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Coupled thermo-hydraulic modelling of heat storage in an embankment

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Under temperate climates, the storage of excess heat collected in summer to compensate for insufficient heat supply during winter corresponds to the concept of long-term heat storage [1]. Fisch et al. [2] analyzed the cost-performance ratios of twenty-seven existing or planned large-scale storage systems in Europe. Their results showed that the seasonal storage model could meet 50-70% of the annual heat demand, while the diurnal model could meet only 10-20%. The storage of thermal energy is possible in different modalities among which heat storage in the form of sensible heat consists of raising the temperature of a material without changing its initial state [3]. Giordano et al. [4] estimated that a volume of 34 m^3 of water could store 10 GJ of sensible heat, whereas 43 m^3 of saturated soil or 62 m^3 of unsaturated soil (S= 50%) would be required to store the same amount of energy.

To store sensible heat in the ground, heat exchanger loops could be buried in the soil [5]. In an embankment, heat exchanger tubes could be installed during construction with no additional drilling or excavation [6]. This is a major advantage making geothermally-equipped embankments quite promising as eco-friendly devices for energy storage. However seasonal energy storage/retrieval from earth structures arises many challenges with respect to: *(i)* controlling heat loss during the intermediate periods (spring/autumn) [7]; *(ii)* managing the moisture transfer within the structure to ensure energetic efficiency and mechanical stability; *(iii)* evaluating the impact of cyclic temperature variations on the thermo-hydro-mechanical properties (THM) of the soil. Therefore, a coupled thermo-hydro-mechanical model would be necessary to correctly predict the long-term behaviour of these systems and ensure their sustainability.

In this study, the possibility of heat storage in backfill structures was investigated from a geotechnical point of view. It is worth mentioning that neither the technical aspects of heat pump design, nor the economic efficiency of the system will be addressed. The thermal efficiency of horizontal heat exchangers in an embankment was numerically investigated using coupled finite element analysis. The thermo-hydro-mechanical properties of the compacted soil, typically used for building embankments, were first investigated through laboratory testing. The tested soil was sampled near Paris, France [8], with an optimum water content of 16% and a maximum dry density of 1.81 $Mg.m^{-3}$. This material was classified as sandy lean clay, CL, according to the Unified Soil Classification System [9].

The finite element software Code_Bright was used to investigate first the TH behaviour of an embankment, equipped with heat exchangers, during energy storage/retrieval phases through thermo-hydraulic numerical simulations. The analysis considered the heat conduction as well as the vapour and liquid water transfer mechanisms in the unsaturated porous medium. The van Genuchten Model for the water retention curve and a power law was selected for the unsaturated hydraulic conductivity. The parameters of these hydraulic constitutive models were fitted from laboratory tests except the power parameter which was estimated based on [10]. The default procedure was used to handle the temperature-dependency of the thermal conductivity of the soil's solid phase with parameters fitted on laboratory measurements while the thermal parameters of the water and air phases were assumed to be constant.

The parallel horizontal heat exchangers composed of tubes of 0.06 m in diameter were modelled in a 10 m height embankment built on a subgrade soil supposed to have similar thermal and hydraulic properties (Figure 1). Based on the literature [3], at summer time the temperature in the heat exchangers ($T_{exchangers}$) was imposed in the range from 25 to 50 °C during the injection phase, and to 5°C during the retrieval period in winter and was maintained constant during each season.

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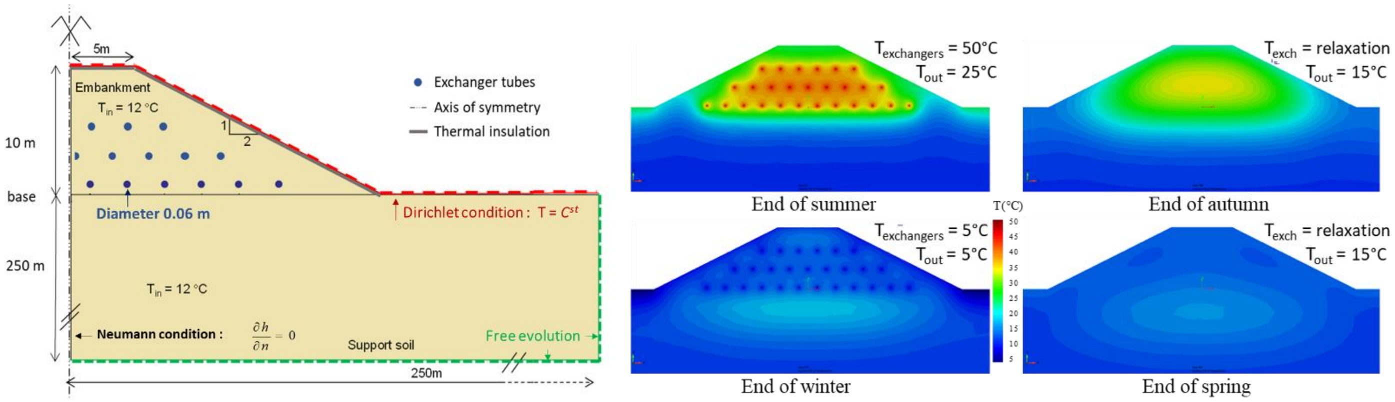
Autumn and spring seasons were considered as relaxation periods during which no temperature variations were applied in the exchangers. Various aspects were investigated such as the exchanger tubes locations and spacing, the heat injection-extraction scenarios, with and without insulation cap, and long-term behaviour over several years [8].

These simulations demonstrated the feasibility of seasonal heat storage in an embankment in temperate climates. Long-term simulations for a 10-year period showed that the heat loss during intermediate seasons tends to decrease reaching a plateau after 7 complete thermal cycles.

For example, in one of the studied cases, 3 staggered rows of exchangers were modelled [Figure 1]. The horizontal distance between the exchangers was considered to be 3 m. To limit the temperature loss, an insulation sheet of 0.05 m thick with a low thermal conductivity of 0.03 W/m.K. [4]. The modelling results showed that the embankment core temperature initially at 12°C, increased evenly up to 34.4°C during summer and then decreased down to 14°C by the end of winter.



a. **b.**

Figure 1: a. Embankment geometry and boundary conditions, b. Temperatures at the end of each season.

Currently the improvement of this approach is under process to consider more realistic climatic conditions (for both temperature and humidity) based on measured meteorological data. The effect of the continuity of the exchangers' loop inducing temperature variations along the path will also be taken into account through a 3D calculation, and would enable the thermal efficiency of the storage to be assessed more accurately. Finally, the consideration of mechanical behaviour should provide an insight on how the stability of the embankment could be affected by the thermal cycles.

References

[1] Xu J., Wang R.Z., Li Y. (2014). A review of available technologies for seasonal thermal energy storage, Solar Energy 103: 610–638.

[2] Fisch M.N., Guigas M., Dalenback J.O. (1998). A review of large-scale solar heating systems in Europe. Solar Energy 63: 355–366.

[3] Pinel P., Cruickshank C.A., Beausoleil-Morrison I., Wills A. (2011). A review of available methods for seasonal storage of solar thermal energy in residential applications. Renewable and Sustainable Energy Reviews, 15/7: 3341-3359.

[4] Giordano N., Comina C., Mandrone G., Cagni A. (2016). BTES, First results from the injection phase of a living lab in Torino. Renewable Energy, 86, 993-1008.

[5] Vieira A., Maranha J., Christodoulides P. (2017). Characterisation of Ground Thermal and Thermo-Mechanical Behaviour for Shallow Geothermal Energy Applications. Energies, MDPI 10/12: 2044-2095.

[6] Le Borgne T., Hamonet V., Rolland S. (2016). Accuther : un stockage géothermique piloté dans un sol reconstitué et structuré, Journées Nationales de Géotechnique et de Géologie de l'Ingénieur, Nancy, France.

[7] Fantucci S., Lorenzati A., Kazas G., Levchenko D., Serale G. (2015). Thermal energy storage with super insulating materials: a parametrical analysis. Energy Procedia, 78, 441-446.

[8] Boukelia A., Rosin-Paumier S., Eslami H., Masrouri F. (2019). Effect of temperature and initial state of fine-grained soils on variation of thermal parameters. European Journal of Environmental and Civil Engineering 23/9: 1125-1138.

[9] ASTM D2487 - 17: Standard Practice for Classification of Soils for Engineering Purposes. Unified Soil Classification System 2017, 10p.

[10] Rutqvist, J., Ijiri, Y. & Yamamoto, H., 2010. Implementation of the Barcelona basic model into TOUGH-FLAC for simulations of the geomechanical behavior of unsaturated soils, LBNL, Office of Scientific and Technical Information, U.S. Dept. of Energy, June, 40 pp.