Analysis of the freeze thaw performance of geothermal heat exchanger borehole grout materials

Étude de la résistance au gel et dégel des sondes géothermiques verticales

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ABSTRACT: If the exposure of vertical borehole heat exchangers even to few freeze-thaw cycles may possibly lead to damage either of the body of backfill grout filling the borehole or it may lead to damage of the structure of the surrounding subsoil is subject of an ongoing discussion. Previous research has been focusing on the damage of the backfill grout body solely. The purpose of the research presented with this paper is to study the performance of the entire system subsoil-grouting body in terms of the freeze-thaw resistance by means of experimental analysis. As no standard procedure is available in codes or literature for these particular applications, a defined test setup and a reproducible procedure for the test conduction have been developed. Experiments were conducted in a cylindrical encasement with a sample of grout and saturated sand. Parallel, experiments with blank samples of each material were carried out. The samples were exposed to a temperature range varying between -20 °C and +20 °C. Analysis and interpretation of the results bases on grain size distributions before and after freeze thaw cycles, evaluation of weathering, temperature and strain measurements.

RÉSUMÉ : L’exposition des sondes géothermiques verticales à un nombre (même faible) de cycles de gel-dégel peut amener à une détérioration du mortier de remblayage assurant la jonction entre la sonde et le sol ou à une modification de la structure du sous-sol environnant. Les recherches antérieures se sont uniquement concentrées sur le mortier de remblayage. Il s’agit ici d’étudier expérimentalement la résistance aux cycles de gel-dégel du système complet constitué à la fois du coulis d’injection et du sol. Aucun protocole standardisé pour ce type d’applications n’est disponible actuellement dans les normes ou dans la littérature, un banc d’essai et un protocole reproductible ont donc été conçus pour réaliser l’expérience. Les tests ont été menés dans une gaine cylindrique sur des échantillons constitués de sable saturé en eau et de matériau de remplissage thermique. Des tests avec des échantillons témoins ont été menés en parallèle pour chaque matériau. Les échantillons ont été exposés à des températures variant entre -20 °C et +20 °C. L’analyse et interprétation des résultats est basée sur l’observation des courbes granulométriques avant et après les cycles de gel et dégel, l’évaluation de l’altération des échantillons et les mesures de températures et déformations.

KEYWORDS: geothermal energy, borehole heat exchanger, freeze thaw, grout material, subsoil, experimental.

1 INTRODUCTION

If the exposure of a borehole heat exchanger to freeze thaw cycles may lead to damage either the grouting or the circumfluent subsoil is subject of an ongoing discussion. Freeze-thaw-cycles occur because of an inaccurate dimensioning of the installation, of temporary high abstraction capacities or of modified terms of use, for example added apartments or buildings (Müller 2009).

Vertical borehole exchangers are composed of pipes in which flows a heat-transfer medium and of a backfill grout body between those cables and the surrounding subsoil. Grouting materials serve to stabilize the borehole during the setting up and to obtain a good thermal connection between heat transfer medium and subsoil. Moreover, those materials have to guarantee a sufficient sealing on target to avoid connections between groundwater aquifers.

Sealing of the borehole is related with the freeze-thaw-resistance of the grouting materials and more widely of the freeze thaw resistance of the whole system composed of grouting materials and circumfluent subsoil. Damages are principally due to the properties of water: volume of water contained in the pores of the material expands of 9 % by freezing, which may lead to deteriorate permanently the structure, even after thawing. Hence are connections between groundwater storeys possible which presents an environmental risk.

2 SET OF PROBLEMS

2.1 *Research significance*

Some cases of damage are documented in line with a project of the engineering companies GEOWATT AG and Ingénieurs-Conseils SA (Bassetti 2006). Various experimental analyses have been in addition carried out on the frost resistance of the backfill grout body in recent decades (Herrmann 2008, Müller 2009, Niederbrucker et al. 2008), but few investigations have been performed to evaluate the resistance of the whole system grouting-subsoil. Purpose is to design and develop a new test stand to determine the effects of the subsoil on the freeze thaw resistance of the whole system, focusing on the damages inside the materials as well as the alteration of contact surface, in accordance with conditions related to borehole heat exchangers.

2.2 *Influence parameters of frost in soils*

According experimental and theoretical analyses referenced in literature (Rückli 1950, Reutel et al. 1992), freeze penetration in the soil is influenced by following parameters:

- Grain structure
- Existing and mobilized water
- Temperature distribution during freeze and thaw periods
- Stress distribution

Presence of water in soil is given as main cause of degradations. Types of frost effects are different between fine and coarse grained soils: coarse grained soils presents some structure alterations after freeze thaw cycles, fine grained soils presents heaves and changes of plasticity index due to water pulling during freezing. Most damages in road structures occur when subsoil on ground surface is made of fine grained soils (ZTVE-StB 94).

Forages of vertical borehole heat exchangers attain depths in order of 100 m. Therefore, increasing of effective pressure with depth reduces the negative effects of freeze, as described by Ruckli (1950): for example, frost heave velocity for soils with a grain size between 0.005 mm and 0.010 mm decreases as pressure increases and is around equal to zero for pressures higher than 30 kN/m². Consequently, stress distribution in the soil and therefore on the borehole heat exchanger is considered as an important influence parameter. It leads to suppose that soil has a positive effect on frost resistance of the whole system, what should be verified here experimentally.

3 ACTUAL STANDARDS AND TESTS

There is actually no guideline for evaluating the frost resistance of vertical borehole heat exchangers. Developing a new procedure consists in defining the test experiments and the criteria regarding freezing resistance of the material. Following, an overview of the existing tests on freeze thaw resistance of different types of materials is given as base for possible procedures; under consideration that it should be further investigate with boundary conditions from vertical borehole heat exchangers.

German and international standards for freeze-thaw experiments on soils exist for natural stones and aggregates. The German standard DIN 52104:1982 which gives instructions regarding freeze-thaw behavior of natural stones was replaced by the standard DIN EN 12371, from which the latest edition appeared in 2010. Details about the determination of the freeze thaw resistance of aggregates are given in the German standard DIN EN 1367-1.

For unconsolidated material such as clay, silt and sand, there are no rules and standards. However, those types of soil are subject of research investigations (Rückli 1950, Simonsen and Isacsson 2001, Andersland and Ladanyi 2004).

For freeze thaw resistance of hardened concrete according to the common standards, a distinction between freeze-thaw-resistance on the one hand with and on the other hand without de-icing agents is made (pre-standard DIN CEN/TS 12390-9:2006). The first one corresponds to the resistance to repeated freeze-thaw cycles in contact with water. In case of the second one, the specimen is in contact with road salt. Usually the de-icing agent corresponds to a 3% NaCl solution. In the pre-standard DIN CEN/TS 12390-9 three methods are described: the slab test as a reference, the cube method and the CF and CDF testing (Capillary Suction) as alternatives. The difference between CF and CDF method is the test fluid (with water or with deicing agent).

Although no standards are available about freeze thaw resistance in application to borehole heat exchanger, some research reports deals specifically with freeze effects on grout materials (Herrmann 2008, Müller 2009, Niederbrucker et al. 2008).

Following test procedure takes care of those different standards and research reports and extends the actual analyses considering effects of freeze thaw with the surrounding soil.

4 EXPERIMENTS AND RESULTS

4.1 *Preliminary tests*

Experiments are conducted in a cylindrical encasement with a sample of grout material and soil. A more detailed description of the system for those tests is available in the next part. Preliminary tests has been conducted on samples with reduced dimensions in order to investigate the influence of water saturation of the surrounding soil and to validate the assembly procedure.

Two samples of cement and sand are represented on figure 1. In both cases, cement characteristics and assembly procedure remains the same. If the surrounding soil has a low saturation degree, a cone appears on the upper part of the cement cylinder. The cement part possesses in this case higher unconfined compressive strength and modulus of elasticity with an increasing rate in the order of 40 %.

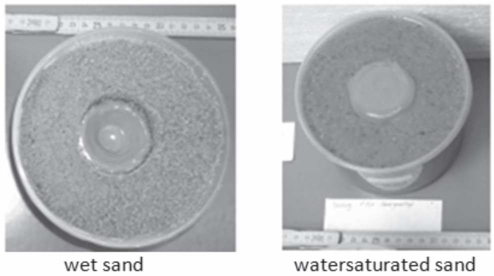

Figure 1: Influence of the water saturation of the surrounding soil

4.2 *Test procedure*

In order to avoid scaling factors, diameter of the grouting material cylinder is in the same range of diameters of real borehole heat exchangers, see figure 2 and 3. Dimensions of the cylindrical encasement were then selected taking in consideration the following statements: on one side, a large distance between rands of grouting material and rands of encasement limits the effects of deformations of the encasement on the grout material due to high temperature changes; on the other side, an increasing quantity of soil may lead to longer procedure time due to freezing and thawing periods and to more constraints regarding transport and storage due to an higher weight of the sample, which are to be considered for a reproductible procedure.

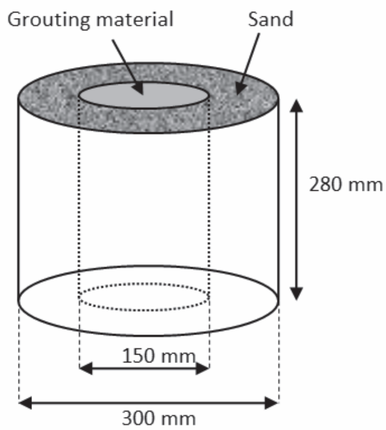

Figure 2: Dimensions of the samples of soil and grouting material

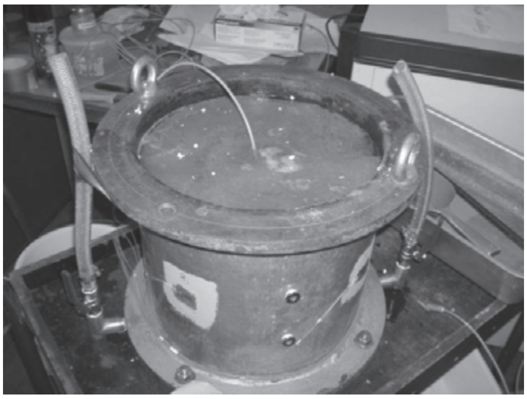

Figure 3: General view after assembly and hardening

As the development of the procedure requires many preliminary tests, the first experiments were conducted with sand for which time for consolidation and water saturation is reduced in comparison with fine grained soils.

The sample represented on figure 4 is as following assembled: firstly, filter plate (see figure 5) is laid in the encasement and the bored part covered with a filter paper. A PVC tube is then inserted in the cut-out of the filter plate, reproducing the use of a tubing casing. Sand is filled around this PVC tube and saturated from the bottom up. At last, grouting material is injected and the PVC tube is vertically removed. Grouting material hardens during 28 days before applying temperature loads. The assembly procedure has been validated and improved on base on experiments with reduced dimensions as related in the previous part.

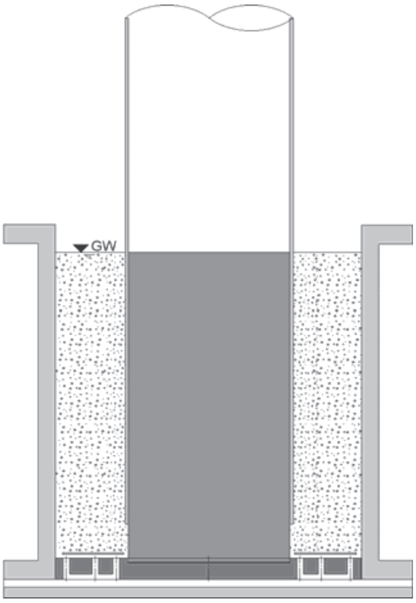

Figure 4: Sectional drawing of the sample during assembly

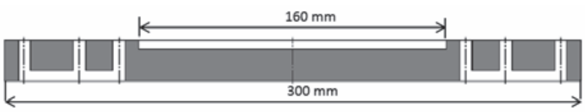

Figure 5: Sectional drawing of the filter plate

4.3 *Temperature measurements*

In case of a borehole heat exchanger, freeze-thaw cycles are mostly due to temperature changes inside the pipes. However, temperature varies during the tests outside the assembled unit in order to keep homogenous samples for performing unconfined compression tests. In the procedures referred in part 3 that deal with other boundary conditions and materials, temperature varies either between -10 °C and +10 °C or between -20 °C and +20 °C. The temperature range selected here between -20 °C and +20 °C is in accordance with the attainable temperatures inside the pipes of a borehole heat exchanger with an additional security factor.

Temperature measures are necessary before execution of the main experiments in order to fix the period of the freeze-thaw cycles, considering that freezing and thawing processes should attain a stable phase. A first sensor is used in order to control the environment temperature, a second sensor measures the temperature on the border of the encasement and a third sensor has been brought during the assembly inside the grouting material. According to those measurements (figure 6), the period of one freeze thaw cycle is fixed to 7 days. Investigations described in next part were carried out after two cycles.

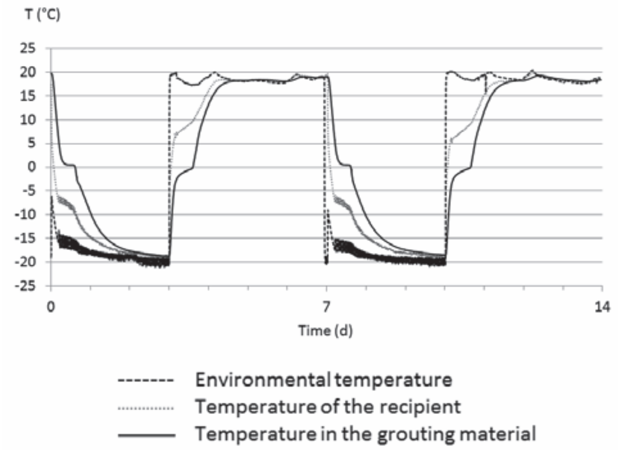

Figure 6: Temperature measurements during freeze thaw cycles on a sample of grouting material and saturated sand

4.4 *Further investigations*

An overview of the tests and investigations which were carried out in the framework of the procedure development is given in table 1.

Table 1: Types of investigations

Sample	Conditions	Investigations
Grouting material and watersaturated sand	With freeze-thaw cycles	Temperature measures, grading curve of sand
Blank sample with watersaturated sand	Without freeze thaw cycles	Grading curve
	With freeze-thaw cycles	Grading curve
Blank sample with grouting material	With freeze-thaw cycles	Surface alteration after each cycle, unconfined compression test
Blank sample with grouting material (in contact with water)	With freeze-thaw cycles	Surface alteration after each cycle, unconfined compression test

Figure 7: Alteration of a blank sample of grout material in contact with air (left) or with water (right) after two cycles

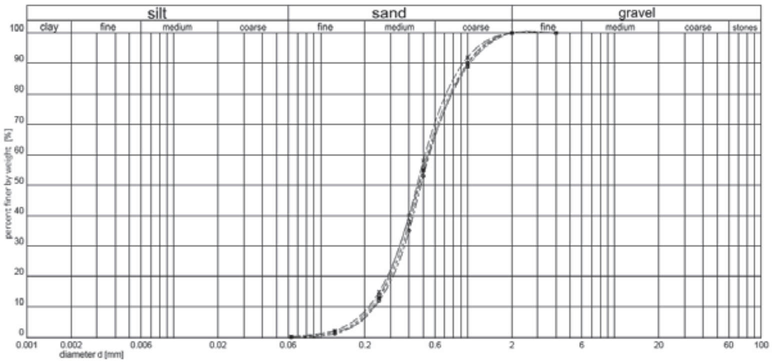

Figure 8: Grade curves of sand used for the experiments before and after freeze thaw cycles

Most frost damages at the surface of grouting material appear when the material is as blank sample directly in contact in water (see figure 7). The unconfined compression tests confirm the fact that freeze thaw cycles have more negative influence on the structure of blank samples of grouting material which are in contact with water, showing in fact a reduced compression strength.

In case of tests with grouting material and watersaturated sand, prelevements of the sand surrounding the grouting material would be carried out. The corresponding grading curves before and after the freeze thaw cycles are similar (figure 8), pointing out that the surface is less altered if sand surronds the sample despite a contact with water and that the presence of this type of soils has a positive effect on the resistance of grouting material regarding freeze thaw resistance. Due to the level of the effective pressure and permeability of the soil, water is pushed out the sample and pore volumes do not increase during icing.

5 CONCLUSIONS

Freeze thaw resistance of the system concerns not only the resistance of the grout material, but also of the surrounding soil and the interface between the two elements. Fine grained soils would be more critical than coarse grained soils regarding freeze thaw effects. Nevertheless, results presented in the literature for those types of soils show that such effects are fastly reduced with increasing effective pressure.

A real alteration of the system does not appear here, confirming a positive influence of the soil on the frost resistance of the system soil-grouting. Considering damages documented in reports, results from the literature and from the present experiments leads therefore to conclude that most frost damages would appear on the ground surface and concern more external elements such as distribution devices or pipes for the connection between building and borehole heat exchanger rather than grouting materials in the forage. Comparing the overall state of stress in the soil along a geothermal borehole heat exchanger with the stresses from freeze-thaw cycles observed in the presented investigations does not suggest the occurance of damages from the operation of a geothermal borehole heat exchanger even in peak load and with freeze-thaw cycles.

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