, airfields etc. need to be designed to avoid the effects of seasonal freezing only. This extends to a depth of only a metre or two (rarely, somewhat more) and the large ice inclusions found in permafrost cannot occur. A general warming of the ground will reduce the depth and thus is of little concern. A cooling may increase the depth and threaten water mains and other conduits, or the stability of road beds. Such structures are however, often built with a significant factor of safety recognising the uncertainties surrounding the depth of annual freezing.

Permafrost provides a (relatively) stable base for foundations. If however, the mean ground temperature is only just below 0 °C, a correspondingly small increase of ambient temperature will cause thawing-out, which advances downwards and, after some time, very slowly from the base of the permafrost upwards as a result of the geothermal heat flux. Subsidence and loss of bearing capacity cause extensive damage to structures but ultimately the ground should be more stable after the permafrost has retreated.

The permafrost does not have to disappear to provide serious problems. Even in the high arctic, where the mean ground temperature may be −10 °C or even colder, a degree or two rise of the mean annual ground surface temperature will cause an increase in summer thawing of 10 cm or so while in less cold situations the annually thawing layer may increase substantially, to a metre or more. This will disrupt foundations to the extent they are dependent on the bearing capacity of the thawed layer – for example in roads or airstrips. The underlying permafrost hinders drainage weakening the soil.

Recently numerical simulations (Riseborough & Smith 1993) indicate that where the permafrost layer is only some tens of metres thick (that is, its temperature is near 0 °C) there can be large fluctuations (a metre or more) in the level of the top of the permafrost over say, a ten year period. The effect is a consequence of the year by year variability of climate (weather) coupled with the greater conductivity of frozen ground compared to unfrozen. It occurs independently of climatic trends and is an element of the inherent problems of geotechnical engineering in permafrost regions.

If there is a continuing warming, atmospheric in origin, the permafrost will disappear from large areas. During the process the zone of the most unstable, that is, the warmest permafrost will move northwards, bringing difficult geotechnical conditions to areas where, previously, the permafrost was a relatively more reliable foundation material. The possible extent of such changes is considered below (§ 6 and § 7).

The warming of frozen ground (as opposed to its thawing) by reducing its creep resistance, reduces the bearing capacity of piles or other footings in permafrost (Nixon 1990). Thus failures may occur even though the pile is still within permafrost, if the temperature rises to −1 or −2 °C.

A perhaps unexpected result of warming is renewed heaving of the frozen soil at such temperatures because of the higher content of unfrozen water and greater permeability. Indeed, Ershov (1996), Cheng (1983) and Mackay (1988) all describe heaving and ice accumulation occurring while thawing of the frozen ground (proceeding from the surface down) is taking place. Water migrates towards the lower temperatures to freeze there ('continuing heave', § 6), even though the system is undergoing warming. This mobility of water in the frozen soil as it warms is also important in respect to movements of pollutants which are often assumed in geotechnical practice to be contained by frozen soils.

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6. Geotechnical problems for the oil and gas industry

The economic significance of pipelines, their high cost and the special geotechnical challenges such extended structures pose, warrant particular consideration. The most sophisticated geotechnical designs yet required in cold regions engineering are those for pipelines.

Oil pipelines, which are inherently warm, are liable to cause thawing and subsidence. Gas pipelines, on the other hand, may be designed to carry gas chilled to below 0 °C in permafrost regions (to avoid thawing the ground) and are liable to produce further freezing of the soil. As pipelines are normally only a metre or so below the surface, most of the effects outlined above are very important.

The TransAlaska oil pipeline was successfully constructed with the pipe above the ground, supported on steel piles which often contain a self-cooling device (cryosiphon), to avoid thawing ice-rich permafrost. The piles reach to depths of some 6–20 m. The belated recognition of the need for such constructions resulted, however, in a rise in costs of billions of dollars (Williams 1989).

The major difficulty for gas pipelines occurs where the permafrost is discontinuous (meaning that it is absent locally because of microclimatic conditions) and the pipe carrying the chilled gas initiates freezing. At such transitions between previously frozen and newly freezing soil and also whereever there is a change in the type of soil, differential frost heaving occurs. Large-scale experimental studies (Williams *et al.* 1993) with a section of 27 cm diameter pipe modelling these circumstances showed stresses and deformations that indicate the operation of a pipeline could be hampered within a few months of construction. The same experiments showed that heaving (accumulation of ice) occurs slowly in a more than 50 cm thick layer of already-frozen soil (under the low temperature gradients prevailing around the pipe, and the near 0 °C temperatures). This example of 'continuing heave' which could be predicted from earlier studies (Burt & Williams 1976; Miller 1980; Ohrai & Yamamoto 1985 and others), illustrates the source of the high stresses (compare equation (1)) which develop in the course of months and represent the continuing and longer term threat to gas pipelines in frozen ground.

If the ground warms, apart from the displacements that result from complete thawing, both the changes in strength and creep properties of frozen ground and the renewed heaving associated with temperatures rising to near 0 °C can be important. The problems described above arising from differential heave at transitions between frozen and unfrozen soil and between types of soil, will probably be worse if there is a changing externally imposed thermal regime.

Any change causing a modification to the water balance such that soil moisture levels increase, a modification of microclimate, of weather or of atmospheric climate may also lead to increased frost heave. The gradient along which the water moves to the freezing layer where the cryosuctions develop, depends on the water pressure conditions in the underlying layers. Heaving will be greater when the water table is elevated. Even though the extent of soil frozen may be less, the concentrations of ice will be greater and, depending on the structure, are more likely to result in dangerous deformations and stresses.

No major gas pipeline has yet been built in the North American Arctic (essentially because of cost) and Russian experience has not been good. Pipes have been variously overstressed, deformed, lifted from the ground and exposed by erosion following freezing and thawing (figure 2).

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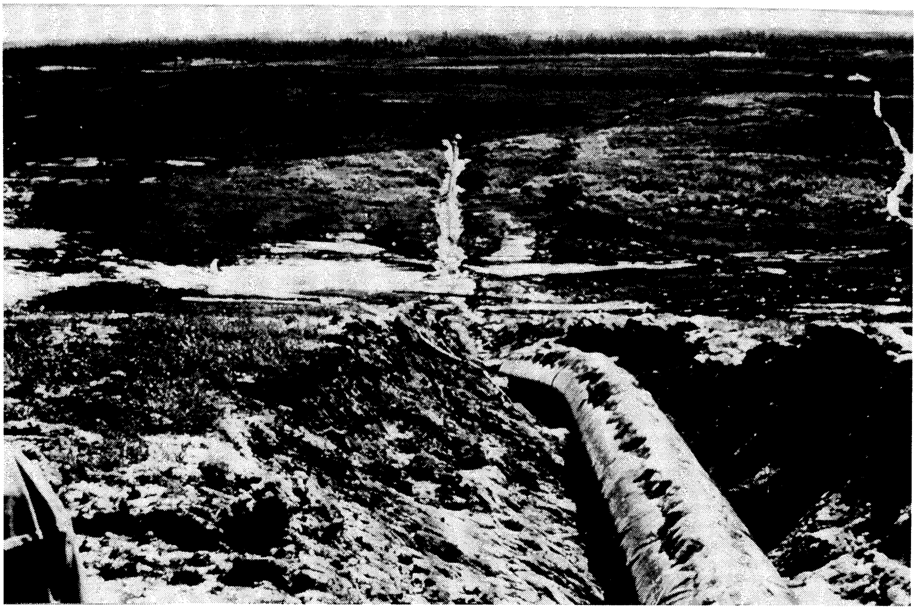

Figure 2. Large pipeline exposed by erosion following freezing, heaving and thawing of near surface layers above permafrost (Siberia). Photograph by E. D. Ershov.

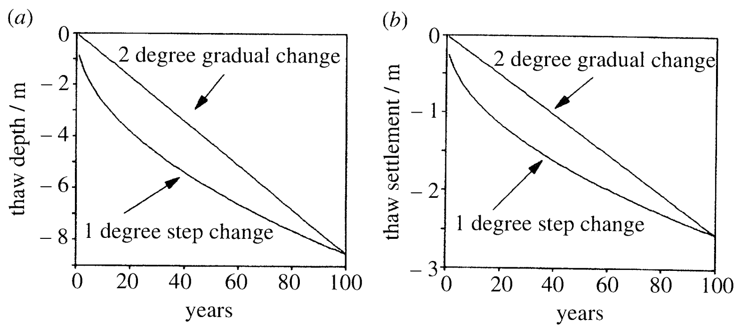

Figure 3. (*a*) Depth of thaw and (*b*) subsidence ('thaw settlement') over 100 years, resulting from a step change of temperature of 1 °C and from a steady temperature rise of 0.2 °C per decade, calculated for soil with 30% excess ice.

7. Relative importance of microclimatic and climatic effects

There are many microclimatic effects, both natural and anthropogenic, which demonstrably cause more abrupt and in the short term greater thaw and subsidence (known as thaw settlement) of the ground than those arising from atmospheric climate trends. This is illustrated by figure 3 which shows the amount of subsidence as a function of time, for two cases: one involving a microclimatically induced thawing, the other thawing due to progressive atmospheric climate change. The microclimatic change is taken to be a step change, for example loss of vegetation cover, which results in a warming of the ground surface, essentially complete within a year or two, by 1 °C (the value might well be greater). A simple approach based on Stefan's equation (Lunardini 1981) was used for the calculations of depth of thaw with the assumption that the permafrost had a temperature of just 0 °C. Although Stefan's equation is not very satisfactory for calculations for specific field locations, it illustrates well the principles involved. Over a century very significant subsidence will have occurred in both cases for ice-rich ground (30% excess ice was assumed) but initially it is much greater for the microclimatic, step change condition. The subsidence becomes equal at 100 years in this example, as a consequence of the assumed values which lead to equal total cooling effects (the thawing index, the product of time and positive temperatures, °C a), for the two cases at that time.

Pipelines usually have an expected operational life of some decades. Over a period of thirty to forty years the effects of warming due to atmospheric climate change are likely to be less than and not easily separable from those due to interannual variability and to microclimate as discussed in previous sections (including those disturbances associated with the construction of the pipeline itself). Thus one can conclude that serious though the soil thermal problems are for pipelines, they are not primarily the result of atmospheric climate change.

Planning for pipelines for fifty or a hundred years hence, however, must take into account the conditions that may prevail at the time. The evolution of the terrain should be an important factor in the timing of pipeline developments for extraction from particular fields. For example, the ice-rich, and relatively warm Yamal area of Russia, already regarded as one of the most difficult, could be considerably more unstable and flooded a century from now and partly below sea level.

8. Long term and extreme scenarios

Because very extensive areas of permafrost have temperatures near to 0 °C, a change of climate which leads to a rise of mean air temperatures of, say, 2 °C, will ultimately cause the disappearance of permafrost from hundreds of thousands of square kilometres of the earth's surface. In mainland Canada (Heginbottom 1994) over 25% of the area underlain by permafrost has permafrost with temperatures warmer than −2 °C. Such permafrost predominates in a broad belt (the 'sub-Arctic') of some 1000 km, south to north, and occurs, decreasingly and more locally, up through the Northwest Territories to the mainland coast. There would be a widespread northward extension in disturbances of the terrain (subsidence, landslides etc.) during the warming wherever the permafrost contained ice in excess of the pore space. Similarly, Nelson & Anisimov (1990) believe that thermokarst formation will be very extensive in Western Siberia and little permafrost left there if the mean air temperature rises 5 °C.

Only with a rather extreme rise in temperature, of perhaps 12 °C, would all the Eurasian permafrost thaw and then only after hundreds of millenia for the deepest parts. But more important is the fact that some 25% of the area has mean ground temperatures of −5 °C or higher (Ershov 1996) and thus would thaw under a temperature rise of that amount. Even small temperature increases of one or two degrees over a century, would eventually have widespread effects and under the more extreme warming scenarios major physiographic changes would occur in that time.

Large quantities of water are held in the permafrost as ice. Although a planned world ice inventory was not completed, it is estimated (Shumskiy & Vtyurin 1963 in UNESCO 1967)) that 0.2–0.5 × 10^6 km^3 or about 1% of the total world volume is held in frozen ground (99% being in glaciers and icecaps). In some regions, 50 to 80% of the upper 20–30 m of the ground is ice. Of this perhaps a third is excess ice which would be expelled as water with corresponding subsidence of the ground when thaw is complete. Vtyrin (1978) concludes that over the greater part of the permafrost area of the former Soviet Union the excess ice content averages out to 1–2 m of thickness. In the far North, notably the Yamal (an important gas extraction region) and northern Sakha regions the figure is 5–10 m. Much of this ice is fairly near the ground surface and would therefore thaw within a century or two (compare figure 3) if surface temperatures increase by a few degrees. A corresponding amount of subsidence would occur and, in many respects, the effects would be similar to those with a rise in sea level, with extensive flooding, coastal erosion etc. Under the more extreme scenarios significant rises in sea level are, of course, also envisaged. The released water should give rise to an increase in river discharge and an increase in landslides, erosion generally and flooding, together with increased sediment loads in the rivers.

Widespread thawing of permafrost may lead to increased release of methane. The complex problems of release of methane, carbon dioxide or other gases under changing near-surface soil conditions are not well understood (Christensen 1991). The breakdown of clathrates has geotechnical implications. These are hydrates of methane which occur at depths of hundreds of metres, in the polar regions, under combinations of high pressure and low temperature (Judge *et al.* 1994). They are both a hazard in drilling operations and a potential source for natural gas. There would generally be a long interval of time (thousands or tens of thousands of years) before a warming at the surface would be transmitted sufficiently to the depths where the clathrates occur, increasing the possibility of a transfer into the gas phase. However there is gas being released currently where marine transgression produced a sudden temperature rise hundreds or thousands of years ago.

Were temperatures to ultimately stabilize at a few degrees higher than present there would be significant positive consequences in those regions lying closest to but outside the (reduced) permafrost regions. These regions would have smaller costs for housing, transportation and infrastructure generally. Also within the coldest parts there would be some benefits. Many marine operations for example, would be favoured by a longer ice-free season (Gerwick 1990).

9. Conclusions

In the Arctic and the cold regions more generally, the thermal-mechanical regime, the stability, of the ground is sensitive to anthropogenic disturbance of two distinct types: direct effects due to disturbance of the natural ground surface and therefore of the surface energy exchange, and less direct effects from changes of atmospheric climate. But analogous processes are occurring naturally and extensively and it can be difficult to distinguish natural from anthropogenic effects.

Ground warming following from anthropogenic atmospheric climate change, as presently estimated, is relatively slow compared to warming due to microclimatic disturbances or in association with interannual variability of climate. Thus for geotechnical constructions such as pipelines (and indeed the majority of structures in the cold regions) the lifetime of which is a few decades, climatic warming does not currently represent a major problem additional to the recognized and geotechnically very demanding, problems of cold climates in general.

Relating to this is an important conclusion from a scientific point of view. Precisely because the near-surface layers in the permafrost regions are so susceptible to temperature change from various causes, they do not, contrary to a more generally held view, represent a sensitive indicator over the short term, of atmospheric climatic change.

Ultimately, if temperatures continue to rise, over the next century, by the predicted values of 2 °C or more, there will be a migration northwards of the areas most affected by terrain instability, through hundreds of thousands of square kilometres. The subsidence, landslides, and loss of bearing capacity will be similar to those occurring at present in regions with extensive warm permafrost and which is the basis of current scientific research for the geotechnical and environmental problems of the cold regions.

Refinements of the global models for predicting future climates are, from the geotechnical viewpoint, less pressing than improving understanding of the ground-atmosphere interface and of the ground itself. Geotechnical problems arising from microclimatic instability are with us now and always will be. If the more extreme climatic scenarios come about, mitigative procedures would have to be applied on a larger scale and in elaborate and extensive construction works to combat effects due to thawing over the next century. Because of the extent and geographical location of ground that will be involved, additional problems of flooding, coastal erosion and river sedimentation etc. will occur. But there will also be ultimately an improvement in geotechnical conditions in areas in which permafrost is no longer present.

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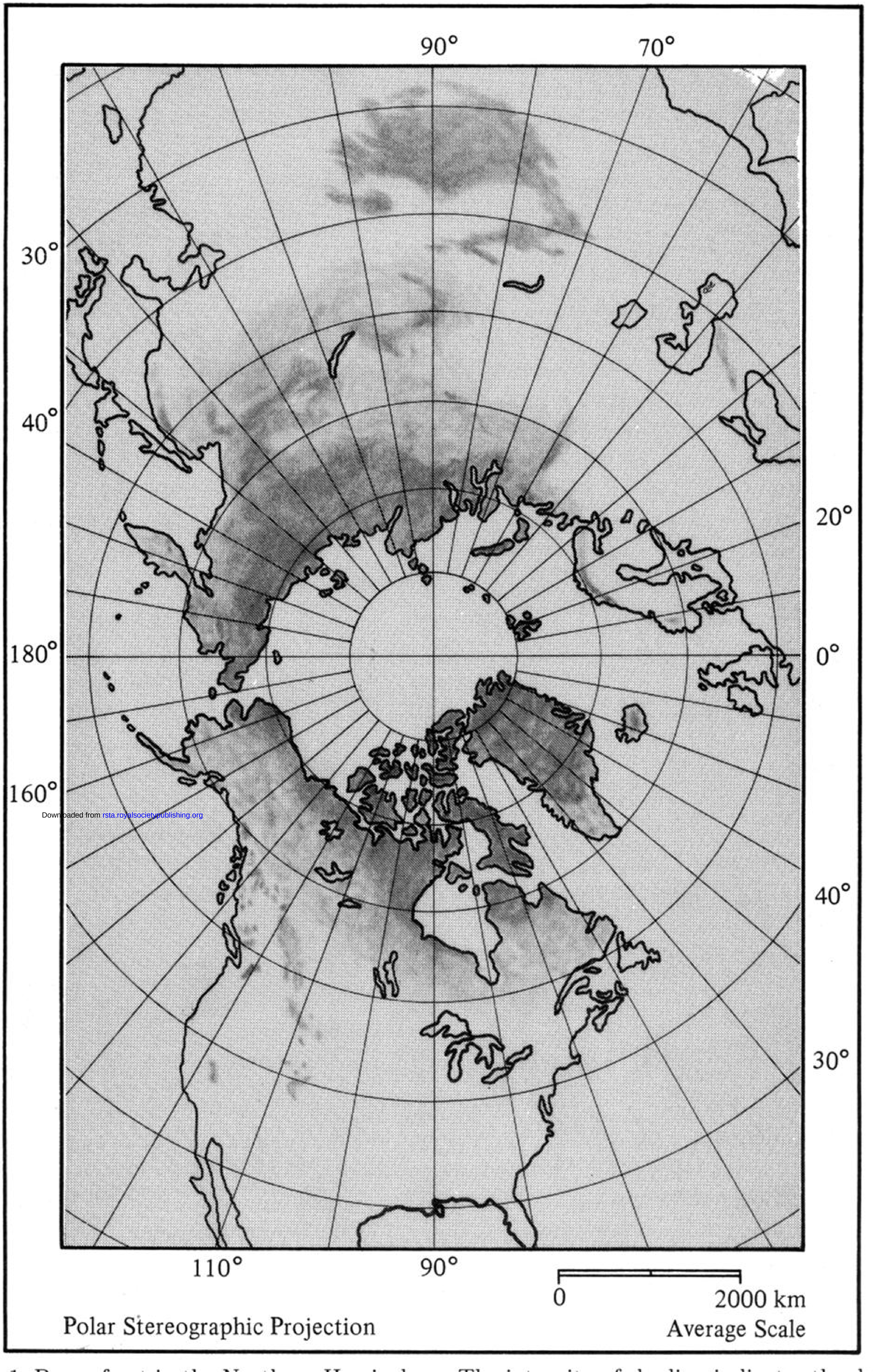
Discussion

M. WALLIS (*University of Wales at Cardiff, Cardiff, UK*). The evaporation from water-logged land decreases air temperatures by around 1–2 °C, comparable to the 2 °C rise considered by Prof Williams. This decrease depends on winds, humidity and boundary layer mixing. So permafrost thawing over 100 km-sized regions would cause more than microclimate changes – e.g. cloud cover and runoff. Emissions of methane are limited via its oxidation by methanotrophizing the water surface layer, and at temperatures close to zero, air-to-water transfer of oxygen is more effective relative to biogeneration: i.e. permafrost swamps will probably generate much less methane than do tropical swamps.

P. J. WILLIAMS. Feedbacks of the kind mentioned by Dr Wallis are complex, numerous, progressive and important especially over decades or centuries. My point, of course, is that geotechnical activity produces microclimatic disturbances which are gross and sudden, if localised, and such effects are crucial in the design of pipelines, for example, even if these are to be relatively short-lived.



igure 1. Permafrost in the Northern Hemisphere. The intensity of shading indicates the degree f continuity, the lightest indicating occasional permafrost which underlies only limited, discrete reas in the terrain (from Williams & Smith 1991).

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gure 2. Large pipeline exposed by erosion following freezing, heaving and thawing of near surface layers above permafrost (Siberia). Photograph by E. D. Ershov.

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