Experimental investigation of the transient thermo-mechanical behavior of a modular sensible heat storage system

Henok Hailemariam^{1,*}, and Frank Wuttke¹

¹Geomechanics and Geotechnics, Kiel University, Ludewig-Meyn-Straße 10, 24118 Kiel, Germany

Abstract. This paper focuses on the experimental investigation of the transient thermo-mechanical behavior of a lab-scale prototype heat storage system. The experiment involves heating of the storage unit up to a set temperature of 70°C followed by a passive cooling, and monitoring the thermally induced strains and stresses in the sensible heat storage module. The results show a significant development of induced thermal strains and stresses in the heat storage unit upon heating, particularly at the interface between the embedded heating element and the soil.

1 Introduction

Heat demand in many places of the world is seasonal, that is, most of the heat energy is generated during the summer while the highest demand is in winter [1]. The difference between the demand and supply of heat energy is problematic for most societies of our world, forcing their continued reliance on fossil fuels and other unsustainable sources of energy.

One way of bridging this gap is via the use of clean and renewable energy schemes, such as borehole thermal energy storage (BTES) systems, where heat or cold from solar collectors or other forms of energy is stored for long periods for use in future industrial and domestic purposes [2, 3]. Detailed studies on the physical modeling of the coupled heat transfer and water flow characteristics in unsaturated soil-BTES systems were reported in [4] and [5].

Such heat storage systems are usually built at underground levels supporting structures and having load bearing capabilities. When the heat storage units or structural elements are heated and cooled, thermally induced strains and stresses are added to the already present mechanical strains and stresses due to structures built on them [6]. Therefore, careful study of the thermo-mechanical behavior of the heat storage systems, and soil-structure interaction studies especially at elevated temperatures are essential [7, 8].

In this paper, the transient thermo-mechanical behavior of a lab-scale prototype borehole thermal energy storage unit is studied experimentally. The heat transport to the app. 0.9 m³ cylindrical heat storage barrel is facilitated via an embedded cemented borehole heat exchanger (BHE) unit placed at the center of the barrel. The set-up is heated up to a maximum storage temperature of 70°C followed by a passive cooling, and the thermally induced strains and stresses of the soil and cemented BHE are monitored.

2 Experimental program

2.1 Experimental set-up

The solid-liquid modular thermal energy storage set-up consists of a cylindrical plastic barrel with a diameter of 100 cm and a height of 110 cm, a cylindrical cemented BHE unit with a diameter of 15 cm and a height of 100 cm, a 20 cm insulation (i.e. PROBAU Mineralwolle-dämmstoff soft insulation + thick Styrodur [9] hard insulation) for the top and bottom bases of the barrel, a flow meter and a 15 liter capacity CC-215B Huber heating pump [10] (Fig. 1).

Fig. 1. Experimental set-up of the modular sensible heat storage system at Kiel University.

The barrel plastic has a side thickness of 10 mm and bottom thickness of 20 mm, and is placed on a heavy duty wooden pallet (Fig. 1). The BHE unit is equipped with two independent U-shaped plastic pipes for the transport of heat to and fro the soil, and rests on 10 cm height of soil placed on the base of the barrel. The soil

* Corresponding author: henok.hailemariam@ifg.uni-kiel.de

layer below the BHE provides extra insulation for the heat losses via the bottom face of the barrel. The heat carrier fluid, i.e. water without any additives, is circulated using the heating pump inside the BHE. To minimize heat losses, all the pipes carrying heated water were properly insulated.

A total of 32 K-type thermocouple temperature sensors [11], numbered T_0 to T_{31} are used to monitor and record temperatures in the storage unit (Fig. 2). 24 of the 32 thermocouples are embedded inside the soil, 5 are embedded in the cemented BHE and 3 are placed outside the barrel to monitor boundary conditions. The thermocouple sensors are attached to a NI data acquisition unit connected to a PC, and have a measurement error of $\pm 0.45^\circ\text{C}$ [11].

Two 1-LY41-100/120 DMS HBM linear strain gauges [12], labeled S_1 and S_2 , one on the BHE-soil interface attached to the BHE and the other on the outside of the barrel are installed to monitor the thermally induced strains (Fig. 2). The strain gauges have an electrical resistance of $120\ \Omega$ and a transverse

sensitivity of 0.1%. The strain measurements are recorded using a datalogger unit connected to the PC.

Four VW push-in pressure cell stress sensors [13], numbered P_1 to P_4 , are used to monitor and record the thermally induced lateral stresses and pore-gas pressures in the soil (Fig. 2). The pressure sensors are attached to a DT2040 40 channel VW and thermistor datalogger unit connected to the PC, and have a measurement capacity of 350 kPa, and a minimum measurement resolution of ± 0.1 kPa.

And finally, eight CS640 three-rod 7.5 cm long TDR probes [14], numbered M_1 to M_8 , are used to monitor and record the volumetric moisture contents in the soil (Fig. 2). The moisture content measurement set-up also includes a 12 Vdc power supply, a TDR100 time domain reflectometer, a SDM8X50 8-channel solid state $50\ \Omega$ coaxial multiplexer, and a CR800 measurement and control datalogger unit connected to the PC. The CS640 TDR set-up is capable of measuring moisture content of soils with bulk electrical conductivity of up to 5 dS/m, and has a timing resolution of 12.2 ps.

Fig. 2. Schematic representation of the sensors used for monitoring the heat storage unit.

Fig. 3. X-ray diffraction (XRD) diagram of the soil.

2.2 Materials used

An air dried naturally occurring fine sand was used as the heat storage medium. Table 1 shows a list of the obtained geotechnical properties of the soil, and in Figs. 3 and 4, results of X-ray diffraction (XRD) mineralogical analysis and grain size distribution of the soil are shown, respectively. The fine sand particles are primarily composed of quartz and albite minerals (Fig. 3).

A commercial cement-based material, named ThermoCem PLUS [15], was used to construct the BHE. After preparing the BHE using a fresh mix of the ThermoCem PLUS powder and water with a water to solids ratio of 0.802, the BHE was cured for a minimum of 28 days to complete the cement's exothermic hydration processes and achieve its operational geotechnical properties. In Table 2, a summary of the obtained physical properties of the cemented BHE material are presented. And in Fig. 5, the set-up after the installation of the soil, BHE and the sensors is shown.

Table 1. Physical properties of the fine sand.

Property	Value
Gravel, > 2 mm (wt.%)	2.65
Sand, 0.063 - 2 mm (wt.%)	95.6
Silt and clay, < 0.063 mm (wt.%)	1.75
Bulk dry density (kg m^{-3})	1790
Porosity (-)	0.33
Specific gravity of solids (-)	2.68
Grain diameter at 10% passing (mm)	0.12
Grain diameter at 50% passing (mm)	0.33
Coefficient of uniformity (-)	3.33
Coefficient of curvature (-)	1.30
Dry eff. thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) ⁽¹⁾	0.309
Dry eff. specific heat capacity ($\text{M J m}^{-3} \text{K}^{-1}$) ⁽¹⁾	1.355
Unified soil classification system (USCS)	SP ⁽²⁾

⁽¹⁾: measured using Decagon KD2 Pro device

⁽²⁾: poorly graded sand

Table 2. Physical properties of the BHE cemented material.

Property	Value
Water to solids ratio (-) ⁽¹⁾	0.802
Suspension density (kg m^{-3})	1460
Bulk saturated density (kg m^{-3})	1583
Effective oven-dried porosity (-)	0.605
Effective air-dried porosity (-)	0.397
Dry eff. thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) ⁽²⁾	0.450
Dry eff. specific heat capacity ($\text{M J m}^{-3} \text{K}^{-1}$) ⁽²⁾	1.001
28-day water cured uni-axial strength (MPa)	3.013

⁽¹⁾: suspension prepared by hand mixing at room temperature

⁽²⁾: measured using Decagon KD2 Pro device

Fig. 4. Grain size distributions of the soil.

Fig. 5. Installation of the soil, sensors and the cemented BHE.

2.3 Experimental procedure

After an initial circulation of water without heating to remove air from the piping system, the heating phase t_{heating} of the experiment was performed at the T_{max} 70°C for around 4 hours.

Fig. 6. Schematic representation of the adopted heating/cooling regimes of the experiment.

The duration of heating was kept relatively short in order to avoid heat reaching the lateral boundary (plastic barrel), thus avoiding extra thermally induced strains of

the plastic barrel and replicating actual field BTES conditions. After the heating phase, the flow/heating of the fluid was stopped to start the passive cooling $t_{cooling}$ process and the data was recorded for around 46 hours. The loading procedure followed for the experiment is schematically shown in Fig. 6.

3 Results and discussion

3.1 Temperature distribution

Figure 7 shows the time plot of the temperature T distributions in the heat storage soil. For the given heating duration and set heating bath temperature T_{max} (70°C), a maximum temperature of around 35°C is recorded at the BHE-soil interface, sensor T_9 (Fig. 7, left), which is significantly lower than the average

maximum temperature measured at the center of the cemented BHE (59°C), indicating a significant heat loss in the BHE, soil and the BHE-soil interface due to the high thermal resistance or low thermal conductivity of both the BHE cement and the surrounding soil. Whereas, the heat loss in the water carrying pipes (i.e. from the heating bath to the BHE inlet) is generally around 4°C, which is comparatively much lower than the heat losses recorded inside the BHE, soil and BHE-soil interface.

The plots also show no considerable increase of temperature at the sensors placed near the outer lateral boundary of the system as assumed earlier (Fig. 7, right) (i.e. similar temperatures recorded at the sensors placed in the soil near the plastic barrel boundary, sensors T_{11} , T_{14} & T_{17} , and the sensor placed outside the barrel, sensor T_{30} , which represents the room temperature).

Fig. 7. Measured temperature profiles at: sensors near the BHE (left) and sensors at/near the outer boundary of the barrel (right).

Fig. 8. Measured thermally induced lateral stress profiles at the four pressure sensors.

3.2 Stress distribution

In Fig. 8, the thermally induced lateral stress profiles at the four sensor positions are shown along with their respective temperature profiles.

As expected, an increase in the measured thermally induced stress σ_{induced} is recorded at sensors P_1 , P_2 and P_4 , following the shape of the time-temperature profile. The maximum value of σ_{induced} is recorded at the BHE-soil interface sensor P_1 with a value of around 27 kPa, and no significant σ_{induced} is measured at the outer boundary sensor P_3 . The generated stresses are primarily attributed to the expansion and rearrangement of the quartz and albite dominated soil grains.

It should be noted that the generated stresses in the heat storage unit may not be isotropic, with the generation of induced stresses in the axial or vertical direction expected to be of different magnitudes to the radial or lateral stresses shown in this study. Due to the direction of installation of the stress sensors used in this research, however, it was not possible to measure these axial/vertical stresses. Nevertheless, considering the direction of heating, the heat insulation system and boundary conditions provided in this study, the magnitudes of the induced vertical stresses may be lower than the lateral/horizontal stresses reported in this study.

In contrast to the thermally induced stresses, very insignificant changes in the generated gas pressures U_{induced} are recorded, with only around < 1 kPa increase

measured at the BHE-soil interface sensor P_1 . However, unlike in this study, which was performed on a soil at or near dry moisture condition, the generation of excess gas or pore water pressures may be significant in the case of partially or fully saturated heat storage soils/systems.

3.3 Strain distribution

The highest thermally induced strain $\epsilon_{\text{induced}}$ is recorded at the BHE-soil interface sensor S_1 with an average maximum value of around 270 $\mu\text{m/m}$, once a peak temperature condition is reached in the BHE (Fig. 9, left). As expected no strain is generated at the strain sensor attached to the outside of the barrel (Fig. 9, right).

3.4 Moisture distribution

In Table 3, the averages of the volumetric water content θ measurements taken by the eight TDR moisture probes M_1 to M_8 throughout the test duration are shown. Overall, no significant changes in moisture content were observed at all sensor locations during the heating/cooling operation. Comparatively speaking, similar average volumetric moisture content θ_{avg} measurements were recorded by all the moisture sensors ranging at near dry conditions between 0.3 and 1.3% (corresponding to degrees of saturation S_r between 0.9 and 3.9%), indicating the homogeneity of the used soil.

Fig. 9. Measured thermally induced strain profiles at the two strain gauges.

Table 3. Average volumetric moisture contents θ_{avg} measured at the 8 TDR probe locations.

Sensor	θ_{avg} (%)
M_1	0.430
M_2	0.866
M_3	0.285
M_4	0.632
M_5	0.454
M_6	1.196
M_7	1.255
M_8	0.574

4 Conclusions

An experimental lab-scale prototype heat storage system was set up to study the transient thermo-mechanical behavior of sensible heat storage systems. The findings of the experiment, which included heating of the storage unit up to a set temperature of 70°C followed by a passive cooling and monitoring the thermally induced strains and stresses of the system, indicated a significant, but tolerable, increases in the measured thermally induced strains and stresses in the heat storage unit, particularly at the borehole heat exchanger-soil interface, where maximum values of induced strain of around 270 µm/m and induced stress of around 27 kPa were recorded.

The induced stress level, which is mainly attributed to the expansion and rearrangement of the quartz and albite dominated soil grains, is equivalent to that generated by an over-burden soil pressure of around 1.5 m depth in field conditions, and would not be expected to cause a significant impact on the safety and operation of most sensible heat storage systems.

The authors gratefully acknowledge the financial support provided by the German Federal Ministry for Economic Affairs and Energy (BMWi) under Grant number 03ET6122A (Project ANGUS II) as well as the support of Project Management Jülich. We thank Paul Liedtke, Johannes Nordbeck, Amir Sattari, Victorien Djotsa and Bo Wang of Kiel University for their support in setting up the prototype heat storage system. We would also like to thank Kerstin Meier zu Beerentrop of Kiel University for her support in analyzing the XRD measurements.

References

1. F. Merten, C. Krüger, A. Nebel, D. Schüwer, S. Lechtenböhmer, M. Gailfuß et al., Klimapolitischer Beitrag kohlenstoffarmer Energieträger in der dezentralen Stromerzeugung sowie ihre Integration als Beitrag zur Stabilisierung der elektrischen Versorgungssysteme. *Climate Change* **8** (2014)
2. D. Bauer, R. Marx, J. Nußbicker-Lux, F. Ochs, W. Heidemann, H. Müller-Steinhagen, German central solar heating plants with seasonal heat storage. *Solar Energy* **84** (2010)
3. R. Marx, J. Nußbicker-Lux, D. Bauer, W. Heidemann, H. Drück, Saisonale Wärmespeicher – Bauarten, Betriebsweise und Anwendungen. *Chemie Ingenieur Technik* **83** (2011)
4. T. Başer, D. Linkowski, J.S. McCartney, *Charging and discharging of soil-borehole thermal energy storage systems in the vadose zone* (Proceedings of the 7th International Congress on Environmental Geotechnics: ICEG 2014, Melbourne, 2014)
5. T. Başer, T. Traore, J.S. McCartney, *Physical modeling of coupled heat transfer and water flow in soil-borehole thermal energy storage systems in the vadose zone*, In *Geothermal Energy: An Emerging Resource*, Geological Society of America Special Paper 519, Boulder, CO (2016)
6. J.S. McCartney, J.S. Murphy, M.A. Stewart, *Thermo-mechanical behavior of energy foundations* (Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, 2013)
7. P. Bourne-Webb, B. Amatya, K. Soga, T. Amis, C. Davidson, P. Payne, Energy pile test at Lambeth College, London: Geotechnical and thermodynamic aspects of pile response to heat cycles. *Géotechnique* **59**, 3 (2009)
8. B. Amatya, K. Soga, P. Bourne-Webb, T. Amis, L. Laloui, Thermo-mechanical behaviour of energy piles. *Géotechnique* **62**, 6 (2012)
9. BASF, *Styrodur technische daten* (2019)
10. Huber Kältemaschinenbau AG, *CC-215B data sheet* (2019)
11. National Instruments, *Thermocouple and RTD sensors data sheet* (2019)
12. K. Hoffmann, *Eine Einführung in die Technik des Messens mit Dehnungsmess-streifen*, Hottinger Baldwin Messtechnik GmbH, HBM (1985)
13. P. Tedd, J.J. Powell, J.A. Charles, I.M. Uglow, *In situ measurement of earth pressures using push-in spade-shaped pressure cells – 10 years experience*, Geotechnical Instrumentation in Practice, Thomas Telford Ltd., London (1990)
14. Campbell Scientific Inc., *Time domain reflectometry system* (2015)
15. HeidelbergCement AG, *Technical data sheet – ThermoCem PLUS* (2016)