Multi-field Coupling Analysis and Hygrothermal Safety Evaluation in High-geothermal Tunnels: A Case Study with Integrated Field-numerical Methodology

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Abstract

To address the challenges of ambiguous multi-physics coupling mechanisms and insufficient evaluation frameworks in assessing hyperthermal environments within high-geothermal tunnels, this study proposes an integrated methodology combining in-situ monitoring and multi-physics numerical simulation. A three-dimensional computational model was developed incorporating coupled heat transfer mechanisms encompassing surrounding rock thermal convection, geothermal water exothermic processes, and forced ventilation dynamics. The Thermodynamic Stress Index (HI) was formulated as a quantitative metric to establish a thermodynamics-driven evaluation system for tunnel hyperthermal environments. Model validation through field monitoring demonstrated high predictive accuracy, with mean relative errors of 4.7% for temperature fields and 7.1% for humidity distributions. Sensitivity analysis revealed significant correlations: Maximum HI values near the working face exhibited strong positive linear relationships with inlet air HI (R^2=0.99) and seepage water volume (R^2=0.99), while demonstrating a negative quadratic correlation with ventilation rate (R^2=0.95). Through multivariate regression analysis, the HI prediction models were derived accounting for ambient thermal parameters, hydrothermal dissipation characteristics, and airflow conditions. The resultant safety assessment framework enables comprehensive evaluation of hyperthermal environments under multi-parameter coupling effects, providing theoretical foundation and methodological support for thermal hazard mitigation in deep-buried tunnel engineering.

Keywords

High-Geothermal Tunnel, Humid-Hot Environment Characteristics, Numerical Simulation, Heat Index, Assessment Mode