Prague Geotechnical Days 2018

Seminar – invited lectures

ENERGY GEOTECHNICS

26th Prague Geotechnical Lecture

Environmental Geotechnics: Looking back, Looking forward

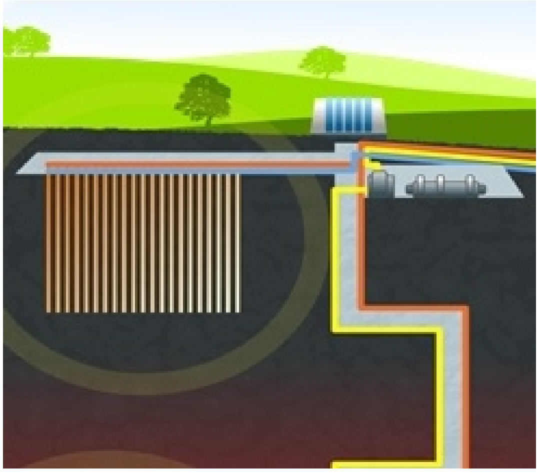
Resume

17 and 21 May 2018

Charles University, Faculty of Science
Albertov 6, Prague 2

and

Czech Academy of Sciences
Národní třída 3, Prague 1



Organisers:

SG Geotechnika a.s.,

Charles University, Faculty of Science,

Czech and Slovak Society for Soil Mechanics and Geotechnical Engineering

under the auspices

of the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences

PRAGUE GEOTECHNICAL DAYS 2018

Resume

Energy Geotechnics

Geo-Energy Applications Involving Heat Exchange with the Ground

Marcelo Sanchez, Michael Maedo, Ghassan Akrouch, Jean-Louis Briaud
Texas A&M University, College Station, Texas, USA

Geothermal Energy

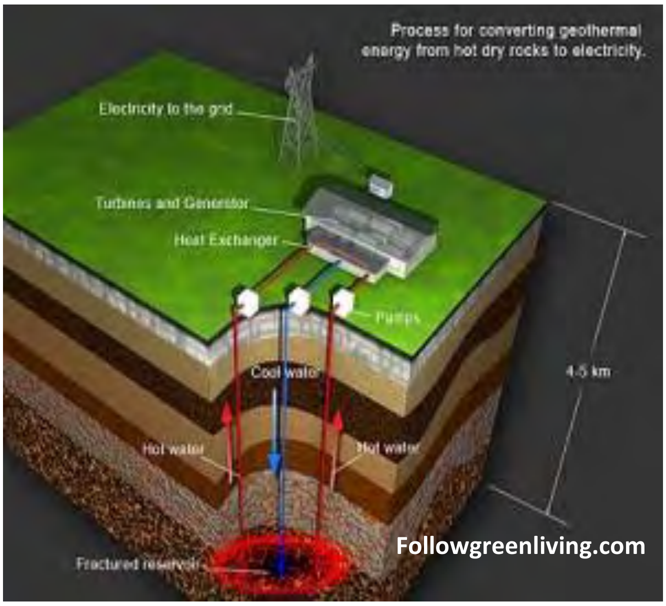
Geothermal energy refers to the use of thermal energy stored beneath the Earth's surface

This thermal energy is usually available anywhere and at any time. This is a significant advantage compared to other renewable energies such as solar energy and wind power. It also has some additional advantages:

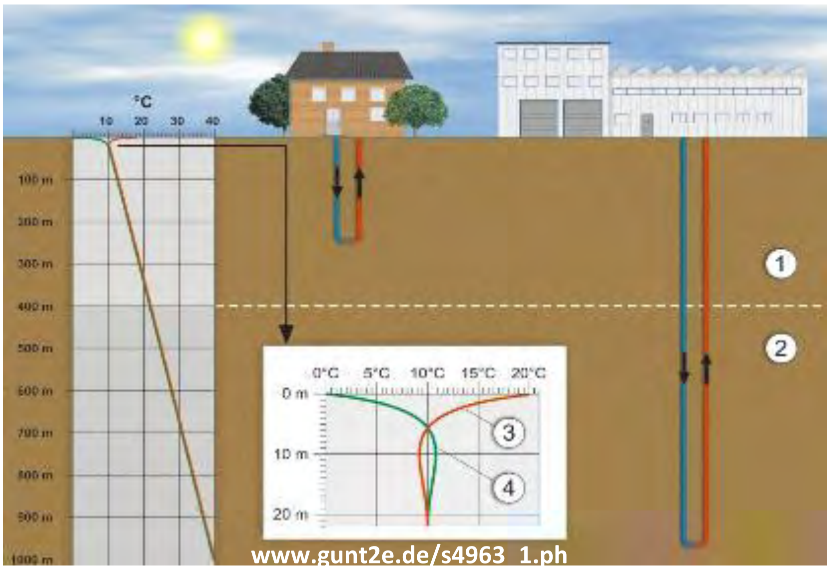
- Low pollution energy
- Low cost
- It can be use in different applications

Two main types of geothermal energy systems:

- Deep geothermal energy
- Shallow geothermal energy



Very deep geothermal system

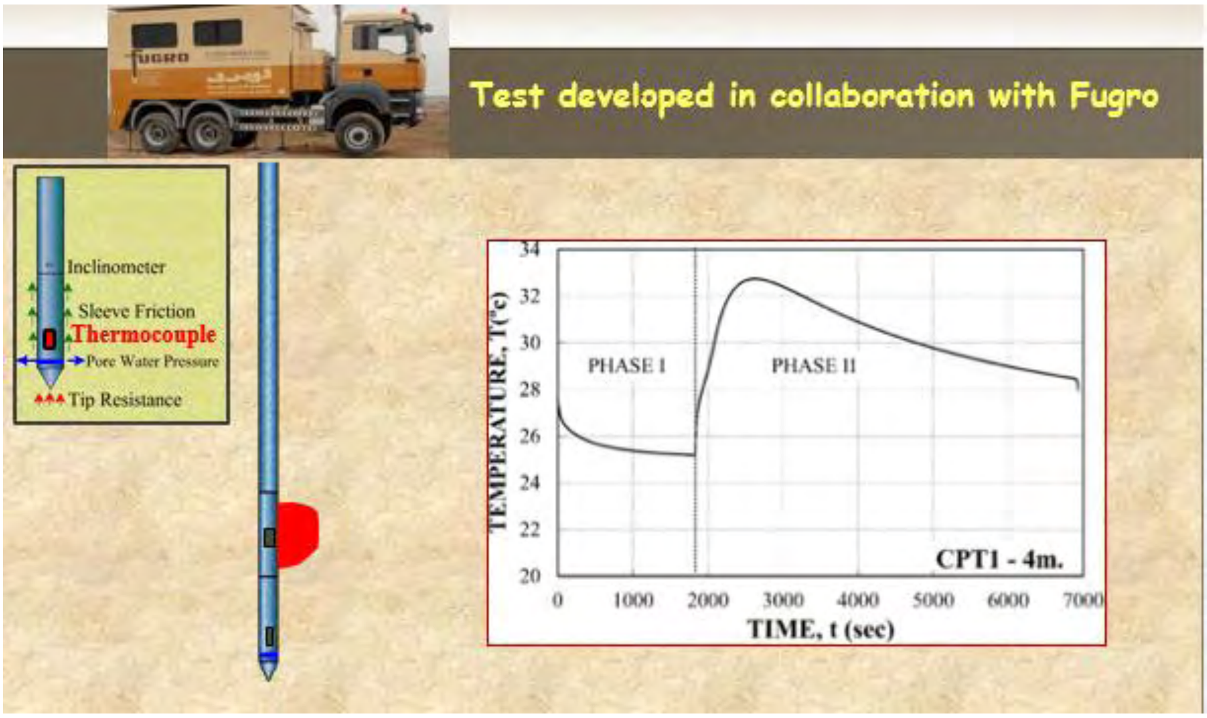


Scheme showing shallow and deep geothermal systems

Thermal Cone Dissipation Test (TCT)

A component of geotechnical applications involving non-isothermal conditions is the determination of the thermal properties of the ground. A new test, called the Thermal Cone Dissipation Test (TCT), which overcomes most of the drawbacks observed in current in-situ techniques used to determine the thermal properties of soils is presented here. The equipment consists of a cone penetrometer equipped with thermocouples located behind the cone point.

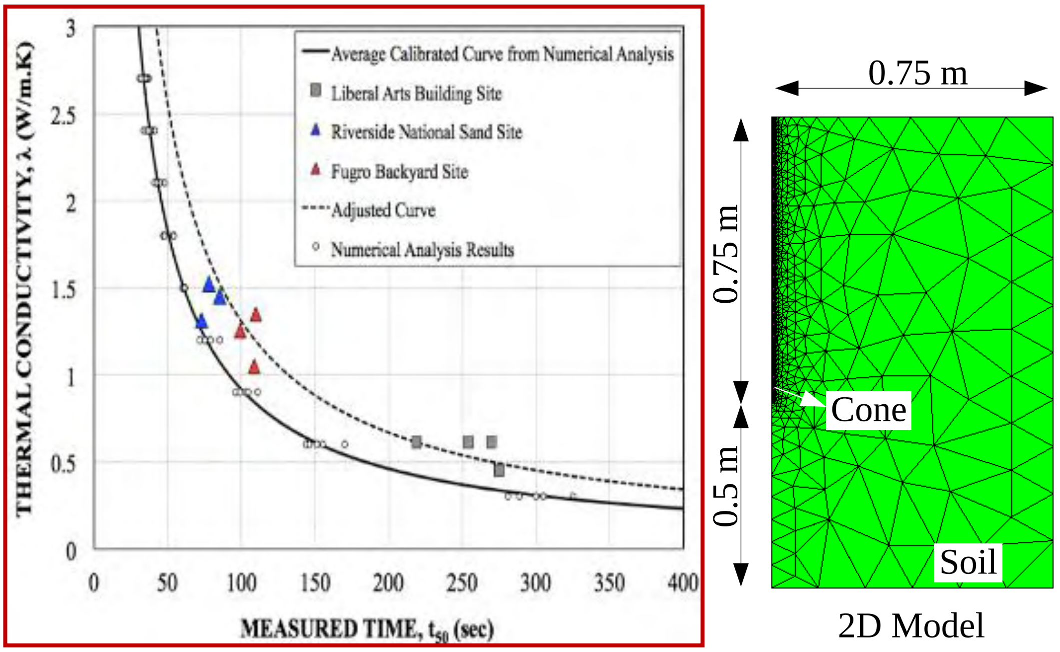
The TCT is pushed in the ground at the standard penetration rate of 2 [cm/s] and the friction between the cone and the soil increases the cone temperature. The temperature decay is recorded as a function of time (for about 30 minutes) and this information is used to estimate the thermal conductivity, and other thermal properties, of soils.



Scheme showing the TCT set-up with a typical test result.

Thermal Cone Dissipation Test (TCT) – Continuation

The calibration curves to estimate the thermal properties of the ground was based on three main activities: i) in-situ experiments, carried out at three different locations involving different soil types; ii) laboratory investigation, aimed at obtaining the thermal conductivity of the soils studied in the field; and iii) numerical simulations, used to validate the proposed numerical models against the experimental data and to populate the proposed calibration curves including ground conditions no explore in the field. Very good agreements between field, laboratory and numerical results were obtained for the eleven TCTs studied in this research. It is expected that the proposed calibration curves will be enhanced in the future as additional experimental data become available.



Comparison between field results and numerical modeling TCT together with geometry and mesh adopted in the numerical analysis.

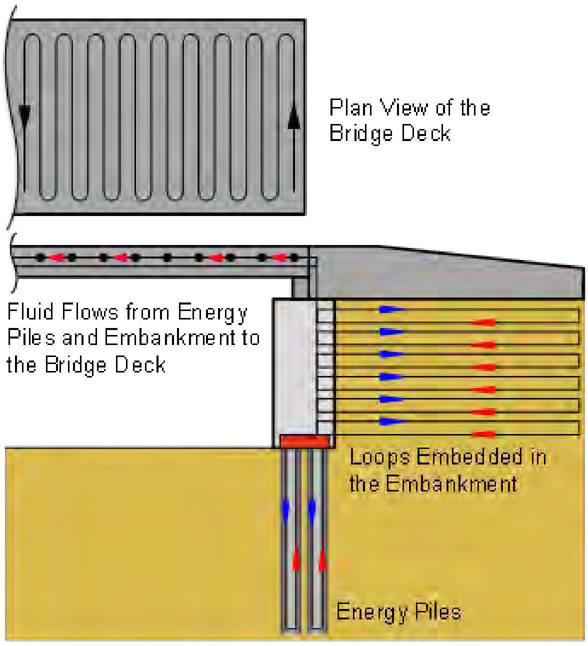
Shallow Geothermal Energy System

Shallow geothermal energy system is one of the most promising renewable energy technologies for an efficient conditioning of buildings because of its relatively low cost, low CO_2 gas emission and high efficiency. This type of geothermal system exchange heat with ground. A shallow geothermal energy system is composed of three main components: i) the geothermal heat pump, ii) the ground heat exchanger, and iii) the duct system that distributes the conditioned air in the building.

Closed horizontal loop field

Closed pond loop field

Closed vertical loop field

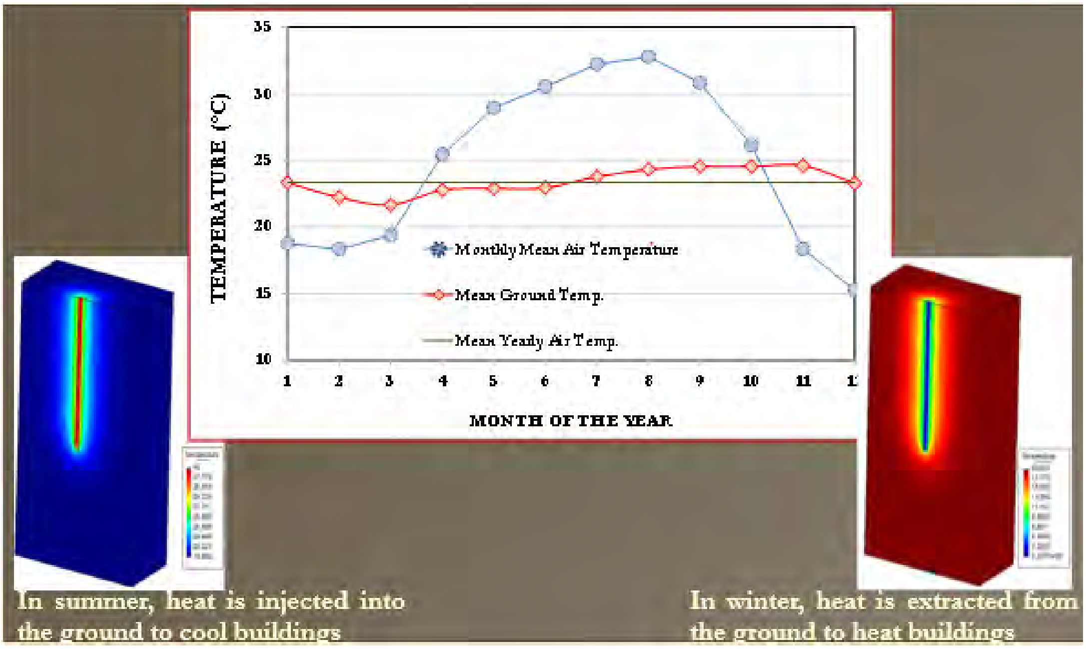


Combination of closed vertical and horizontal loops

Figures illustrating different types of closed loop arrangements

Energy Piles

Energy piles are bi-functional foundation elements used as structural support as well as ground heat exchanger for shallow geothermal energy systems. In winter energy piles take advantage of the warmer ground to exchange heat with it via the heat carrying fluids that circulate through the embedded pipes. In summer the inversed situation occur. In this manner the cost associated with air conditioning of buildings is reduced.



Typical annual variation of temperature in Texas together with thermal fields around energy piles in summer and winter

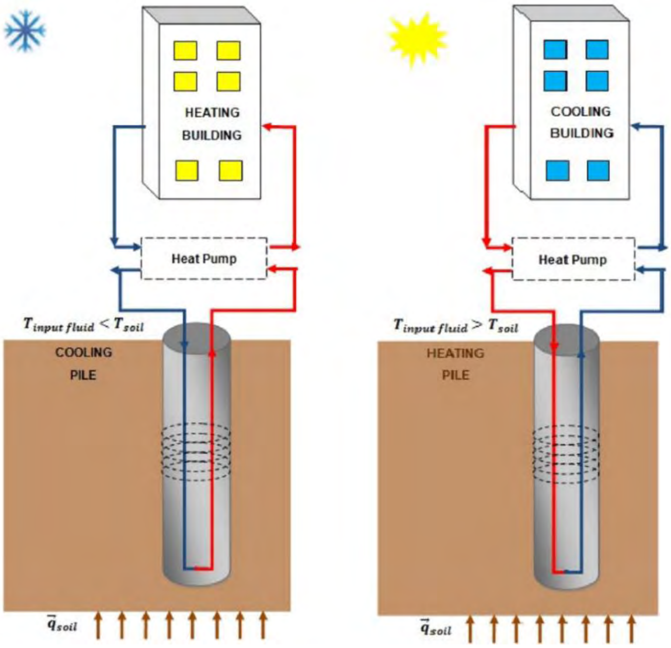
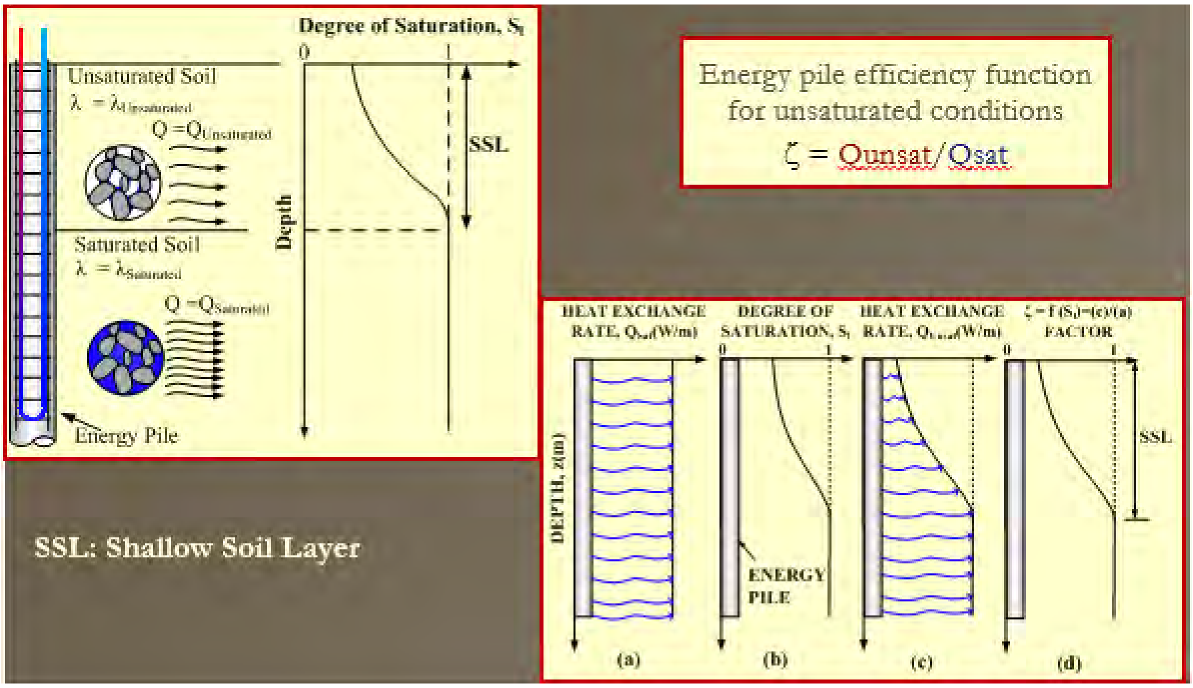


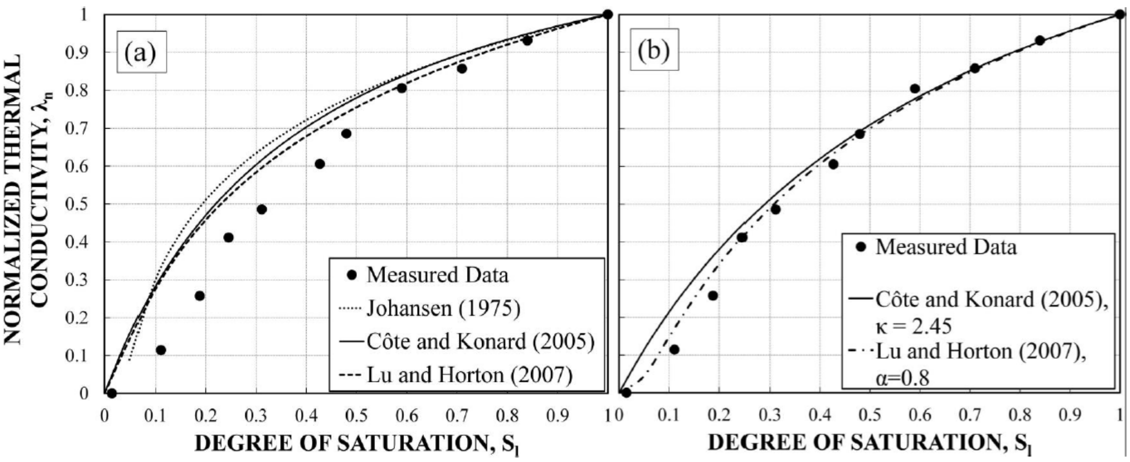
Illustration of energy piles operation in winter and summer

Energy Piles (continuation)

Because energy piles are relatively short, they may be partially embedded in unsaturated soils. Saturation conditions influence the thermal properties of the ground and therefore the heat exchange rate, which in turn affects the efficiency of energy piles. The effect of soil saturation on the heat exchange rate has received practically no attention. In this work we studying the influence of the unsaturated ground condition on the thermal performance of energy piles through, experimental, analytical and numerical investigations. The ratio between the (exchange) heat flux at unsaturated conditions respect to the saturated one is called 'average efficiency ratio' (i.e. ζ = Qunsat/Qsat)



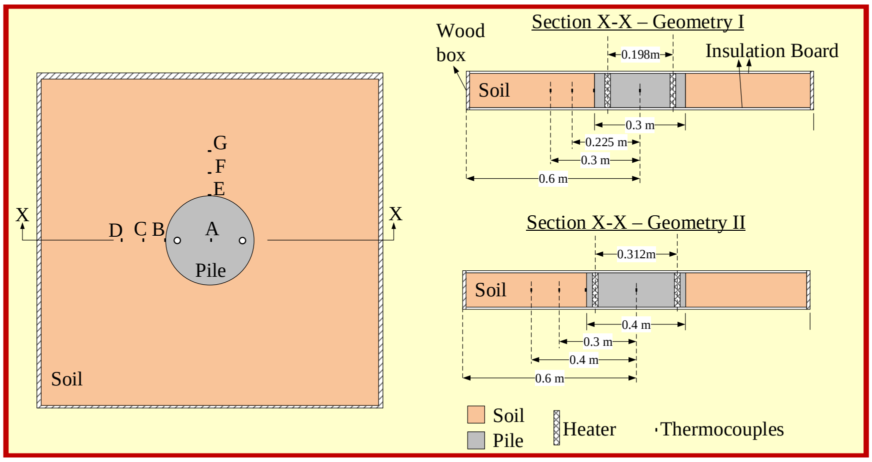
Energy piles in unsaturated and saturated soils



Measured and calculated normalized thermal conductivity λ_n vs. S_l

Energy Piles (continuation)

To validate the numerical solutions a series of laboratory tests were condcuted to study the effect of soil saturation on the thermal performance of energy piles. A total of twelve laboratory experiments on energy pile sections in sand were conducted. Different soil conditions, ranging from dry to fully saturated, were considered. The thermal response of the soil was gathered during the tests.



Geometry I

diameter 300 mm

Geometry II

diameter 400 mm

Test 1 ~ S_l =0.015

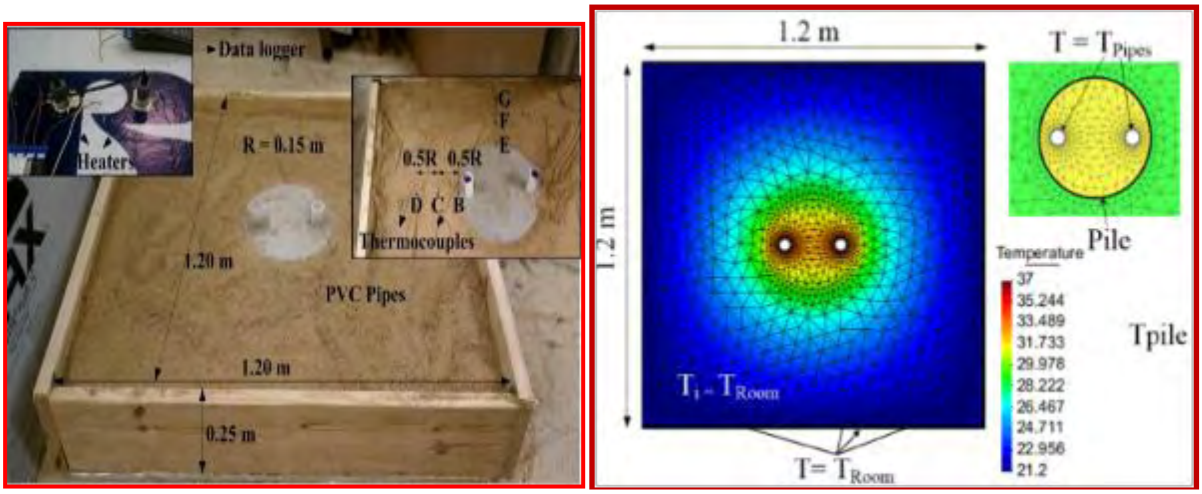
Test 2 ~ S_l = 0.200

Test 3 ~ S_l = 0.300

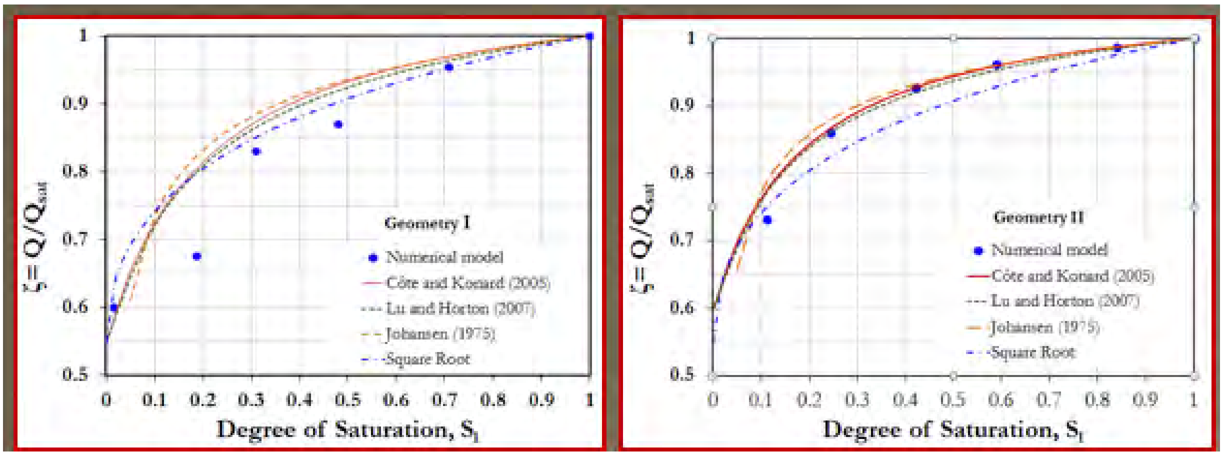
Test 4 ~ S_l = 0.500

Test 5 ~ S_l = 0.700

Test 6 ~ S_l = 1.000



Laboratory test setup and model geometry and mesh

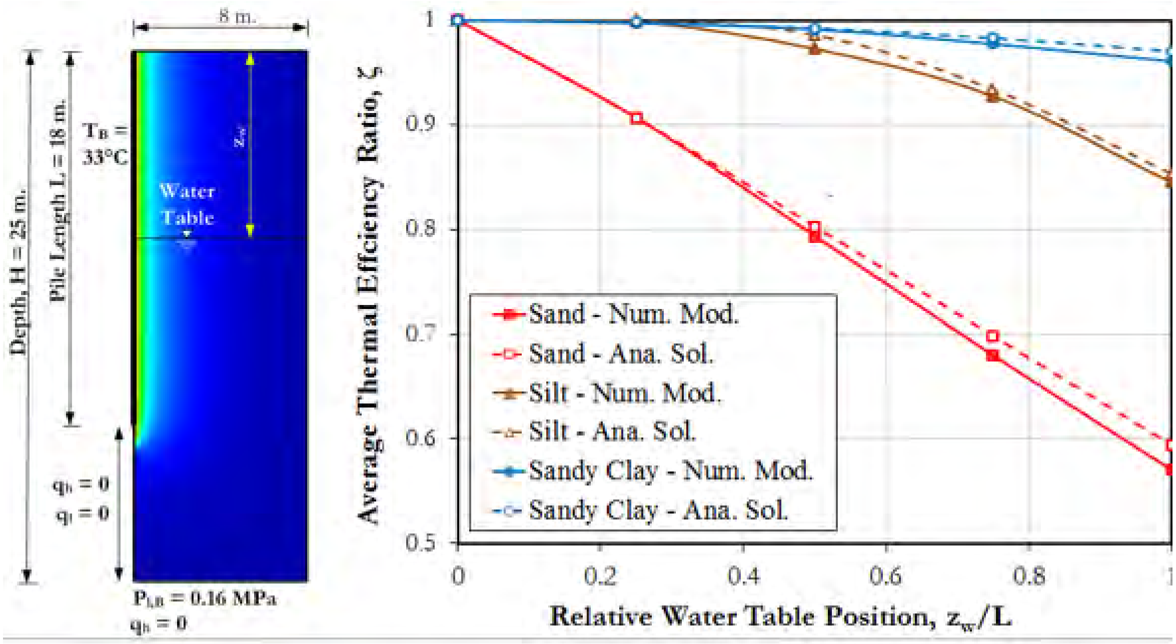


Tests and numerical results comparisons

Energy Piles (continuation)

To analyzed a typical shaft profile the slice section based on Geometry I was extended to the entire length (L) of a pile, assuming L = 18 m. It was considered that water table was located at a (variable) depth (zw m) from the ground level. Three different soil types were adopted for the numerical simulations, which were characterized by different van Genuchten models. For each soil type five different water table elevations were considered. The five positions of the water table are expressed in terms of zw/L as follows: 0.0 (Case 1), 0.25 (Case 2), 0.5 (Case 3), 0.75 (Case 4), and 1.0 (Case 5).

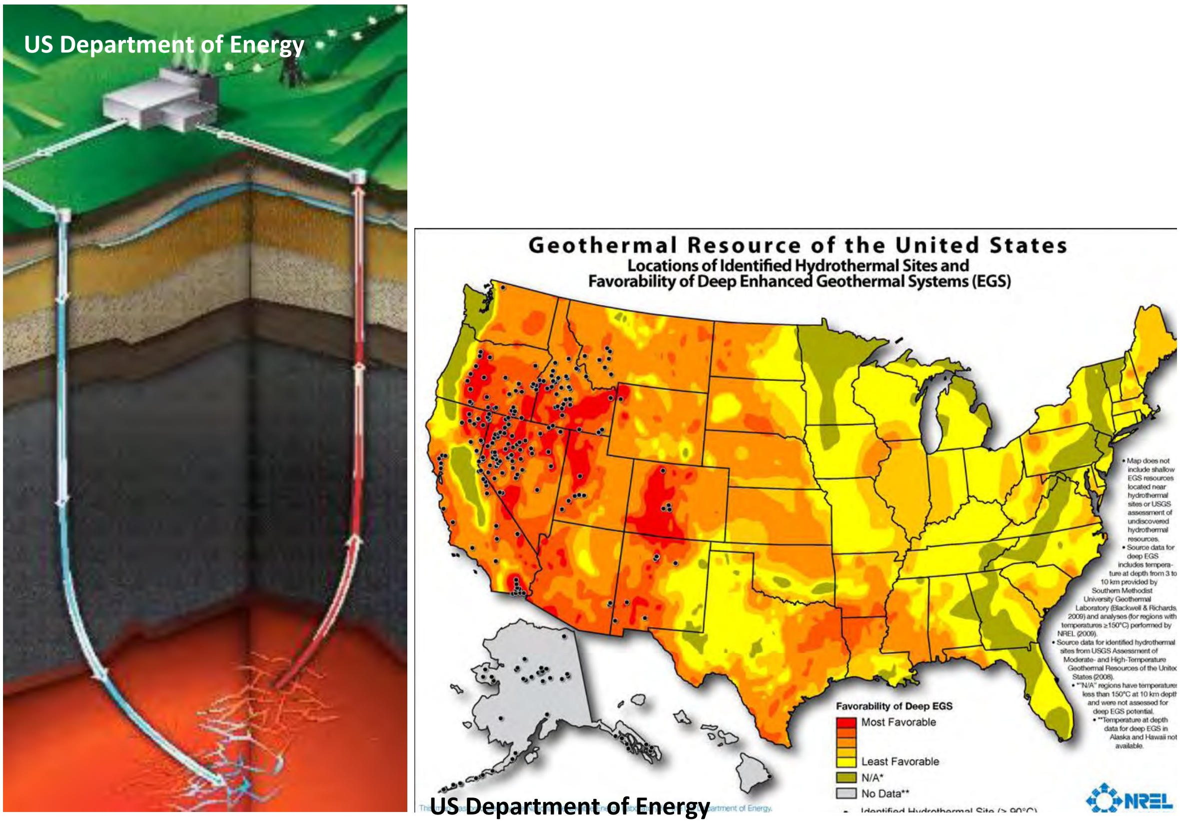
The changes in the water table elevation resulted in different soil saturation profiles. Case 1 corresponds to a fully saturated condition with the water table at the ground surface, while Case 5 corresponds to the water table at the bottom of the pile. For each case, the soil saturation and heat flux profiles were derived from the numerical models, and then the ζ profile was evaluated and compared to the values calculated from the analytical solution. Quite low values of ζ (as low as 0.57) were obtained for sands (implying a significant effect of the unsaturated condition), while practically no impact of the water table level variations was obtained for sandy clays (i.e. minimum ζ around 0.95).



Variation of the average thermal efficiency ratio □ with the water level

Enhanced Geothermal Systems

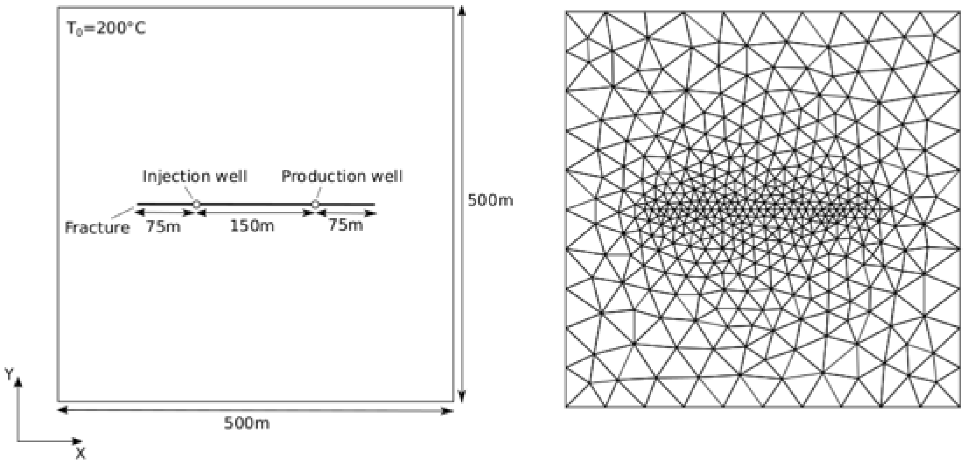
Conventional geothermal power systems produce electrical energy from hot rocks with adequate permeability to allow heat extraction at economic flow rates. However, most of the geothermal resource is in impermeable and dry rock formations. In Enhanced Geothermal Systems (EGS) a fracture network is generated in hot rock with insufficient or little natural permeability by ejecting cold water or other cold fluids. Fluid is circulated and heat is then transported to the surface to generate electricity.



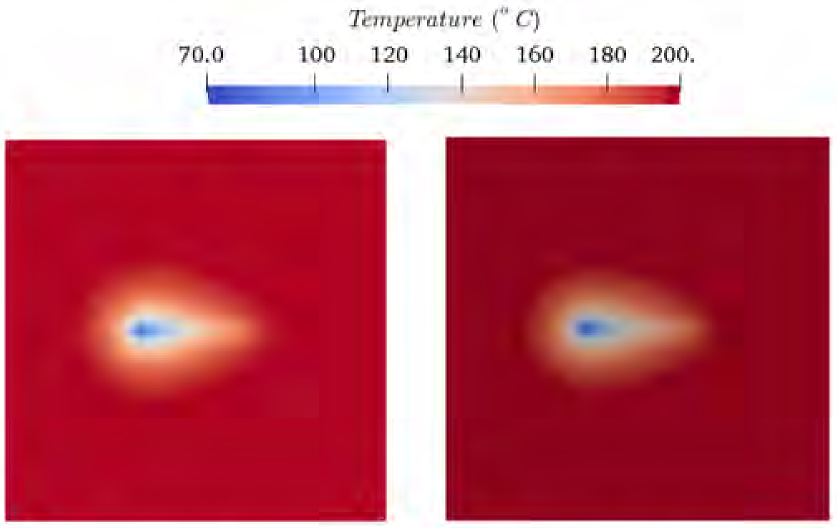
Scheme showing the formation of thermal-fractures in dry hot reservoirs (left), distribution of geothermal resources in the US (right)

Enhanced Geothermal Systems (continuation)

The benchmark proposed by Watanabe et al (2016) considers a reservoir located at a depth of 4 km and with temperatures of 200^{o}C. The energy production system consists of two wells separated by a distance of 150 m. Although the name "2D hot dry rock benchmark", the reservoir was considered fully saturated. The reservoir is modeled with a finite element mesh of 500 m×500 m. The initials pressure is P_o=10 MPa. In addition, water circulates at a rate of 1/300 kg/s, and the injection temperature is 70^{o}C. The parameters of the rock are: $k_r = 10^{-17}$ m^2, $\varphi_r = 0.01$, $\rho_s = 2600$ kg/m^3 and $\lambda_T = 3$ W/m/K. The water density was kept constant, while the water viscosity depended on temperature. This case was modeled here using the mesh fragmentation technique (MFT) and compared against Watanabe et al. (2016) solution (i.e. Watanabe N, Blöcher G, Cacace M, Held S, and Kohl T (2016). Geoenergy modeling III: Enhanced Geothermal Systems. Springer, 2017).



Hot dry rock benchmark: geometry and boundary conditions (left) finite element mesh (right)



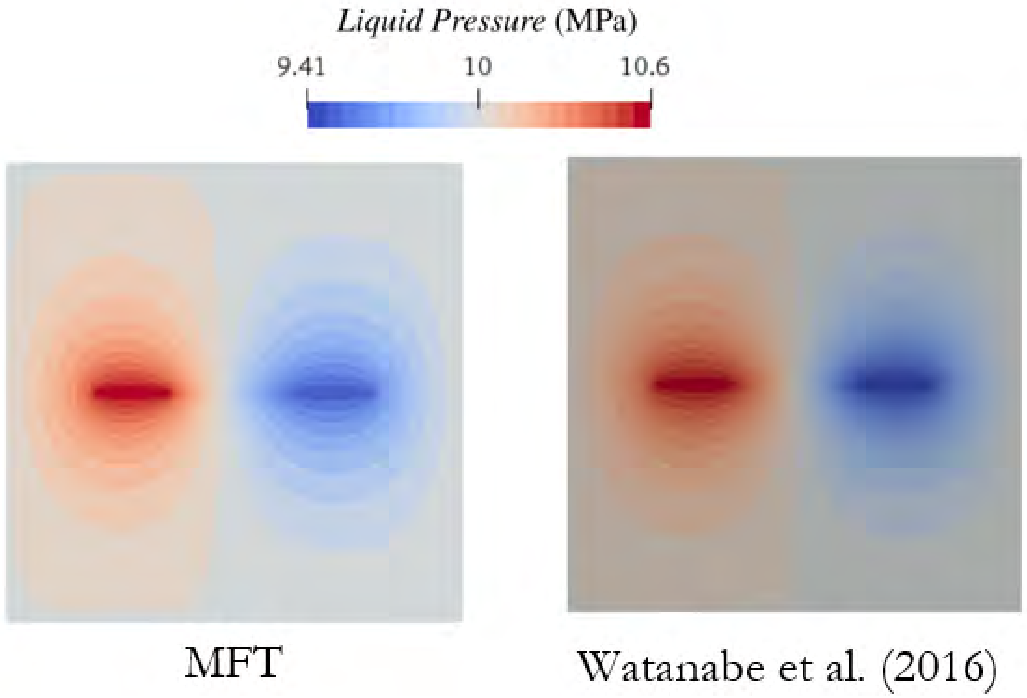
MFT

Watanabe et al. (2016)

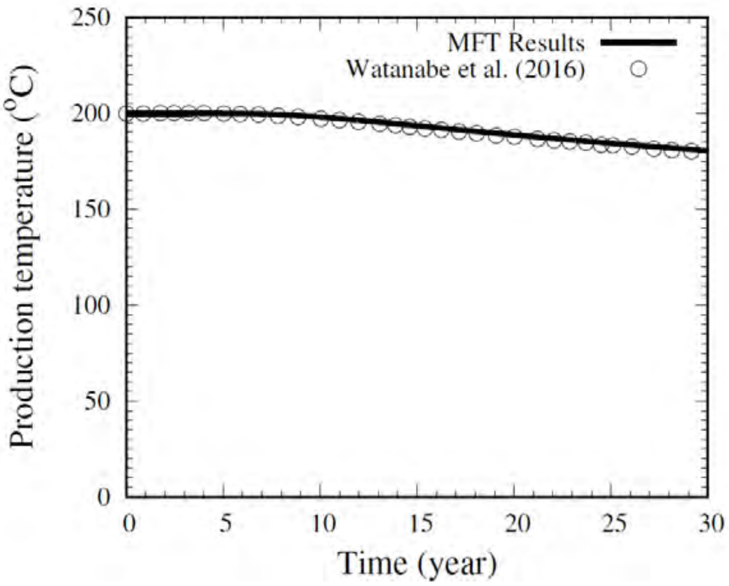
Simulated temperature distribution after 30 years

Enhanced Geothermal Systems (continuation)

The low permeability of the rock limit the penetration of water, and therefore, the heat exchange concentrates in the fracture mainly. The pressure field shows that the system is in equilibrium at the end of the analyzed period. The temporal evolution of production temperature shows a very satisfactory match between the MFT results with those reported by Watanabe et al. (2016). Cases aimed at designing optimal energy production strategies under actual operational scenarios are under study currently.



Simulated stead-state pressure distribution



Temporal evolution of production temperature of the 2D hot dry rock reservoir

Monotonic and Cyclic Lateral Loading of Wind Tower Foundations

Giovanna Biscontin
University of Cambridge

The number of offshore facilities in use and in development is increasing around the world, including traditional and non-traditional oil and gas infrastructure, alternative energy structures, marginal or developmental oil rigs, and recreational structures. Many of these structures require lightweight, low-cost foundations, for which low-aspect ratio piles could work well (Fig. 1). Foundations with aspect ratios larger than 10 in soft clay are classified as "flexible", while foundations with low aspect ratios are typically considered "rigid". Previous work on piles with aspect ratios greater than 3 use the terms pile or monopile, while work on foundations with aspect ratios lower than one have used bucket, "skirted foundation, or mat. The foundations tested in this work are hollow monopiles with short aspect ratio (L/D = 2).

Traditional offshore structures have very large vertical gravity loads and smaller horizontal loads. Wind towers, on the other hand, will have moderate vertical gravity loads with large horizontal loads and moments in proportion to vertical loads. Design paradigms which evolved in the offshore oil and gas industry are not readily applicable to the design of wind tower foundations offshore. Design codes for offshore wind towers are still very much in their infancy and do not provide sufficient guidance for designers.

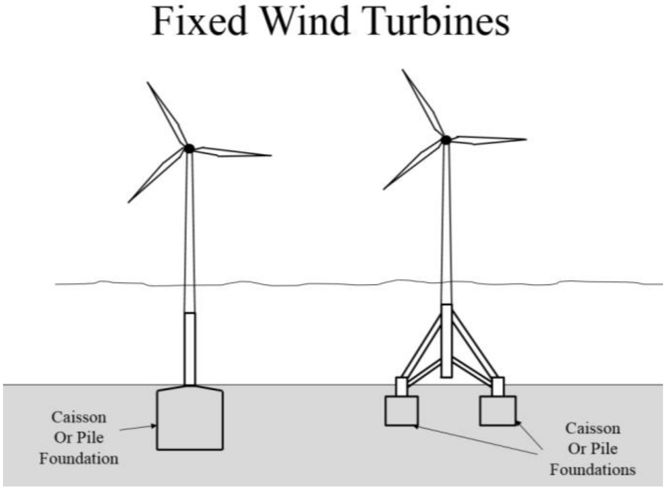


Figure 1 - Different foundation configurations for fixed offshore wind towers

Figure 3 - Adapter and pile cap connectors for rotation and translation.

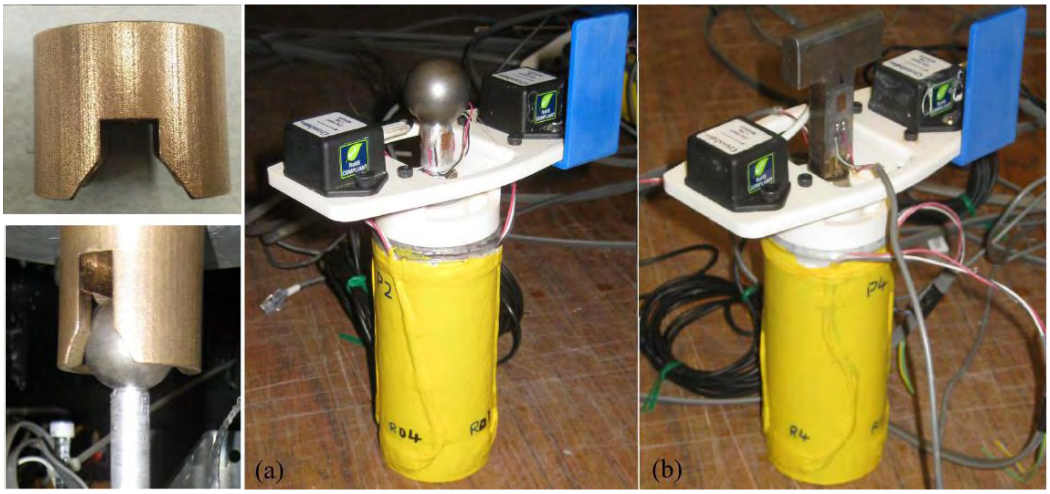
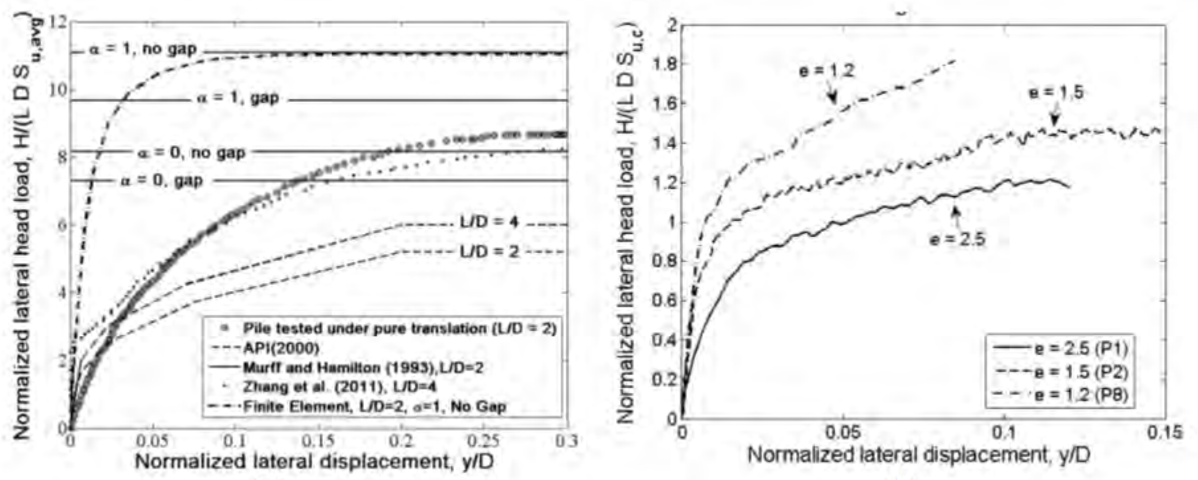


Figure 2 - Adapter and pile cap connectors for rotation and translation.

A series of centrifuge model tests were carried out to investigate the response of short aspect ratio monopiles (L/D = 2) with both fixed and rotating head subjected to lateral loads in soft, normally consolidated clay (Fig. 2). The centrifuge testing was carried out at the Network of Earthquake Engineering Simulations (NEES) facility at Rensselaer Polytechnic Institute. Loads were applied on the model foundations using the 4-degree of freedom in-flight robot with a customized tool, consisting of an adaptor designed and fabricated to latch onto the in-flight robot. This adapter is used with 2 different types of pile caps to achieve both pinned and rigid connectors (Fig. 3).

The load-deflection curve for the pile tested in pure translation is presented in Fig. 4a along with the calculated ultimate lateral capacity using methods proposed by Murff and Hamilton (1993), the API method (API, 2000) and finite element analysis for comparison. The lateral head load, H, is normalized by the product of the projected vertical area, LD, and a shear strength profile based on the T-bar and water content strength profiles over the depth of pile embedment.



(a) (b)

Figure 4 - Force-displacement curves for pile tested in; a) translation; b) rotation.

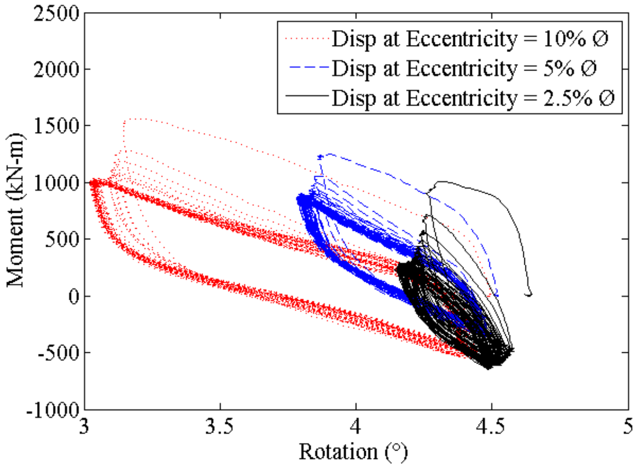


Figure 5 – Moment – rotation behaviour of pile loaded at an eccentricity of 2.5 diameters.

The monotonic response of the monopile subject to rotation was examined for four different eccentricities; 1.2D, 1.5D, 2.5D and 3.5D and is presented in Figure 2b. Similarly to the pile tested in translation, the lateral head load, H, at the top of the pile cap was computed and normalized by the product of the projected vertical area, LD, and an average shear strength profile over the depth of pile embedment. The lateral displacement, y, was computed at the mudline using the tilt and displacement measurements and normalized by the pile diameter, D.

The ultimate capacity of the pile tested in translation is found to be slightly lower (12.7% lower) than Murff and Hamilton’s upper bound solution for the case of a rough pile (α = 1) with the formation of a gap behind the pile. The solution for the case of a smooth pile (α = 0) without gapping was found to be 7% lower than the measured ultimate capacity. The API method was conservative by about 40% for this aspect ratio. FEM analysis, computed for a rough pile assuming no gapping compares well with Murff’s solution and was found to be 27% higher than the measured experimental data.

A set of piles was also subjected to displacement controlled cyclic loading at different eccentricities (Fig. 5). After a few cycles, the response stabilizes, but becomes increasingly nonlinear and hysteretic. The piles settled a significant amount during cyclic loading. This may have been the result of combined vertical-horizontal-moment loading causing vertical plastic deformation. Moment resistance appeared dependent on depth of rotation, not load eccentricity.

References

API, 2000. Recommended practice for planning, designing, and constructing fixed offshore platforms working stress design.

Beemer, R.D., Murali, M., Biscontin, G., and Aubeny, C.P. (2016) “Rotational behavior of squat monopiles in soft clay from centrifuge experiments,” *Geo-Chicago 2016: Sustainability, Energy, and the Geoenvironment*, Chicago, Illinois, USA, August 14-16, 2016.

Murff, J., and Hamilton, J., 1993. “P-ultimate for undrained analysis of laterally loaded piles.” ASCE Journal of Geotechnical Engineering, 119 (1), pp. 91–107.

Zhang, C., White, D., and Randolph, M. (2011). “Centrifuge modeling of the cyclic lateral response of a rigid pile in soft clay.” Journal of Geotechnical and Geoenvironmental Engineering, 137(7), 717–729.

Acknowledgements

The author acknowledges the National Science Foundation, NEES, and the project Capacity and Performance of Foundations for Offshore Wind Towers, Award Number: 1041604.

Development and modelling of an adaptive energy storage under and around buildings

F. Wuttke[1], S. Bauer[1], A. Dahmke[1], O. Kolditz[2], C. Kinias[3], T. Nagel[2], Z.H. Rizvi[1], H. Hailemariam[1], J. Nordbeck[1], X.-Y. Miao[2], K. zu Beerentrup[1]
[1]Kiel University, Ludewig-Meyn-Street 10, 24118 Kiel, Germany
[2]Helmholtz-Centre Environmental Research Leipzig, Germany
[3]Scheer Heating Systems GmbH, Wöhrden, Germany

Keywords: Thermal energy storage, Cement based storage material, THM simulation method

Extended Abstract

One of the common technologies and needs for balancing the energy demand and supply in district heating, domestic hot water production, thermal power plants and thermal process industries in general is thermal energy storage. Thermal energy storage in general, and sensible heat storage in particular as compared to latent heat storage and thermo-chemical storage, has recently gained much interest in the renewable energy storage sector due to its comparatively low cost and technical development. Sensible heat storages work on the principle of storing thermal energy by raising or lowering the temperature of liquid (commonly water) or solid media, and do not involve material phase change or conversion of thermal energy by chemical reactions or adsorption processes as in latent heat and thermo-chemical storages, respectively.

The idea of the presented development is the use of common solar and house heating systems in combination with the heat storage system, figure 1. The whole system runs under the typical cyclic recharge (solar panels) and discharge (house heating system) patterns of common households. The multi-phase storage systems are typically built under or beside buildings in the underground, to conserve space in close urban districts. To understand the behavior of the closed and open heat storage systems in interaction with the urban and natural environment detailed lab and field test are done. In this research, the thermo-hydro-mechanical behaviour of cement-based thermal energy storages for domestic applications is numerically and experimentally analysed in dry, saturated and unsaturated conditions. The general design of the heat storage system is based on extended numerical simulations. For the purpose of model validation, a large-scale prototype model and field tests were performed, figures 1 and 2.

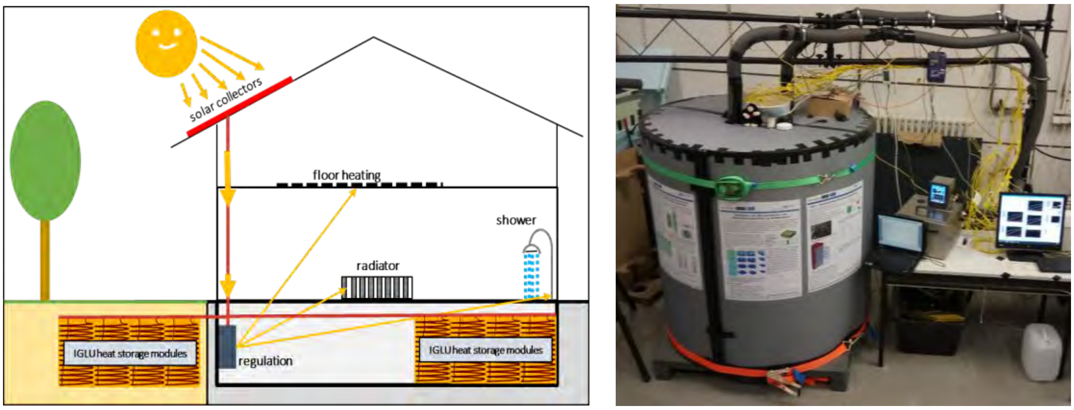


Figure 1: General idea of the multi-phase heat storage system in urban environment and the unit cell large-scale lab test.

The physico-chemical parameters such as temperature, heat distribution, mechanics, ground water influence and chemical dissolution of the system was investigated under specific thermo-hydro-mechanical conditions and for different thermal energy storage materials.

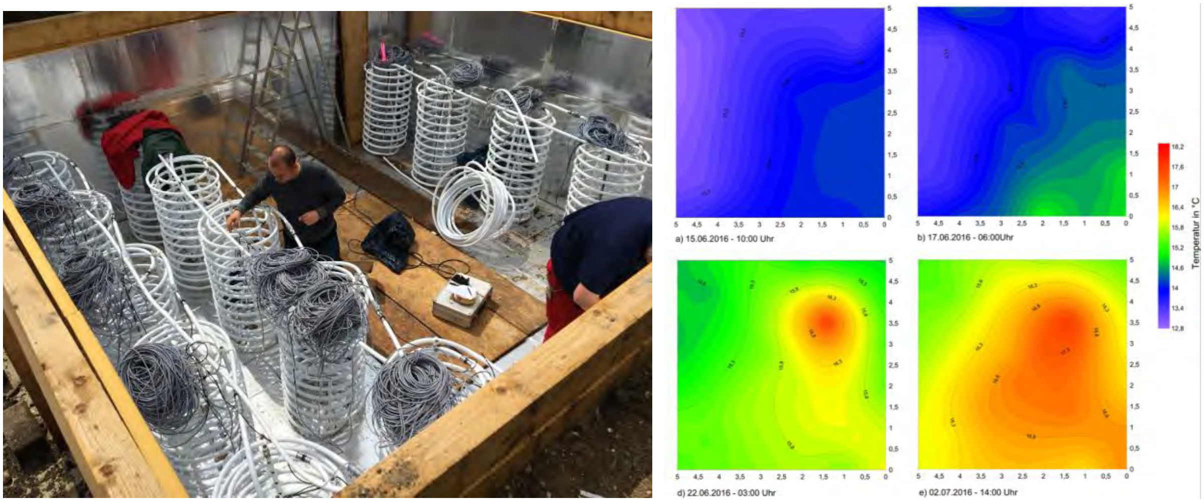


Figure 2: Preparation of the field test and temperature measurements over heating period.

From the point of view of geomechanics, geotechnics, environmental and geochemical behaviour, the influences on ground water, storage material and build environment are extensively analysed. Main results of the numerical simulation and experimental analysis of the ongoing research are presented. More emphasis is given in particular to the behavior of the heat storage geomaterial in terms of its thermal and hydraulic conductivity, specific heat capacity and linear coefficient of thermal expansion as well as the mechanical and cyclic strength and strain, and aging, figure 3.

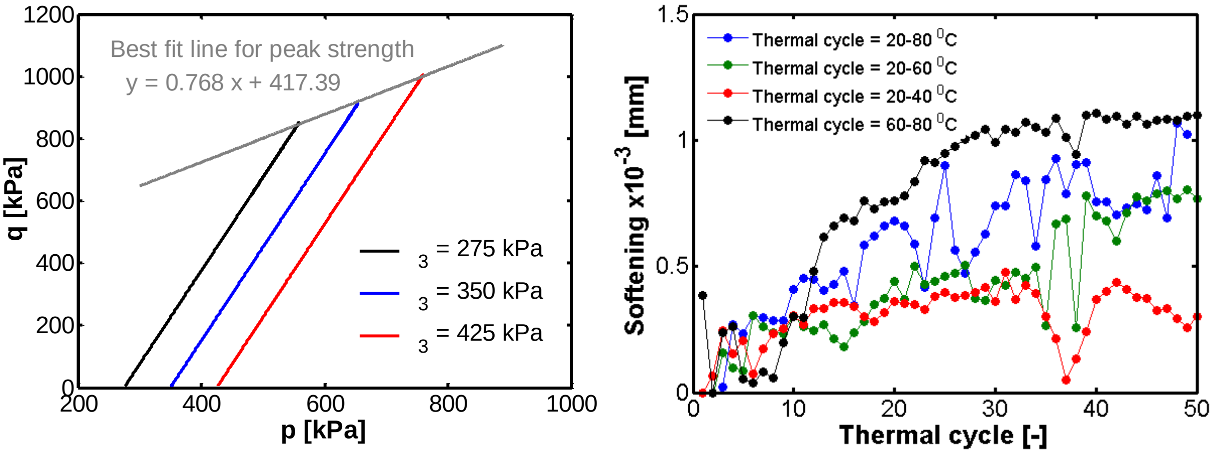


Figure 3: Triaxial and cyclic testing of the cemented heat storage geomaterial.

The development is still ongoing with respect to the modification and realization of the prototypes in view of geotechnical or civil engineering factors and financial aspects.

Acknowledgement

The authors wish to acknowledge the financial support provided by the German Federal Ministry for Environment, Nature Conservation, Nuclear Safety and Energy under Grant number 0325547B 'IGLU'.

Utilization of Deep Geothermal Energy in the Czech Republic: Potential, Present State and Prospect

Dr. Karel Pošmourný, Dr. Miroslav Coubal, Dr. Jan Valenta
Geoterm CZ, Institute of Geology CAS, Institute of Rock Structure and Mechanics CAS,
all Czech Republic

The recently completed studies on the possible utilization of geothermal energy in the Czech Republic (Myslil et al., 2007, Kloz, Pošmourný, 2017 etc.) revealed that the only possible resource to be used for electricity and heat production is the deep geothermal energy at a level of ca. 5 km under the earth surface. At the given geological conditions, specifically those in the Bohemian Massif, we presume especially the utilization of a principle previously known as HDR (hot dry rock), lately called the EGS (*Engineering/Enhancing Geothermal System*). This entails a construction of an underground heat exchanger at a depth with temperatures of 150 °C or preferably around 200 °C. Within Europe, the closest example of such system is known from Alsace, France, where a geothermal power plant is in operation at Soultz-sous-Forets. The exploratory geothermal borehole PVGT-LT1 in Litoměřice represents the first specialized experiment to obtain information on geothermal conditions, as yet from a depth of max. 2110 m. It is a future prospect to build a geothermal heat plant and power plant at this site. The essential problem in the utilization of deep geothermal energy in the Czech Republic is the absolute absence of temperature data from deeper levels. In Bohemia, only 8 boreholes adjusted to temperature measurements deeper than 1500 m are available. About 40 such boreholes lie in Moravia. Another problem is the very uneven distribution of exploratory boreholes and also a lower reliability of measurements from older boreholes drilled for other purposes than the study of geothermal heat. Deeper boreholes with elevated temperatures mostly concentrate to certain small areas formerly subjected to mineral exploration, particularly those focused on lignite and bituminous coal or, in rare cases, oil exploration. In general, a prominent relationship between geothermally prospective areas and deep-seated faults and areas of young Tertiary volcanism (and its deeply rooted ascent path) can be observed in geological conditions of the Czech Republic. The most obvious links between heat anomalies and geological factors in the Czech Republic exist in the Krušné hory Mts. piedmont area and a part of the Krušné hory Mts., and the whole region of the Elbe Fault Zone. A coincidence of heat anomalies and several different fault systems is also observed in the Permo-Carboniferous basins in this region. Another area with a relatively high concentration of heat anomalies is the Upper Silesian Basin, where elevated temperatures are probably associated with deep-reaching ascent paths as well as Mesozoic basic volcanism. An important progress in the knowledge of geothermal heat in the Bohemian Massif can be achieved by the implementation of results of deep refraction profiles within the Celebration project and the reflection seismic profile within the Dekorp project.

References

Kloz, M. & Pošmourný, K. (2014): Revize geotermických map ČR pro vyčlenění geotermicky vhodných oblastí v hloubkové úrovni kolem 5 km. RESTEP. Coordinator: Czech University of Life Sciences Prague; Joint Researchers: Research Institute for Soil and Water Conservation, ECO trend Research centre, s.r.o., CZ Biom, Ministry of the Environment of the Czech Republic. LIFE10 ENV/CZ000649 RESTEP. (Realized with a contribution from financial tool EU LIFE+).

Myslil V., Kukal Z., Pošmourný K., Frydrych V. (2007): Geotermální energie, Ekologická energie z hlubin Země – současné možnosti využívání. Planeta, č. 4/2007, Ministry of the Environment of the Czech Republic, Prague, 32 p.

Deep Geothermal Energy Shaft

Prof, Jana Frankovská, Mgr. Martin Ondrášik, PhD.
STU Bratislava, Slovakia

The Geothermal Energy Survey in Slovakia was launched in the 1960s to realize geothermal wells. The summary information on the geothermal survey of Slovakia is summarized in the Atlas of Geothermal Energy of Slovakia (Franko, eds., 1995). The geothermal energy has high potential in Slovakia. It started to be intensively used especially after 1989, when political orientation turned toward democracy and free movement of capital, which is especially important because of high initial cost of any geothermal project. By 1989 the utilization of the geothermal energy was on the platform of thermal spas and hot springs only. There have been about 16 spas with thermal water all over Slovakia. The spa with the highest temperature of hot spring are in Piešťany, where the water originating from depth 2 000m has temperature 67-69°C. After 1989 many entrepreneurs started their business on geothermal energy where hot water played the first role (spas, aquaparks, greenhouse farms, central heating). At present, geothermal energy in Slovakia is used in 82 locations with a heat output installed capacity of 163,86 MWt, which represents 1 342.3 $l.s^{-1}$ of geothermal water.

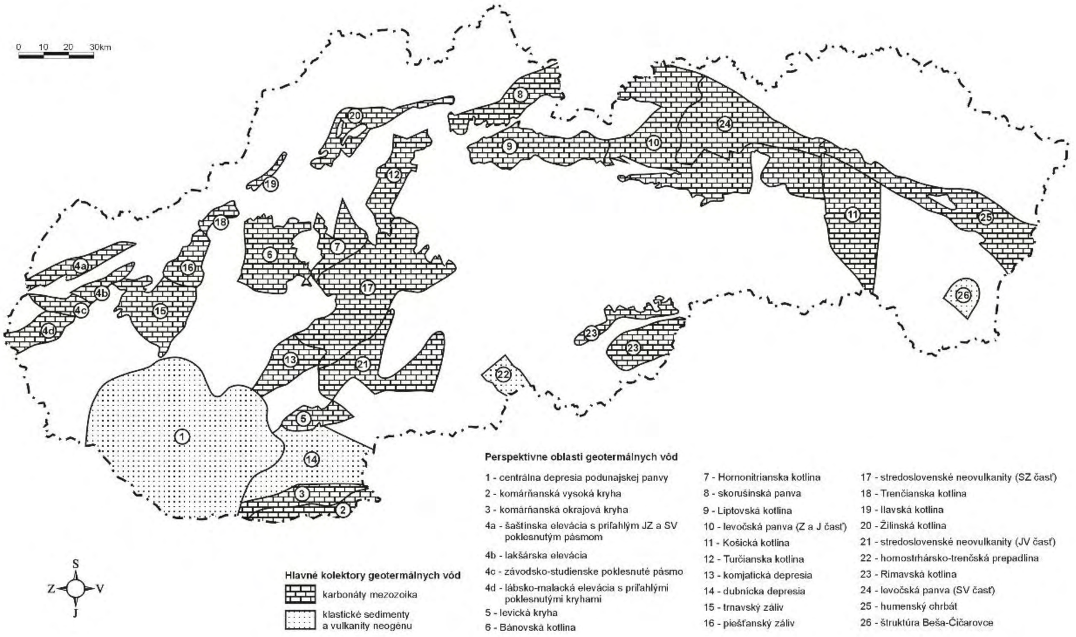
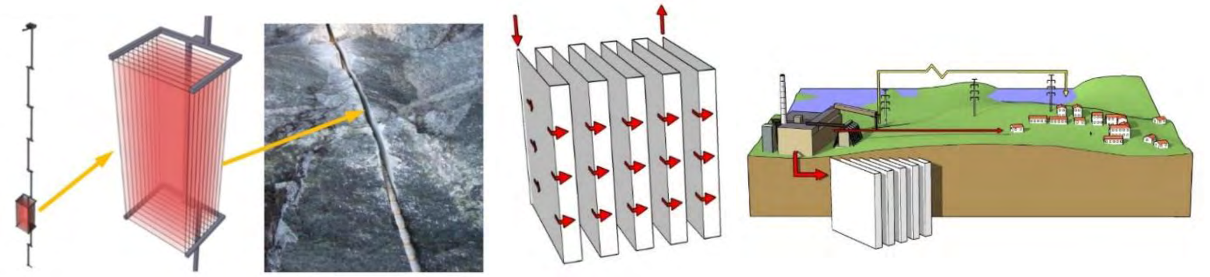


Fig. 1 Perspective areas with sources of geothermal waters in Slovakia (Franko et al., 1995)

Within Slovakia, 27 prospective areas for the use of geothermal energy were allocated. (Fig. 1). The sources of geothermal energy are represented mainly by geothermal waters, which are connected to the Triassic dolostones and limestones of the Carpathian basins. Some geothermal waters are connected also to lowlands filled with Neogene sands, sandstones and conglomerates. Finally, the geothermal water also occurs in the area of Neo-vulcanites where geothermal waters are bound to andesites and their pyroclastic rocks. These rocks with geothermal waters are located at a depth of 200 - 5,000 m, and they contain geothermal water with temperature of 15-240 °C. The geothermal data are from 159 geothermal wells and deep wells conducted to search for oil and gas deposits with depths from 100 to 3616 m.

At the Slovak University of Technology in Bratislava in cooperation with our project partner Dividend Industries, Sweden we are developing a new technology of dry geothermal energy storage and extraction in deep geological environment. The new concept is based on narrow, open and controlled artificial fractures cut from large diameter shafts and galleries. The cutting is made with use of diamond rope (fig. 2). Several parallel fissures can be cut in each section to provide sufficient surface for heat exchange and rock volume for sufficient capacity of the heat storage or extraction. Surface of one wall of the fissure in a section can be up to 5 000 m^2, and we can make up to 100 fissures in a section. The resulting exchange surface is much greater than surface provided by systems based on drilling. Its main features are shafts and galleries; large energy exchange contact surface; controlled heat exchange fissure/slot; nondestructive technology of shaft and gallery excavation; deposition and extraction of the energy; valuable commercially usable by products.



a) b) c) d) e)

Figure 2. Distribution of shaft, galleries and the open fissures of the heat exchanger (a, b). Detail of the diamond rope cut fissure (c), direction of water flow within the heat exchanger from parallel fissures (d) municipality profiting from the geothermal energy storage and extraction (e).

The technologies needed for the development of large volume energy wells are tested on the first pilot testing field located in Stockholm archipelago (Sweden) on an island of Stora Höggarn (Fig. 3).

a) b) c)

Figure 3. Stora Höggarn island, Sweden (a), deep geothermal shaft starting in the middle gallery located inside the island (b, c), cutting and drilling platform above the shaft

The presented concept for storage and extraction of the geothermal energy from the large energy wells is not for single user purposes, but for large urban municipalities with seasonal excess of, and need for the energy which can be deposited or extracted. Solving the problems related to development of the deep energy well in geological environment is only one part of the complex system of green energy management which includes excessive energy production, distribution, accumulation, and storage.