Doctoral Dissertation
Doctoral Program in Civil and Environmental Engineering (37thcycle)

Energy retrofitting of existing tunnels

from conceptualization to full-scale implementation

By

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Declaration

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The global transition to renewable energy sources is at a critical juncture, necessitating immediate and innovative solutions to address the climate impacts associated with historical energy practices. In this regard, shallow geothermal energy emerges as a renewable, reliable and easy-to-access solution offering decentralized, low-carbon heating and cooling. This technology may be crucial in aligning with the objectives outlined in recent climate agreements, including the Paris Agreement of 2015, the European Green Deal of 2019 and the Glasgow COP26 of 2021. Notably, energy geostructures deserve noteworthy attention, as these can promote the sustainability of the carbon-intensive construction industry, thereby advancing environmental goals. Among them, energy tunnels have gained considerable engagement in recent years due to the larger ground-contact volume than other energy geostructures and the possibility of harnessing heat also from inside the underground environment.

This Doctoral Dissertation presents a comprehensive investigation into innovative technologies aimed at instrumenting the existing heritage of tunnels for geothermal energy exploitation. In this regard, their ageing and decay context is properly taken into account, thus developing systematic approaches to fit varying states of repair and diverse levels of refurbishment necessity.

The Dissertation commences with a twofold bibliographic study that explores the latest advancements in energy tunnel technology, as well as the most established strategies worldwide to manage and refurbish existing tunnels. Regarding the former, following a brief review of the available methodologies to thermally activate newly built tunnel linings based on the excavation method, the geothermal performance of energy tunnels is thoroughly investigated with specific reference to well-known case studies. About the latter, instead, after going through worldwide tunnel management guidelines of proven relevance, the current most established interventions for maintaining, rehabilitating and upgrading existing tunnels are deeply examined. Finally, some noteworthy cases of repurposed tunnels are presented and discussed.

Subsequently, the solutions developed to thermally activate existing tunnels are disclosed. For each of them, characteristics and advantages are outlined, the expected installation details and issues described and the possibility of real implementations analysed. Significant attention is devoted to integrating the setup phase of the heat

exchanger pipes into standard refurbishment workflows. The geothermal potential of each energy retrofitting solution is assessed through thermo-hydraulic numerical modelling, investigating a wide variety of thermal, hydrogeological and aerothermal settings. Their economic viability and attractiveness are also evaluated in comparison to other carbon-intensive thermal energy sources.

The feasibility assessment of the aforementioned technology has culminated in the realisation of a new full-scale experimental prototype. This embodies the second energy tunnel implementation in Italy and is noteworthy as the first in the world to leverage rehabilitation works for thermal activation. Situated in a motorway tunnel in the North-West of Italy, this installation functions as a demonstrator for the effective utilization of geothermal heat in anti-icing applications on motorway pavements, facilitating the recharge of the geothermal reservoir through solar heat storage. By means of interactive thermo-hydraulic numerical modelling, the geothermal-based anti-icing solar-collecting system is demonstrated to heat the pavement surface by 3.0°C during winter and to store around 60.0 kW h per day during summer.

The last part of the Doctoral Dissertation focuses on field testing to prove the functionality of the prototype, testifying to the integrity and watertightness of the heat exchanger pipes and the hydraulic connections and highlighting geothermal efficiencies of 15.0 W m^{-2}. In conclusion, a brief payback analysis is carried out to assess the benefits of widely adopting the proposed geothermal technology.

Keywords: Shallow geothermal energy, Energy geostructures, Energy tunnels, Tunnel management, Tunnel refurbishment, Numerical modelling, Full-scale prototype, Hydronic heated pavement, Pavement solar collector, Laboratory testing, Field testing.