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Parametric analysis, numerical modelling, and machine learning-based prediction of tunnel crown displacement in EPB tunnelling

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ABSTRACT

Accurate prediction of tunnel displacement is vital for ensuring underground stability and safety. This study presents an integrated methodology that combines numerical simulation, field calibration, sensitivity analysis, Taguchi experimental design, and machine learning to predict tunnel crown displacement with high accuracy. FLAC3D modelling with the Mohr–Coulomb elastoplastic model was calibrated using field data from Isfahan Subway Line 2. A Taguchi design of 27 scenarios evaluated six parameters, with sensitivity analysis identifying tunnel diameter (25%) and overburden height (22%) as the most influential, followed by internal friction angle (20%) and elastic modulus (15%), while cohesion (10%) and Poisson's ratio (8%) showed limited impact. Numerical results were benchmarked against Hoek's empirical model, with deviations attributed to face pressure and operational conditions. To enhance predictive capability, a machine learning framework using MultiOutputRegressor with Gradient Boosting was employed to estimate Hoek's coefficients. Optimization with bootstrap sampling, K-fold cross-validation, and grid search produced near-zero MSE and R^2 values close to 1. The proposed hybrid approach demonstrates strong predictive capacity, offering a robust tool for optimizing tunnel design and advancing underground construction planning.

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Tunnel displacement profile; EPB tunnelling; numerical modelling; Gradient Boosting; MultiOutputRegressor; Bootstrap Sampling

1. Introduction

Along with the rapid urbanisation and increasing density of cities, the demand for sustainable public transportation systems has grown significantly (Barton *et al.* 1974, Lee and Pietruszczak 2008, Hamidi *et al.* 2010, Spagnoli *et al.* 2016). Traffic congestion and pollution in major metropolitan areas have highlighted the necessity of efficient public transport solutions (Eberhardt 2001, Ocak 2008, Yan *et al.* 2018). The scarcity of surface space in urban environments has made underground subway tunnel construction an optimal approach to address these issues. As an integral part of urban infrastructure, subway tunnels support economic growth and facilitate urban expansion (Rabcewicz 1964, Alejano *et al.* 2012, Jeong *et al.* 2014). Consequently, the excavation of subway tunnels to meet urban transportation demands has risen substantially, contributing to the planned and orderly growth of cities (Zhu *et al.* 2003, Sakurai *et al.* 2003, Sari *et al.* 2008, Vlachopoulos and Diederichs 2014). In modern urban tunnelling, mechanised excavation methods, particularly the use of Tunnel Boring Machines (TBMs), have become the standard for constructing subway tunnels (Sharan 2008, Vlachopoulos and Diederichs 2009). However, the tunnel excavation changes the in-situ stresses, which can lead to soil displacement around the cavity. Given the typically shallow overburden in urban settings, such displacements can lead to surface subsidences, potentially causing significant damage to existing infrastructure (Ghaboussi and Ranken 1977, Carranza-Torres and Fairhurst 1999, Oreste 2009, Do *et al.* 2014). The stability of the tunnel face is therefore crucial, not only for ensuring the quality and efficiency of the excavation but also for safeguarding public safety and minimising risks to nearby structures (Bizjak and Petkovšek 2004, Hasanpour *et al.* 2012, Wang *et al.* 2017). A comprehensive examination of tunnel crown displacement and resulting subsidences during TBM excavation is critical for optimising mitigation strategies that reduce the adverse effects of tunnelling (Carranza-Torres and Fairhurst 2000, Addenbrooke and Potts 2001; Nawel and Salah 2015; Unlu and Gercek 2003). Techniques that ensure the stability of the tunnel face and crown are not only important for reducing ground subsidence but also for preventing TBM entrapment, thereby allowing for uninterrupted excavation progress (Park and Park 2014, Miranda *et al.* 2015, Enieb *et al.* 2015, Yalcin *et al.*

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