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Thermo-mechanical analysis of energy tunnels accounting for thermo-plasticity

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Energy tunnels are typically comprised of tunnel linings that are equipped with heat transfer pipes, thereby converting them into tunnel ground heat exchangers (tunnel GHEs). This innovative technology offers renewable methods of space heating, cooling and hot water production. While still relatively uncommon, it is becoming increasingly popular due to the growing interest in sustainability and innovation, particularly in large infrastructure projects [8, 7, 10]. Additionally, the increasing need for clean and renewable sources of energy has made energy tunnels an attractive solution for addressing the global climate challenge [7, 11, 1].

The geotechnical behaviour of energy tunnels that subject the soil to thermal loads is still not fully understood. Numerical analyses conducted in the past use simple soil constitutive models, such as the linear elastic model [2, 3, 9] and elastic-perfectly plastic Mohr-Coulomb model [6, 4, 5]. Using simple constitutive models for tunnel design may not accurately depict the complex behaviour of soil materials under different conditions, and the complex interplay among the deformation, flow and thermal models governing the soil behaviour. This can lead to calculated stresses and strains that differ from actual values, resulting in potentially unsafe designs [12, 13].

Due to their multi-phase nature, saturated soils exhibit both reversible and irreversible thermal volumetric changes. The reversible volumetric change, resulting from thermal expansion/contraction, is typically assumed to occur within the elastic thermo-mechanical response of the soil. Conversely, the irreversible change is more appropriately treated within the elasto-plastic response regime.

In addition to volumetric changes, thermal effects can impact the stiffness and strength of soil, ultimately influencing the load transfer mechanisms and stress distributions within the system. These changes, in turn, can lead to additional deformations in both the tunnel and the surrounding soil. It should be noted that simply applying proportional stress paths to any of the Mohr-Coulomb models will result in solely elastic responses and fail to reproduce the irrecoverability of the volumetric response. Therefore, the incorporation of an elasto-plastic framework for analysing thermo-mechanical coupling is required to obtain more accurate predictions with respect to changes in effective stress and ground displacement.

In this study, the coupled thermo-mechanical behaviour of energy tunnels is investigated employing a thermo-elasto-plastic constitutive model developed in the framework of the critical state soil mechanics and considering incorporating thermally induced volumetric change in the model that involves adding a thermal strain component to the model. This is achieved by including a temperature-dependent parameter that accounts for the volumetric change due to change in temperature. The model is implemented in the finite element package COMSOL Multiphysics and used to study the thermo-mechanical behaviour of an energy tunnel in 2D plane strain condition (see Figure 1). The in-situ state of stress is reproduced, and the construction sequence is simulated (soil-structure convergence). The analysis focuses on the stresses and deformations that develop within and around energy tunnels due to the influence of geothermal operation.

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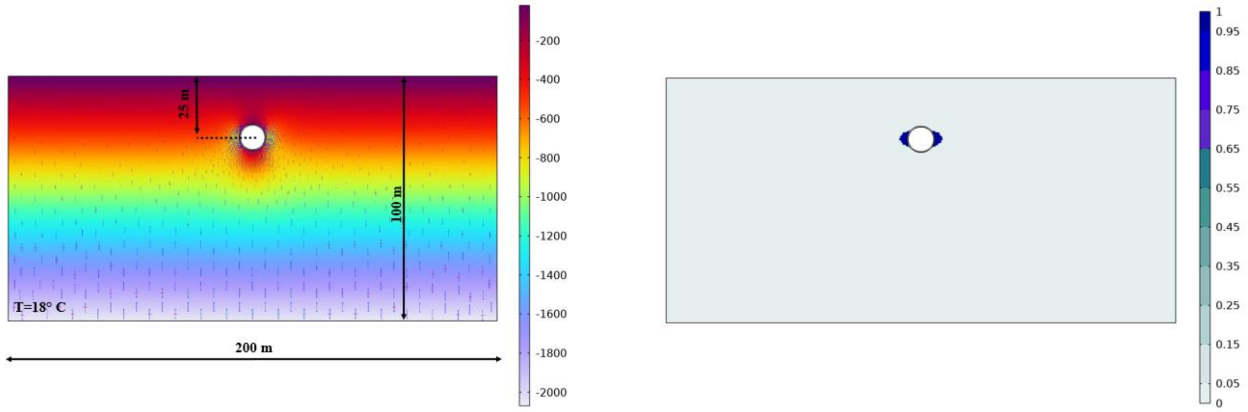
The proposed model is validated following several steps. First, the mechanical model is calibrated against field data from tunnels constructed in soft soils [10]. Then, thermo-mechanical effects are validated using existing monitoring data from real-scale tunnels available in literature [3,4,10,14]. For further validation, model estimations are compared with results from small-scale thermal-mechanical tests, such as thermal-triaxial tests. This comprehensive validation strategy thus ensures a rigorous and reliable assessment of our model's performance in replicating soil behaviour near energy tunnels.



(a) (b)

Figure 1: Tunnel behaviour: (a) Stress field [kPa] and principal stress distribution, and (b) plastic region after excavation.

Contributor statement

Maria Julieta Rottemberg: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft. Asal Bidarmaghz, Arman Khoshghalb and Alejo O. Sfriso: Conceptualization, Writing - review & editing.

References

[1] A. Bidarmaghz and G. A. Narsilio, "Heat exchange mechanisms in energy tunnel systems," Geomechanics for Energy and the Environment, vol. 16, pp. 83–95, 2018.
[2] A. F. R. Loria, "The thermal energy storage potential of underground tunnels used as heat exchangers," Renewable Energy, vol. 176, pp. 214–227, 2021.
[3] A. F. R. Loria, A. Di Donna, and M. Zhang, "Stresses and deformations induced by geothermal operations of energy tunnels," Tunnelling and Underground Space Technology, vol. 124, p. 104438, 2022.
[4] A. Insana, M. Barla, and J. Sulem, "Energy tunnel linings thermomechanical performance: comparison between field observations and numerical modelling," in E3S Web of Conferences, vol. 205. EDP Sciences, 2020, p. 06008.
[5] C. Ma, A. Di Donna, and D. Dias, "Numerical study on the thermo-hydromechanical behaviour of an energy tunnel in a coarse soil," Computers and Geotechnics, vol. 151, p. 105003, 2022.
[6] D. P. Nicholson, Q. Chen, M. de Silva, A. Winter, and R. Winterling, "The design of thermal tunnel energy segments for crossrail, uk," in Proceedings of the Institution of Civil Engineers-Engineering Sustainability, vol. 167, no. 3. Thomas Telford Ltd, 2014, pp. 118–134.
[7] F. Loveridge, J. S. McCartney, G. A. Narsilio, and M. Sanchez, "Energy geostructures: a review of analysis approaches, in situ testing and model scale experiments," Geomechanics for Energy and the Environment, vol. 22, p. 100173, 2020.
[8] G. A. Narsilio and L. Aye, "Shallow geothermal energy: an emerging technology," in Low Carbon Energy Supply. Springer, 2018, pp. 387–411.
[9] J. Zannin, A. Ferrari, T. Kazerani, A. Koliji, and L. Laloui, "Experimental analysis of a thermoactive underground railway station," Geomechanics for Energy and the Environment, vol. 29, p. 100275, 2022.
[10] K. A. Gawecka, W. Cui, D. M. Taborda, D. M. Potts, L. Zdravković, and A. Loukas, "Predictive modelling of thermo-active tunnels in London clay," Géotechnique, vol. 71, no. 8, pp. 735–748, 2021.
[11] M. Barla, A. Di Donna, and A. Perino, "Application of energy tunnels to an urban environment," Geothermics, vol. 61, pp. 104–113, 2016.
[12] Mašın, D., & Herle, I. (2005). Numerical analyses of a tunnel in London clay using different constitutive models. In *Proceedings of the 5th international symposium TC28 geotechnical aspects of underground construction in soft ground, Amsterdam, The Netherlands* (pp. 595-600).
[13] Potts, D. M., Zdravković, L., Addenbrooke, T. I., Higgins, K. G., & Kovačević, N. (2001). *Finite element analysis in geotechnical engineering: application* (Vol. 2, pp. 35-72). London: Thomas Telford.
[14] Avgerinos, V., Potts, D. M., Standing, J. R., & Wan, M. S. P. (2018). Predicting tunnelling-induced ground movements and interpreting field measurements using numerical analysis: Crossrail case study at Hyde Park. Géotechnique, 68(1), 31-49.
[15] Barla, M., Di Donna, A., & Insana, A. (2019). A novel real-scale experimental prototype of energy tunnel. Tunnelling and Underground Space Technology, 87, 1-14.