General Report TCs 307+212
Thermal Geomechanics with Emphasis on Geothermal Energy

Rapport général TCs 307+212
Géomécanique thermique avec une attention particulière portée sur l'énergie géothermique

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ABSTRACT: Thermal geomechanics is an important area of soil and rock mechanics, and has applications in important areas related to sustainable development like energy extraction and storage, waste containment, forest fire, explosions in soil, and climate change. In this general report, a brief overview of thermal geomechanics is presented in the context of the papers allocated to the thermal geomechanics session of the 18th ICSMGE. A review of these papers is provided in the report. The topics covered by the papers can be broadly grouped into two sub-themes: thermal geomechanics and geothermal energy. The papers in the thermal geomechanics category focussed on the fundamental thermo-hydro-chemo-mechanical behavior of soil and rock while the papers on the geothermal category emphasized the application of thermal geomechanics in geothermal energy extraction through ground-source heat pumps and energy piles.

RÉSUMÉ: La thermogéomécanique est un domaine important la mécanique des sols et des roches avec des applications dans des domaines importants liés au développement durable, comme l'extraction et le stockage d'énergie, la maîtrise des déchets, les incendies de forêt, les explosions dans les sols et le changement climatique. Dans ce rapport général, on présente un bref aperçu de la thermogéomécanique basé sur les articles acceptés à la session correspondante du 18e CIMSG. Un examen de ces documents est présenté dans le rapport. Les sujets abordés par les articles peuvent être regroupés en deux sous-thèmes: thermogéomécanique et géothermie. Les articles de thermogéomécanique fondamentale sont consacrés à la thermo-hydro-chimio-mécanique des sols et des roches, tandis que les articles de géothermie traitent des applications de thermogéomécanique dans l'extraction de l'énergie géothermique par pompes à chaleur géothermiques et pieux énergétiques.

KEYWORDS: thermo-mechanics, geothermal energy, energy pile, sustainability, renewable energy, thermal conductivity.

1 INTRODUCTION

The 18th ICSMGE is being held at an interesting time of shifting paradigms at the backdrop of global climate change, economic downturn, population growth, advocacy for renewable energy use, and natural hazards. These factors have made governing bodies all over the world rethink the ways of day-to-day business, and the rather recent emphasis on sustainable development, that advocates a triple bottom line approach of balancing environment, economy and social equity, is an obvious outcome of such efforts. Consistent with this approach, the geotechnical profession has been motivated by the mantra of 'achieving maximum utilizing minimum', which is particularly important because the profession lies at the interface of the natural and built environments, and can significantly influence the economy, society and environment. Extraction of renewable energy, safe disposal of wastes, construction and maintenance of civil infrastructure and lifelines, and security against natural and man-made hazards are some of the far-reaching areas that geotechnical engineering contributes to, and this report on thermal geotechnics and its applications is, in part, a testimony of the variegated efforts that geotechnical engineers have put in towards sustainable development of civil infrastructure.

Thermal geomechanics is an important topic related to sustainable development. Heating and cooling of buildings using geo-structures like piles, walls and slabs, in situ burning of oil spill, oil recovery from reservoirs at high pressure and temperature, underground disposal of nuclear wastes, explosion on or inside the soil mass, forest fire, and global climate change affecting the freeze-thaw cycle of permafrost are some examples which may cause the soil temperature to vary from around −40°C to 300°C or more. It is well documented that temperature fluctuations have an effect on the soil strength and stiffness as well as on the pore pressure development. With an increase in temperature, the initial shear modulus and compressibility of clay increase and the drained and undrained shear strength decrease. Therefore, temperature fluctuations in soil may affect the stability of the civil infrastructure. Differential settlement of buildings due to heating and cooling using geothermal piles, changes in groundwater flow patterns and groundwater advection caused by geothermal heat pumps, temperature-imbalance induced seismic activities, distress in underground pipelines due to freeze-thaw cycles, debris flow and landslide are some examples in which the civil infrastructure is negatively impacted by alterations in soil temperature. It is thus imperative that research efforts are made toward understanding soil and rock behavior influenced by temperature change and heat flow.

An important application of thermal geomechanics is extraction of geothermal energy. Geothermal energy is a clean and renewable form of energy that is extracted from the deep and near-surface soil and rock strata by various means. Shallow geothermal energy is commonly extracted using ground-source heat pumps (GSHPs) from the shallow depths beneath the ground surface where the temperature remains stable within a narrow range of 7°-21°C. A GSHP typically consists of a heat pump, an air delivery system, and a heat exchanger, and uses the ground as a heat source and sink in winter and summer, respectively, to heat and cool buildings (Hughes 2008). Although several research studies have been performed on geothermal heat pumps, most of these studies focused on the thermal and thermodynamics aspects. It is only recently that the importance of the thermo-mechanical behavior of soil has come to the fore, particularly in the context of geothermal energy piles, which are now commonly used in some European countries to perform the dual role of supporting buildings and extracting shallow geothermal energy (Brandl 2006, de Moel et al. 2010). The thermo-mechanical stresses induced in the energy pile and the surrounding soil affect the pile-soil interaction and alter the pile capacity. Therefore, several research studies investigating the thermo-mechanical behavior of energy piles have been initiated in the recent past. It goes without saying that the practice of extraction of geothermal energy through heat pumps, pile foundations and other geo-structures can significantly reduce the use of fossil fuel and carbon dioxide emission, and is therefore an important part of sustainable geotechnical practices.

As mentioned previously, there are several applications of thermal geomechanics other than geothermal energy extraction, an important one being deep injection of nuclear wastes. For all these applications, it is important to understand the relevant thermo-hydro-chemo-mechanical behavior of soil and rock, and relate the fundamental behavior to the corresponding applications. Thus, studies related to thermal geomechanics can be classified into (i) study of elemental soil and rock behavior through laboratory tests and constitutive model development, and (ii) study of the applications using centrifuge and field experiments, and through theoretical modeling of the corresponding boundary value problems.

This general report provides a review of 18 papers related to thermal geomechanics that are accepted for publication in the proceedings of 18th ICSMGE. The topics covered by these papers can be grouped into the following broad areas: (i) thermal geomechanics, and (ii) geothermal energy. As the general theme in all these papers is closely linked with sustainable development and a few papers deal with geothermal piles, these papers were assigned to the Sustainability (TC 307) and Deep Foundations (TC 212) committees of ISSMGE with the responsibility of organizing a discussion session and producing a general report based on these papers. In the following section, a summary of the papers is provided and the salient information put forward by each paper are outlined.

2 REVIEW OF PAPERS

2.1 Thermal geomechanics

This sub-section includes the papers that describe the fundamental thermo-hydro-chemo-mechanical behavior of soil and rock through experimentation and modeling studies. Eight papers focus on this fundamental aspect of thermal geomechanics.

Tsutsumi and Tanaka studied the consolidation behavior of clayey soil under the combined effects of strain rate and temperature using a constant rate of strain (CRS) loading apparatus (Figure 1). The CRS apparatus was built based on the Japanese Industrial Standard (JIS) A 1227 (2009) and holds soil specimens with a diameter of 60 mm and an initial height of 20 mm. The water pressure was measured by connecting the bottom of the specimen to a transducer. The soil specimens were subjected to a back pressure of 100 kPa for ensuring full saturation. The displacement was obtained by counting the number of revolutions of the step motor and correcting for the deformation of the apparatus system. The displacement values were used to calculate the nominal strain, void ratio and nominal strain rate. The tests were conducted on reconstituted Louiseville clay samples (collected from Louiseville, Quebec, Canada) at temperatures varying between 10°C and 50°C with strain rates varying over 3×10^{-6} s^{-1} to 3×10^{-8} s^{-1}. Tsutsumi and Tanaka observed that the clay hydraulic conductivity was strongly dependent on temperature, that the preconsolidation stress decreased with increase in temperature, and that the viscous behavior disappeared with decrease in the void ratio (Figure 2). The authors also examined the ageing effects of the clay samples and inferred that it was caused by the acceleration of secondary consolidation wherein the clay particles are rearranged closely because an increase in temperature reduce the viscosity of the adsorbed water layer on the surface of the soil particles. Thus, the specimen developed a new structure exhibiting higher stiffness against subsequent loading.

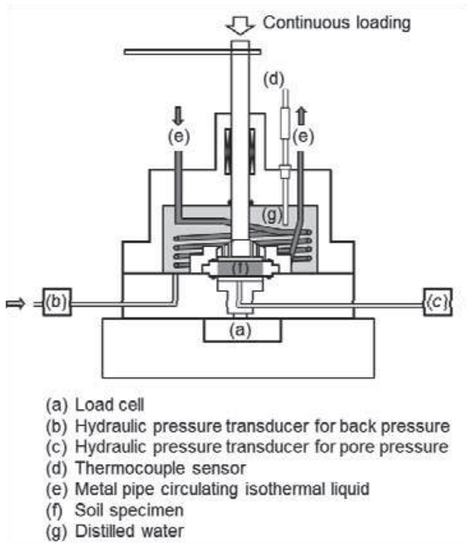


Figure 1. A schematic view of CRS testing apparatus for controlling temperature (Figure 2 of Tsutsumi and Tanaka).

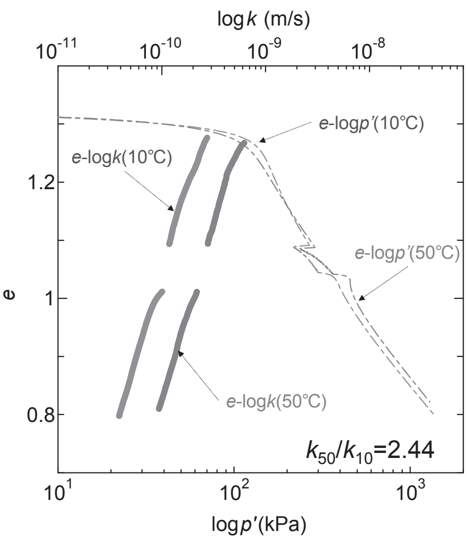


Figure 2. Variation of hydraulic conductivity k with void ratio e and effective stress p' (Figure 4 of Tsutsumi and Tanaka).

Zihms et al. described the effect of high temperature on soil properties. Soils are subjected to high temperatures due to several natural and man-made processes including wild fires, forest fires, and thermal remediation technologies. High temperature affects the particle size distribution, mass loss, mineralogy and permeability of soil. In sandy soils, the particle size decreases with increase in temperature because of mobilization of fines. In clayey soils, the overall particle size increases with increasing temperature owing to aggregation and cementation of the clay fraction. The authors studied the effects of moderate and high temperatures and of smoldering on soil properties and used the results to determine the changes in the soil composition due to temperature change and to predict possible complications that may arise during or after the remediation treatments. Both kaolin clay and its mixture with silica sand were tested, and it was observed that high temperature affects the shear-, plasticity- and infiltration-related soil characteristics. Zihms et al. recommended that more testing should be done to better understand the high-temperature effects on natural materials.

Monfared et al. presented an experimental work on the thermal pressurization of Boom clay, a host geologic formation for potential radioactive waste disposal in Belgium. Undrained heating test was performed under in-situ stress state conditions using a recently developed hollow cylinder triaxial apparatus (Figure 3) that offers a short water drainage path out of soil samples making it favorable for testing low permeability clay and claystone samples. During the heating phase, the thermal pressurization coefficient was determined from the change in pore pressure and the undrained thermal dilation coefficient was calculated from the measurement of volume change. Subsequently, a cooling phase was induced under drained conditions that allowed the determination of the thermo-elastic dilation coefficient. The parameters identified from the tests are important for modeling the thermal behavior of clay at the radioactive waste disposal site.

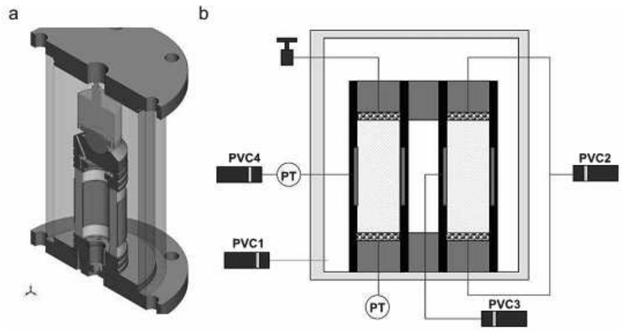


Figure 3. Schematic diagram of hollow cylinder triaxial apparatus (Figure 1 of Monfared et al.).

The study by Romero et al. also involves Boom clay. They investigated the thermal and hydraulic behavior of Boom clay by performing heating pulse tests on intact borehole samples using an axisymmetric and constant volume heating cell (Figure 4) with controlled hydraulic boundary conditions. The study focussed on the time evolution of temperature and pore pressure changes along heating and cooling paths including pore pressure development during quasi-undrained heating and subsequent dissipation according to the applied hydraulic boundary conditions (Figure 5). Romero et al. also performed a coupled thermo-hydro-mechanical (THM) finite element analysis to determine the thermal parameters by back-analysis and then to simulate the experimental results. The study helped in the identification of the main features of the hydro-thermal coupling under test conditions.

Low et al. focused only on the thermal aspects and described two methods to measure the thermal conductivity of soils. They compared the performance of two laboratory-test equipments: the thermal cell which uses a steady state method, and the needle probe which uses a transient method (Figures 6 and 7). Both the methods have their advantages and disadvantages. The needle probe provides results quickly, and hence, is not affected by moisture migration during testing. The thermal cell, on the other hand, requires longer time, and hence, the results from the thermal cell may be affected by moisture migration during testing. The authors performed the tests on London clay samples with the intent that these measurements will help in the analysis and design of energy foundations. They noted that the thermal cell approach is probably more suitable in the context of energy foundations as it can be used to measure the thermal conductivities of other relevant materials such as grout and concrete.

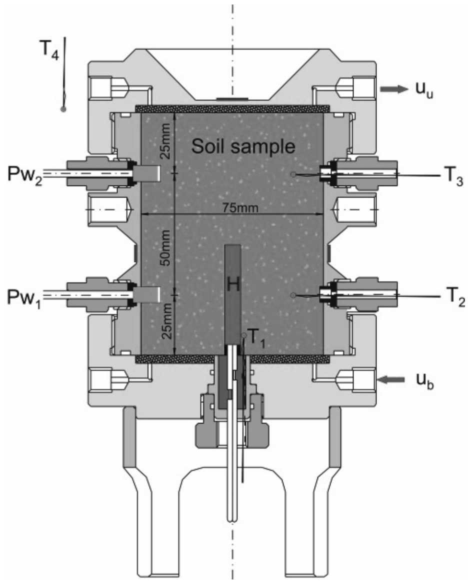


Figure 4. Axisymmetric heating cell and transducers (Figure 1 of Romero et al.).

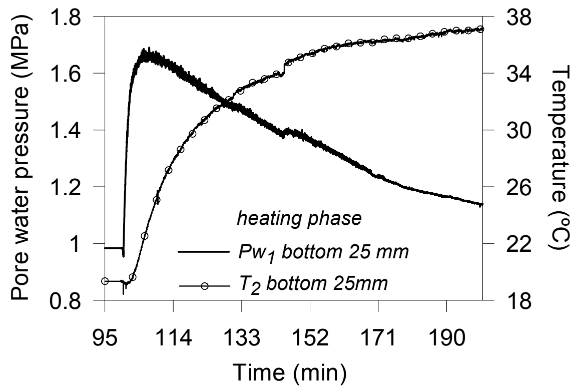


Figure 5. Time evolution of temperature and pore water pressure during heating (Figure 3 of Romero et al.).

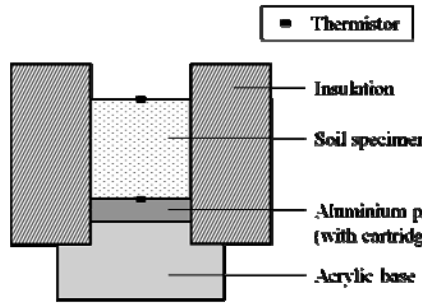


Figure 6. Thermal cell for thermal conductivity measurement (Figure 2 of Low et al.).

Xiong et al. developed a finite element software, SOFT, to simulate the THM behavior of soft rock. They simulated drained triaxial tests performed on soft rock and a field heating test performed by the Mont Terri underground laboratory in a soft rock known as Opalinus clay. The authors simulated the thermal heating isotropic drained triaxial test on soft rock as a boundary value problem with different values of overconsolidation ratio (OCR) and observed that the thermo-mechanical behavior of the soft rock depends on OCR. They simulated the field test with 4275 cubic iso-parametric elements using back-calculated model parameters obtained from a separate simulation of laboratory tests performed earlier on Opalinus clay. Xiong et al. studied the evolution of the temperature, excess pore pressure, and strain fields as functions hydro-thermal coupling under the test conditions can be adequately captured.

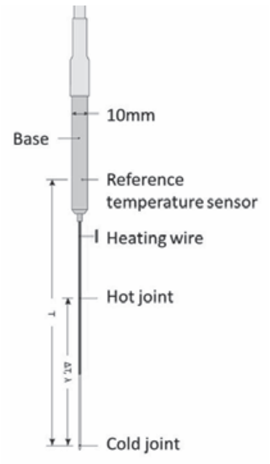


Figure 7. Needle probe for thermal conductivity measurement (Figure 1of Low et al.).

Nishimura et al. presented a multi-scale study in which a local-scale THM analysis of soil was connected to regional-scale geothermal analyses based on regional climatic prediction data, which was, in turn, obtained from the atmosphere ocean general circulation models (AOGCM) after applying statistical and locally informed down-scaling techniques. The purpose of the study was to develop an analytical framework for predicting soil-structure response to climate change in the cold regions. The main intent was to provide broad-scale predictions of geothermal responses at a regional scale that offer hazard zoning schemes related to permafrost thawing. The work will allow engineers to design infrastructure with better resistance to permafrost induced distress. 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 (middle) level (Figure 8) combines engineering geology with nonlinear, one-dimensional thermal conduction finite element modeling to generate extensive analytical databases from which regional geocryological maps can be created that provide information on both hazard mapping and strategic planning of infrastructure. The lowest level of analysis includes soil-structure interaction modeling using a new THM constitutive model to help predict the complex soil-structure interactions expected as a consequence of temperature-change induced permafrost warming and degradation. The analysis approach and THM models were checked against regional geothermal maps in Eastern Siberia and against field tests on chilled pipelines in Calgary, Canada, and both the checks confirmed the predictions to be realistic.

Komine investigated the variations of swelling pressure and deformation of bentonites, sodium-type bentonite A, (Kunigel-V1) and calcium-type Bentonite C (Kunibond), that are produced in Japan and contain 57% and 80% montmorillonite, respectively. Bentonite is used as buffers for disposal of high-level radioactive wastes because its high swelling behavior helps in sealing wastes. However, the swelling characteristics of bentonite degrade because of the decay-heat from the radioactive wastes. Komine subjected the bentonite samples to different temperatures over different periods of time and then performed swell tests on the samples. The swelling pressure and strains were investigated as functions of the initial dry density and vertical stress and it was observed that the thermal effect on swelling deformation characteristics of sodium-type bentonite A is dependent on the vertical stress condition and that the swelling deformation characteristics of calcium-type bentonite C are markedly reduced by thermal exposure at vertical stress of 1000 kPa and by heating temperatures greater than 90°C for all heating durations (see, for example, Figure 9). Komine also performed chemical analyses such as measurement of cation concentration of water around the bentonite specimens, methylene blue absorption test, and X-ray powder method on the bentonite samples to study how the different cations influence the thermal behavior of the bentonites.

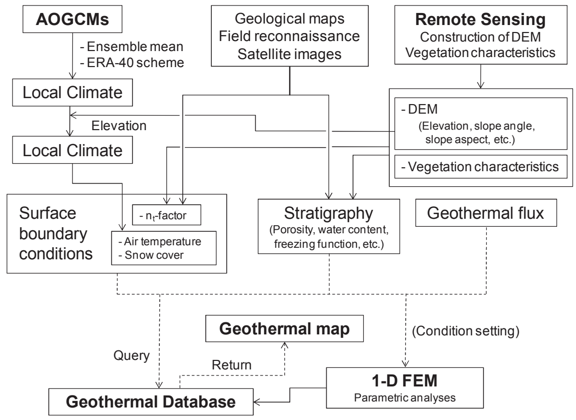
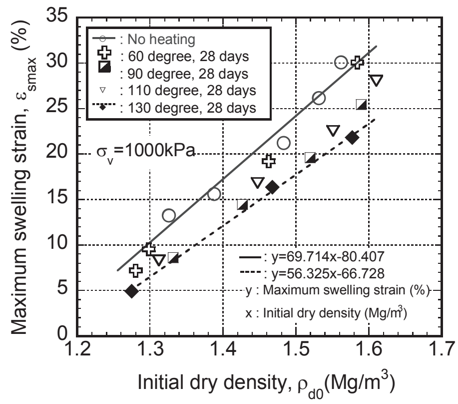
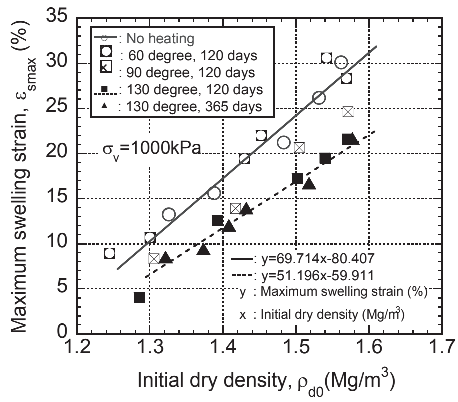


Figure 8. Structure of middle-level analysis to obtain local geothermal predictions based on climate predictions and local geography (Figure 2 of Nishimura et al.).



(a) Heating duration 28 days



(b) Heating duration 120 days and 365 days

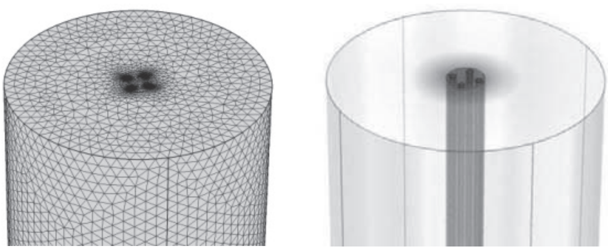
Figure 9. Relation between maximum swelling strain and initial dry density of calcium-type bentonite C at vertical stress of 1000 kPa (Figure 5 of Komine).

2.2 Geothermal energy

This sub-section includes the papers that deal with thermal energy extraction and storage. Out of the ten papers summarized here, four papers deal with different ground heat exchanger systems, five papers deal with geothermal piles, and one paper deals with thermal energy storage.

Bidarmaghz et al. studied the effects of different design parameters such as pipe configuration and fluid flow rate on the rate of heat extraction, and provided information that may aid engineers to design an energy-efficient and cost-effective ground heat exchanger (GHE) system. Finite element analyses were performed, as shown in Figure 10, to model different pipe-loop configurations, fluid flow rates and pipe separation, and to investigate their impacts on the total system efficiency.

Based on the analysis results on a large diameter borehole and for a given borehole length, Bidarmaghz et al. concluded that, as long as the same pipe length is embedded inside the borehole, thermal performance of the system is not significantly affected by pipe geometry placement. In small diameter ground heat exchangers (GHEs), the use of double and double cross U-pipe showed improved performance. The addition of a second U-pipe to both small and large diameter GHEs achieved significant additional (40-90%) thermal performance, and this can lead to major cost savings when compared to single pipe systems. The analysis also indicated that, when considering the size of the fluid circulating pump and its operational cost, highly turbulent fluid flow will not necessarily result in a more efficient system.



(a) (b)

Figure 10. Typical finite element model section: (a) mesh of a GHE with two U-pipes; (b) details of temperature distribution (Figure 2 of Bidarmaghz et al.).

Katzenbach and Clauss advocated the use of thermosiphon heat pipes in place of conventional heat exchanger U-pipes in GHEs because heat pipes eliminate the use of circulation pumps as the energy is driven through gravity and buoyancy in heat-pipe borehole heat-exchangers (Figure 11). The thermal performance of a heat pipe depends on a number of factors like driving temperature difference, mechanical and thermal properties (e.g., enthalpy) of the heat-carrying fluid, thermal conductivity and capacity, energy withdrawal rate on the condenser side, the geometric dimensions, and the inside pressure. The authors performed numerical analysis to investigate the sensitivity of various parameters like the length and diameter of heat pipe and borehole on the GHE performance. They found that the relationship between length and diameter has a large influence on the specific power (heat) and suggested an optimization of these dimensions in design. Katzenbach and Clauss concluded that the efficient energy transport within the heat pipe allows a relative increase in the coefficient of performance (COP) of 10% or more. They also collected temperature data from an instrumented geothermal heat pipe borehole heat exchanger system installed for new, single-family home. The data was used to compute the expected heat -power output and to assess the operation efficiency of the system.

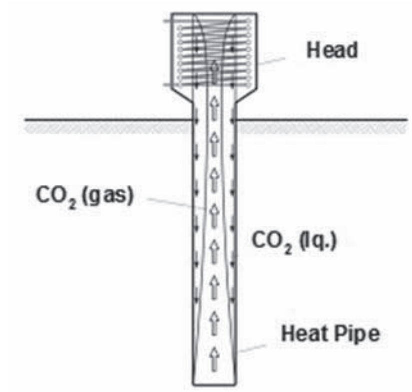


Figure 11. Geothermal heat pipe (Figure 2 of Katzenbach and Clauss).

Grabe at al. simulated the performance of a borehole heat exchanger operated in conjunction with air-sparging induced groundwater circulation using the multiphysics finite element software COMSOL. Groundwater circulation around GHE systems increases the heat-transfer efficiency because heat flow can then happen through convection in addition to the conductive flow that occurs in regular closed-loop GHEs. The authors considered a three-dimensional model in which the heat exchanger borehole is fitted with heat-exchanger and air-injection pipes (Figure 12). They neglected flow inside the well and heat pipes, and considered a homogeneous, sandy aquifer. The computations were performed by assuming that the hydraulic and thermal properties of soil are temperature independent, which implied that groundwater flow is not influenced by heat transport. Grabe at al. simulated the groundwater flow till the attainment of stationary conditions. The results obtained were superimposed with heat propagation in soil. A parametric study was performed by varying the density of air-water mixture inside the well, and the thermal and hydraulic conductivities of soil. A profitability analyses was also performed based on the numerical results. The authors concluded that air-sparging well combined with borehole heat exchanger increased the heat-abstraction capacity and that the system worked well for soil with high hydraulic conductivity.

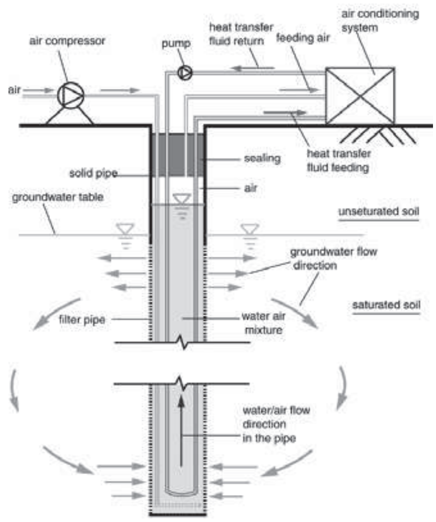


Figure 12. Combination of an air-sparging downhole heat exchanger with an air conditioning system (Figure 1 of Grabe at al.).

Ziegler and Kürten described two examples of novel geothermal energy utilization technique. In the first example, the thermal utilization of smouldering mining dump in the Ruhr area of Germany was described. Three heat-exchange fields consisting of borehole heat exchangers and temperature gauges were installed. Several thermal response tests determining the short-term behavior of the plants and long-term tests were carried out. Numerical simulations and analytical investigations were also performed to identify the important parameters that influence the heat output.

In the second example, Ziegler and Kürten described the use of thermo-active seal panels with integrated heat-exchange pipes (Figure 13) used in underground structures in direct contact with groundwater. The authors tested the efficiency of the panels through laboratory experiments. They noted the importance of heat transfer between soil and heat exchanger for achieving high efficiency. Because both these examples require plane heat-flow models (instead of axisymmetric models) to describe the heat flow, Ziegler and Kürten introduced a new equivalent thermal-resistance model (Figure 14) for describing heat transfer through plane structures.

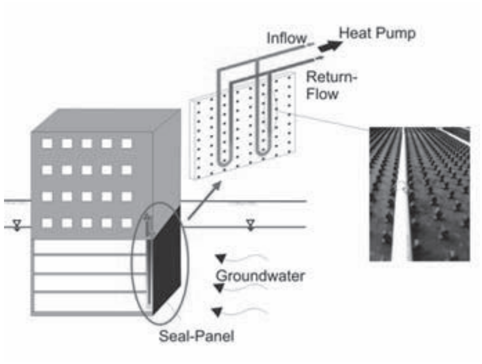


Figure 13. Thermo-active seal panel (Figure 2 of Ziegler and Kürten).

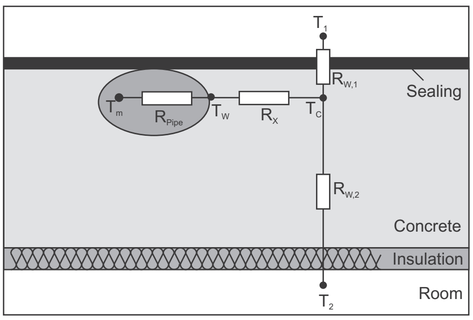


Figure 14. Equivalent star-network thermal resistance model for thermo-active seal panel (Figure 7 of Ziegler and Kürten).

The problem of energy piles is more complicated than that of geothermal heat pumps because of the coupled thermo-mechanical response. The coupled behavior of energy piles is highlighted in the study by McCartney et al. in which they investigated the impact of the pile-head boundary condition on the response of end bearing geothermal piles using a centrifuge test and monitoring a full-scale pile beneath an 8-story building at Denver, CO, USA. In the centrifuge test (Figure 15), the pile had a length of 533.4 mm and a diameter of 25 mm, and the scaling factor was 24. The pile was maintained at a constant temperature and then analyzed for thermally induced stresses and strains with load (no restraint) boundary condition at the head. The full-scale end-bearing drilled shaft (Figure 16) of length 14.8 m and diameter of 0.91 m has three heat-exchanger loops and is restrained at the head due to the presence of grade beams. The authors recognized the difference in the soil profiles and boundary conditions of the two piles and concluded that the boundary condition at the pile head has a significant effect on the magnitude and shape of stress distributions in energy piles.

Wang et al. also investigated through a field test the impact of the coupled thermo-mechanical response of energy pile on its capacity. A full-scale in situ geothermal energy pile equipped with ground loops for heating and cooling, multi-level Osterberg cells, thermistors, strain gages and transducers was installed at Monash University, Australia in an unsaturated, very dense sand profile. It was observed that the shaft capacity increased when the pile was heated and returned to its initial value when the pile was cooled (see Figure 17). The authors noted that energy piles have the potential to reduce the energy demand in built structures. They concluded that further research is required to understand the pile shaft behavior in different soil conditions and to assess the thermal properties of the energy pile ground heat exchanger and the surrounding soil for different field conditions.

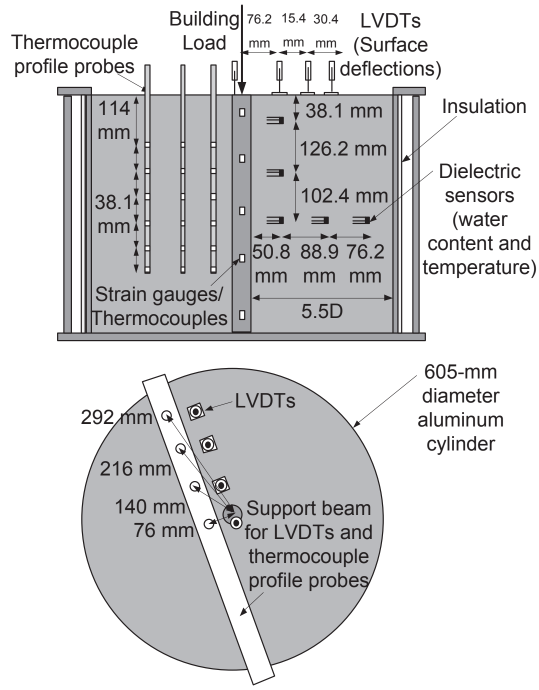


Figure 15. Schematics of the centrifuge-scale energy foundation test (Figure 2 of McCartney et al.).

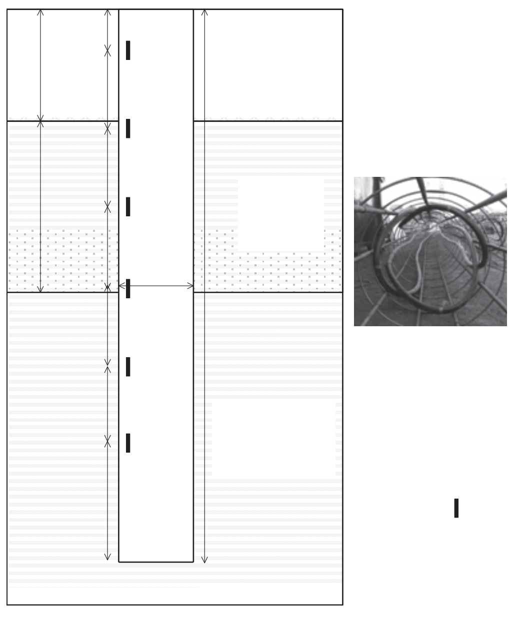


Figure 16. Soil stratigraphy and layout of energy drilled-shaft instrumentation (Figure 3 of McCartney et al.).

Suryatriyastuti et al. presented a theoretical analysis of geothermal piles subjected to heating-cooling cycles and mechanical loading. Two analysis methods were presented to predict the evolution of pile head displacement, axial stresses, and the mobilized soil resistance. The first method is commonly used for design of axially loaded pile, and is based on a model that describes the mobilization of the soil shear strength along the pile-soil interface. The effect of temperature is introduced in the calculation by imposing axial dilation or contraction of the pile corresponding to its thermal dilation or contraction. The analysis produced axial stresses along the pile and pile head displacement under different temperature changes and different pile head conditions. The second method takes into account the effect of thermal cycles. A more complex constitutive model Modjoin was used to simulate the soil-pile interface. Simulations using this model showed that thermal cycles can induce cumulative settlement at the pile head or generate axial stresses along the pile.

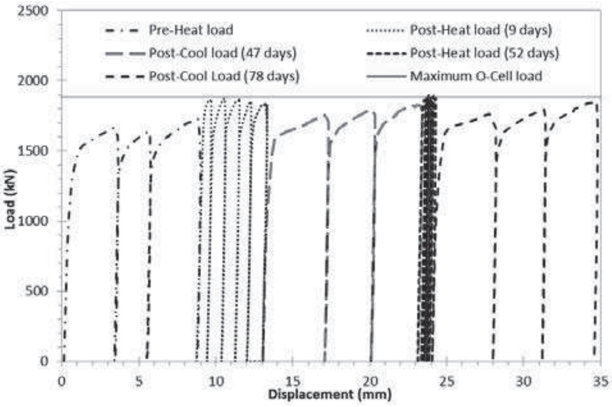


Figure 17. Load versus pile upper-section average shaft displacement – initial, after heating and after cooling (Figure 3 of Wang et al.).

Loveridge and Powrie focussed on the thermal aspects of energy piles. As part of their study, the authors monitored an instrumented pile heat-exchanger system in East London and presented the initial data from the first few months of operation of the energy system. Each pile in the system was installed with a pair of plastic U-pipes, which were inserted into the center of the pile (Figure 18) after the pile cage had been plunged into the concrete. Loveridge and Powrie described the ground conditions and the details of the instrumentation, and analyzed the initially collected data (Figure 19). The data demonstrated the transient nature of the heat transfer within the pile which is not taken into account in most existing design methods. The pile concrete was found to store thermal energy in the short term. The authors concluded that neglecting the short term storage capacity of concrete makes the design over conservative, underestimates the thermal capacity of the pile, and leads to an over estimation of the risk of ground freezing for large diameter piles.

Figure 18. Typical pile heat exchanger at the East London site (Figure 1 of Loveridge and Powrie).

Ponomarov and Zakhrov reported another energy pile foundation application in Russia. Field studies were carried out in a pilot site to determine the temperature distribution in the ground mass, the change of groundwater level, and the physical-mechanical and thermal-physical characteristics of the ground mass. The temperature distribution in the ground and its seasonal variations were obtained from the field monitoring data. In addition, numerical simulations were performed for quantitative evaluation of the thermal energy extracted from different energy foundations under the given climatic and hydro-geologic conditions.

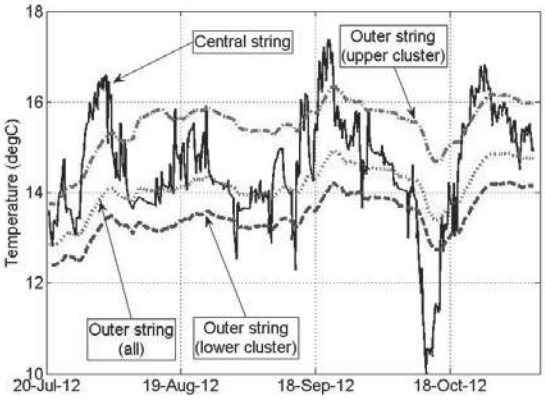


Figure 19. Mean thermistor string temperatures (Figure 6 of Loveridge and Powrie).

The study by Andersen et al. is not related to geothermal energy extraction but to thermal energy storage in an excavated pit in Marstal, Denmark. Thermal energy is usually stored by heating up a material using the available external source of energy (e.g., solar energy), and then this heat is recycled to the consumers using a heat pump. Several thermal energy storage systems using tanks, aquifer, pits, and boreholes are currently used or being considered in Denmark. Andersen et al. described the Marstal town pit-based thermal storage system (PTES), which aims at storing 100% renewable energies in the near future. The authors were involved with the various geotechnical difficulties that occurred during the construction of the PTES shown in Figure 20, which included the excavation stability, the groundwater and soil handling during the construction phase, and the long term consequences of thermal influence on deformations during the operational phase. According to the authors, PTES is applicable to other sites, and the utilization of renewable energy using PTES will enhance the renewable energy resources of other cities in Denmark.

Figure 20. PTES at Marstal, Denmark during completion of excavation and laying out of membrane (Figure 3 of Anderson et al.).

3 SUMMARY

Thermal geomechanincs is an important sub-discipline of geotechnical engineering that has applications in geothermal-energy extraction and thermal-energy storage, soil-structure response due to climate change, storage of nuclear wastes, and several other areas that contribute to the sustainable development of civil infrastructure. This general report summarizes 18 papers on thermal geomechanics and geothermal energy published in the proceedings of the 18th ICSMGE. The papers report a variety of studies encompassing laboratory and field experiments, and modeling. Out of these 18 papers, four papers were submitted from the UK, three from Japan, two each from Australia and France, and one each from Denmark, Russia, Spain, and USA. This indirectly shows the relative early stage of the current state-of-the-art on the thermal and geothermal energy related topics in geotechnical engineering. Eight papers focussed on the fundamental aspects of thermal geomechanics related to the thermo-hydro-chemo-mechanical behavior of soil and rock, four papers dealt with ground heat exchanger systems, five papers dealt with geothermal piles, and one paper dealt with thermal energy storage.

4 ACKNOWLEDGEMENT

Dr. Anh Minh Tang, Senior Researcher at Ecole des Ponts Paris Tech, France helped us in interpreting the papers written in French for which we are grateful.

5 REFERENCES

Andersen J, D., Bodker L. and Jensen M.V. 2013. Large Thermal Energy Storage at Marstal District Heating. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2398.

Bidarmaghz A., Narsilio G. and Johnston I. 2013. Numerical Modelling of Ground Heat Exchangers with Different Ground Loop Configurations for Direct Geothermal Applications. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2816.

Brandl, H. 2006. Energy Foundations and other Energy Ground Structures. *Géotechnique*. 56(2), 81-122.

de Moel, M., Bach, P. M., Bouazza, A., Rao, R. M. and Sun, J. O. 2010. Technological advances and applications of geothermal energy pile foundations and their feasibility in Australia. *Renewable and Sustainable Energy Reviews*, 14, 2683–2696.

Grabe J., Menzel F. and Ma X. 2013. Combination of borehole heat exchangers and air sparging to increase geothermal efficiency. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2356.

Hughes, P.J. 2008. Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers. *Oak Ridge Nat. Lab. Report* ORNL-2008/232.

Katzenbach R. and Clauss F. 2013. Geothermal Heat Pipe Borehole Heat – Exchangers Computational Simulation and Analysis of Measurement Data. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2373.

Komine H. 2013. Thermal influences on swelling pressure and swelling deformations of bentonites and investigations of its factors. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2010.

Loveridge F. and Powrie W. 2013. Performance of Piled Foundations Used as Heat Exchangers. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2521.

Low J. E., Loveridge F. A. and Powrie W. 2013. Measuring soil thermal properties for use in energy foundation design. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2492.

McCartney J.S., Murphy K.D. and Stewart M.A. 2013. Thermo – Mechanical Behaviour of Energy Foundations. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 1822.

Monfared M., Delage P., Sulem J., Mohajerani M., Tang A.M. 2013. Pressurisation thermique dans l'argile de Boom. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 1862.

Nishimura S., Jardine, R. J., Fenton C. H., Olivella S., Gens A. and Martin C. J. 2013. Development of a predictive framework for geothermal and geotechnical responses in cold regions experiencing climate change. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2481.

Ponomaryov A. and Zakharov A. 2013. Numerical simulation of the process of geothermal low-potential ground energy extraction in Perm region (Russia). *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2672.

Romero E., Lima A., Gens A. and Vaunat J. 2013. Determination of the thermal parameters of a clay from heating cell tests. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2829.

Suryatriyastuti M., Mroueh H., Burlon S., Habert J. 2013. Analyse de la portance des pieux géothermiques. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 1742.

Tsutsumi A. and Tanaka H. 2013. One – dimensional compressive behaviour of reconstituted clays under high temperature and small strain state. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2067.

Wang B., Bouazza A., Singh R. M., Barry-Macaulay D., Haberfield C., Chapman G. and Baycan S. 2013. Field investigation of a geothermal energy pile: Initial observations. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2622.

Xiong Y.L., Zhang F., Nishimura T. and Kurimoto Y. 2013. THM simulations for laboratory heating test and real – scale field test. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2290.

Ziegler M., and Kurten S. 2013. New Developments in near-surface geothermal energy systems. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2390.

Zihms S. G., Switzer C., Karstunen M. and Tarantitno A. 2013. Understanding the effects of high temperature processes on the engineering properties of soils. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paper No. 2513.