Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 17ecsmge-2019-Y-XXXX

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Energy sheet pile walls – Experimental and numiercal investigation of innovative energy geostructures

Murs de palplanches énergétiques - Étude expérimentale et numérique de géostructures énergétiques innovantes

M. Ziegler, D. Koppmann
Chair of Geotechnical Engineering, RWTH Aachen University, Aachen, Germany

R. Pechnig, D. Knapp
Geophysica Beratungsgesellschaft mbH, Aachen, Germany

ABSTRACT: With the use of thermally activated sheet pile walls renewable energy of the shallow subsurface and especially of open waters can be exploited. This can either be done by prefabricated energy sheet pile walls or by add-on elements for a subsequent thermal activation of existing constructions. For the dimensioning of these innovative systems, it is necessary to have detailed information on possible heat extraction rates and to be able to calculate the short and long-term behaviour of the entire geothermal system. Therefore, large-scale tests were carried out to determine possible heat extraction rates. In addition, a calculation approach was developed, which enables the realistic numerical simulation of energy sheet pile walls.

RÉSUMÉ: A l'aide des palplanches activées thermiquement, l'énergie renouvelable peut être exploitée du sous-sol peu profond et en particulier des eaux ouvertes. Cela est réalisable soit par des palplanches énergétiques préfabriquées ou bien par des éléments additifs aux constructions palplanches existantes pour une activation thermique ultérieure. Afin de pouvoir évaluer le dimensionnement de ces systèmes innovants, il est nécessaire de disposer des informations détaillées en ce qui concerne la performance d'extraction thermique possible. Par ailleurs, il est essentiel de pouvoir calculer le comportement de l'installation géothermique entière à court et long terme. Par conséquent, des tests de grande taille étaient effectués pour déterminer l'extraction thermique possible. De plus, une approche de calcul était développée permettant une simulation numérique réaliste des palplanches énergétiques.

Keywords: sheet pile wall; energy geostructures; large-scale tests; renewables

1 INTRODUCTION

The Chair of Geotechnical Engineering at RWTH Aachen University is investigating energy sheet pile wall systems in cooperation with the Geophysica Beratungsgesellschaft mbH and the SPS Energy GmbH. The research project is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and has the goal to study the efficiency and applicability of energy sheet pile wall systems. Furthermore, a calculation approach for the dimensioning should be developed. The systems under consideration are either prefabricated energy sheet pile walls or add-on elements for a subsequent thermal activation of existing sheet piling constructions. With both systems, the thermal energy of the shallow subsurface and of open waters can be exploited. The latter have a particularly large energy potential due to the high heat capacity of water. The dimensioning of energy sheet pile wall systems requires knowledge of possible heat extraction rates and of the best operating conditions. Therefore, heat extraction tests are performed to determine the heat extraction rates under different boundary conditions. For this purpose, a large-scale test station was built, which recreates the scenario of a sheet pile wall at a waterfront.

For a proper dimensioning, the short and long-term behaviour of energy sheet pile wall systems should be considered. Therefore, a calculation approach was developed based on the results of the large-scale tests. The approach was implemented in an existing finite-differences software to enable the general numerical simulation of energy sheet pile walls.

2 ENERGY GEOSTRUCTURES

Energy geostructures are a special form of closed-loop, geothermal systems. Here, structural or any required components are supplemented with the function of a heat exchanger by integrating additional absorber pipes. These pipes represent the primary circuit of the geothermal system. A heat carrier fluid circulating in these pipes is used to extract or dissipate heat for heating or cooling purposes, respectively. In general, every structural component with contact to the ground can be thermally activated according to this principle, as long as the primary static or sealing function is not affected.

The most common shallow geothermal systems are borehole heat exchangers or ground heat collectors. However, in the last 20 years, more and more energy geostructures have been implemented. In particular, the thermal activation of concrete components in contact to the shallow subsurface has proven to be effective, since the absober pipes can be attached to the reinforcement. Examples of this type of energy geostructures are foundation piles (energy piles), floor slabs, diaphragm walls, pile walls, basement walls (energy walls) or thermally activated tunnels.

The dimensioning of a geothermal system can be performed by means of reference values for the extraction capacity, with the aid of analytical calculation approaches or based on numerical simulations. Energy sheet pile walls differ fundamentally from existing concrete energy geostrucutres in terms of geometry and thermal properties. For this reason, existing reference values or calculation approaches cannot directly be transferred to energy sheet pile walls. Thus, there is a need for the determination of possible heat extraction rates and for the developement of a suitable calculation approach.

3 ENERGY SHEET PILE WALL SYSTEMS

Energy sheet pile walls transfer the principle of energy geostructures to the sheet piling technology. Due to the significantly higher thermal conductivity of steel (ca. 50 W/m/K) in comparison to concrete (ca. 2.5 W/m/K), sheet pile walls are perfectly suited for a thermal activation. SPS Energy GmbH has developed and patented different systems for the thermal activation of sheet pile walls.

One of these systems, the energy sheet pile wall, consist of conventional sheet pile sections equipped with absorber pipes. For an ideal heat transfer and a durable connection the pipes are welded on the soil side of the sheet pile wall (*Figure 1*). This offers the advantage that both the absorber pipes and the connection pipes of the geothermal system are protected from external impacts and are not visible from the outside. The pipe geometry can be flexibly adapted to the sheet pile section. In the lower area, the pipes are additionally protected by a bulkhead plate allowing the energy sheet pile wall to be driven, pressed or vibrated into the ground. Technical advantages of sheet pile walls, such as immediate load-bearing capacity or a possible recovery and multiple use, are still retained. In the area of civil and hydraulic engineering, a wide range of possibilities for an efficient use of energy sheet pile walls can be found. Depending on the area of application, energy can be extracted from the surrounding subsurface, but especially from open waters.

The principle of the energy sheet pile walls has been further developed for the thermal activation of existing sheet piling constructions. For this purpose prefabricated add-on elements consisting of absorber pipes mounted on a steel support plate were designed. These elements are attached to the sheet pile wall on the water side, in a way that the absorber pipes are permanently below the water level (*Figure 1*). In contrast to the energy sheet pile walls the add-on elements primarily use the open water as an energy source. However, this implies that the application is only feasible for sheet piling constructions in contact with open waters (e.g. on river banks) and that the length of the absorber pipes is limited by the depth of the water.

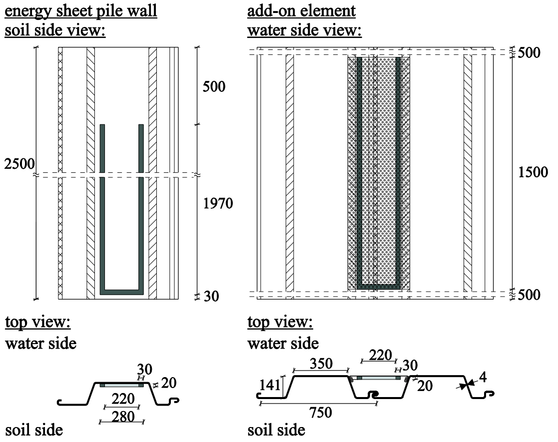

Figure 1. Schematic illustration of a sheet pile section and an add-on element in the test station

4 EXPERIMENTAL INVESTIGATION

To estimate possible extraction rates of energy sheet pile walls and add-on elements large-scale tests have been carried out. A test station, which recreates the scenario of a sheet pile wall at a waterfront has been designed to study the heat transport mechanisms between the sheet pile wall and the soil as well as the open water. These mechanisms are influenced by the thermal properties, the velocity of a groundwater flow or an open water stream and the operating parameters of the geothermal plant, which can be controlled and continuosly measured in the tests.

4.1 Large-scale test station

For the large-scale tests a 2.5 m deep steel basin was constructed on a surface area of 3.0 m times 3.0 m. The basin was insulated to avoid any external thermal influence (*Figure 2*). It is divided into two areas of equal size by an energy sheet pile wall consisting of four sections of type HP 140 S-4. Each of the sections has 2.5 m length and is equipped with an absorber pipe (U-loop) over a length of 1.97 m (*see Figure 1*). Thus, four seperate absorber circuits are available. On the side of the absorber pipes, the basin was completely filled with sand (sand side). On the other side, a layer of sand of 0.5 m thickness was initially added. Subsequently the basin was filled with water up to a height of 2.0 m (water side).

Beside the study of energy sheet pile walls, the test station also enables the investigation of add-on elements. For this purpose, two elements were installed on the water side between sections no. 2 and no. 3 as well as no. 3 and no. 4. Corresponding to the open water depth, 1.5 m long elements respectively absorber pipes of the same pipe geometry as applicated to the energy sheet pile wall were installed.

The velocity of the groundwater flow on the sand side and the velocity of the open water stream can be regulated by two separate circuits. Groundwater velocities of $v_f \leq 2.0$ m/d and water stream velocities $v_w \leq 0.3$ m/s can be set. The volumetric flow Q_i of the heat carrier fluid in the absorber pipes can be controlled by a third circuit. The maximum total volumetric flow Q_{total} in the absorber circuits is 4.0 m³/h. As a heat carrier fluid water is used.

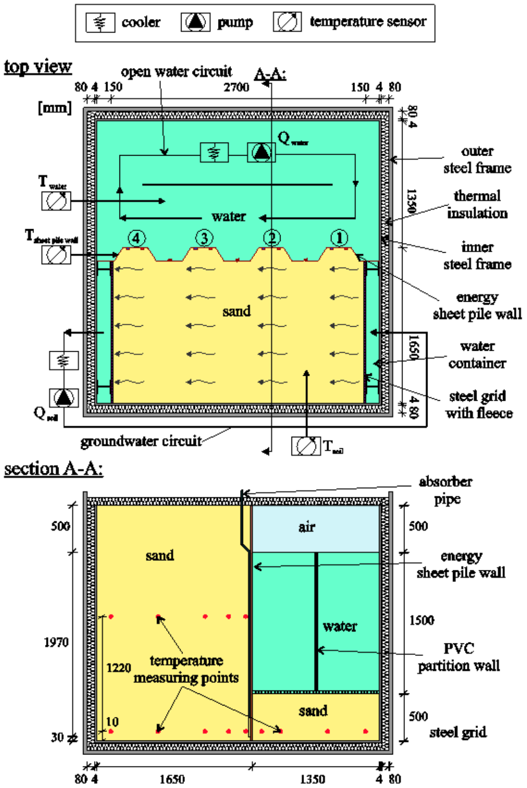

Figure 2. Schematic illustration of the test station

4.2 Monitoring

The temperature of the sand, the sheet pile wall, the open water and the heat carrier fluid in the inlet and outlet of the absorber circuits is measured at a total of 105 measuring positions using high-precision platinum resistance thermometers. In addition, the volumetric flow rates in the four absorber circuits are measured using electromagnetic flowmeters installed in the outlets of the absorber circuits.

The initial temperature of the sand and water side is between 12 - 13 °C. Each test scenario has a duration of 8 h, in which the absorber circuits are operated with an inlet temperature (T_{in}) of approx. 3 °C. During this time, a quasi-stationary state in the temperature distribution occurs due to the convective heat input by the groundwater flow or the forced or natural streams on the water side. The average heat extraction rate P_m [W/m] is calculated for the stationary state by the temperature difference ΔT [K] between inlet and outlet flow (T_{out}), the volumetric heat capacity of the heat carrier fluid $c_{v,w}$ [J/m³/K] and the volumetric flow in the absorber circuits Q [m³/s] related to the thermally activated sheet pile length $L_{act.}$ [m].

$$P_m = \Delta T \cdot c_{v,w} \cdot Q/L_{act.} \qquad (1)$$

5 TEST PROGRAMM AND RESULTS

In the large-scale tests, the influence of a groundwater flow, the volumetric flow in the absorber pipes and the velocity of an open water stream on the heat extraction rates was investigated. In addition, the effect of a parallel or series connection of absorber pipes was tested.

A significant influence of the groundwater flow could not be determined. In case of the energy sheet pile walls the influence of the temperature of the open water as a result of forced or natural convection prevails (Koppmann et. al, 2017). Therefore, only results of experiments with a groundwater flow velocity v_f of 2.0 m/d will be discussed.

For the add-on elements a groundwater flow is of no importance, as they are used directly in the open water.

5.1 Energy sheet pile wall

Figure 2 shows the mean extraction rates and the mean temperature difference of selected large-scale test without (v_w = 0 m/s) and with an open water stream (v_w = 0,15 - 0,30 m/s) in relation to the volumetric flow in the absorber pipes. In addition to the results of two U-loops operated in parallel connection, the results of two U-loops operating in series connection are presented.

Regarding the influence of the volumetric flow in the absorber pipes, it is obvious that an increase of the volumetric flow leads to a slight increase of the mean heat extraction rate. In contrast, the temperature difference between the inlet and outlet of the absorber circuit decreases exponentially. The volumetric flow determines the flow velocity of the heat carrier fluid in the absorber pipes and the flow conditions respectively. For an ideal convective heat transport, a turbulent flow condition should be achieved. Accordingly, the highest extraction rates with up to 285 W/m without and up to 430 W/m with an open water stream were achieved at volumetric flows between 1.0 m³/h and 2.5 m³/h. These volumetric flows lead to a flow conditon in the transition zone or a fully developed turbulent flow. The resulting flow velocities imply a shorter dwell time of the fluid in the absorber pipes, which explains the decrease in the temperature difference. However, this temperature difference should be as large as possible for an efficient and economical operation of the heat pump in a geothermal system. Therefore, an ideal operating point with regard to the required performance and the flow conditions in the absorber circuits must be determined while dimensioning an energy sheet pile wall system.

The considerable differences between the extraction rates achieved with and without an open water stream prove the tremendous energy potential of open waters and the significant influence of an open water stream. At velocities of up to 0.3 m/s in the large-scale tests, turbulent flow conditions are present on the water side. These result in a homogeneous temperature distribution in the water body and an immediate regeneration of the temperature at the sheet pile wall throughout the duration of the tests. The consequence is a steady convective heat flux from the thermal storage of the water into the absorber pipes. Consequently, an open water stream leads to a significant increase in the mean heat extraction rate of the energy sheet pile walls and the mean temperature difference (*Figure 3*). In the large-scale tests, the influence of an open water stream resulted in maximum increases of both values of up to 70 %.

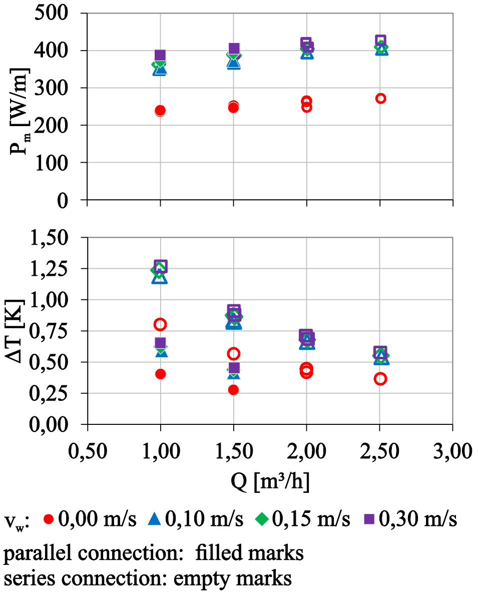

Figure 3. Heat extraction rate P_m and temperature difference ΔT of energy sheet pile walls for different stream velocities v_w related to the volumetric flow Q

In comparison to borehole heat exchangers or horizontal collectors, the absorber circuits on a single sheet pile section (U-loop) are significantly shorter. In order to extend these, individual U-loops can be connected in a series connection. This leads to larger temperature differences being achieved at the same volumetric flow rate. *Figure 3* shows a comparison of the extraction rates and temperature differences of two absorber pipes in parallel and two in series connection. With the series-connected absorber pipes, an almost identical average heat extraction rate could be achieved as with the parallel-connected absorber pipes in the large-scale tests. This is why the marks for the mean extraction rate in the aforementioned figure are difficult to distinct. Correspondingly, the temperature difference between inlet and outlet is almost doubled by a series connection. The higher the temperature difference, the more efficient the heat pump of an geothermal system is operating. Therefore, it is recommended to extend the absorber circuits by connecting individual U-loops in series connection when dimensioning the overall system.

5.2 *Add-on elements*

Figure 4 shows the mean heat extraction rates and mean temperature differences obtained with an add-on element in the large-scale tests with and without an open water stream in relation to the volumetric flow.

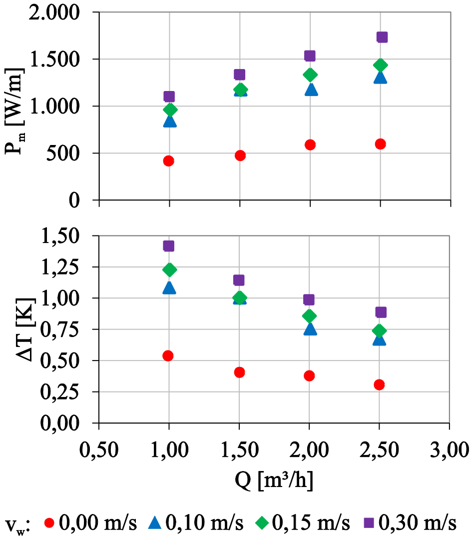

Figure 4. Heat extraction rate P_m and temperature difference ΔT of an add-on element at different stream velocities v_w related to the volumetric flow Q

Even without an open water stream considerably higher extraction rates are obtained with the add-on element compared to the energy sheet pile wall (*see Figure 3*). Due to the direct installation of the element in the open water, the absorber pipe is completely surrounded by water. As a result of the heat extraction at the absorber pipe, a natural convection occurs due to density differences, causing a continous regeneration of the water temperature. The natural convection stream also generates a convective heat flux leading to extraction rates up to 550 W/m. The magnitude of the convective heat flux significantly depends on the stream velocity. The induced streams in the large-scale tests have significantly higher velocities (0,15 - 0,30 m/s) than a natural convection. Consequently, a further increase in performance is achieved leading to extraction rates up to 1.750 W/m.

The outstanding results achieved with the add-on elements confirm the aforementioned energy potential of open waters and the advantage of an installation of absorber pipes directly in open waters. However, the limitations to the installation of add-on elements mentioned in *section 3* must generally be considered.

6 NUMERICAL INVESTIGATION

A complete analysis of energy sheet pile walls requires the use of complex thermo-hydraulical simulations. These types of simulation consider the coupled flow and heat transport processes in the soil, in the open water and in the sheet pile wall. Fully coupled numerical simulations are time-consuming and require high computational capacities. "Model-in-model" - approaches can be used to reduce the computational effort. These are a combination of semi-analytical calculation approaches with classical numerical methods. They have already been successfully implemented for the simulation of geothermal systems.

A "model-in-model" approach for energy sheet pile walls was developed and implemented in the software SHEMAT-Suite (Rath et. al., 2006). This software is based on the finite-difference code (FDM) SHEMAT, which enables the numerical simulation of two- and three-dimensional, (in)stationary flow, heat and mass transfer processes in porous media (Clauser, 2003). The developed approach is based on existing calculation approaches for thermally activated seal panels (Kürten, 2014) and deep borehole heat exchangers (Motthagy and Dijkshoorn, 2012).

6.1 *„Model-in-model" – approach*

In the finite difference model in SHEMAT-Suite the sheet pile wall and the surroundings are modelled. The absorber pipes are depicted by volume-equivalent "pipe cells". One U-loop consists of two vertical cell stacks which are connected by a horizontal cell row (*Figure 5*). The heat transport processes in the absorber pipe are calculated semi-analytically in the "model-in-model" - aproach, which is coupled with the FDM by two interfaces.

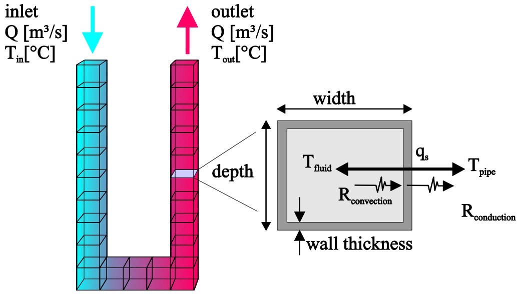

Figure 5. Conceptual model of an absorber pipe in the calculation approach

The temperature at the absorber pipe T_{pipe} in the numerical model represents the first interface. Based on that temperature, the volumetric heat flow between the outer pipe wall and the heat carrier fluid is calculated semi-analytically in the „model-in-model“-approach using a connection of thermal resistances. By the use of thermal resistances the pipe geometry and the volumetric flow can be taken into account in the form of dimensionless parameters. Depending on the heat flow the temperature distribution within the heat carrier fluid is calculated.

The volumetric heat flow is subsequently returned to the numerical model - representing the second interface - causing a change in the temperature at the absorber pipe. The calculation of the temperature distribution in the vicinity of the energy sheet pile wall is carried out using numerical methods. The described routine is repeated in each time step of the numerical simulation.

The calculation approach enables the modelling of individual U-loops or any series connections of different absorber pipes. For each absorber circuit the volumetric flow and the operating mode can be preset time-dependently. As an operating mode a fixed inlet temperature, a fixed temperature difference between inlet and outlet of an absorber circuit as well as a desired heat extraction capacity can be selected.

6.2 Numerical simulations

To validate the developed calculation approach, selected large-scale tests were numerically recalculated. For this purpose the temperature of soil, sheet pile wall and water measured at the beginning of the selected test are set as initial conditions in the numerical model. The inlet temperature and the volumetric flow in the absorber pipes measured in the large-scale tests are accounted for by means of a transient boundary condition. The results of the numerical simulations are the temperature at the outlet of an absober circuit and the temperature distribution in the surrounding soil. Since streaming water cannot be modelled in SHEMAT-Suite, the water is depicted as a solid given the thermal properties of water. The water temperature measured in the large-scale tests is assigned to the solid by a time-dependend Dirichlet boundary condition. An additional convective heat flow due to an open water stream is recreated by an increased thermal conductivity in the contact area between water and sheet pile wall. For this purpose, the heat transfer coefficient α (W/m²/K) is estimated using an analytical approach for the Nusselt-Number for longitudnial flow along a plate (VDI, 2013). The equivalent thermal conductivity λ_m (W/m/K) is then calculated using the relationship of a merely convective (*equation 2*) to a merely conductive heat flux (*equation 3*).

$$\dot{Q}_{conv} = \alpha \cdot A \cdot (T_{water} - T_{wall}) \tag{2}$$

$$\dot{Q}_{cond} = \frac{\lambda_m}{\delta} \cdot A \cdot (T_{water} - T_{wall}) \tag{3}$$

Figure 6 shows the result of a selected large-scale test. To verify the calculation approach and the simplified modelling of the convective heat flow an additional comparative simulation was carried out using a fully dicretized model in the finiteelemente software COMSOL Multiphysics (FEM). The FEM model was assigend the same boundary conditions as the FDM Model, except for a fully coupled simulation of the flow and heat transport processes in the open water using a low-Reynolds k-ε turbulence model.

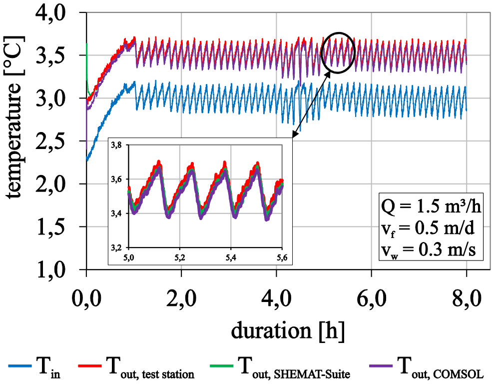

Figure 6. Comparison of the results of numerical simulations with results of selected large-scale test

The numerically calculated oulet temperatures show a very good agreement with the results of the large-scale tests with a maximum deviation of approximately 4 % (*Figure 6*). The results of the FEM and the FDM Model are nearly identical. Thus, the developed calculation approach is a suitable tool for a simplified, but realistic numerical simulation of energy sheet pile walls.

7 CONCLUSIONS

Innovative energy sheet pile walls and add-on elements enable the exploitation of renewable energy from the shallow subsurface and especially from open waters. Heat extraction tests carried out in the context of a recent research project confirm the great energy potential and the special advantage of an installation at open waters. Even without an open water stream, energy sheet pile walls can achieve average heat extraction rates up to 285 W/m. The contact to streaming water leads to a significant increase of performance up to 70 %. By the direct installation of add-on elements in open water bodies heat extraction rates of more than 1 kW/m were obtained in the conducted large-scale tests. By developing a system-adapted calculation approach and implementing it in the software SHEMAT-Suite, a realistig numerical simulation of energy sheet pile walls can be performed. Thus, reliable reference values for possible heat extraction rates and a suitable dimensioning tool for the energy sheet pile wall systems are available.

8 REFERENCES

Bauer, M., Freeden, W., Neu, T., 2018. Handbuch Oberflächennahe Geothermie. Springer Spektrum, Berlin, Heidelberg.

Clauser, C. 2003. Numerical simulation of re-active flow in hot aquifers using SHEMAT and processing SHEMAT. Springer.

Koppmann, D., Ziegler, M., Knapp, D., Pechnig, R., Semmling, T., 2018. Energiespundwände – Erschließung regenerativer Energie mittels thermisch aktivierten Stahlspundwänden. bbr-Fachmagazin **03**, 46-53.

Kürten, S., 2014. Zur thermischen Nutzung des Untergrunds mit flächigen thermo-aktiven Bauteilen. Dissertation, RWTH Aachen University.

Rath, V., Wolf, A., Bücker, M., 2006. Joint three-dimensional inversion of coupled groundwater flow and heat transfer based on automatic differentiation: sensitivity calculation, verification and synthetic examples. Geophyscial Journal International **167(1)**, 453-466.

VDI, 2013. VDI-Wärmeatlas. Springer, Berlin, Heidelberg.