

POSSIBILITIES OF USING NUMERICAL SIMULATIONS IN THE DESIGN OF ENERGY TUNNEL

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ABSTRACT: This paper presents a numerical investigation of an energy tunnel lining, focusing on a practical and computationally efficient thermal modelling strategy, using the MIDAS GTS NX finite element software. The analysis is based on a model in which heat transfer in the ground is governed by conduction only. Groundwater flow is not modelled explicitly, but its potential influence is approximated using an equivalent thermal conductivity derived from thermal dispersion theory. Due to software limitations, it was not possible to implement anisotropic thermal conductivity directly, so a single averaged effective conductivity was assigned uniformly to the ground domain instead.

The numerical model simulates the thermal interaction between the tunnel lining, the embedded heat exchange pipes, and the surrounding ground. The thermal response is evaluated in terms of the thermal distribution within the tunnel lining, the surrounding ground and pipes, as well as the heat flux distribution along the tunnel perimeter. The results are compared with reference numerical studies of the Torino metro that are available in the literature and were presented by Barla et al.

Despite the modelling approach's simplifying assumptions, the computed thermal performance shows good agreement with the reference solutions. This suggests that for preliminary design studies and parametric analyses, a conduction-based model enhanced by equivalent dispersive thermal conductivity could reliably estimate the overall energy potential of tunnel linings. The proposed methodology offers a practical alternative to fully coupled thermo-hydraulic modelling, while still capturing the essential features that govern the thermal behaviour of energy tunnels.

1. INTRODUCTION

The growing demand for sustainable, low-carbon energy systems has stimulated increased interest in using underground structures for geothermal energy. Energy tunnels, which incorporate heat exchange pipes in their linings, provide a means of exploiting shallow geothermal energy without the need for additional drilling (Fig.1). Newly constructed tunnels in particular can therefore contribute to the supply of renewable energy for heating and cooling applications.

In practice, two different technologies for integrating heat exchanger pipes into tunnel linings are typically employed. With conventional tunnelling methods (e.g. the New Austrian Tunnelling Method, or NATM), the absorber pipes are typically attached to non-woven geosynthetics off-site before being placed between the primary and secondary linings (Adam & Markiewicz 2009). When mechanised tunnelling is used, tunnel-lining segments containing the heat-exchange pipes are precast in a factory and then placed on site by a Tunnel Boring Machine (TBM) (Barla et al. 2016). The heat exchanger pipes used for these applications are made of polyethylene and are able to withstand high pressures and temperatures, resist corrosion, and guarantee high durability. The most common pipe diameters used in tunnel applications are 25 mm and 32 mm, with respective wall thicknesses of 2.3 mm and 2.9 mm. These pipe geometries are a compromise between mechanical fatigue and heat transfer. The thermo-fluid inside the pipes is typically propylene glycol mixed with water. Heat is exchanged between the fluid and the surrounding ground through the concrete lining, enabling heat to be extracted or injected depending on the season.

Despite their potential, energy tunnels present several challenges for numerical modelling. The complex geometry of tunnel linings, the curved layout of embedded pipes and the coupled processes

between the fluid, the concrete lining and the surrounding ground require a comprehensive numerical approach and tools. Although finite element methods (FEM) have proven effective for modelling energy piles and borehole heat exchangers, their application to energy tunnels remains comparatively limited. The physical processes occurring throughout the modelled system are complex, involving mechanical, thermal, hydro and chemical processes and impacts in particular. Heat transfer occurs by both conduction (through the rock mass, lining material and pipes) and convection (through the heat transfer fluid in the pipes, the groundwater flowing in the surrounding ground and the air flowing inside the tunnel). Standard numerical models for practical use do not include all of these processes and influences and always require a certain degree of simplification, as well as the selection of the most essential processes and influences to be taken into account in the numerical model.

This paper aims to demonstrate the application of the finite element method for an energy tunnel lining segment using the thermal module of the commercial software MIDAS GTS NX (Korea). The focus is on thermo simulation aspects relevant to engineering practice.

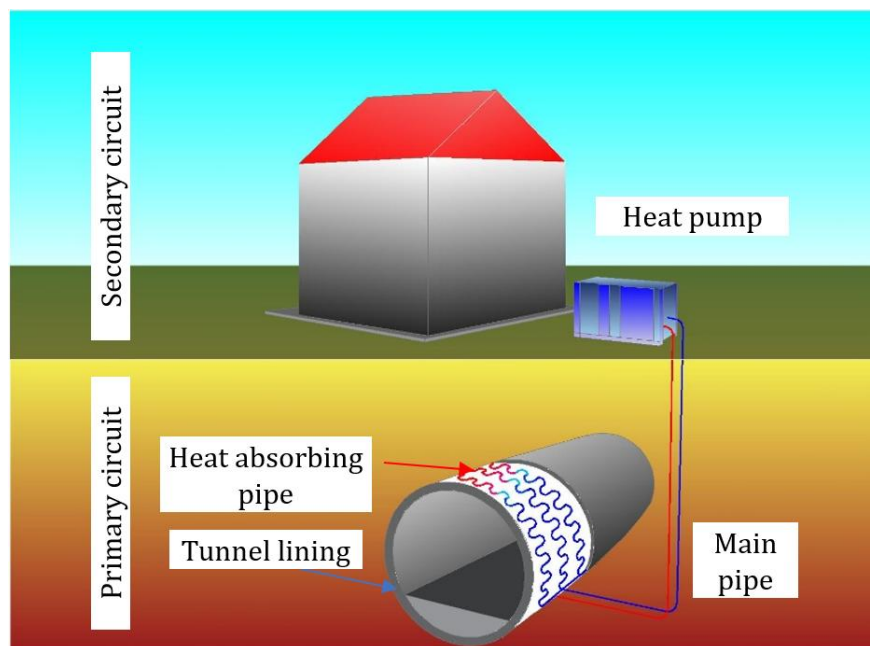


Figure 1: Scheme for the use of technology for the implementation of heat exchangers in the tunnel lining for heating or cooling

2. A CONCEPTUAL APPROACH TO CREATING A NUMERICAL MODEL USING MIDAS GTS NX

To compare the results of the 3D conduction numerical model of an energy tunnel presented in this paper using MIDAS GTS NX software, the input geometric and material characteristics of the numerical model corresponded to those of the model presented by Prof. Barla et al. in (Barla et al. 2016), which we assume to be the reference model in our paper. In the aforementioned paper, Prof. Barla and his team presented a thermo-hydro numerical model of an energy tunnel segment of the Torino metro using FEFLOW software.

The 3D numerical model that we present includes:

- conduction heat transfer inside the tunnel segment;
- conduction heat transfer inside the ground;
- conduction heat transfer in the pipe walls;
- convection heat transfer inside the fluid in the pipes.

The numerical model does not explicitly consider groundwater flow or advective heat transport resulting from it. To account for the potential influence of groundwater flow on heat transfer, a

simplified thermal dispersion approach was adopted. Unlike the reference model, the tunnel ventilation and operational heat sources inside the tunnel were not included in the model.

The numerical model consists of the following geometric parts:

- solid 3D elements representing the 30 cm-thick segmental concrete tunnel lining;
- solid 3D elements representing the surrounding ground;
- one-dimensional (1D) elements representing the heat exchange pipes, which are arranged in a curved (serpentine) configuration within the lining.

The effect of advection was represented in the presented model by an enhanced effective thermal conductivity λ_{ef} , using the following approximative formula (Yang & Nakayama 2010; Afshari et al. 2019):

$$\lambda_{ef} = \lambda_{stagnant} + \lambda_{disp.} \quad (1)$$

where $\lambda_{stagnant}$ corresponds to the thermal conductivity of ground in the absence of groundwater flow and $\lambda_{disp.}$ to the thermal dispersion conductivity assuming convective heat transfer resulting from underground water flow.

The contribution of thermal conductivity due to dispersion was estimated based on classical porous media heat transport theory. The thermal dispersion conductivity component can be approximated using the formula (Yang & Nakayama 2010):

$$\lambda_{disp.} = \rho_w c_w \alpha \frac{v_D}{n} = 4.18 \times 10^6 \text{ J/m}^3\text{K} \times \alpha \frac{v_D}{n} \quad (2)$$

where ρ_w is water density (1000 kg/m³), c_w specific heat capacity of water (4180 J/(kg K)), α - dispersivity, v_D - corresponding Darcy velocity, n - porosity.

The longitudinal thermal dispersivity α_L is defined along the preferential groundwater flow direction (i.e. downstream direction) and the transversal dispersivity α_T denotes thermal dispersivity perpendicular to the flow direction.

Based on this approach, different thermal dispersion conductivities $\lambda_{disp.,L}$ a $\lambda_{disp.,T}$ can be obtained in longitudinal (flow-parallel) direction and transverse (flow-perpendicular) direction. Consequently, different values of effective conductivity are obtained in different directions.

Since the MIDAS GTS NX software does not allow thermal anisotropy to be taken into account in the model, harmonic averaging of the effective conductivity values was used instead (assuming the two transverse conductivity components perpendicular to the groundwater flow direction are equal):

$$\lambda_{ef.,average} = \frac{3}{\frac{1}{\lambda_{ef.,L}} + \frac{2}{\lambda_{ef.,T}}} \quad (3)$$

The average value of effective thermal conductivity $\lambda_{ef.,average}$ (isotropic effective thermal conductivity), as determined in this way, was considered throughout the model. Thus, unlike the reference modelling framework adopted by Barla et al., the present approach is a conductive model only and does not explicitly account for the preferential direction of groundwater flow. A uniform enhanced conductivity case was considered only as an upper-bound limit, bearing in mind that this approach overestimates advective heat transport by increasing heat conduction throughout the domain in all directions.

3. INPUT PARAMETERS OF THE NUMERICAL MODEL

Figure 2 shows a simulated tunnel with a circular cross-section and an internal diameter of 6.8 metres, located 21.5 metres below ground level. The width of the model is 120 m and the height is 78 m. The segmented concrete lining is 30 cm thick. The pipe loops are placed at 30 cm intervals in the lining segment, with an external pipe diameter of 25 mm and a thickness of 2.3 mm (see Figure 3). The 'Pipe Cooling' tool, which is part of the MIDAS GTS NX software, was used to describe the medium fluctuation in the pipe. The internal diameter of pipe is 0.0204 m, convection coefficient is 1000 W/(m²K), specific heat 3.8 10³ J/(kg K). The assumed Darcy groundwater flow velocity is $v_D = 1.5$ m/day. The assumed inlet temperature to the pipe heat exchanger system (T_{inlet}) corresponds to values of 28 °C in summer

and 4 °C in winter, respectively. The initial ground temperature is assumed to be 10 °C. The flow velocity of the heat transfer fluid in the pipes is assumed to be 0.4 m/s (turbulent regime).

Based on formulas (1) and (2), the following values of effective conductivities in both directions are determined:

$$\lambda_{ef,L} = 906.97 \text{ W/(mK)} \text{ a } \lambda_{ef,T} = 90.30 \text{ W/(mK)} \quad (4)$$

According to equation (3), the isotropic equivalent effective thermal conductivity has a value of $\lambda_{ef,average} = 129 \text{ W/mK}$. The thermal characteristics of ground material (Torino subsoil) are mentioned in Table 1 (Barla et al. 2016).

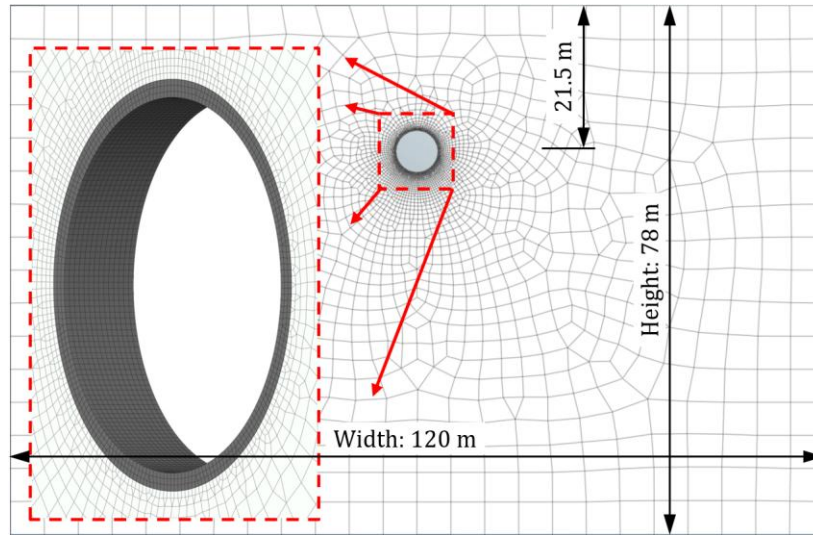


Figure 2: Scheme of the numerical model

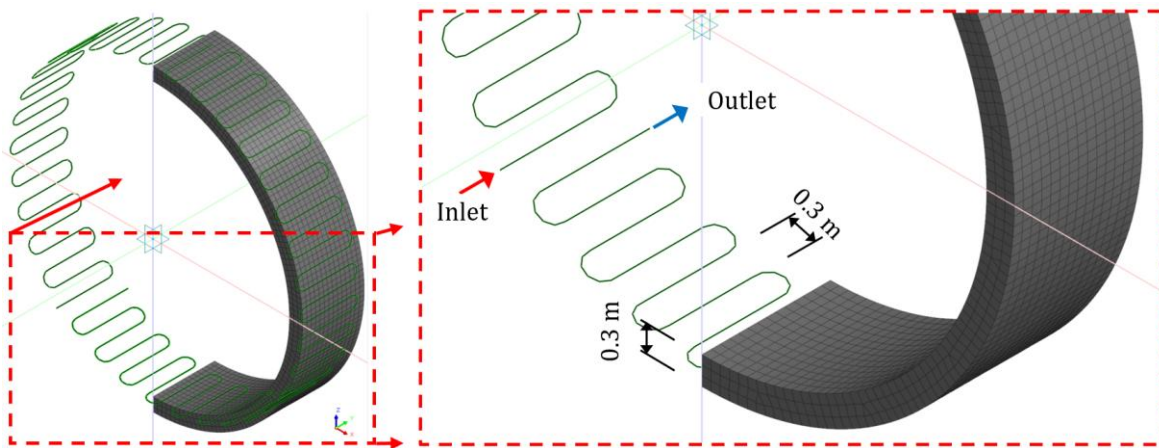


Figure 3: Detail of the pipes system in the tunnel lining

Table 1: Thermal parameters of the Torino ground (Barla et al. 2016)

Parameter	Value
Porosity n [-]	0.25
Bulk volumetric heat capacity of water $\rho_w c_w$ [MJ/m ³ /K]	4.2
Bulk volumetric heat capacity of the solid $\rho_s c_s$ [MJ/m ³ /K]	2
Thermal conductivity of the water λ_w [W/m/K]	0.65
Thermal conductivity of soil solid particles λ_s [W/m/K]	2.8
Longitudinal dispersivity a_L [m]	3.1
Transversal dispersivity a_T [m]	0.3

4. RESULTS OF THE 3D NUMERICAL ENERGY TUNNEL AND ITS COMPARISON WITH A REFERENCE STUDY

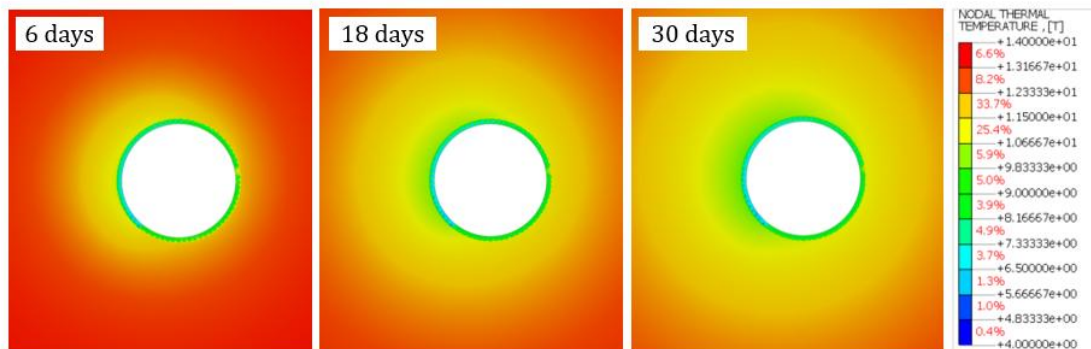
The results of the 3D numerical model created using MIDAS GTS NX software are as follows:

- time distribution of temperatures in the tunnel lining, surrounding ground and in pipes;
- development of heat transfer in the tunnel lining and surrounding ground.

The obtained temperature and heat flow results are then compared with those of the reference numerical model created in FEFLOW software and presented in (Barla et al. 2016).

Comparative graphs showing the results of thermal 3D numerical model created in MIDAS GTS NX software, with the influence of groundwater flow approximated by dispersive conductivity, alongside the results of the reference coupled thermo-hydro 3D numerical model created in FEFLOW software, are shown in Figures 4 to 6.

a) Temperature redistribution in mass



b) Temperature redistribution in lining

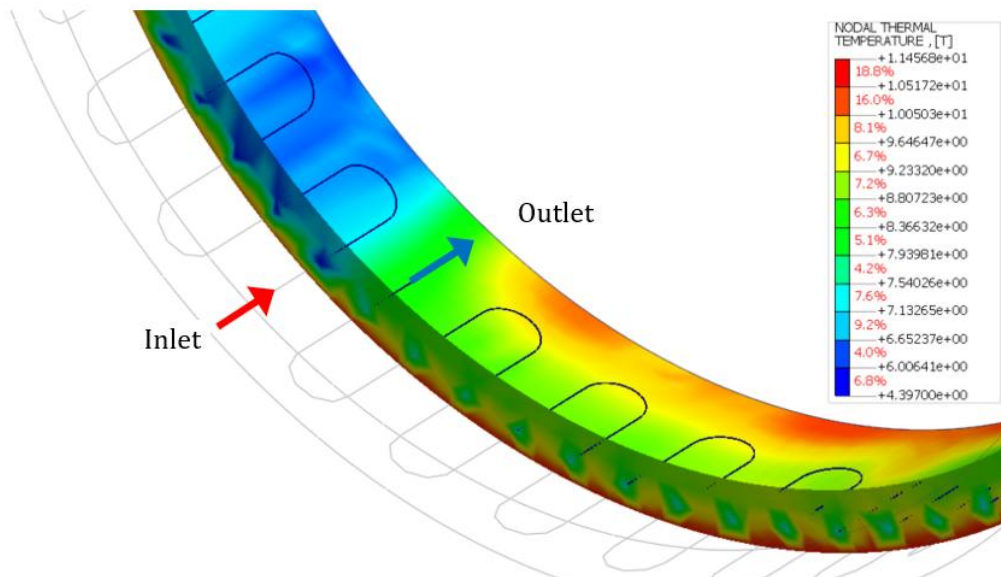


Figure 4: Temperature redistribution in a) mass (ground) and b) in segmental tunnel lining (winter)

The heat flux along the tunnel is not uniform. In winter lower values are observed near the inlet point due to the lower temperature difference between the circulating fluid and the surrounding ground. The heat flux then increases progressively towards the outlet point. In summer condition the situation is opposite.

Nevertheless, this simplification enables the overall thermal response of the tunnel lining to be quantified. Notably, the resulting heat flux provides a meaningful estimate of the total thermal power exchanged between the energy tunnel and the surrounding ground — the primary performance indicator for energy tunnel applications.

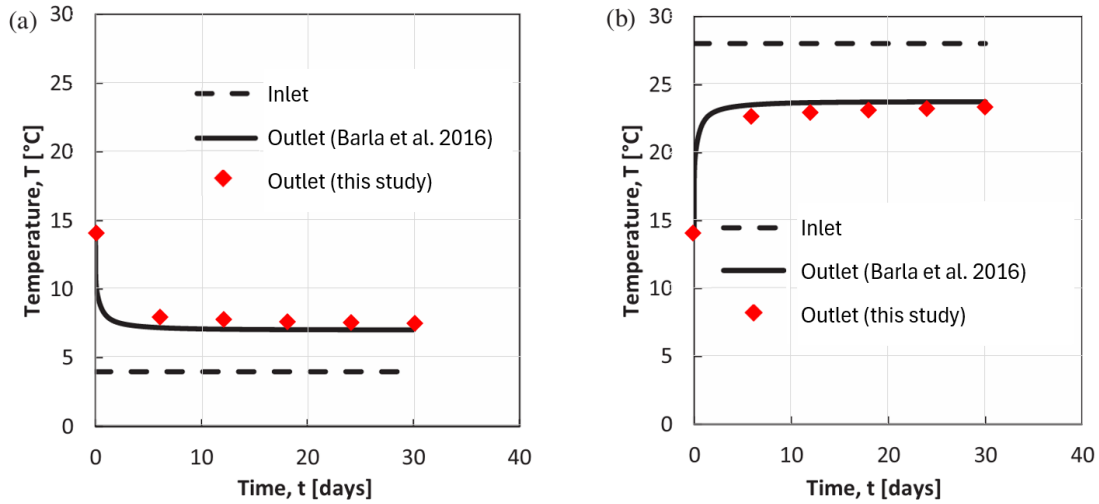


Figure 5: Imposed inlet and computed outlet temperature for (a) winter and (b) summer (adapted from Barla et al. 2016)

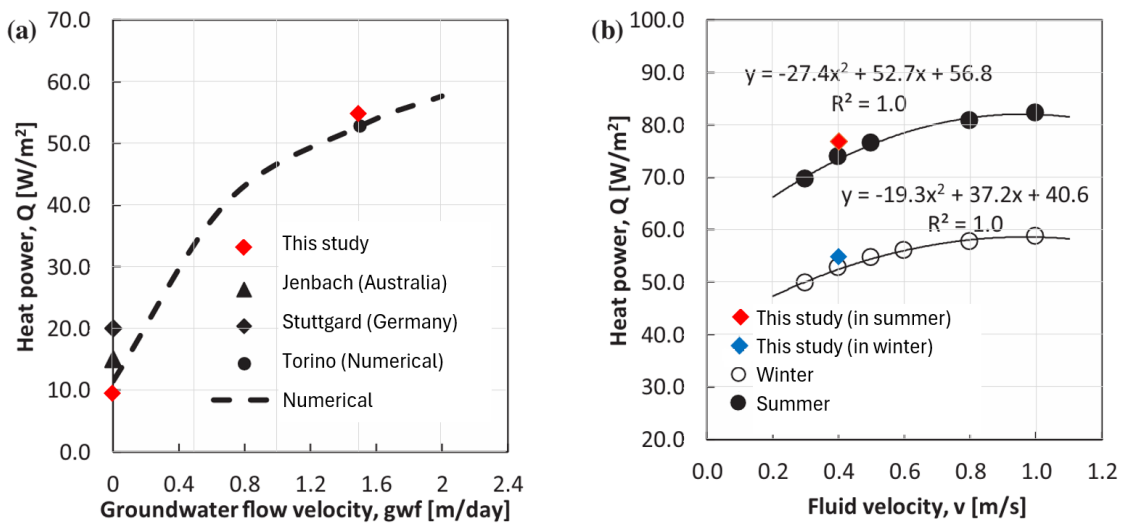


Figure 6: Effect of (a) groundwater flow velocity in winter and (b) heat transfer fluid flow rate in pipes (adapted from Barla et al. 2016)

The results of the temperature distribution and heat flux simulation obtained using the simplified model presented here, utilizing MIDAS GTS NX software, illustrate very good agreement with the results of the reference model.

Without the influence of thermal convection, the simplified conduction 3D numerical model shows, in agreement with the reference model, a heat power value of 10 W/m², while considering a groundwater flow velocity of 1.5 m/day, a heat power value of 55 W/m² (Fig. 6(a)).

The heat power value corresponding to a heat transfer fluid velocity of 0.4 m/s in the pipe also yields identical results to those in the reference study, under both summer and winter conditions (see Fig. 6(b)).

5. CONCLUSIONS

This paper investigated the thermal performance of an energy tunnel by developing a numerical model in MIDAS GTS NX software. The model focused on the thermal response of the tunnel lining, the surrounding ground and thermal transfer fluid. Particular attention was paid to representing the effects of groundwater flow within the limitations of a conduction-based finite element framework.

Groundwater flow was not modelled explicitly. Instead, its potential influence on advective heat transport was approximated by introducing an effective thermal conductivity derived from thermal dispersion theory. Due to software constraints, anisotropic thermal effective conductivity could not be

implemented directly, therefore, a single, averaged, effective conductivity was uniformly assigned to the model domain. This approach does not reproduce the preferential direction of groundwater flow, which is considered explicitly in advanced thermo-hydraulic reference models.

Despite these simplifications, the numerical results show good agreement with the reference modelling framework presented by Barla et al. in terms of the overall thermal response and total heat exchange between the tunnel lining, ground and thermal transfer fluid. This suggests that, when assessing the integral thermal performance of energy tunnel, a simplified conduction-based model with equivalent dispersive conductivity can deliver reliable and consistent results.

The adopted methodology offers a practical, computationally efficient alternative for preliminary design studies and parametric analyses of energy tunnels where the primary interest lies in total thermal power rather than detailed groundwater flow patterns. In order to analyse and design an energy tunnel from primary static and energy perspectives, a combined thermo-mechanical model must be implemented.

LITERATURE

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