Development of a predictive framework for geothermal and geotechnical responses in cold regions experiencing climate change

Développement d'un cadre conceptuel pour les réponses géotechniques et géothermales dans une zone polaire sous l'influence du changement climatique

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ABSTRACT: Cold regions, which are expected to suffer particularly severe future climate effects, will pose very challenging geotechnical conditions in the 21st century involving ground freezing and thawing. Given the uncertainty of future environmental changes and the vast expanses of the cold regions, it is appropriate to address problems such as pipeline or road construction with analytical methods that have multiple scales and layers. High- and middle-level predictive tools are described that integrate climatic predictions from AOGCMs and their down-scaling schemes, geological and topographical (DEM) information, remotely-sensed vegetation data and non-linear finite element analysis for soil freezing and thawing. These tools output broad scale predictions of geothermal responses, at a regional scale, that offer hazard zoning schemes related to permafrost thawing. A more intensive local-scale predictive tool is then outlined that considers fully-coupled thermo-hydro-mechanical processes occurring at the soil-element level and outputs detailed predictions for temperature changes, pore water behaviour, ground stresses and deformation in and around geotechnical structures. Applications of these tools to specific problems set in Eastern Siberia and pipeline heave tests are illustrated.

RÉSUMÉ : Les conditions géotechniques des régions polaires représentent un défi pour le future car ces dernières sont plus susceptibles aux effets du réchauffement climatique, tels que les cycles de gel-dégel. Etant donné les incertitudes existantes concernant les futures variations climatiques ainsi que l'étendue des zones concernées, l'utilisation de méthodes analytiques multicouches est requise pour étudier les problèmes liés aux infrastructures linéaires. Cet article décrit un outil de prévision de haut niveau qui intègre : les prévisions climatiques des AOGCMs, des informations sur la géologie et la topographie (DEM) du terrain, des données sur la couverture végétale obtenues par télédétection et enfin des analyses par éléments finis des cycles de gel-dégel. Cet outil prédit approximativement la réponse géothermique à l'échelle régionale, et découpe la zone étudiée en fonction du risque de dégel du permagel. Un outil plus précis basé sur l'échelle locale est ensuite présenté. Il inclut un modèle avec couplage thermo-hydro-mécanique et prédit plus en détails les changements de température, les variations de pressions interstitielles et de contraintes ainsi que les déformations à l'intérieur et autour de structures géotechniques. Des applications pratiques de ces outils sont aussi présentées.

KEYWORDS: Climate change, permafrost, geothermal analysis, THM-analysis

1 INTRODUCTION

Anthropogenic climate change is expected to impact most severely in cold regions where the ground is currently frozen. Marked air warming may produce undesirable engineering consequences, including permafrost degradation over large areas where rich natural resources are being developed. Infrastructure design in such regions needs to consider how to cope with change through rational approaches that couple climatic, environmental, geotechnical, geological and structural modelling. Scale is a key problem in establishing such links. The powerful earth science predictive Atmosphere Ocean General Circulation Models (AOGCM) work at a much higher level, and over much broader areas, with consequently less spatial resolution than conventional geotechnical analyses. Moreover, the latter need to be relatively sophisticated to give realistic results. It appears infeasible to combine the two approaches directly in any monolithic, unified analysis package.

The present study considered three different scales, cascading predictions from the higher level analyses down as boundary conditions for each underlying tier. The highest-level involves manipulating data from AOGCM outputs, applying statistical and locally informed down-scaling techniques to produce regional climate change predictions. The middle-level starts with engineering geological ground modelling, classifying regions into broad stereotypes informed by local and remote sensing data. Regional climatic predictions are applied to this by using broad scale geothermal analyses to consider thermal changes through potentially great thicknesses of ground, accounting for background geothermal flux, local geology and topography. Annually varying thermal profiles and predictions of permafrost state emerge as inputs to smaller scale fully-coupled Thermo-Hydro-Mechanical (THM) analyses that predict engineering outcomes as ground displacement and/or stress responses to climate change. Such tools allow alternative infrastructure designs and mitigation measures to be assessed so that the most rational development strategies may be adopted.

The research described in this paper was part of a BP funded project to assess cold region climate change impacts. The initial focus was on Eastern Siberia. An interim overview and summary of approach was published by Clarke et al. (2008) while the detailed analytical treatments were set out by Nishimura et al. (2009a and b). This paper provides an updated summary of the project's outputs.

2 HIGH-LEVEL CLIMATIC PREDICTIONS

The study area considered is located in Eastern Siberia. A regional engineering geology evaluation was made first based on desk study data, remote sensing information and limited ground reconnaissance. A set of five stereotypical terrain units was established. Global climate data were derived for the area by considering the full ensemble of predictions from the 17 coupled AOGCM models included in the IPCC Fourth Assessment Report (IPCC, 2007). Their outputs depend on future greenhouse gas emission emissions using the SRES A2 scenario; a standard, marginally pessimistic projection. Statistical assessments were made by a team from Department of Physics at Imperial College to provide multi-model ensemble mean trends for future, seasonally varying, air temperatures (2 m above ground) and mean snow depth. These were compared with the locally observed dataset (ERA-40, from the European Centre for Medium-Range Weather) covering 1958–1998. Corrections were applied to the entire AOGCM ensemble time-series based on the differences between modelled and monthly mean temperatures over the observed period to eliminate model bias.

The AOGCM ensemble outputs were discretised into 2.5° x 2.5° (latitude and longitude) grid blocks, equivalent to ≈150km east-west by 280km north-south blocks in the study area. Ground elevation corrections were applied based on local topography to produce mean monthly air temperature and snow depth time-series, combined with models that described local orographic enhancement of precipitation and solar radiation. More details are given by Clarke et al. (2008) and Nishimura et al. (2009a). These processes led to time-series at set elevation intervals Above Sea Level (ASL) for each terrain type, which were fed directly into the middle-level analysis. Examples for the Rolling Hills terrain unit at 643mASL are shown in Figure 1.

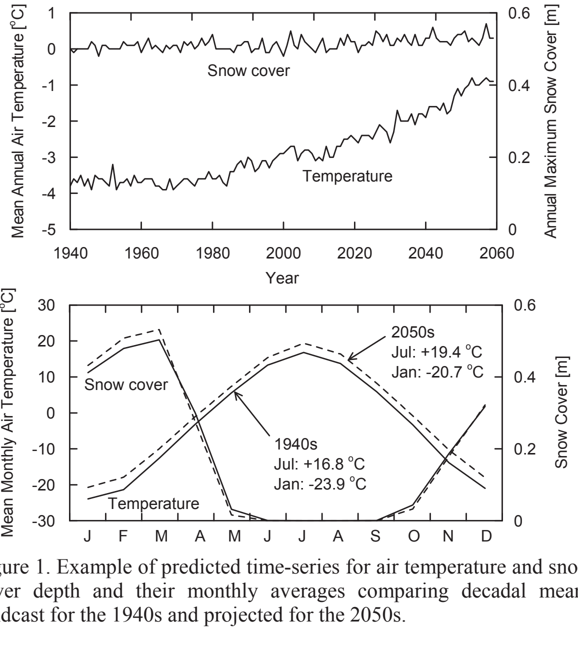


Figure 1. Example of predicted time-series for air temperature and snow cover depth and their monthly averages comparing decadal means hindcast for the 1940s and projected for the 2050s.

3 MIDDLE-LEVEL GEOTHERMAL PREDICTIONS

Horizontal heat flux is likely to be minor compared to vertical flow, except in very steeply sloping locations and other limited localities, so one-dimensional thermal finite element analysis offered a simple and efficient way of computing time-dependent, non-linear, ground responses to climatic changes. Air temperature, snow cover depth and upward background geothermal flux provided the key boundary conditions. However, quantitative analysis also required site-specific geotechnical profiles and topographic information, which is difficult to assign over wide areas involving variable climate and geography. The thermal analyses were therefore set into the broader scheme illustrated in Figure 2 in which a wide range of potential variables were considered analytically. For example, local climatic time-series were generated at Rolling Hills elevations of 343m, 643m, 943m and 1243mASL. Three different porosity-depth profiles were considered for each to represent a spread of stratigraphies. Six different 'n-factors' were assigned to each to defining a spread of the air-to-ground heat transfer efficiencies (Lunardini, 1978) that depend on surface characteristics, such as vegetation type. Finally, two underlying geothermal flux values were set and a total of 144 analyses run to cover the full range of conditions expected. The one-dimensional FE analysis outputs were stored and formatted so that specific information such as temperature at the active layer base (TTOP), temperature at Zero Annual Amplitude (TZAA) or permafrost table depth could be recovered swiftly from the analytical database.

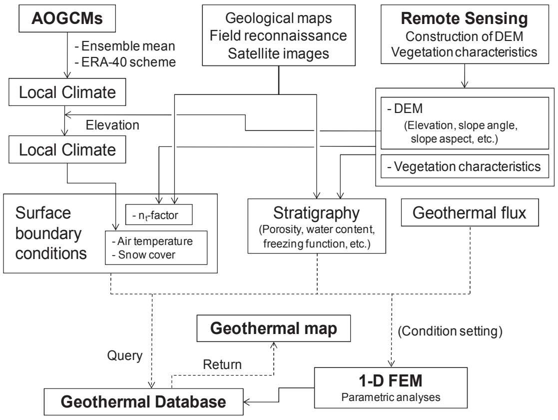


Figure 2. Structure of middle-level analysis to obtain local geothermal predictions based on climate predictions and local geography.

The one-dimensional thermal conduction finite element analysis involved a purpose-written code in which ground profiles were discretised as shown in Figure 3. Strong non-linearity in the geomaterials' temperature-energy relationships and latent heat effects are captured as well as porosity/temperature-dependent thermal conductivity. The conductivity is expressed as a geometric mean of the soil mineral, liquid water and ice components; the unfrozen water content below 0°C was expressed mathematically. The ground conditions expected for the 1940-50 decade were hindcasted by applying the 1940-1950 climate for around 1000 years before this date to obtain a fully stable initial state. From this point onwards the computed 1950 to 2050 climate time series were applied as boundary conditions and the ground response predicted; see Nishimura et al. (2009a) for details.

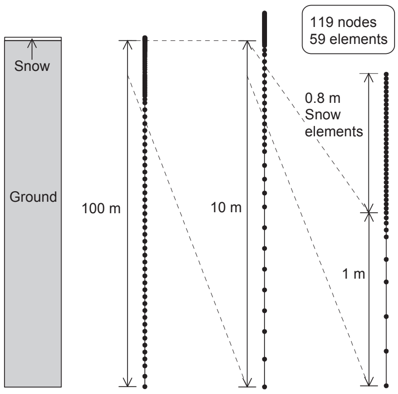


Figure 3. Discretisation of the ground in 1-D thermal analysis: Temperature boundary conditions are applied at different snow elements at different time of a year according to input snow cover depth data.

An example of the computational output is given in Figure 4, showing seasonally transient ground temperature-depth ‘trumpet’ curves for years 2000 and 2050. The climate warming effects are clear, with the permafrost table lowering and permafrost warming; effects are more dramatic near the surface than at depth.

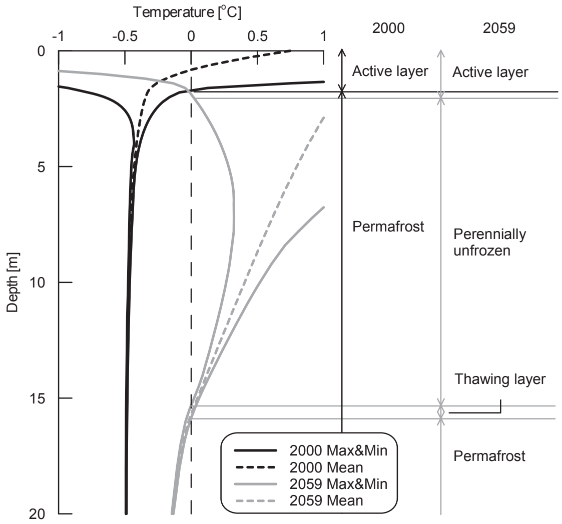
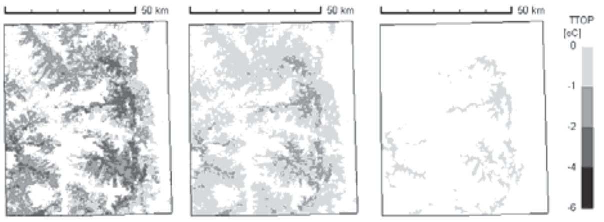


Figure 4. Computed annual temperature profiles for 2000 and 2059; Rolling Hills study area at 643mASL, n-factor = 0.6. Stratigraphy involves 1-m surface layer with porosity 0.4, decreasing to 0.04 at 15m depth.



(a) 1940 (b) 2000 (c) 2059

Figure 5. Example of computed TTOP (annual mean temperature at active layer bottom) for a segment of studied area.

While site-specific geothermal computation is sufficient for small-scale engineering, strategic planning of large scale transport or pipeline infrastructure requires regional geothermal predictions for potentially changing permafrost characteristics. The three level approach generated maps of key parameters. The first step was to integrate primary data from remotely sensed Digital Elevation Models (DEMs) and ground information such as vegetation canopy cover with geological databases. These datasets are established with the aid of site reconnaissance and codified so that a best matching 1-D analysis case could be associated with any given landscape point. Once this correspondence has been made, thermal predictions could be retrieved for the given point from the 1-D analysis output database. Repeating the process and adopting a tight grid over the whole surface area allows maps to be drawn. The first task was to check whether the permafrost distributions predicted between the 1940s and present times matched current geothermal and permafrost conditions. Checks against the regional observations showed that the hindcasts were generally good, adding confidence to forward predictions. Figure 5 presents examples of TTOP maps at three stages of the analysis in a 60km by 80km study area showing clear warming of the permafrost being predicted at higher elevations of the Rolling Hills study area (after Nishimura et al., 2009a).

4 SOIL-STRUCTURE RESPONSE LEVEL PREDICTIONS

The lowest-level analyses aim to predict how soil-structure systems will respond to changing geothermal regimes. These interactions involve coupled physical processes, such as frost-heave in roads and around chilled pipelines, slope instabilities due to ground thawing and bearing capacity losses in piles and shallow foundations due to ground warming. Such problems are most rationally approached by adopting fully coupled THM analyses. The details of the THM model developed for this purpose are described by Nishimura et al. (2009b) and its essence is summarised below.

The broad framework of the proposed model involves the classical THM elements described by Gens (2007): equilibrium of forces; coupled mass and heat conservation; the Clausius-Clapeyron equation of phase equilibrium; permeability and thermal conductivity functions and a variety of models describing non-linear freezing and mechanical behaviour. The state variables include the total stresses, σ, the pore liquid water pressure, P_l, and the pore ice pressure, P_i. A novel feature of the proposed model is its mechanical constitutive mode expressing seamless transitions between frozen and unfrozen states. The mechanical model is developed from the Barcelona Basic Model (Alonso et al., 1990) for unsaturated soils, noting a close analogy between phase interactions in unsaturated soils and frozen soils. By adopting the ‘net stress’, σ-max(P_l, P_i), and the ‘suction-equivalent’, *max*(0, P_l -P_i), a Critical-State type elasto-plastic formulation was made possible while capturing temperature’s effects via changes in these stress variables, as illustrated in Figure 6. The Clausius-Clapeyron equation is the key relationship relating pressure variables to temperature.

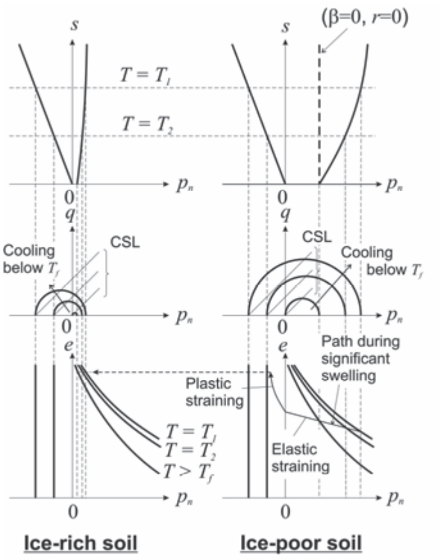


Figure 6. Schematic illustration of yield surface changes according to temperature changes in the newly developed mechanical model

Examples of the model’s predictions for triaxial compression are shown in Figure 7. In the top-left diagram, higher strength develops at lower temperatures, a well-known feature of frozen soils. The stress-paths followed in accordance with the elasto-plastic scheme illustrated in Figure 6, are plotted in the right-hand side diagrams.

Validation of the THM-analysis was performed by simulating the Calgary field tests reported by Slusarchuk et al. (1978) on buried chilled pipelines. Pipes of 1.22m diameter were buried in initially unfrozen silty ground with the invert at 2.0m depth (‘control’ case C) and at 2.9m (the ‘deep burial’ case D). The pipelines were cooled internally from +6.5°C to -8.5°C over 50 days, after which the temperature was kept constant. Figure 8 shows the computed and observed ground

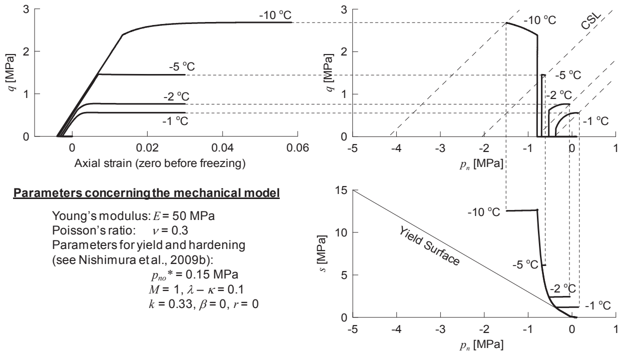


Figure 7. Example of model performance in triaxial compression at different temperatures; see Nishimura et al (2009b).

heave for the two cases, confirming the model's ability to capture the field heaving behaviour. The values of input parameters and the processes of their determination are described by Nishimura et al. (2009b). The control case was simulated with two different scenarios for the air temperature; it was set either constant at +6.5°C, or varied monthly, oscillating between +16.5°C in July and -8°C in January.

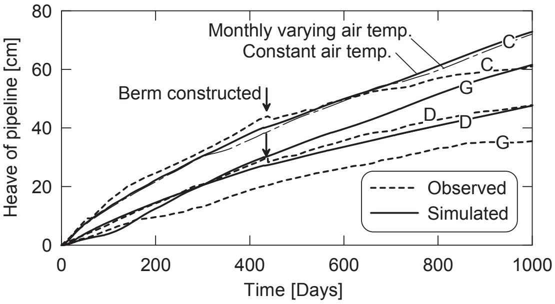
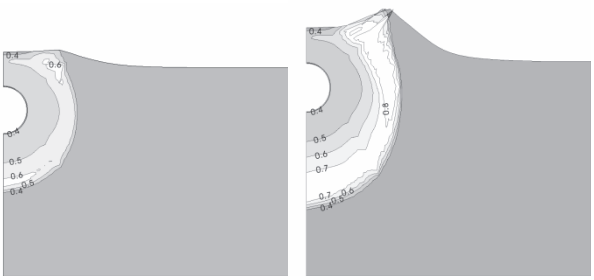
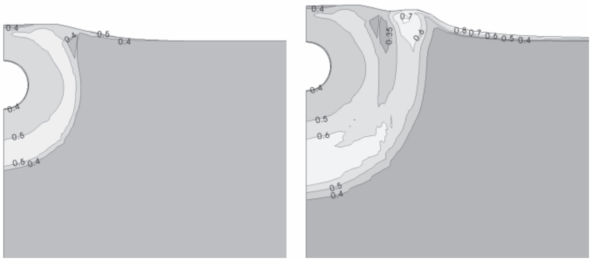


Figure 8. Computed and observed heaves of pipelines: Observation data from Slusarchuk et al. (1978). The 'G' case is a gravel-matted case; see the original literature for details.



(a) Const. temp.: Day 300 (b) Const. temp.: Day 1000



(c) Varying. temp.: Day 300 (d) Varying. temp.: Day 1000

Figure 9. Computed geometry changes and porosity distributions.

The difference in the air temperature boundary conditions affected the surface movement patterns, as shown in Figure 9, despite the limited effect on overall pipe heave. Maintaining a fixed temperature difference between the ground surface and the chilled pipeline resulted in excessively large heave away from the centreline and movements that could not be considered reliably by the model's small-strain formulation. In the case with monthly variable ground surface temperature, surface freezing during winter disrupted the frost heave and permitted a more stable expansion of the frozen zones. The porosity distribution shown in Figure 9 indicate highly dilated, ice-rich areas around the pipeline, created by the influx of water drawn in by the 'suction' P_l-P_i,. The Calgary dataset allowed a critical validation of the-THM model's realistic performance. Inputting longer-time, transient future local climatic/geothermal trends from the middle-level analyses would allow the THM analyses to predict the site-specific soil-structure response against expected climate change.

5 CONCLUSIONS

A multiple-level analytical framework is proposed for predicting soil-structure responses to climate change in those cold regions where permafrost degradation plays an important role. The framework places climate prediction at the highest global level, and applies AOGCM data that is downscaled and calibrated against local climate datasets. The next level combines engineering geology with non-linear 1-D modelling to generate extensive analytical databases from which regional geocryological maps may be created that both inform hazard mapping and strategic planning of extensive infrastructure. As well as providing a middle-level screening tool, the geothermal analysis can set the conditions for lower-level, site-specific engineering analyses. A new THM-model with a novel mechanical constitutive model has been proposed to help predict the complex soil-structure interactions expected as temperature changes encourage permafrost warming and degradation. The mid-level approach was checked against regional geothermal maps in Eastern Siberia, while the THM analysis was tested against field tests on chilled pipelines in Canada, confirming the predictions to be realistic in both cases.

6 ACKNOWLEDGEMENTS

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