Feasibility and energy performance of an energy segmental lining for a subway tunnel

Benoît Cousin[1], Alessandro F. Rotta Loria[1], Andrew Bourget[2], Fabrice Rognon[2], Lyesse Laloui[1].

[1] Swiss Federal Institute of Technology in Lausanne, EPFL, Laboratory of Soil Mechanics, Lausanne, Switzerland.
[2] CSD INGÉNIEURS SA, Lausanne, Switzerland.
* benoit.cousin@epfl.ch

Introduction and motivation

So-called energy segmental linings couple the structural support role of the lining of tunnel boring machine (TBM) excavated tunnels with the heating (or cooling) role of the geothermal heat exchanger through the principle of both shallow geothermal and aerothermal energy. Currently, a literature review and a market analysis suggest that only one segmental tunnel lining project has been constructed with a subsequent actual energy exploitation, while a few other applications considered the thermal activation of tunnels as energy tunnels. As a consequence, very limited knowledge is available in this scope. To address this challenge, this paper tackles the analysis and understanding of the innovative energy tunnel lining technology through the study of the influence of numerous design solutions applicable to such technology on the related energy performance. Being the current major urban tunnelling project in Europe, the Grand Paris Express project for the future subway infrastructure of the Paris region is considered as the case study for the investigations presented, focusing on a section of the line 16 in the area of Chelles.

Features of the study

First, this work defines a practical methodology for the integration of the heat exchanger system in the segmental lining from the segments manufacturing to the pipe connection at the rear of the TBM, focusing on minimising the impact of such an installation on the TBM advancement. Then, this study investigates the energy performance of the energy segmental lining through time-dependent thermo-mechanical finite element analysis. For a given ring dimension, several design solutions, such as the pipe layout (considering minimum pipe spacing for different pipe dimensions), the heat carrier fluid flow regime and the concrete thermal properties are examined. Finally, this work presents a business model for energy tunnel lining and assesses the influence of the aforementioned design solutions together with the thermally activated tunnel length on the profitability of such a system, considering the various contractual dispositions during the geothermal plant operation.

Results and discussion

As for other ground heat exchanger systems, the results show that the energy performance of the energy segmental lining is strongly impacted by the adopted design solutions. Among the four pipe layouts considered, (horizontal or vertical layout pattern with 20 mm or 32 mm pipes diameter), selecting the smaller diameter pipes with a vertical pattern allows to install the longest heat exchanger pipe per segment and represents the optimal solution in terms of lining surface extracted thermal power. The influence of additional design solutions on this layout energy performance is illustrated in Figure 1. Increasing the heat carrier fluid flow rate to achieve more turbulent conditions in the pipes represents one way to improve the energy performance of energy tunnels. This influence decreases for a successive increase of the Reynolds number as well as with time. Improving the segment thermal conductivity through the use of silica rich aggregates in the concrete mix is also a way to improve the energy efficiency. This influence increases with increasing values of the Reynolds number and time, but decreases for a successive increase of this parameter. All the aforementioned design solutions influence the capital investments (pipe length and diameter) and/or the operation costs (head loss and resulting pumping power) of the ground heat exchanger power plant. Nonetheless, the profitability of the energy segmental lining is reached between 5 to 10 years depending on the system design.

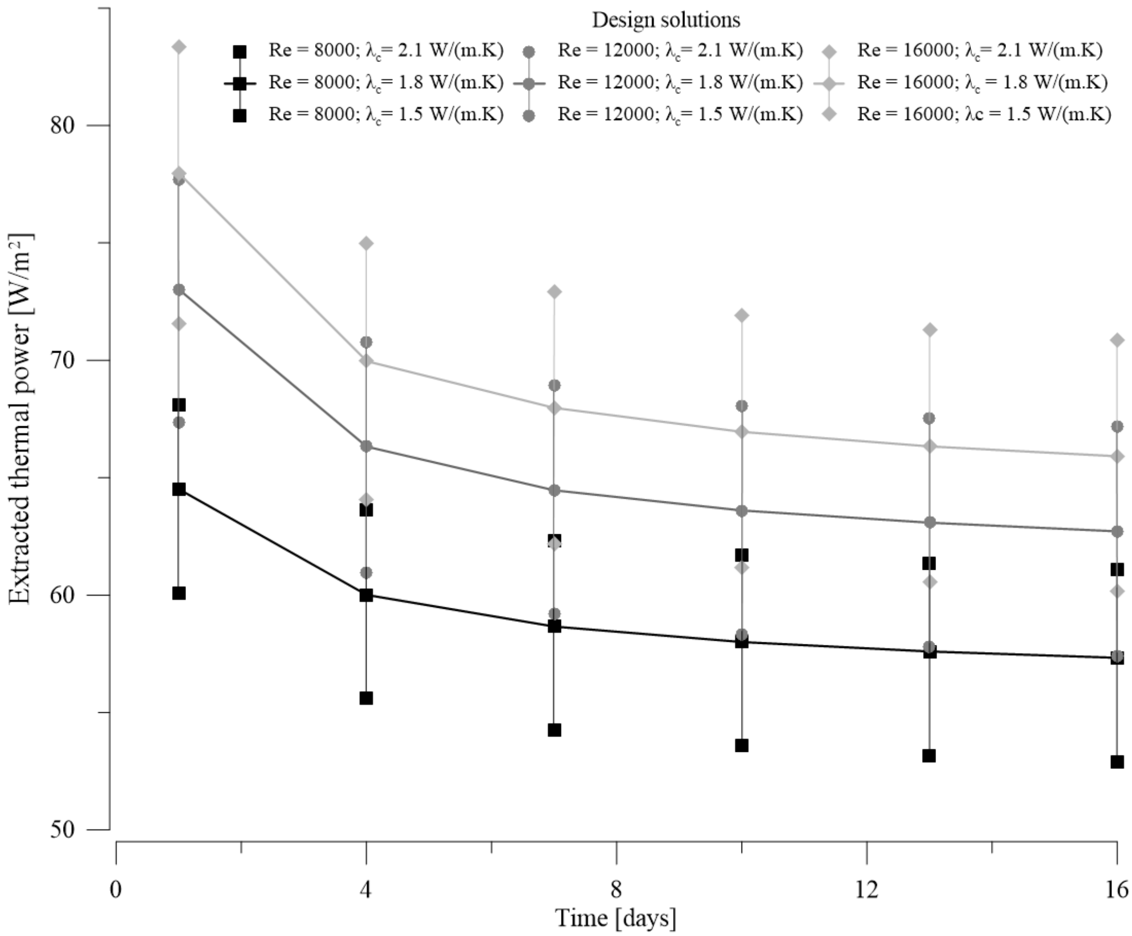

Fig. 1: Extracted thermal power of a given pipe layout for different flow regime and concrete thermal conductivity (Re [-]: Reynolds number; λ_c [W/(m · K)]: concrete thermal conductivity)

Concluding remarks

This study presents a first advanced analysis of the energy efficiency of an energy segmental lining. While a segmental lining may suitably be used for geothermal and aerothermal heat exchange, the design of the latter must consider the several influence of design solutions on the system energy efficiency (independently as well as with each other). Moreover, when the geothermal heat exchange can be quantified based on present knowledge, the aerothermal heat exchange requires further work to be accurately assessed, in particular regarding the convective boundary condition at the tunnel wall interface.

References

Barla, Marco; Di Donna, Alice; Perino, Andrea (2016). Application of energy tunnels to an urban environment In: GEOTHERMICS, vol. 61, pp. 104-113. - ISSN0375-6505

Bourne-Webb, P.J., Bodas Freitas, T.M. & da Costa Gonçalves, R.A., 2016. Thermal and mechanical aspects of the response of embedded retaining walls used as shallow geothermal heat exchangers. Energy and Buildings, doi:10.1016/j.enbuild.2016.04.075

Di Donna, Alice, Francesco Cecinato, Fleur Loveridge, et Marco Barla. « Energy performance of diaphragm walls used as heat exchangers ». Proceedings of the Institution of Civil Engineers-Geotechnical Engineering 170, nº 3 (2017): 232-45

Franzius JN and Pralle N (2011) Turning segmental tunnels into sources of renewable energy. Proceedings of the Institution of Civil Engineers – Civil Engineering 164: 35–40

Nicholson, D.P., Chen, de Silva M., Winter A., Winterling R., 2014. The design of thermal tunnel energy segments for Crossrail, UK. ICE Engineering Sustainability 167 (ES3), 118-134

Laloui, L. and Di Donna, A., 2013. Energy geostructures: innovation in underground engineering, ISTE Ltd and John Wiley & Sons Inc

Société du Grand Paris. (2016). Lot 3 – Mémoire de synthèse géologique, hydrogéologique et géotechnique

Ravn, S. and Reinke, P. (2004), Twin-tube, single-track high-speed rail tunnels and consequences for aerodynamics, climate, equipment and ventilation, Proceedings of Tunnelling Asia 2004, New Delhi, India, Vol. 1, No. 1, pp. III/11-III/26