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

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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 tunneling 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.
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

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