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Hydrogeological Impact Assessment of Tunnel Excavation Using the TOUGH3–FLAC3D Coupled Modeling Approach

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Abstract: Tunnel excavation in complex geological settings often induces groundwater inflow, which poses substantial engineering and environmental challenges. Excessive inflow can cause flooding, collapse, and structural instability, leading to delays and increased construction costs. This study employs a coupled TOUGH3–FLAC3D model to investigate the hydro-mechanical interactions between groundwater flow and rock deformation during tunnel excavation. The three-dimensional hydrogeological conceptual model was established based on field geological data and digital terrain to simulate groundwater responses. Simulation results indicate that excavation in the Kangkou Formation may induce a groundwater head decline of 7–10 m near the tunnel and increase local inflow rates up to 7.7 L/min when intersecting the Waiao Fault. The results reveal that under bare rock conditions, tunnel inflow has a negligible effect on reservoir recharge. However, when the tunnel intersects high-permeability fault zones, mitigation measures such as grouting or water-blocking tunnel designs should be implemented to reduce potential impacts on the groundwater system.

Keywords: ***Hydrogeological model, TOUGH3–FLAC3D coupling, Groundwater inflow.***

Introduction

In geologically complex environments, tunnel excavation faces numerous challenges, with groundwater inflow being one of the most critical issues during construction. Domestic cases, such as the New Yungchuen Tunnel of the Eastern Railway Improvement Project and the Hsuehshan Tunnel of National Freeway No. 5, have demonstrated significant increases in budget and construction duration due to large inflows. Yang (2009) compiled domestic and international cases of tunnel water inflow and identified potential hazards that may occur when tunnels encounter highly permeable ground conditions, including flooding inside the tunnel, ground collapse, loss of self-supporting capacity, tunnel burial, and reduced bearing capacity of the support structures. Therefore, accurately predicting and evaluating the risk of tunnel water inflow during the design and construction stages is essential for ensuring safety and project feasibility.

Methodology

This study integrates TOUGH3 and FLAC3D for coupled hydro-mechanical analysis (Figure 1). TOUGH3, developed by the Lawrence Berkeley National Laboratory, uses the finite volume method to solve mass and energy conservation equations for multiphase, non-isothermal flow. It simulates gas-liquid flow, phase changes, and solute transport with flexible equation-of-state modules. FLAC3D, developed by Itasca Consulting Group, is a three-dimensional finite difference analysis program used to simulate the deformation behavior and failure mechanisms of geotechnical materials under external loading.

The coupling is achieved through a sequential approach: TOUGH3 computes fluid pressure, temperature, and saturation, which are then passed to FLAC3D to update the stress and porosity field. The updated permeability is recalculated and returned to TOUGH3 for the next iteration until convergence is reached.

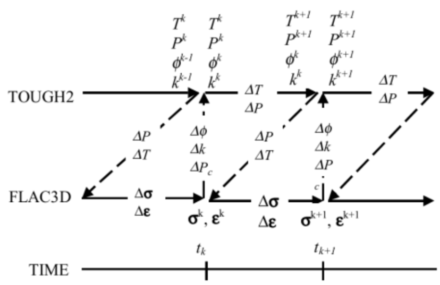


Figure 1, Numerical procedure of a linked FLAC3D and TOUGH2 simulation with sequential solutions. (Rutqvist et al., 2002)

Hydrogeological numerical model

The study area is primarily composed of the Kangkou Formation, consisting of gray hard shale interbedded with argillaceous fine sandstone or siltstone. The major structural feature is the Waiao Fault, which transects the area (Figure 2 and Figure 3).

A 6-meter resolution digital terrain model (DTM) was used to delineate slope gradients and drainage systems to define model boundaries. The initial steady-state simulation was conducted under natural groundwater conditions to analyze hydraulic head distribution and flow patterns. Transient simulations were subsequently performed to evaluate the effects of tunnel excavation on groundwater dynamics. Boundary conditions include: (1) Neumann boundaries for flux control at recharge or no-flow zones, (2) Dirichlet boundaries to fix hydraulic head at known pressure zones such as aquifer limits, and (3) atmospheric boundaries for rainfall infiltration and evapotranspiration. Hydrogeological parameters are summarized in Table 1.

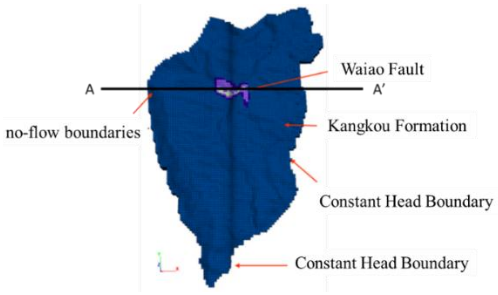


Figure 2, Three-dimensional numerical model showing boundary and hydraulic conditions.

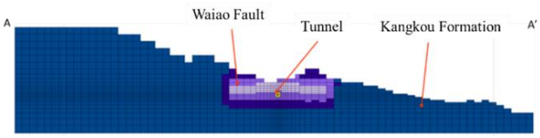


Figure 3, Cross-sectional view of the numerical model showing geological layers and boundary conditions.

Table 1, Hydrogeological Parameters of the Study Area.

	Kangkou Formation	Waiao Fault
Young's Modulus (GPa)	10	2
Poisson's Ratio	0.3	0.3
Rock Strength (MPa)	26	5
Permeability (cm/sec)	5×10^{-7}	1×10^{-6}
Porosity (%)	7	15

Results and discussion

Simulation results reveal that tunnel excavation causes a decline in groundwater head by approximately 7–10 m near the tunnel alignment. The head reduction is particularly evident when the tunnel intersects the Waiao Fault, where permeability is higher by nearly two orders of magnitude compared to the surrounding Kangkou Formation. The localized increase in permeability forms preferential flow paths that accelerate groundwater movement toward the tunnel face. Flow monitoring points placed every 300 m along the tunnel alignment show a stable inflow of 5 L/min in the Kangkou Formation, rising to 7.7 L/min at the fault zone (Figure 4). This indicates that fault permeability plays a key role in inflow variability. Water level drawdown and pore pressure variations around the tunnel reach up to 0.0079 MPa within 50 m from the excavation boundary. The simulation demonstrates that groundwater predominantly flows from high-head regions toward the tunnel axis, consistent with the topographic gradient (Figure 5). In the future, adopting waterproofing measures such as lining or grouting could reduce tunnel inflow to less than 10% of that under bare rock conditions, thereby effectively minimizing hydrological impacts and alleviating long-term groundwater drawdown within the catchment area.

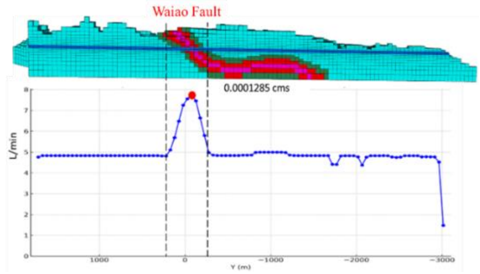
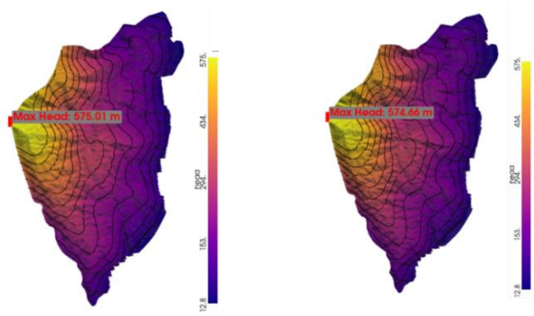


Figure 4, Flow rate analysis along tunnel alignment.



Before tunnel excavation After tunnel excavation

Figure 5, Groundwater Head Distribution.

Conclusion

This study employed advanced coupled numerical simulation software TOUGH3-FLAC3D to construct a three-dimensional geological model and investigate the potential effects of tunnel excavation on the regional groundwater system. The simulation results show that, under bare rock conditions, groundwater inflow into the tunnel has a minimal impact on the reservoir inflow of adjacent catchments. However, when the tunnel passes through high-permeability fault zones, appropriate engineering measures—such as grouting to reduce ground permeability or adopting water-blocking tunnel designs—should be implemented to effectively mitigate the potential impacts of excavation on the groundwater system.

References

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