Postprint: In-situ Experimental Study on Thermal Performance and Thermo-mechanical Response of Energy Slabs in Subway Stations

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Abstract

This study focuses on the application of ground source heat pump systems in subway stations, concentrating on the thermo-mechanical coupling response and heat exchange mechanism of energy slabs. Currently, the thermal performance and structural safety of such structures under real operating conditions have not been adequately investigated. Based on the Dalian Metro Line 4 project, two sets of in-situ field tests were conducted: one employing a constant inlet water temperature mode to analyze the effects of inlet water temperature, flow rate, groundwater conditions, and operation mode on heat exchange performance; the other using a constant heating power mode to investigate the influence of heating power and flow rate variations on heat transfer characteristics. The test results demonstrate that increasing both inlet water temperature and flow rate contributes to enhanced heat exchange efficiency. Under intermittent operation conditions, the average heat flux per unit area reaches 57 W/m^2, representing a 14.7% improvement over continuous operation. The thermo-mechanical response is significantly influenced by inlet water temperature, flow rate, and stratum permeability. During the pump shutdown phase of intermittent operation, a reverse temperature gradient and the resulting increase in thermally induced compressive stress can be observed. In heterogeneous soil layers, uneven flow distribution tends to cause local heat exchange enhancement while reducing overall efficiency. During long-term operation, the structural response remains within the elastic range, with a maximum thermal stress of 4.15 MPa and a maximum vertical displacement of 2.84 mm, both far below the limits specified in current codes. This study systematically reveals the working mechanism of energy slabs under multi-field coupling effects, providing theoretical basis and experimental support for their design and application in thermally activated underground structures.

Full Text

Preamble

Title: In-situ Experimental Study on the Thermal Performance and Thermo-mechanical Response of Energy Slabs in a Subway Station

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Abstract

This study investigates the thermomechanical coupling response and heat transfer mechanisms of energy slabs deployed in subway stations with ground-source heat pump systems. Despite increasing implementation, the thermal performance and structural safety of these structures under actual operating conditions remain insufficiently understood. Based on the Dalian Metro Line 4 project, two series of in-situ field experiments were conducted: one using a constant inlet temperature mode to examine the effects of inlet temperature, flow rate, groundwater conditions, and operational strategy on heat transfer performance; the other employing a constant heating power mode to investigate the influence of heating power and flow rate variations on heat transfer characteristics.

The results demonstrate that increasing both inlet temperature and flow rate enhances heat transfer efficiency. Intermittent operation achieved an average heat flux of 57 W/m^2 per unit area, a 14.7% improvement over continuous operation. The thermomechanical response is significantly affected by inlet temperature, flow rate, and stratum permeability. During pump-off periods in intermittent operation, reverse temperature gradients were observed, leading to increased thermally induced compressive stress. In heterogeneous soil layers, non-uniform flow distribution causes localized heat transfer enhancement while reducing overall efficiency. Long-term monitoring shows that structural responses remain within the elastic range, with maximum thermal stress of 4.15 MPa and maximum vertical displacement of 2.84 mm, both well below current code limits. This study systematically reveals the working mechanism of energy slabs under multi-field coupling, providing theoretical foundations and experimental support for the design and application of thermally activated underground structures.

Keywords: Energy slabs; Shallow geothermal energy; Heat exchange power; Thermomechanical coupling; Subway station; In-situ test

Note: Figure translations are in progress. See original paper for figures.