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A comparative study on 2D numerical modelling methods for tunnel junctions

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ABSTRACT: Tunnel junction effects in underground engineering challenge accurate prediction of displacement and liner reaction. While 3D models offer higher accuracy, 2D models are often preferred in design for efficiency. However, limited guidance exists on assessing inherently 3D tunnel junction problems in 2D. This paper compares two 2D numerical modelling approaches for tunnel junctions: the Diagonal Span Method, representing the junction as an ellipse with width equal to its 45° diagonal span, and the Weakened Ground Method, simulating the junction by tripling the surrounding ground's j_n value. Their performance is evaluated against 3D model results to examine how effectively they capture the complex interactions within tunnel junctions, highlighting each method's strengths and limitations.

1 INTRODUCTION

In recent years, authors have contributed to studying the behaviour of rock mass and supports within or around an underground junction. For instance, Hsiao et al (2009) has pointed out that the rock mass strength/stress ratio plays an important role in junction roof settlement. Chortis & Kavvadas (2021) performed a series of 3D models with Abaqus code, studying the junction effect under a wide range of factors including construction sequence, rock mass strength, field stress, lateral stress and deconfinement. His work not only proved the relevance of these parameters to junction settlement and stress behaviour, but also proposed a design chart for junction zone design normalising tangential axial force under "modified geotechnical conditions". Gkikas & Nomikos (2021) proposed equations and tables to estimate the additional displacement and changes in hoop axial force to the main tunnel lining induced by the formation of junction, the predictions were compared with FLAC3D models with good agreement.

Despite the numerous efforts made in studying junction zones and proving the capabilities of three-dimensional numerical models in simulating junction behaviour, up to this date, less than enough spotlight has been put on linking two-dimensional numerical modelling methods with its three-dimensional counterparts, considering the comparatively excessive computing time and effort often needed to perform three-dimensional analyses. Cohen et al (2023) has made effort in studying the correlation between 3D and 2D modelling results for horseshoe shaped T-junctions under simplified conditions. The established methodology and findings have laid good foundation for further study into the topic that has encouraged this research.

2 MODELLING METHODOLOGY

2.1 *Modelling parameters*

In this study, series of 2D and 3D finite element models have been computed with Plaxis 2D and 3D. All models are circular openings with elastic liners, set in dry and elastic grounds with varying parameters , including Young's modulus, main tunnel – cross adit span ratios (only varying in main tunnel sizes and keeping the cross adit size constant) and in-situ stress as represented by overburden ground stress and Coefficient of earth pressure at rest (K_0), which are the important factors to junction behaviour as identified by Hsiao et al. (2009) and Chortis & Kavvadas (2021). Each varying parameter was assigned four discrete values, with the resulting combinations forming the basis of the analysis. The varying model parameters used are summarised in Table 1. The rock strength parameters with relevance to the Q values adopted, with reference being made to Hong Kong Granite rock mass strength data from past projects, is presented in Table 2.

Table 1. Model Parameters

Fixed Parameters				
Cross Adit Radius (m)	4			
Intersection Angle (deg.)	90			
Coefficient of earth pressure at rest , K_0	1			
Poisson's ratio, *v*	0.3			
Hoek–Brown material constant (slope of the failure envelope), mi	32			
Proposed Alternating Variables				
Main Tunnel Radius (m)	4.4	4.8	6	8
NGI Q System Rock Mass Quality Index, Q	0.1	0.3	1	3
Initial In-situ Stress, P_0 (MPa)	2.6	4.4	7.5	13

Table 2. Rock Strength Parameters of Hong Kong Granite from Past Projects.

NGI Q System Rock Mass Quality Index (Q)	Geological Strength Index (GSI)	Uniaxial Compressive Strength of Intact Rock (σ_{ci})	Young's Modulus of Intact Rock (Ei)	mi*	Disturbance Factor (D*)	mb #*	s #*	a #*	Deformation Modulus of Rock Mass (E_{rm})	Rock Mass Uniaxial Compressive Strength (σ_{cm})
		MPa	GPa						MPa	MPa
0.1	23.3	40	16	32	0	2.07	0.0002	0.535	870	6.7
0.3	33.2	75	30	32	0	2.94	0.0006	0.518	3013	16.2
1	44	100	40	32	0	4.33	0.0020	0.509	8372	27.2
3	53.9	120	48	32	0	6.17	0.0060	0.504	18471	39.8

* mi, mb#, s# and a# are the Hoek-Brown material constants for slope of failure envelope, fractured rock, rock mass strength and non-linearity of rock mass strength respectively.

2.2 *Model set-up*

A simple geometric set-up inspired by Cohen et al. (2023) is adopted. Although horseshoe shaped tunnels are the most common in real life projects, circular openings that are just as common are adopted in this study. As the focus will be on the liner displacement and stress reaction at tunnel crown and springline, considering that horseshoe shaped and circular shaped tunnel have comparable geometries above springline, the results are also argued to be comparable for both types of tunnels, while circular tunnels provide sufficiently more computation efficiency. The tunnel intersection angles are also kept at 90 degrees, as this has been proven by numerous studies to be the most critical intersection angle in terms of junction zone deformation and support reaction.

Two commonly adopted modelling techniques were used and compared for the 2D models, namely (i) the Diagonal Span Method, which models a tunnel junction with an ellipse of width equivalent to the diagonal span of the junction at 45 degrees; and (ii) the Weakened Ground Method, which models a tunnel junction by weakening the surrounding ground with a tripled Jn value. The model geometries of the 2D models are shown in Figure 1 and 2. As presented in the figures, the 2D models are set with a boundary of minimum 10x main tunnel span, to ensure that boundary effects would be negligible. Tunnel linings (blue line) and interface between lining and ground (green line) are applied. The overburden load from ground material above tunnel opening is modelled by directly applying a vertical line load on top, for numerical modelling calculation efficiency and simplicity. The green (Y) and red (X) arrows shown indicate the axis of plane that the plane-strain model lays on.

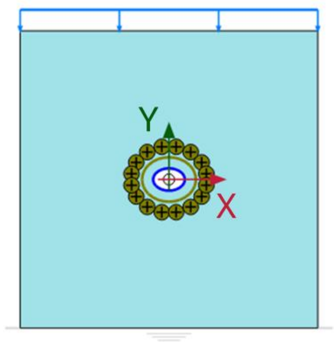

Figure 1. Example setup of Diagonal Span Method Model in Plaxis 2D, with an elliptical opening.

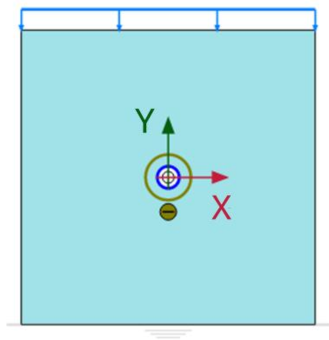

Figure 2. Example setup of Weakened Ground Method Model, with a circular opening.

The 2D models contain three stages:
(i) Initial stage before excavation
(ii) Main Tunnel excavation and liner installation
(iii) Cross adit excavation

The model setups for both methods in stages (i) and (ii) are identical. They only vary in stage (iii) where the Diagonal Span Method represents the action of cross adit excavation by enlarging the circular excavation to an ellipse equivalent to the diagonal span of the junction. The Weakened Ground Method would perform such action by weakening the surrounding ground strength parameters.

For the 3D models, the model geometry is illustrated in Figure 3. They have an almost identical staging as the 2D models. In stage (iii), an adit would be excavated up to a conservative 5x adit radius without support to model the effect of junction opening before any support is installed at the newly formed adit, which is usually considered to be one of the most critical steps in junction construction.

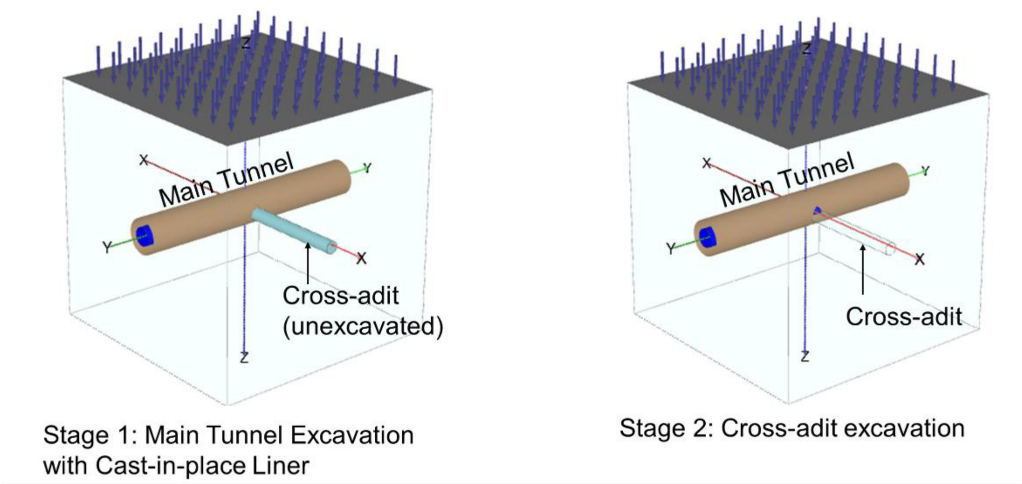

Figure 3. Setup of staged 3D model.

3 RESULTS AND INTERPRETATION

3.1 *Data extraction and analysis method*

A total of 64 sets of models were computed and analysed. Data was extracted from the monitoring points in the 2D and 3D models as illustrated in Figures 4 and 5. In Figure 4,

- Section 1 is in the middle of the junction.
- Section 2 is located at one cross adit radius from middle of junction.
- Section 3 is at one main tunnel radius from middle of junction.
- Section 4 is at 3 main tunnel radius from middle of junction.

Data will be collected from all 4 sections for the 3D models; Figure 5 shows that 3 data points on the crown (point a) and two sides of the springline (point b and c) of the main tunnel are referenced to for both 3D and 2D models.

To assess the accuracy between the 2D predictions and 3D model results, the coefficient of determination (R^2) values were calculated. This metric measures how well the 2D predictions match the 3D model results, with a score of 1.0 representing a perfect match (where all data points fall exactly on the y=x line. Linear fitted lines are also proposed to help diagnose systematic bias where the fit's R^2 (R_{fit}^2) measures linearity, and its slope and intercept quantify scaling and offset biases. To evaluate the relationship between model parameters and the accuracy of 2D predictions relative to 3D results, Pearson correlation coefficients were calculated between each parameter and the mean absolute error (MAE) of the 2D results. A modified geotechnical condition ratio $(\sigma_{cm}/P_o)^{0.55}$(Overburden Height/Tunnel Diameter)$^{0.45}$ proposed by Chortis & Kavvadas (2021), which represents the incorporated effect of overburden height ratio on geotechnical conditions ratio, is also included in the analysis as a proven relating parameter to junction effects.

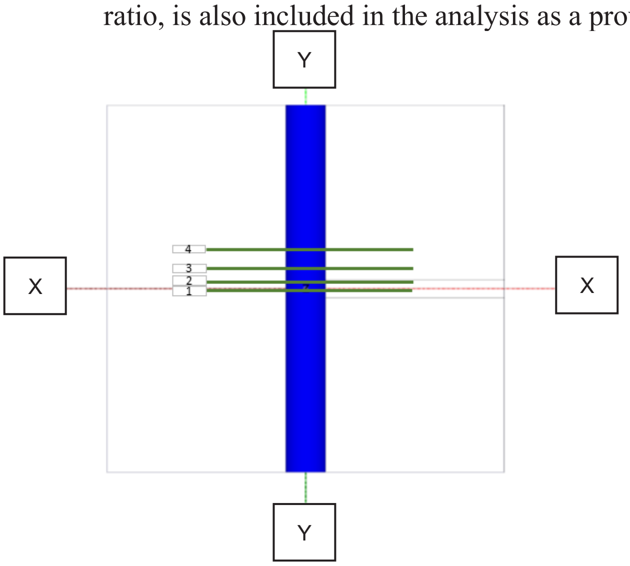

Figure 4. Illustration of sections where data points are on located in 3D models.

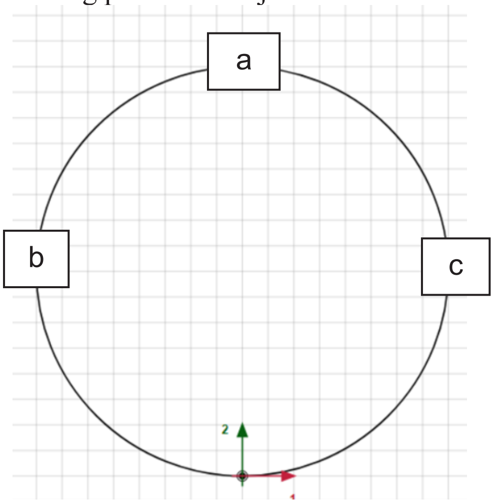

Figure 5. Illustration of data point locations on a cross section of the main tunnel.

3.2 *Comparative Accuracy of 2D vs. 3D Results at Tunnel Crown (Location a)*

To evaluate the reliability of simplified 2D approaches in capturing the structural response of the tunnel junction, a detailed comparison was conducted between the 2D Diagonal Span and Weakened Ground methods and the 3D model results at Location a (crown), across four representative cross-sections at the Cross Adit stage.

The vertical displacement (Uy) demonstrated strong linear correlation between the 2D prediction and 3D model results for both methods, with R_{fit}^2 close to 1.0. The Diagonal Span method showed excellent agreement ($R^2 = 0.99$) with the 3D results, only slightly overestimating the Uy magnitude. The Weakened Ground method showed poorer accuracy ($R^2 = 0.56$) and tends to overestimate Uy magnitude by roughly 50%. Both methods show poor agreement with horizontal displacement (Ux), with R^2 below 0, from the extremely limited horizontal movement at tunnel crowns across all sections in 3D models compared to 2D results, while in theory the Ux at crown in 2D models should be extremely close to 0, the noticeable Ux recorded is possibly due to modelling artifact like mesh bias.

In terms of axial force (Nx2D), both methods exhibited strong linear correlation with the 3D model data ($R_{fit}^2 > 0.96$). The Diagonal Span method produced estimates that are slightly under-predicted in magnitude while maintaining a considerable extent of agreement ($R^2 = 0.88$). The Weakened Ground method gives a higher degree of accuracy ($R^2 = 0.91$). For this method, it is observed that 3D model data from section 4 are the closest to the y=x line, while the section 1 data lies above both the y=x line and linear fit line, indicating that it gives slight overpredictions to the axial force magnitude in the middle of junction.

Predictions for shear force (Q2D) and bending moment (M2D) were notably less reliable in both methods. The Diagonal Span method produced highly variable Q2D results, with errors ranging from moderate underestimation to extreme overestimation for all sections ($R^2 < 0$) with poor linear correlation ($R_{fit}^2 = 0.35$). Under the same method, the M2D predicted had limited accuracy ($R^2 < 0$) and poor linear correlation ($R_{fit}^2 = 0.23$), suggesting a curve may be a better fit. While the Weakened method tended to significantly underestimate shear response with poor agreement ($R^2 < 0$), for M2D results, the agreement was also poor with R^2 below 0 but the linear fitted line achieves a considerable prediction accuracy of $R_{fit}^2 = 0.87$ with the tendency to over-predict.

These findings underscore that the Diagonal Span method gives the most accurate approximation of vertical displacements at the tunnel crown during junction excavation, while the Weakened Ground method offers robust estimations for axial and bending load. However, simplified 2D models remain limited in capturing stress redistributions associated with complex 3D effects such as shear, particularly in geometrically discontinuous regions like tunnel intersections.

A correlation analysis was conducted to evaluate the influence of key geomechanical and geometric parameters on the accuracy of 2D model results relative to 3D outcomes at the tunnel crown (Location a). The analysis focused on mean absolute error (MAE) across all five key response variables (Ux, Uy, Nx2D, Q2D, M2D), calculated for each model configuration.

For the 2D Diagonal Span method, strong negative correlations were observed between MAE and several rock mass strength indicators, including σ_{cm}/P_o (-0.63), σ_{cm} (-0.57), GSI (-0.57), and Erm (-0.54). This suggests that the Diagonal Span method performs more accurately in stronger, more competent ground conditions, where simplifications inherent to 2D modelling have reduced impact. The most substantial positive correlation was observed with P_0 (+0.64), indicating that models with higher initial in-situ stress are associated with increased 2D-3D discrepancies.

The Weakened Ground method showed similar trends but generally weaker correlations, with top contributors including Q, σ_{cm}/P_0, and E_{rm} (correlation coefficients around -0.6). These findings reinforce that both 2D methods are sensitive to ground condition strength, but the Diagonal Span method is more strongly influenced by parameter variation.

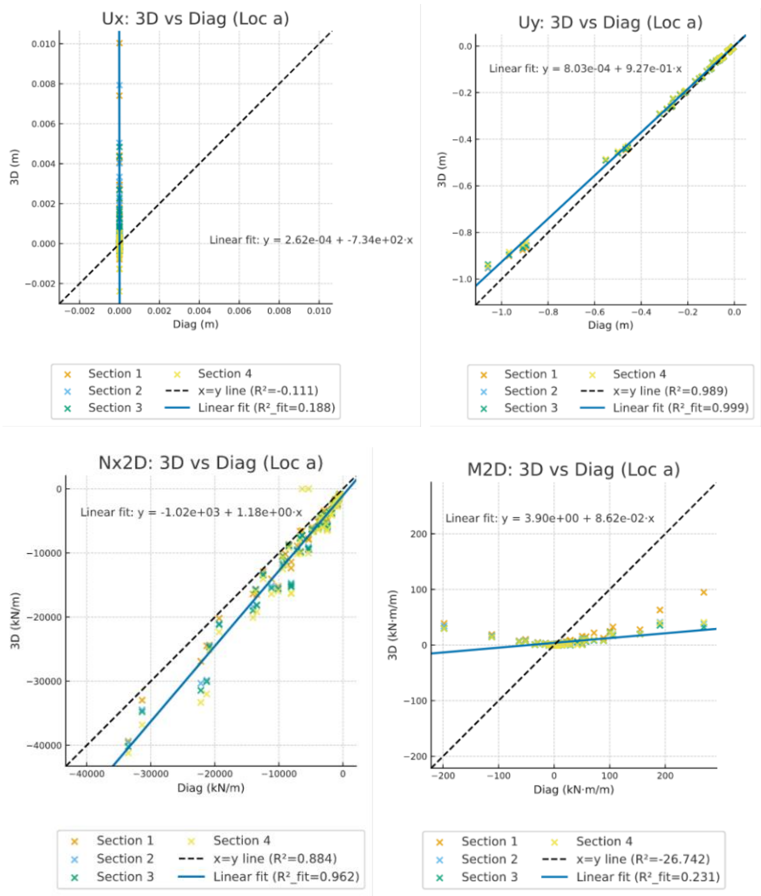

Figure 6 (Diagonal Span Method) Comparison between 2D and 3D model results at the tunnel crown (Location a) during the Cross Adit excavation stage, Plot of Ux, Uy, Nx2D and M2D shown.

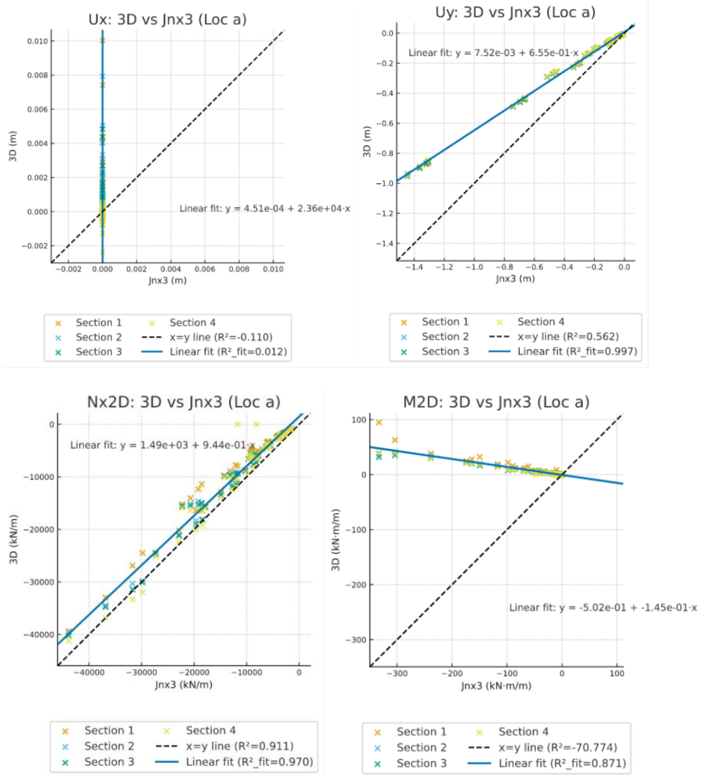

Figure 7 (Weakened Ground Method) Comparison between 2D and 3D model results at the tunnel crown (Location a) during the Cross Adit excavation stage, Plot of Ux, Uy, Nx2D and M2D shown.

3.3 *Comparative Accuracy of 2D vs. 3D Results at Tunnel Springline (Location b & c)*

Across both springline locations, the Diagonal Span method closely matched 3D results for displacements and axial force but poorly predicted shear force (Q2D) and bending moment (M2D). At Location b, vertical displacement (Uy) showed near-perfect agreement (R^2 close to 1). Lateral displacement (Ux) showed low direct agreement ($R^2<0$), while axial force (Nx2D) showed considerable accuracy ($R^2=0.90$). The results were affected by varying degrees of systematic over-prediction, although both Ux and Nx2D still maintained a high linear correlation ($R_{fit}^2 > 0.89$) between the 2D and 3D data. However, the Q2D and M2D predictions were highly unreliable ($R^2< 0$ and R_{fit}^2 close to 0). Location c, excluding Section 1 due to adit excavation, showed similar trends: Uy and Nx2D showed considerable accuracy and linearity ($R^2 > 0.84$ and $R_{fit}^2 > 0.85$) while Q2D, and especially M2D, had poor agreement and linear correlation. Similar to location a, an exponential curve would serve better M2D predictions. Correlation analysis of mean absolute error versus geotechnical parameters highlighted how model accuracy varies with rock mass strength, stiffness, and stress state. At Locations b and c, the errors of the 2D Diagonal Span method showed strong negative correlation with parameters such as σ_{cm} /Po (-0.55 to -0.63), GSI (-0.58 to -0.59) and Erm (-0.51 to -0.53). These results indicate that the Diagonal Span method performs best in stronger, more competent rock masses. A strong positive correlation was observed with in-situ stress Po (+0.5 to +0.61), suggesting that high stress magnitudes reduce 2D-3D agreement.

In contrast, the Weakened Ground method provides stronger Ux estimations (R^2 ranges from 0.44 to 0.66, and R_{fit}^2 >0.83). For Nx2D, it gives slightly less accurate yet still reliable results with R^2 >0.7 and R_{fit}^2>0.78. Similar to location a, the Q2D at locations b and c are highly dispersed, while the M2D at location b shows good linearity but poor agreement ($R^2< 0$ and R_{fit}^2 =0.98). However, at the side of adit opening location c, the M2D predicted have both poor agreement and linearity. At locations b and c, the mean absolute errors of the Weakened Ground method showed moderately negative correlations with Q, GSI, and Modified Geotechnical Condition Ratio (-0.38 to -0.67 range), while demonstrating strong positive correlation with Po at location b (+0.81) and moderately strong at location c (+0.50), revealing similar trends as that of the Diagonal Span method.

3.4 *Summary*

The results from all three observation points - Location a (crown), Location b (left springline), and Location c (right springline) - reveal consistent trends in the reliability and limitations of simplified 2D numerical modelling in tunnel junction scenarios. Across all locations, the 2D Diagonal Span method consistently demonstrated strong agreement with the 3D model results in reflecting vertical displacement and axial load, while the Weakened Ground method gives reliable predictions to axial load at all locations.

In contrast, both 2D methods exhibited poor performance in estimating shear force (Q2D), with large relative errors often >1000% and weak agreement ($R^2 < 0$).

The Weakened Ground method followed similar trends but generally showed larger deviations and weaker R^2 values than the Diagonal Span method, particularly in vertical displacement and axial force prediction. Correlation analysis between 2D-3D error and model parameters revealed that 2D model accuracy improves significantly in stronger, stiffer ground conditions, and degrades under high in-situ stress. It is concluded that the key influencing parameters (highest correlations with reduced error) includes σ_{cm} /P_o, E_{rm}, σ_{cm}, GSI, Q, and the modified geotechnical condition ratio.

The overall findings are summarized as follows:

- The 2D Diagonal Span method provides reliable estimates for vertical displacement and axial load across all junction locations, especially in competent rock masses under moderate stress.
- The Weakened Ground Method provides good estimation for axial responses at crown, and its estimate for horizontal displacement at the springline is better than that of the Diagonal Span method.

- Shear behaviors cannot be confidently captured by 2D simplifications and require full 3D modelling for critical analysis.
- The Diagonal Span method is more sensitive to parameter changes than the Weakened Ground method, making it more responsive but also more vulnerable to deviation under poor ground conditions.

4 CONCLUSION

In effort of investigating the relationship and comparability between two- and three-dimensional numerical modelling results of a junction zone, an extensive study was undertaken involving a series of Plaxis 2D and 3D models. In this study, it is concluded that the Diagonal Span method generates closer results to the 3D models in terms of crown settlement, along with consistent accuracy in predicting axial load in liners, while the Weakened Ground method yields better predictions on springline horizontal displacements. These findings would justify using 2D models as a first pass analysis in early stage designs, though it shows potential at current stage of studies, more in-depth research would need to be undertaken for 2D models to act as a replacement for 3D modelling. Further studies are recommended to better understand and develop two-dimensional modelling methods that can produce comparable predictions with its three-dimensional counterparts, for example, different main tunnel and adit shapes can be included, and K0 values not limited to 1 can also be used.

5 REFERENCES

Chortis, F., & Kavvadas, M. (2020). Three-Dimensional numerical analyses of perpendicular tunnel intersections. *Geotechnical and Geological Engineering, 39(3), 1771–1793*. https://doi.org/10.1007/s10706-020-01587-w

Cohen, S., Mitelman, A., & Elmo, D. (2023). A methodology for the analysis of tunnel intersections using two-dimensional numerical modeling. *IOP Conference Series Earth and Environmental Science, 1124(1), 012069*. https://doi.org/10.1088/1755-1315/1124/1/012069

Gkikas, V. I., & Nomikos, P. P. (2021). Primary support design for sequentially excavated tunnel junctions in Strain-Softening Hoek–Brown Rock Mass. *Geotechnical and Geological Engineering, 39(3), 1997–2018*. https://doi.org/10.1007/s10706-020-01602-0

Hsiao, F., Wang, C., & Chern, J. (2009). Numerical simulation of rock deformation for support design in tunnel intersection area. *Tunnelling and Underground Space Technology, 24(1), 14–21.* https://doi.org/10.1016/j.tust.2008.01.003