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Angle of incidence on geothermal tunnel plants – a calculation concept

Angle d'incidence sur les tunnels géothermiques - un concept de calcul

P. Buhmann / primary author
Institute of Geotechnical Engineering, University of Stuttgart, Germany

C. Moormann, B. Westrich additional authors (from same institution)
Institute of Geotechnical Engineering, University of Stuttgart, Germany

ABSTRACT: Shallow geothermal energy provides an essential contribution to the base load of heating energy. The thermal activation of tunnels is an interesting alternative and an economically appropriate supplement to the present hybrid systems in the field of ground engineering. An essential difference between the tunnel absorber and structures such as activated piles and diaphragm wall elements is the use of heat fluxes from the ground, as well as from the inside of the tunnel. Due to this circumstance, the tunnel absorber is assigned to the group of the duo-hybrid systems. The 3.5 km long, double-track tunnel Jenbach is part of the trans-European axis TEN1 Berlin-Palermo and is located in the state of Tirol (Austria) in the vicinity of the river Inn. A tunnel section of 54 m is equipped with absorber pipelines and thereby activates the tunnel geothermally. Due to the proximity of the geothermal tunnel system to the Inn and the fact that the ground has a high hydraulic conductivity, this article focuses on the description of the groundwater flow and its orientation to the activated tunnel section. To quantify the influence of the groundwater flow on the heat extraction performance of the tunnel geothermal plant, numerical simulations had be carried out to show essential dependencies between the tunnel geometry, the angle of incidence and the filter velocity. Based on these calculations a concept has been developed to open up the possibility to take the angle of incidence into account also in two-dimensional calculation models.

RÉSUMÉ: L'énergie géothermique peu profonde apporte une contribution essentielle à la charge de base de l'énergie de chauffage. L'activation thermique des tunnels est une alternative intéressante et un complément économiquement approprié aux systèmes hybrides actuels dans le domaine de l'ingénierie du sol. L'utilisation de flux de chaleur provenant du sol et de l'intérieur du tunnel constitue une différence essentielle entre l'absorbeur de tunnel et les structures telles que les pieux activés et les éléments de paroi moulée. En raison de cette circonstance, l'absorbeur tunnel est affecté au groupe des systèmes duo-hybrides. Le tunnel à double voie Jenbach, d'une longueur de 3,5 km, fait partie de l'axe transeuropéen TEN1 Berlin-Palerme et est situé dans l'état du Tyrol (Autriche), à proximité du fleuve Inn. Une section de tunnel de 54 m est équipée de canalisations d'absorption et active ainsi le tunnel de manière géothermique. En raison de la proximité du système de tunnel géothermique de l'auberge et du fait que le sol présente une conductivité hydraulique élevée, cet article se concentre sur la description de l'écoulement des eaux souterraines et sur son orientation par rapport à la section de tunnel activée. Pour quantifier l'influence de l'écoulement des eaux souterraines sur les performances d'extraction de chaleur de la centrale géothermique à tunnel, des simulations numériques ont été réalisées pour montrer les dépendances essentielles entre la géométrie du tunnel, l'angle d'incidence et la vitesse de filtration.

Sur la base de ces calculs, un concept a été développé pour permettre de prendre en compte l'angle d'incidence également dans les modèles de calcul bidimensionnel.

Keywords: Geothermal tunnel; groundwater; angle of incidence

1 INTRODUCTION

Approximately 32% of the total energy demand is accounted for the temperature control of residential and office buildings (24% for residential buildings and 8% for office buildings), which accounts for approximately 30% of total CO_2 emissions. To cover these thermal loads, approximately 23% of the world's primary energy needs to be expended [10]. Near-surface geothermal energy has the energetic potential to make a significant contribution to meeting the primary energy demand. In addition to the well known systems, such as borehole heat exchangers or surface collectors since the 80s of the last millennium components of the field of ground engineering such as piles or diaphragm walls are thermally activated [3], which leads to a reduction of the installation costs of the ground heat exchanger. A further development of these hybrid systems is the thermal activation of road and rail tunnels, which in contrast to the classic geothermal absorbers also activate heat fluxes from inside the structure. There are approximately 10 tunnel geothermal plants using absorbertechnology worldwide whose heat exchanger is formed by pipes which are located in the concrete of the tunnel shell. Parts of these tunnels are operated as pure pilot plants [2, 4, 7], only a few of them are used to provide heating energy for a specific application [6, 8, 9]. The documented heat flux densities of the existing plants are in the range between 5 and 170 W/m² (average over all plants approx. 37 W/m²). Together with the large surface of a tunnel, geothermel energy from tunnels become an economic alternative in the area of near-surface geothermal energy.

In addition to the large portion of the thermally activated area and the different heat fluxes from the subsoil and the tunnel air space, another special characteristic of tunnel geothermal energy is its thermal behavior in a groundwater flow. While for vertical heat exchangers such as borehole heat exchangers, the thermal extraction rate is unaffected from the direction of the groundwater flow, the geothermal potential of a horizontal heat exchanger changes significantely depending on the direction of the groundwater flow direction.

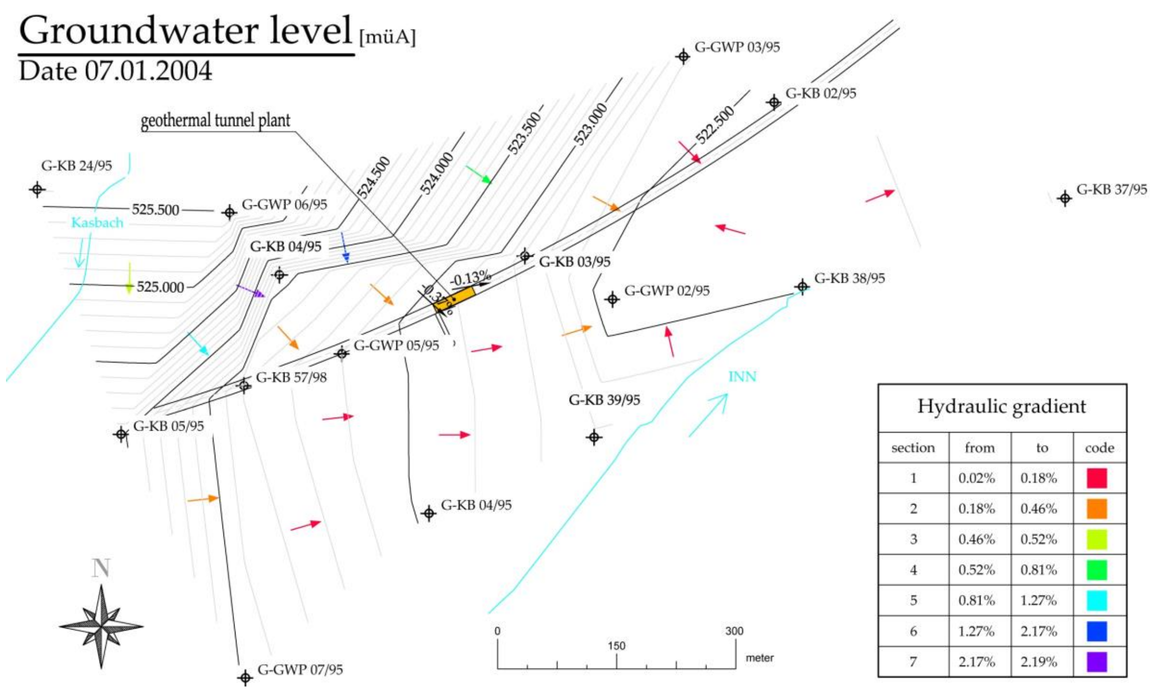
The 3.5 km long, double-track tunnel Jenbach is part of the 10 Trans-European axis TEN1 Berlin-Palermo and is located in the state of Tirol 11 (Austria) in proximity of the river Inn. A tunnel section of 54m is equipped with absorber pipes and thereby activates the tunnel geothermally [5]. The tunnel Jenbach demonstrates how, in addition to the groundwater temperature and the filter velocity, the angle of incidence can have a decisive influence on the heat extraction rate of a tunnel geothermal plant.

This article first introduces the hydrogeological situation at the tunnel Jenbach and how this makes it difficult to replicate the heat transport conditions on the basis of a numerical simulation. The derivation of a calculation approach to take into account an oblique groundwater flow in the dimensioning of a tunnel geothermal plant forms the conclusion of this article.

2 HYDRO-GEOLOGICAL REGIME

The Tunnel Jenbach is situated in the Lower Inn Valley, which separates the northern limestone Alps from the southern central Alps. The geothermal plant is located entirely in fluvial sediments and deposits of the river Inn, whose basis is formed by the gravels of so called Innschotter. The monitoring for the assessment of hydrogeological conditions dates back to 1995. The data base of the groundwater models developed is based on the results of core drilling, short pumping test, level pumping test and experimental wells. Furthermore, a large-scale network of measuring stations was set up in order to be able to understand the hydrogeological conditions and relationships in particular (see Figure 1).

partly stony gravel with a high hydraulic conductivity of $1 \cdot 10^{-2} < \mathrm{k_f} < 1 \cdot 10^{-4}\,\mathrm{m/s}$. Reasons for this large range of hydraulic conductivities are to be seen in the filter sections of the observation levels which extend over several soil layers and the existense of alternation in soil layers. It can be assumed that the water level of the river Inn corresponds with the groundwater level. As an example, Figure 1 shows the groundwater situation evaluated for 07.01.2004. The location of the thermally activated area of the tunnel geothermal plant is highlighted in orange. At the western and eastern end of the geothermal absorber for the upstream the hydraulic gradient i as well as the resulting groundwater velocity v_f according to equation (1) were evaluated.



section	from	to	code
1	0.02%	0.18%	
2	0.18%	0.46%	
3	0.46%	0.52%	
4	0.52%	0.81%	
5	0.81%	1.27%	
6	1.27%	2.17%	
7	2.17%	2.19%	

Figure 1. Network of groundwater monitoring wells in the area of the geothermal tunnel plant

In addition to the survey of the actual groundwater level, the other on-site parameters electrical conductivity, possibly pH / turbidity and the temperature are measured. The Innschotter are formed by mostly fine-grained,

$$v_f = k_f \cdot i \tag{1}$$

The evaluation shows, that on the basis of the analysed groundwater level network, very different flow directions are to be assumed for the tunnel geothermal plant. While the groundwater flow in the west is expected to be almost normal to the tunnel axis, the groundwater flow in the eastern part is almost parallel to the geothermal plant. In a synopsis of the hydraulic gradients and the investigated hydraulic conductivity, filter velocities between 0.1 and 3.5 m/d can be expected over the course of a year in the area of the tunnel geothermal plant. This large spread has a significant influence on the heat extraction rate of a tunnel geothermal system and must be taken into account when dimensioning the heat exchanger accordingly. However, the tunnel Jenbach example also shows that even with a relatively dense network of measuring stations and the performance of numerous tests to determine the hydraulic permeability, it is difficult to determine the absolute filter velocities.

3 NUMERICAL INVESTIGATION

Three-dimensional numerical calculations were performed to estimate the influence of the direction of groundwater flow and the flow velocity on the heat extraction rates of the tunnel geothermal plant. The calculations were carried out with the computer software COMSOL Multiphysics, version 5.3, using the finite element method. The temperature field in the multiphase medium soil is hereby solved for effective thermal subsoil properties as a result of heat conduction and advective heat transfer. For this purpose, the groundwater flow velocity is coupled to the transient heat transport in accordance with equation (2).

$$(\rho c_p)_{eff}\frac{\partial T}{\partial t} + \rho_f c_{p,f} v_f \Delta T + \nabla(-\lambda_{eff}\nabla T) = \dot{Q} \qquad (2)$$

Thermal equilibrium is assumed between the constituent water and soil. Figure 2 shows the calculation model for the investigations. A cuboid calculation area was depicted, in which the tunnel is represented by a cut-off body.

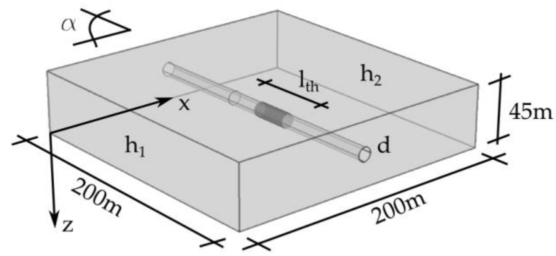


Figure 2. Isometric view of the calculation model to investigate an oblique ground water flow onto a tunnel geothermal plant

The thermal interaction of the tunnel geothermal plant with the subsoil is achieved by specifying a constant temperature boundary condition of 0°C over the length $l_{th} = 54.0m$ on the surface of the cut-off body. The chosen lenght corresponds to the length of the tunnel geothermal plant Jenbach. Outside the thermally activated area, the cut-off body leads to a two-dimensional flow field around the tunnel, which is caused by the potential difference between the hydraulic heads h1 and h2. By rotating the tunnel axis around the vertical axis, the groundwater flows normally to the tunnel axis (90°) or parallel to it (0°). Figure 3 shows the resulting temperature fields around the tunnel resulting from these boundary conditions.

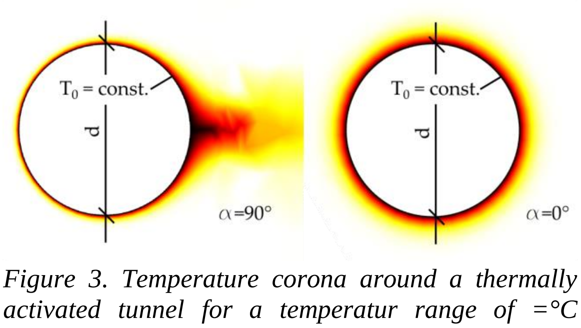


Figure 3. Temperature corona around a thermally activated tunnel for a temperatur range of =°C (dark) to 10°C (light)

It can be seen that an asymmetrical temperature distribution around the tunnel occurs under a flow normal to the tunnel axis, causing high temperature gradients and thus high heat fluxes in the upstream area. As expected, a symmetrical temperature profile with shallower temperature gradients appears for a parallel flow. The temperature field around the tunnel depends not only on the direction of flow but also on the duration of the heat extraction (see Figure 4).

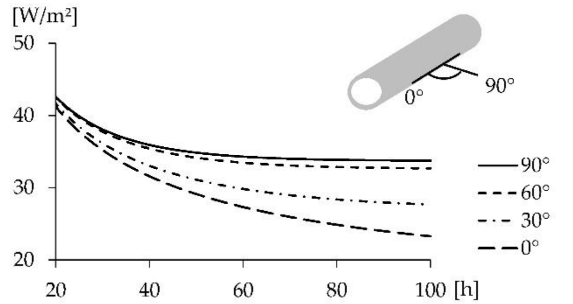


Figure 4. Time-dependent behaviour of the extractable heat flux density under different ground water flow directions

While quasi-stationary heat fluxes have already been established in the case of a flow normal to the tunnel axis, this condition is not reached even after approx. 4 days of operation with a parallel flow. Figure 4 further shows that the extractable heat flux density in the range between 90 ° and 60 ° is only slightly influenced by the angle of the groundwater flow.

This gets also clear when, as in Figure 5, the development of the integral heat flux along the tunnel axis is plotted. On the left hand side of the diagram the area where the thermally unchanged groundwater gets into contact with the tunnel geothermal plant is shown. Starting at a thermal inflow length of approx. 3 m, for a tunnel geothermal plant where the groundwater flow direction is about 60°, the thermal extraction rate is almost congruently to a tunnel where the groundwater flow direction is normal to the tunnel axis.

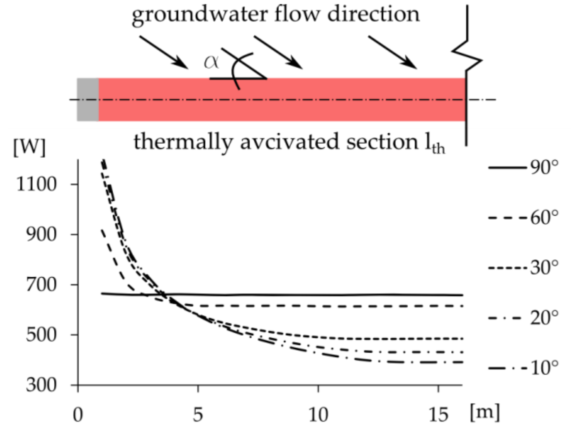


Figure 5. Integral heat flux for each meter of tunnel along the tunnel axis

The thermal inflow effects shown here all show a strongly nonlinear behaviour, which can not be explained solely on the basis of the flow field according to the potential theory. The temporal and spatial development of the heat extraction depends not only on the groundwater flow velocity but also on the characteristic contact length L of the flow around the tunnel. Together with the indisturbed groundwater velocity v_f the contact time t_c of the fluid with the tempered component can be described in accordance with equation 3.

$$t_c = \frac{L}{v_f} \tag{3}$$

If the calculated heat flux densities are related to the reciprocal value of the contact time t_c, linear relationships arise between the extractable heat energy and the geometry of the groundwater flow around the tunnel. The physical unit [J/m²] resulting from this procedure can be interpreted as a specific heat work that is performed per unit area overflown by the groundwater. Figure 6 shows the specific heat work for different tunnel diameters under varying groundwater flow directions.

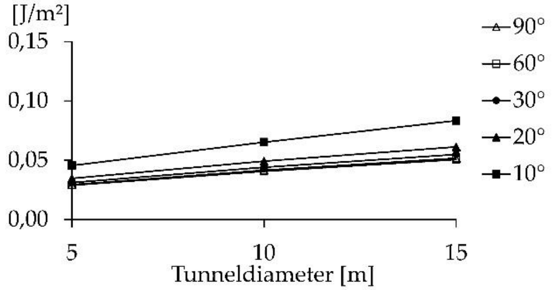


Figure 6. Linear relation between the specific heat work and the flow geometry

4 CALCULATION CONCEPT

The complete discretization of a tunnel geothermal system in three room dimensions is currently not possible due to the computer capacities available in engineering practice. If a two-dimensional computation area is chosen, the heat fluxes from the subsoil to the tunnel absorber have to be corrected by the influence of the groundwater flow angle. In order to correctly take into account the thermal inflow length as shown in Figure 5, investigations must first be carried out on a three-dimensional calculation model as shown in Figure 2. On this basis, factors for correcting the earth facing heat fluxes under a flow orientated normal to the tunnel axis can be derived. Table 1 shows corresponding correction factors for the tunnel geothermal plant Jenbach.

Table 1. Resulting overall heat fluxes at the western and eastern corner of the geothermal plant for different groundwater flow directions, correction factor

Location	90°	70°/20°	factor
	[kW]	[kW]	[-]
West	102	98	0,96
East	58	36	0,62

With the help of these correction factors, the results of the earth facing heat fluxes of a two-dimensional calculation can now be corrected.
For rough estimates of the influence of an oblique groundwater flow to the tunnel geothermal system, earth facing heat fluxes $\dot{q}_{90°}$ of a two-dimensional simulation can be corrected via the relationship according to equation(4).

$$\dot{q}_{\alpha} = \frac{\dot{q}_{90°}}{-0.7 \cdot ln(\alpha) + 1.06} \tag{4}$$

In this equation, enter the angle of the groundwater flow according to the convention in Figure 4 and in radians. This equation was derived on the basis of the numerical calculation results for a finite tunnel geothermal system and is valid for a range of $10° < \alpha < 60°$.

5 CONCLUSIONS

The analyzes of the geological and hydrological boundary conditions using the example of the Jenbach tunnel show that even with a narrow network of measuring networks and numerous tests to determine the hydraulic permeability, it is possible that the filter velocity spreds over a wide range. In addition to this, for tunnel geothermal system which are located in direct proximity to an open water body, tidal fluctuations can influence the groundwater flow in time [1]. Numerical basic investigations on the influence of an inclined groundwater inflow of a tunnel geothermal plant on the heat extraction rate have shown that the influence of flow angles of $90° < \alpha < 60°$ can be negleted and the groundwater flow direction can be assumed to be normal to the tunnel axis. This is confirmed for free flow by [11]. For flow angles between 0° (parallel to the tunnel axis) and 60° special investigations have to be carried out both for the evaluation of the thermal potential and for its evolution in time. The earth facing heat flux density of a tunnel geothermal system flowing in parallel amounts to approx. 50% of the heat flux density, if there is a groundwater flow normal to the tunnel axis (see Figure 5). Consequently, when designing a tunnel geothermal system, the influence of an inclined groundwater inflow can not be neglected.Using the approaches presented in this work, it is possible to correct the results of two-dimensional calculations of tunnel geothermal plants by the influence of an oblique groundwater flow.

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