—Plenary Paper—

Recent Advances in Permafrost Geotechnics

S.M. Springman
Institute for Geotechnical Engineering, ETH Zurich, Switzerland
L.U. Arenson
BGC Engineering Inc., Vancouver, Canada

Abstract

Tribute is paid to progress in Permafrost Science and Engineering, from a geotechnical point of view, since the Millennium. Advances and concerns will be presented, embellished with thoughts about geotechnical aspects of the Ultimate and Serviceability Limit State requirements for cold regions infrastructure "Soil Structure Interaction," to be able to answer the challenges posed by climate change on a warming planet. Improvements and new developments have been described, briefly, for laboratory testing, physical and coupled numerical modeling. However, recent research progress in geotechnical aspects has not always permeated into practice, and a fundamental need remains to develop, calibrate and validate fully coupled thermo-hydro-mechanical models. This short review paper does not claim to cover all research and developments and will attempt to summarise topical findings in cold regions geotechnics.

Keywords: field Investigation; laboratory testing; modeling, permafrost engineering; review.

Introduction

This paper was commissioned to focus on geotechnical advances in Permafrost Science and Engineering, which can not be decoupled from the effects of global climate change. This has dominated recent work, as researchers seek ways of identifying the hazards to infrastructure in cold regions (ACIA 2005, IPCC 2007, U.S.A. RCPTF 2003), to establish distinct uncertainties through a risk based consideration of sensitivity and consequences and thereby mitigate the risk of permafrost degradation (e.g., Hayley & Horne 2006).

Reliable climate modeling on a regional scale for 30 to 100 years in the future is essential, as geotechnical engineering should also play an important role in integrated strategies. Designers of new infrastructure or rehabilitation measures wish to guarantee that both Ultimate (failure: ULS) and Serviceability (deformation: SLS) Limit States will be achieved throughout the life cycle of their project. Allowable deformations will be dependent upon the structure concerned. Allowable movements are more restrictive for a machinery hall than for a "flexible" pipeline that can sustain greater average and differential settlements.

Hayley & Horne (2006) condemn broad generalisations, which they comment are misleading. The same is true with geotechnical aspects. Each project must be treated on its own merits, to the level of detail required. Some progress has been made on long term solutions to practical issues relating to "Soil-Structure-Environment Interaction." This paper argues that significant fundamental work still remains to be done on geotechnical issues, and outlines contributions required over the next quadrennial. Examples are cited from mainly northern hemisphere polar and mountain permafrost: from America, Canada, Russia, China and Europe.

The authors recognise early literature on topics discussed herein, and have elected to concentrate on recent progress. References of earlier works are in the publications cited.

The Influence of Climate Modeling

When designing structures, engineers are challenged with forecasting future trends in soil properties over the entire expected lifetime. Since the deformation behaviour and strength of foundations in frozen soils depend on soil temperature (e.g., Arenson et al. 2007a), some predictions are required of combinations of permafrost temperatures, active layer thicknesses, freeze thaw cycles or frost penetration. Ultimately, all these parameters, of which further technical detail can be found elsewhere in this conference volume, depend on the climate and hence geotechnical engineers have to understand the strengths and limitations of climate models. Climate trends predicted by such models not only influence the design method, but also form the basis for site investigations and/or monitoring that has to be performed.

In addition to air temperatures, precipitation strongly influences the ground temperatures, and this has increased in toto over the past century, at a rate of about 1% per decade (ACIA 2005, Instanes 2006). Trends in precipitation are hard to assess because precise measurement is difficult in the cold arctic environment. Snow cover extent around the periphery of the Arctic also appears to have decreased.

The latest IPCC report (IPCC 2007) summarises past permafrost and snow conditions, with temperature increasing at the top of the permafrost layer in the Arctic by ≤ 3°C since the 1980s. The permafrost base has been thawing at a rate ranging up to 0.04 m/yr in Alaska since 1992 and 0.02 m/yr on the Tibetan Plateau since the 1960s. Permafrost degradation is also causing changes in land surface characteristics and drainage systems. Furthermore, snow cover has decreased in most regions, especially in spring and summer. Where snow cover or snowpack decreased, temperature often dominated; where snow increased, precipitation almost always dominated, reflecting the feedback between snow and temperature. Decline in snow cover area in the mountains of western North America and in the Swiss Alps has been greatest at lower elevations.

Even with physical evidence of ground property changes, predicting the future is challenging. Global climate models (GCMs) do not represent permafrost dynamics and potential critical feedbacks on climate. Nicolsky et al. (2007) and Alexeev et al. (2007) evaluate the land surface scheme Community Land Model (CLM3), against observations, and identify potential modifications to improve fidelity of permafrost and soil temperature simulations. Soil thickness should be > 30 m, to compute annual temperature dynamics cycle for cold permafrost. Decadal-to-century time scales require significantly deeper soil layers, e.g., > 100 m.

Vegetation changes and thermal disturbances in lowland permafrost environments due to forest fire activities, lead to increased active layer depth through reduction of the insulating quality of the surface and potentially greater likelihood of instabilities (Anisimov & Reneva 2006, Dyke 2004). This further complicates prediction of future ground temperature trends and hence the effect on frozen soil properties (Yoshikawa et al. 2003).

Site Investigation and Monitoring

The basis of any geotechnical input is an effective mixture of site investigation and monitoring of response to environmental conditions, especially of deformations in conjunction with thermal details. More progress has been made in the latter area than the former recently, although there remains significant potential for in situ tests in fine grained permafrost, in more advanced forms, or as combinations of pressuremeter, cone penetration (e.g., Buteau et al. 2005, with seismic measurement LeBlanc et al. 2004, 2006) or dilatometer testing in order to determine selected soil parameters such as shear strength, small and large strain stiffness for subsequent modeling. Obtaining basic classification data from disturbed samples, without mineralogical or strength testing, is currently the industry standard (e.g., Couture et al. 2000), with thermal properties estimated empirically from earlier consulting reports.

Sometimes, insitu permeability tests may be helpful if drainage conditions in degrading permafrost are relevant. Using probes to determine associated thermal properties is also advantageous (Overduin et al. 2006). However, thermal disturbances due to drilling, or through variations in thermal contact resistance between sensor and soil, make insitu determination of these properties challenging.

Samples must be extracted with minimal disturbance in terms of melting of the frozen phase and rearrangement of soil grains, and protected during transport for storage and subsequent testing in the laboratory for obtaining accurate soil parameters for constitutive modeling (e.g., Arenson & Springman 2005b). While this does not necessarily pose significant difficulties in polar permafrost, inevitably, this is further complicated by altitude and the blocky nature of the soils encountered when dealing with mountain permafrost. Despite additional expense during drilling, further studies are required on natural soil samples under permafrost conditions to investigate responses under selected stress-strain paths, suitable for a slowly warming environment from below to above zero °C (see laboratory testing).

Geophysical approaches are now common for spatial determination of frozen/unfrozen zones (Hauck et al. 2007, Kneisel & Kääb 2007, Maurer & Hauck 2007, Wu et al. 2005, Musil et al. 2002). Tomographic inversion techniques are adopted to reveal ground structure and for monitoring thaw in the seasonal active layer (Hauck et al. 2003, Ribolini & Fabre 2007). The challenge is to determine geotechnical parameters. This is possible through seismic approaches, although the small strain stiffness obtained can not represent stiffness over the entire strain range to failure and particularly less so in a creeping soil. Consequently, adopting geophysical approaches to determine a ground model and associated parameters is not the sole solution.

In parallel with site investigations, it is essential to plan monitoring experiments to deliver optimal data for design decisions, considering geotechnical aspects in conjunction with predictions of the conditions pertaining over the lifecycle. Monitoring should be used for design of a structure and as a part of ongoing observation that regulates future maintenace requirements. A conservative prognosis should be made of lifetime deformations, including surface deformation fields (e.g., Kääb et al. 2007, Kääb et al. 2005) as well as the deformation fields and structure (e.g., Arenson et al. 2003, Hausmann et al. 2007). GTN-P, CALM, PERMOS 2000-4 provide data of standard temperature measurements with depth, and will not be discussed here.

Inclinometers are effective only when they are able to move with the surrounding soil and when a measuring probe is able to pass through the deflecting tubing (Arenson et al. 2003). Shearing of the tube may occur eventually in slopes demonstrating considerable creep. Recent advances have been made by using TDR cables in a rock glacier to locate a concentrated creep zone, but the data are inconclusive, and the magnitude of strains can not be measured. Novel techniques for fibre optic strain measurements in boreholes, are becoming available and might be valuable in the future.

Laboratory Testing

Some recent papers report the mechanical properties of alpine permafrost both in a natural state (undisturbed) or reconstituted from soil particles extracted by “undisturbed” sampling in boreholes (Vonder Mühll et al. 2003, Arenson et al. 2004, Arenson & Springman 2005a). Issues remain about selecting an appropriate laboratory test to represent stress history and path, as well as to allow for sample heterogeneity and size effects. Interface tests have also been carried out on ice filled joints and between active layer and underlying permafrost (Günzel 2008, Rist 2007, Arnold et al. 2005). Additionally, thermal properties are required to be able to carry out integrated “thermo-hydraulic-mechanical” (THM) modeling, although their determination is well established and will not be discussed further in this paper.

Triaxial testing

Triaxial constant strain rate and constant stress tests have been performed on artificially frozen soil specimens as well as samples won from, for example, rock glaciers (Arenson et al. 2004, Arenson & Springman 2005a). Mainly two types of tests were carried out: constant strain rate (CSR) and constant stress, creep (CSC) tests, to study the effect of the volumetric ice-solid-air fractions, temperature, strain rate and also confining stress on the mobilised shear strength.

Peak shear strengths of artificial samples increased with lower volumetric ice content and faster strain rates. Loading conditions influenced modes of deformation and eventual mechanical failure. The existence of significant percentages of air within the frozen matrix changed mobilised stiffness, strength and volumetric response from ongoing dilatancy, interlocking particles, higher stiffness and strength, in conjunction with increasing volume and rubblisation (see Yasufuku et al. 2003, Da Re et al. 2003 for artificial samples with no air) to lower stiffnesses and strength, with ductile contraction (Arenson & Springman 2005a).

Hydrate bearing soils are important because they contain natural gas (energy resource), and function as a source or sink for atmospheric methane, which may influence global warming (Brouchkov & Fukuda 2002). They are suspected to be a potential factor in the initiation and propagation of submarine slope failures (Anuruddhika & Grozic 2007, Nixon & Grozic 2007). Determining geotechnical properties of such "gassy" deposits may prove to be much more important in future. Tomographic imaging techniques (e.g., Calmels & Allard 2004 determined gas content) offer potential for integration into geotechnical laboratory studies on frozen soils. Other recent advances focus on improved methods of examining cylindrical sample response through the entire stress strain range in triaxial compression, under confining pressures as great as 20 MPa, by including small strain measurement (Da Re et al. 2003) or with radial laser measurements (e.g., Messerklinger & Springman 2007).

Interface testing

Arnold et al. (2005) conducted direct shear tests on active layer material from a 38° rock glacier slope (Pontresina-Schafberg), in support of Rist (2007). Significant dilation under low normal stresses was obtained for elongated rough particles excavated within the active zone, mobilising maximum angles of friction > 60°, and confirming that the active layer was stable for insitu conditions. Replacing the bottom half of the shear box with smooth clean ice reduced the interface friction to just over 30°. It is unlikely that such a smooth surface will form during annual freezing and thawing processes at the base of the active layer. Reliable interface friction values will lie between these two limits.

Rist (2007) created an inclinable sled model filled with active layer material to slide on a permafrost surface to investigate the shear resistance and hence to determine an interface friction angle. Grain size and volumetric water content of an artificial active layer and the degree of ice saturation of the permafrost were varied, with the latter proving to be the most important influencing factor. Soil grains embedded in an ice matrix at the permafrost surface increased the mobilised friction angle by 8° compared to a dry permafrost block, without ice. This implies a probable long term decrease of the active layer slope stability in alpine permafrost terrain under warming conditions.

Günzel (2008) carried out direct shear tests on analogue models of ice filled rock joints to determine the temperature dependent strength. She confirmed earlier findings by Davies et al. (2003) that the strength is lowest for temperatures fractionally below 0°C.

Physical Modeling

Physical modeling offers good opportunities to expose mechanisms of deformation and failure in frozen soil and in interaction with structures. Harris et al. (2003) summarise scaled, centrifuge modeling experiments in fine sandy silt, designed to simulate multi cycle thaw-related gelifluction. They concluded, from considerations of scaling laws, that flow was elastoplastic in nature with a "flow" law based on the "Cam Clay" constitutive model for soils, in which frictional shear strength is dependent on effective stress. Response was not time dependent and viscosity controlled.

Stability of model ice filled jointed rocks has been studied in a geotechnical centrifuge by Davies et al. (2003). Warming rock joints through permafrost degradation can lead to increased instabilities and rock fall events in high mountain permafrost areas. This trend was also noted by Gruber et al. (2004) and Gruber & Haeberli, (2007), who studied Alpine rock walls, and Schwab et al. (2003) for rock avalanches in West Central British Columbia, Canada.

A further series of centrifuge tests (Günzel & Davies 2006) was performed with an ice filled joint within a model rock slope, reinforced by rock bolts, and allowed to thaw. The slope was instrumented with thermocouples, displacement transducers and load cells for observation of stress development and movement during the experiment.

The combination of centrifuge experiments and direct shear tests confirmed that warming of ice inside a joint critical to the stability of a slope could lead to slope failure, even if the slope had an initial safety margin of over 200%, when the joint was filled with "cold" ice or was dry. Reinforcing a slope with pre-stressed bolts should be effective, although the bolts would need to be tested regularly in practice in case of loss of tension during joint closure. The findings from these experiments may offer a valuable means of mitigating the consequences of slope failure in high mountain areas, if the thickness of permafrost ice inside a joint can be assessed and measurements of temperature, displacement, and bolt tension are carried out regularly. Validation of these results with instrumented field tests would be most valuable.

Coupled Modeling

Constitutive and numerical modeling

Existing geotechnical models have become increasingly complex as demands to represent specific aspects of soil response become essential when designing to ULS and SLS. Mohr Coulomb approaches based on one value of cohesion and angle of friction are too simplified to account for the effects of temperature, strain magnitude and rate, relative density and opposing effects of dilatancy and crushing.

Various forms of elastoplasticity offer a modeling basis for coupled thermo-hydro-mechanical (THM) response of soils and rocks. Significant improvements are due to long term investment from the unsaturated soil community (e.g., Sánchez et al. 2002, Khalili et al. 2000). Hydromechanical (HM) aspects are well reproduced by critical state concepts of plasticity. Models for surface cracking at low stresses have also been presented in the literature.

Thermal aspects have mainly been related to temperatures > 0°C, e.g., for radioactive waste disposal. Phase change around 0°C is not covered, although applications such as ground freezing offer interesting perspectives. The representation of thawing and freezing under variable groundwater flow regimes is well modelled (e.g., Pimentel et al. 2007). However links to volume change, ice lensing and the related mechanical behaviour are not yet established.

Recent creep modeling (e.g., Haeberli et al. 2006, Arenson & Springman 2005a) is able to represent time dependent deformations, however, imposing a valid failure criterion remains somewhat empirical. Since large strains have a significant influence on the mobilised strength of frozen geomaterials, establishing insitu strain states is necessary when analysing stability of frozen slopes.

While TH modeling has advanced from one up to three dimensions (Liu et al. 2006), more advanced approaches, (e.g., Zhang et al. 2007a, who couple water flow and heat transfer in soil with water phase change) may still only be available in 1D to date. This can be problematical when the prototype "structure" investigated is multidimensional.

Despite new findings from laboratory and field investigations, no novel constitutive relationships have been presented in recent years for frozen soils. Often only one or two dimensional solutions are adopted, when reality is three dimensional. It is no surprise then that limited progress has been made in developing new numerical models. To the authors' knowledge, none exist for practical engineers to couple thermo-hydro-mechanical processes fully. Mostly, only two elements are modelled and used as an input in the third. Future research efforts should therefore focus on such coupling. Realistic risk assessments in permafrost environments due to changing climatic conditions can benefit significantly from simulation of transient conditions under varying boundary conditions that continuously alter thermal, hydrological and mechanical soil properties. It is important to remember that a true risk analysis incorporates the variability in the predictions, which is extremely challenging for cold region climates.

Challenges for continuum analysis methods lie in the inability to model penetration installation effects or to deal with tension cracking and discontinuities. Future advances are expected in discrete element modeling, in conjunction with validation from physical modeling or field monitoring.

GIS-based modeling

GIS technologies are increasingly powerful and have recently been used for risk assessments or as visualisation tools (Giardino et al. 2004, Heggem et al. 2006, Kneisel et al. 2007, Romanovsky et al. 2006). However, they are only as powerful as the constitutive relationships and the risk determination behind the GIS model when they are used for more than visualisation or database purposes. Insufficient information on the complex interaction between the atmosphere and the ground currently limits the area of applications, which would be a helpful instrument for stakeholders and decision makers.

Phenomena

Frost heave

Frost heave presents severe challenges to owners of infrastructure threatened by temperature and groundwater dependent volume change. Segregation potential or the discrete ice lens theory are still used in practice to estimate frost heave. However, ongoing developments in the laboratory are generating opportunities to achieve greater certainty about soil parameters derived (e.g., Konrad 2005).

Côté & Konrad (2007) demonstrate the use of a heat balance model at the freezing front to compute the frost depth and the frost heave as a routine tool for moderately cold regions pavement designs based on the concept of segregation potential. Studies on the influence of fines on the frost susceptibility of base-course crushed aggregates showed that for a given kaolinite fraction, the segregation potential increases linearly with fines content, until the fines create a matrix in which the coarser particles are embedded (Konrad & Lemieux 2005). Uthus et al. (2006) present frost heave data showing sensitivity, with significantly different heave rates for almost equally graded materials. The occurrence of temperature induced vapour flow in a non-frost-susceptible granular material of pavement base layer was studied by Guthrie et al. (2006). Their laboratory tests demonstrated increased water contents, which may lead to frost heave and thaw weakening behaviour typical of that associated with water ingress through capillary action.

Based on freezing tests on small physical clay models tested under 1g as well as in a centrifuge, Han & Goodings (2006) confirm that low permeability clays experience closed freezing conditions that limit the frost heave.

Improvements in measuring techniques led to detailed observations of ice lens formation and driving mechanisms behind frost heave. Water migrated through the frozen fringe from the unfrozen soil towards the warmest ice lens, while colder ice lenses continued to grow without access to the unfrozen zone, because water was sucked from soil beds between ice lenses (Arenson et al. 2006, 2007b).

Application to road pavements has confirmed again from case histories that frost heave contributes to thermal cracking and unstable permafrost (Dunn & Gross 2006, Mills et al. 2006, Doré et al. 2006). The number of freeze thaw cycles combined with precipitation, particularly on low volume roads in seasonal frost areas, plays a role in the vulnerability of this type of lifeline (Kestler 2003).

Impurities within frozen soils may change thermo-mechanical behaviour completely. Hydrocarbons affect soil properties, such as the unfrozen water content (Siciliano et al. 2007), or the permeability of the permafrost and how contaminants spread (Fourie et al. 2007). They change not only contaminant transport but also the frost heave behaviour of a soil, because chemicals may alter the availability of unfrozen water to migrate towards the freezing front. Laboratory investigations and theoretical considerations have demonstrated the relevance of pore water chemistry on frost heave potential and ice formation (e.g., Beier et al. 2007, Vidstrand 2007, Arenson & Sego 2006b, Arenson et al. 2006, Torrance & Schellekens 2006).

Slope stability

Local physiographic landforms will experience different modes of failure in slopes, despite the same temperature change signatures. Thickening of the active layer and subsequent detachment failures, formation of taliks, debris flows, bi-modal flows, retrogressive slumps, deep seated rotational slides are some of the failure modes reported recently by authors in China, Canada and Russia (Chenji et al. 2006, Wei et al. 2006, Lyle et al. 2004, Dyke 2004, Mazhitova et al. 2004). The presence and exposure of massive ice that released moisture into the slope was found to be critical during permafrost degradation.

Wei et al. (2006) also investigated thaw induced gelifluction in cut slopes along the Qinghai Tibet railway. Thaw slump and retrogressive debris flows developed after only one year, causing unexpected damage to the lifelines. Local erosion due to floods, waves or sea ice (e.g., at lake margins or undercutting coastal tundra blocks; Forbes 2004) or the influence of clay and mineralogy should also be accounted for. Dyke (2004) discussed the loss of both thickness and cohesive strength in an ice bonded surface layer that cracked in tension, due to thaw settlement initiating bending in the ice slab.

Such events are episodic and of a spatially discontinuous nature. Future global climatic conditions will influence site-level slope stability and require transcendence of multiple levels of uncertainty and complexity (Huscroft et al. 2004).

As in any unfrozen geotechnical system, pore water is also the critical element in frozen soil mechanics. An understanding of the pore water pressure response in thawing permafrost is key to ensuring the slopes along linear structures such as roads, railways and pipelines, remain stable. Analysis of over 20 years of pore water pressure data from the Norman Wells pipeline suggests that the sites monitored encountered lower excess pore water pressures than expected and that many slopes experienced long-term drainage as the permafrost degraded (Oswell et al. 2007). Likewise, pore pressure changes induced by sea level rise in coastal regions will cause reduced effective stresses and hence lower stiffness and strength.

But also in other permafrost environments, large slope failures, mainly active layer detachments (e.g., Lewkowicz 2007), are observed that may jeopardise engineered structures. In addition, thermal regime changes can cause slope instability to develop so that mitigation measures must be implemented (e.g., Niu et al. 2005). Field studies on solifluction processes, currently ongoing in Svalbard, highlight the correlation between thaw consolidation, reduced effective stress and pore pressures in the active layer (Harris et al. 2007). These data confirm earlier field measurements by Kinnard & Lewkowicz (2005).

Simple decoupled analyses can be carried out using a combination of conduction and convective heat flow caused by water flow in the active layer. Limit equilibrium slope stability analyses can then be used to examine the effect of degrading permafrost and different water regimes on a traditional global factor of safety. However, neither these nor coupled finite element analyses can represent large strain problems close to the ULS and caution is required in the analysis of the results. Back analysis and verification with field mesurements are crucial in the interpretation of such numerical simulations.

Natural convection

Some progress has been made in numerical TH modeling of natural convection in granular soils in cold regions to demonstrate the cooling generated in embankments or heaps of coarse stones (e.g., Cheng et al. 2007, Lebeau & Konrad 2007, Sun et al. 2007, Arenson & Sego 2006). Ventilation properties (He et al. 2007), wind direction (Zhang et al. 2006, Pham et al. 2008) and embankment surface permeability, geometry of slopes, layers and revetments (Klassen et al. 2007, Sun et al. 2007, 2005, Lai et al. 2004) influence the convection potential, and conditions should be optimised to promote cell formation.

Winter convection effects benefit from embankment surface air permeability, and largely eliminate the 0°C horizon within the subsoil, even after a few summer seasons, apart from at the embankment toe. Davies et al. (2003) have already pointed out that temperatures even marginally below 0°C can still be critical. So, geotechnical implications are that stiffness and strength are raised through reduction of the underlying thaw bulb. Settlements and possibility of failure decrease and the embankment system will be more sustainable, with reduced maintenance costs over the lifetime of the structure. However, load transfer inside embankments brings greater loads onto the toes through arching (e.g., Ellis & Springman 2001), coinciding with zones marginally softened by partial thawing. This must be allowed for in predictions of relative settlement (SLS).

Sun et al. (2005) recognise that reality differs from numerical assumptions made, although many simulations are supported by laboratory and field investigations (e.g., Zhang et al. 2006, 2007a, b, Yu et al. 2006, Goering 2003). Indeed, there is some danger in performing numerical experiments without due consideration of geotechnical effects such as abrasion and long term, often cyclic, mechanical and clastic effects in dense, coarse grained fill (e.g., McDowell 2003). For example, compaction is essential during construction to densify the fill and minimise subsequent settlement. This will cause dilatancy on shearing as well as abrasion and crushing of the coarse stone layers and possible cyclic shakedown (settlements) in long term (Festag 2002). This will lead to fouling, whereby smaller particles will trickle down through the voids creating anisotropy, particularly in respect of water and air permeability in the fill, and will block development of the convection cells over the lifetime of the structure. In addition, layers of low air permeability that form during construction change the formation of convective cells, hence the cooling effect of the embankment/pile. Even though innovative solutions might be derived from numerical modeling with adjacent layers of coarse and fine grained material, the fundamental basics of soil mechanics must not be forgotten, such as maintaining filter relationships to prevent internal erosion.

Soil Structure Interaction – SLS & ULS

Soil Structure Interaction (SSI) represents the interdependent reaction between ground and structure, in which both ULS and SLS must be assured. Foundations for typical infrastructure, including linear structures such as pipelines, road pavements, railway beds, communication cables, electrical power lines, or more two dimensional loading problems typical in oil tanks, buildings, airports, embankments, dams, mines, encapsulated landfill sites, are all susceptible to thaw and creep settlement (SLS) and reduced bearing capacity (ULS), under warming planetary conditions, as well as mobility of groundwater (and any related soluble or immiscible contaminants) (e.g., Mills et al. 2006, Mazhitova et al. 2004, Hayley et al. 2004, Cole 2002, Couture et al. 2000). Furthermore, relative or interactive seasonal effects (such as thermal cracking and frost heave, Tighe et al. 2006, frost heave and upheaval of pipelines buried in cold regions, Kanie et al. 2006, Palmer & Williams 2003, or creep of pylons founded on creeping permafrost, Phillips et al. 2007) may threaten the integrity of structures and exacerbate damage.

Mazhitova et al. (2004) call for long term investments in adequate infrastructure in Russia, with consideration of lifetime effects, for oil and gas pipelines, given the potential for serious environmental disasters. Adaptability must also be well thought out, so that design can be enhanced for most vulnerable infrastructure, as geotechnical risk is minimised within an integrated risk approach that considers the entire lifecycle (e.g., Auld et al. 2006).

Solutions that promote improved SSI performance can be described as either active or passive by ensuring the ground remains frozen (e.g., assisted by thermosyphons or thermopiles) or by avoiding, changing or modifying the SSI conditions. Innovative thermosyphon technology that will be operational to 100 m depth, was investigated within a large scale field experiment by Noël & Hockley (2004) and offers tremendous opportunities for future active measures. Managing the effects of thaw in a controlled fashion, or by adding berms to prevent thaw softening developing under the toe of embankments by natural convective air flow are other examples. Numerical modeling confirmed that thermal insulation (e.g., using expanded polystyrene at different embedment depths combined with construction in the cold season, Wang & Dou 2007) can contribute to active measures, although the long term performance at SLS must be guaranteed as well.

Innovative long term solutions are required:

- to place constraints on perennially frozen ground by maintaining a frozen state (Bjella 2006), or
- for structural measures by developing devices to permit superstructures to be realigned on foundations to fulfill SLS requirements (Phillips et al. 2007), or by adopting stabilising measures such as rock bolts and anchors.

Conclusions

Contemporary advances in frozen soil mechanics and geotechnical engineering in cold regions have been described for application to natural permafrost and infrastructure built on or within permafrost. Recent work on field studies, laboratory investigations, physical modeling and coupled simulations are reviewed, in connection with warming planetary conditions, under which permafrost has been recognised as an indicator for climate change. Some phenomena related to frost heave during cyclic freezing and thawing, slope and active layer stability, and convection cooling in coarse granular fill, are discussed within this framework as well.

Urgent need has been identified for ongoing basic geotechnical research in permafrost engineering and science. Investment must be made in site investigations for high risk projects, supported by effective monitoring regimes and advanced laboratory testing to determine key parameters. Challenges were also pinpointed relating to understanding the thermo-hydro-mechanical behaviour of frozen soils and implementing new constitutive relationships into numerical models to represent this behaviour. Physical models, especially those exposed to the correct stresses and environmental conditions, were accepted as providing excellent opportunities for validating and calibrating such codes.

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