



Numerical Study of Effective Parameters on Tunnel Lining's Internal Stress in Tunnel-Fault Intersection Zone

Milad Manafi¹, Hamed Molladovoodi^{1*}, and Hamid Chakeri²

1. Department of Mining Engineering, Amirkabir University of Technology, Tehran, Iran

2. Department of Mining Engineering, Sahand University of Technology, Tabriz, Iran

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Abstract

Tunneling in urban areas is associated with various challenges that must be carefully evaluated during pre-construction studies. Among these challenges, tunnel excavation through fault zones is particularly critical and has been widely investigated. Previous studies have primarily focused on the displacement of tunnel linings under different fault movement conditions. In the present study, the effects of three key parameters, ground movement magnitude, grout layer thickness, and fault plane angle, on the induced bending moments and normal forces were examined. The numerical results indicate that ground movement magnitude has the most significant influence on induced stresses, whereas grout layer thickness and fault plane angle exhibit comparable effects. The analyses further show that a 100% increase in ground movement leads to a 60.67% rise in the induced normal force. Increasing the grout layer thickness reduces the induced forces by 32.9%, while a larger fault plane angle decreases the normal force by 34.52%. The modeling outcomes also reveal that grout layer thickness is the most influential factor effecting the induced bending moments. These findings provide valuable insights for evaluating the structural capacity and potential failure of tunnel lining crossing fault zones.

1. Introduction

Tunnels crossing fault zones is a challenging case in mechanized tunnelling which should be considered in pre-construction steps. Ground movement in fault zone can cause severe damages to lining structure which should be minimized in construction process. Studying fault movement effects show that induced forces and stresses in lining structures are considerably high. Various studies have investigated the effects of these induced stresses on tunnel lining and suggested various policies to overcome the condition. Based on literature, segmental lining stands better while ground movement occurs [1]. Better sufficiency of segmental lining is because of its flexible characteristic which gives more freedom when the ground starts to move. As declared in various studies, the ground induced stresses are critical in the intersection point of fault-tunnel; which has been studied in various papers which have considered the stress magnitude increase from the

beginning of tunnel line till the end part [2]. As discussed in the referenced paper, the bottom part of tunnel lining is more prone to vulnerable stresses than the upper part. Koohrang III, water-transfer tunnel is a constructed project in which the numerically predicted stresses ended in a segmental water transmission tunnel which will stand the induced large amounts of stresses on the pipe line structure [3]. The referenced paper concludes that the applied bending moment and shear force on tunnel lining increases when it reaches the intersection point of tunnel-fault zone. Based on these declarations it is obvious that controlling and analyzing applied forces on tunnel structure before the construction step is completely necessary.

Designing a proper lining structure needs considering the applied normal stress and bending moment on each segment part. Induced ground stresses shouldn't be more than designed maximum



stress amount. Normally, the segmental linings produced of reinforced concretes, are able to stand an induced total stress of 35-45 MPa, without considering safety factor magnitudes. Since, the total applied stress on lining structure in tunnel-fault intersection is considerably high, this challenging case should be solved before the construction process.

Numerical modelling is a helpful method of study in tunnelling projects. Modelling the proper face pressure, surface settlements, grout pressure, and interaction models, have been studied in several studies [4-7]. In this study the magnitudes of induced normal stress and bending moment in various conditions of tunnel-fault intersection geometry is being study using FLAC3D package. Based on the existing technical literature, the influence of fault-plane displacement on the design parameters of bending moment and internal forces has not been comprehensively investigated with respect to the three governing factors of: displacement magnitude, grout layer thickness, and fault plane angle. In this study, by examining this issue, not only the effects of these parameters on the analytical results are determined, but the extent of each parameter's influence is also evaluated [8-16].

2. Methodology

Numerical modelling is a sufficient method of problem solving that brings more opportunity in solving complex problems. FLAC3D is an explicit Lagrangian finite-volume program for engineering mechanics computation. The basis of this program is the great numerical formulation used by the two-dimensional FLAC program. In 3D version of FLAC, three-dimensional modelling is used for simulating the behavior of 3D structures include soil, rock or other material that exhibit path-dependent behavior [17]. The software is a user-definable package which solves and models based on defined 3D model, boundary-condition, material property, mesh cells and the behavior of assigned materials. Numerical modelling in FLAC3D is a phased operation which involves: 1) Modelling the geometry 2) Material property assign 3) Boundary condition defining 4) Mesh-cell count 5) Problem solving. These phases

continue respectively till the defined condition reaches its equilibrium and convergence [17].

Mechanized tunnelling with FLAC3D has been studied in diverse investigations and papers; since, it is able to calculate the proper face pressure, settlement magnitudes in all mesh cells, grout pressure, ground reactions and induced lining stresses. Chakeri et al. used FLAC3D to model the effects of Tehran line 4 metro tunnel construction on Tohid twin tunnels [18]. They confess that underground tunnel extension results in various underground space interactions which needs to be studied. Their interactions will cause in different stress distributions which needs being controlled to reduce the possible surface settlements and lining demolition [18]. Since, FLAC3D has the ability of induced stress calculation, it is a sufficient tool for the aim of pre-controls. Safa et al. studied the effective parameters of mechanized tunnelling on the existed canal structure [19]. Utilizing FLAC3D for calculating the effects of face pressure, distance, geometry and material property in the referenced study, shows the sufficiency of FLAC3D in calculating different parameters. Crossing Fault zones, as one of the most challenging conditions in TBM operation in urban areas, has been studied by different researchers. Although, this challenge can be modelled in both numerical and experimental methods, numerical modelling is more economical and time-saving than the experimental one. Li et al. state that the ground movements caused by fault zone dislocation, will produce high amounts of stresses which threatens the safety of tunnel lining structure. These induced stresses will make noticeable damages or will be able to completely destruct the segmental lining. They used numerical simulation to calculate lining's induced stresses resulted by grounds possible movements [20]. The induced stresses of ground movement are mostly shear type. These applied stresses will cause lining shape changes, crack production, structural damage or lining's complete failure. Pre-controlling the possible induced stresses will reduce damage amount after fault movement. This will help designers to exploit precautions and benefit some extra construction methods to gain more safety. Figure 1, depicts sequential excavation chart-flow of utilized modeling steps.

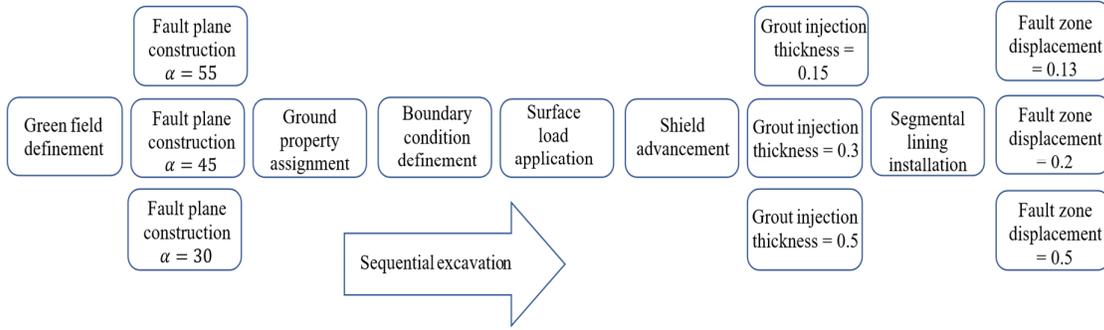


Figure 1. Sequential excavation chart-flow

3. Modelling Tunnel-Fault Interaction

Geometry creation, modelling, condition simulation, and calculation defining will be assigned in FLAC3D, with user-definable codes in an open-source software base. To define real-case parameters and obtain more realistic results, we use Tabriz-Baghmisheh Chay fault interaction parameters. Since ground properties such as cohesion, friction, bulk and shear modulus, density, water level, and layer thicknesses are important initial assignable properties in FLAC3D modelling, we used data from the referenced study [21]. The soil properties in this area indicate that the predominant material is sand, overlain by layers of clay. The Baghmisheh-Chay fault located within this zone has a maximum displacement of 20 cm [22].

The ground domain can be modelled by defining different shaped elements such as brick, shell, cylindrical-shell, cylinder, etc. The geometry of the modelled ground is 120 meters in length, 70 meters in width, and 51.5 meters in height. The modelling step length is defined as the real-case of excavation width, which is 1.5 m, in each advancement sequence.

As seen on Figure 2, ground geometry is defined in five soil layers. Soil layer properties are defined based on obtained data from Tabriz line 2 urban subway [21], so, the imported property magnitudes will be realistic. The behavior of soil layers is defined in Mohr-Coulomb. This type of behavior is able to calculate the effects of cohesion and friction in Lagrangian finite-volume solvent which will result in more accurate magnitudes when the applied forces are affected. Table 1 shows defined property magnitudes.

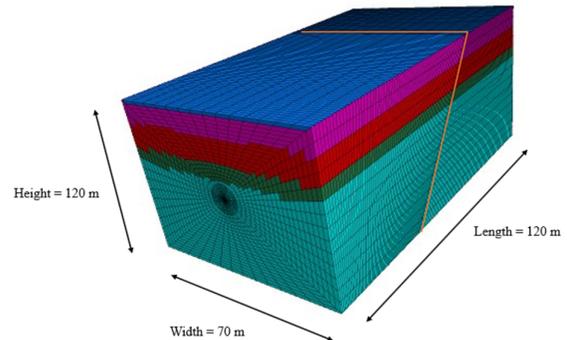


Figure 2. Modelled geometry of fault zone intersecting tunnel's path

Table 1. Ground Layer Properties

Layer	Bulk Modulus (Pa)	Shear Modulus (Pa)	Cohesion (Pa)	Friction (degree)	Density (gr/cm ³)	Thickness (m)
1	9.839e6	3.759e6	5000	27	1.65	1.505
1	37.878e6	8.992e6	10000	24	1.75	5.5
2	46.296e6	18.39e6	7000	32	1.75	8
3	53.030e6	12.589e6	25000	23	1.75	5
4	55.555e6	22.773e6	5000	32	1.85	31.495
5	9.839e6	3.759e6	5000	27	1.65	1.505

After defining these parameters as ground properties, boundary conditions must be assigned. The model domain will be fixed in Xmin and max, Ymin and max and Zmin. Since, ground surface settlement will be studied, Zmax plane should stay free to displace in -Z direction. To

model the surface structures a normal stress equal to 5e4 Pa is assigned on the Zmax plane. This stress magnitude is equal to surface buildings, streets and pavements. After defining ground condition, tunnelling parameters such as TBM properties and location, grouting operation and lining construction

will be defined step by step. Figure 3, generated from FLAC3D modelling shows: a) Applied boundary condition b) Surface Load c) Lining construction.

Lining construction in FLAC3D is a stepped operation; first the tunnel boring step should be modelled and then the lining construction will be done. Segmental lining of TBM operated tunnels is made of reinforced concrete with elastic modulus of 3×10^4 Pa, Poisson's ratio of 0.1, thickness of 0.35 m and density of 2.6 gr/cm³. As an important part of EPB tunnelling, grout material and the injected layer must be defined in properties and layer thickness; in this modelling, injected grout material of foam concrete has 1.47×10^7 bulk modulus, 8.8×10^6 shear modulus, 0.58 gr/cm³ density and 0.15 m thickness.

Modelling fault plane which separates ground's front zone from the back one, is assigned as interface between two zones. The properties of this interface are defined as an interface with normal stiffness of 2×10^9 Pa, shear stiffness of 2×10^9 Pa and a

friction of 15. Based on geology studies, a fault plane occurs when one of the ground zones stay firm while the other one moves toward it. Such a phenomena, causes vertical and horizontal displacements which produces huge amounts of stresses and the stress disturbance changes in the underground layers [23, 24, 25, 26]. Based on the possible movement of ground zones, the amount of induced stress changes; so, tunnel lining will stand diverse amounts of stresses while such a catastrophe happens.

After assigning tunnel construction phase in software, ground motion should be modelled. The front zone of ground domain will displace vertically and induced stresses will affect the tunnel lining. Model validation is considered utilizing Kirsch equations in elastic formation. Modeling in elastic defined behavioral model results in the same stress magnitudes of Kirsch equations. These equations are being used in geotechnical and rock mechanics to calculate the stresses around a circular excavation [27].

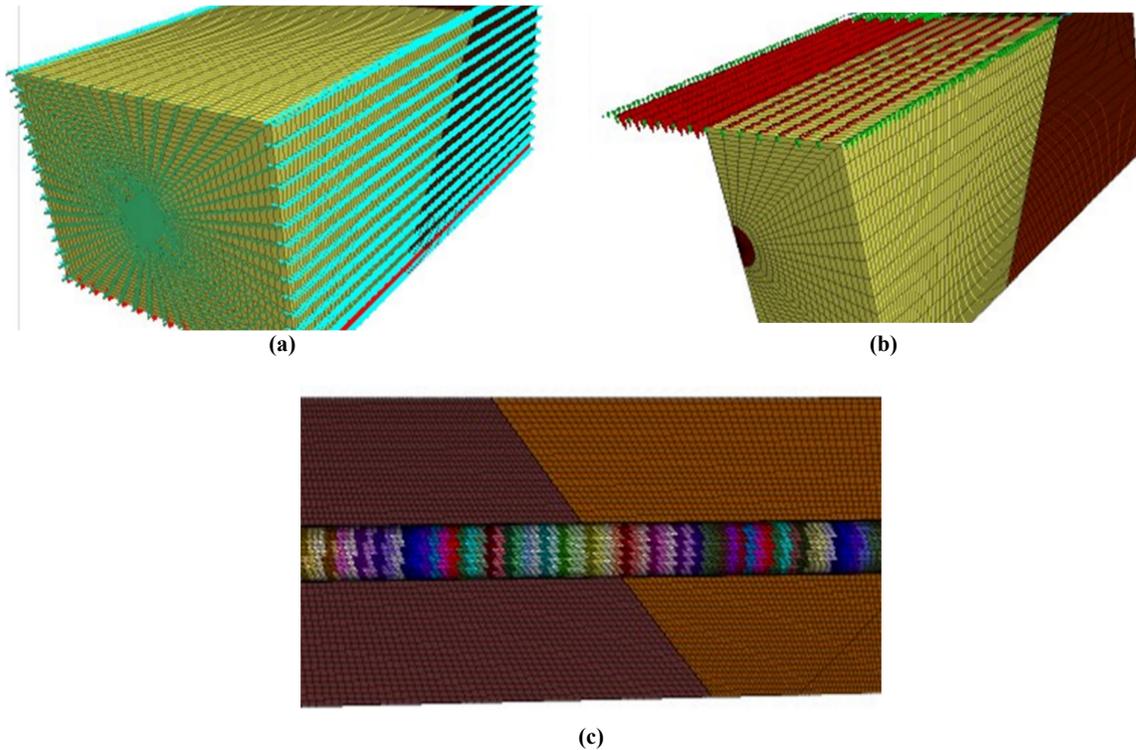


Figure 3. FLAC3D generated results: (a) boundary condition (b) surface load (c) lining construction

$$\sigma_r = \frac{P_1 + P_2}{2} \left(1 - \frac{\alpha^2}{r^2} \right) + \frac{P_1 - P_2}{2} \left(1 - \frac{4\alpha^2}{r^2} + \frac{3\alpha^4}{r^4} \right) \cos 2\theta \quad (1)$$

$$\sigma_\theta = \frac{P_1 + P_2}{2} \left(1 + \frac{\alpha^2}{r^2} \right) - \frac{P_1 - P_2}{2} \left(1 + \frac{3\alpha^4}{r^4} \right) \cos 2\theta \quad (2)$$

4. Results and Discussion

There are some effective parameters that can change the stress disturbance of ground and also the induced stress on tunnel lining. Fault plane angle, vertical displacement and grout layer thickness are the parameters that should be studied. Based on literature, the fault movement changes peak tension moment and compressive axial force which the lining can stand. Jayakumar and Visuvasam numerically investigated the effects of fault angle and GSI changes on lining structure. The results show that, under fault movement, the peak bending moment in tension reduces to 15% for dip angles from 60° to 90° , and the peak bending moment in compression increases to 50% for dip angles from 30° to 90° . The peak bending moment in tension reduces to 25% for GSI values from 20° to 80° . It shows that the flexural behavior of the lining is significantly affected by fault dip angles up to 60° [28]. Studying the effects of fault properties and characteristic on the induced internal stresses, hasn't been completely considered [22].

Table 2, shows the number of modelling cases in FLAC3D. As seen on the table 2, each case has a special magnitude of fault plate angle, grout layer thickness and zone displacement.

Fault plane and grout layer thickness are geometrical properties which should be defined properly in the geometry phase modelling, while,

displacement will be defined in the applied condition phase. Figure 4, shows case models. Case (a) shows the geometry model of a zone with 55° fault angle, case (b) is for a zone with 30° angle, case (c) shows the grout layer thickness of 0.5 m and case (d) shows the geometry of a zone with grout layer thickness of 0.15 m.

After modelling geometries, applying displacement magnitudes of 13, 20 and 50 cm will result in diverse internal moment and stress magnitudes. Figure 5, shows the results of induced internal moments and stresses by applying ground movements.

Table 2. Modelling Cases

Case No.	Fault plane angle ($^\circ$)	Grout layer thickness (m)	Fault zone displacement (m)
1	55	0.15	0.13
1	55	0.3	0.2
2	55	0.5	0.2
3	55	0.15	0.2
4	55	0.15	0.5
5	45	0.15	0.13
6	45	0.3	0.2
7	45	0.5	0.2
8	45	0.15	0.2
9	45	0.15	0.5
10	30	0.15	0.13
11	30	0.3	0.2
12	30	0.5	0.2
13	30	0.15	0.2
14	30	0.15	0.5
15	55	0.15	0.13

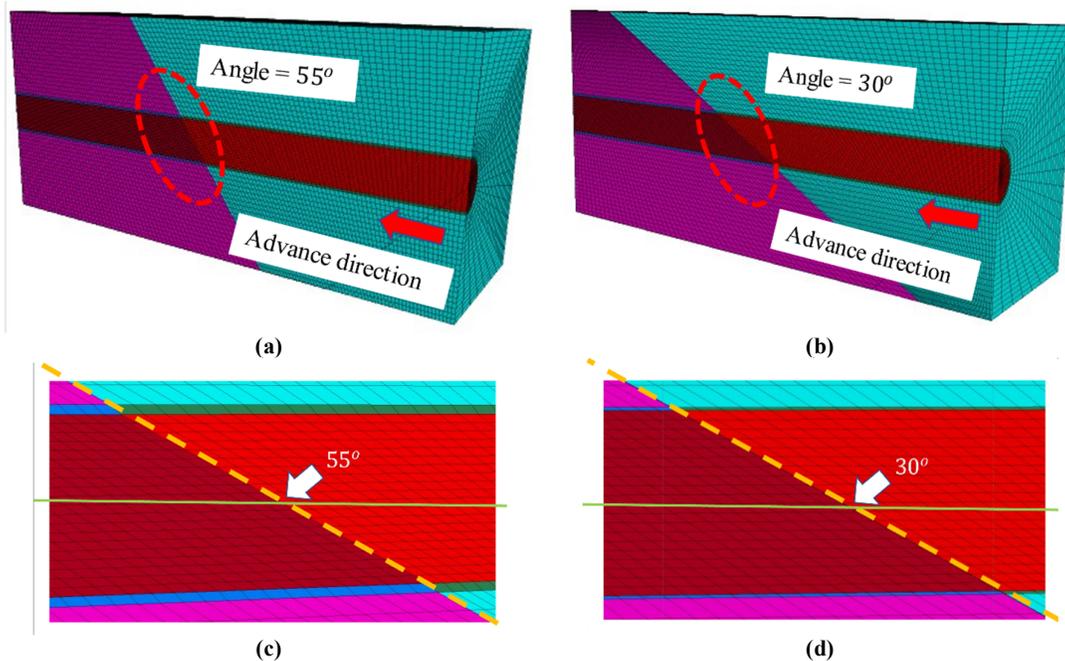


Figure 4. Model geometries: (a) Fault angle = 55° (b) Fault angle = 30° (c) Grout layer thickness = 0.15 m (d) Grout layer thickness = 0.5 m

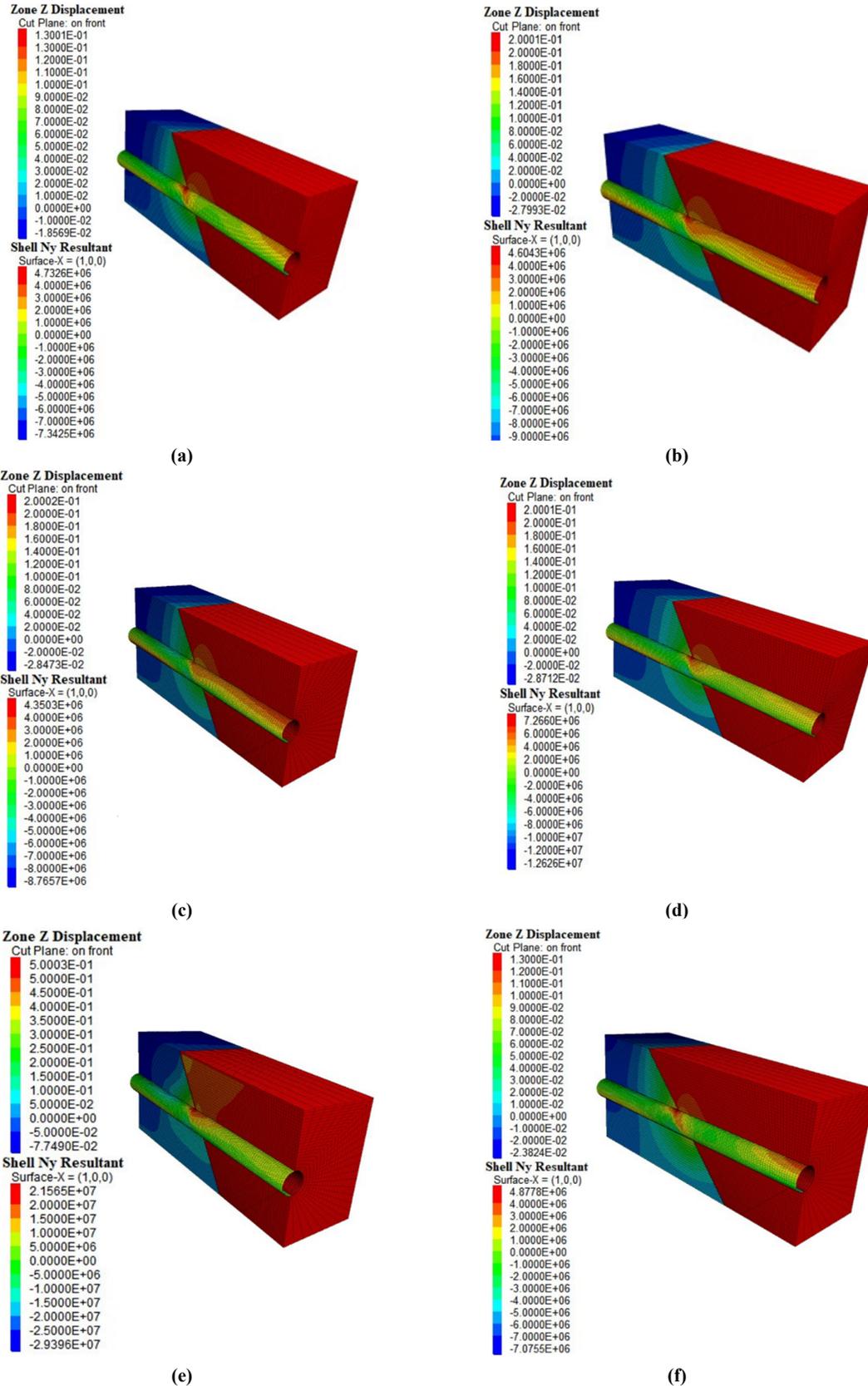


Figure 5. Numerical modelling results: (a) A=55, D=13, G=0.15| (b) A=55, D=20, G=0.3| (c) A=55, D=20, G=0.5| (d) A=55, D=20, G=0.15| (e) A=55, D=50, G=0.15| (f) A=45, D=13, G=0.15| (g) A=45, D=20, G=0.3| (h) A=45, D=20, G=0.5| (i) A=45, D=20, G=0.15| (j) A=45, D=50, G=0.15| (k) A=30, D=13, G=0.15| (l) A=30, D=20, G=0.3| (m) A=30, D=20, G=0.5| (n) A=30, D=20, G=0.15| (p) A=30, D=50, G=0.15

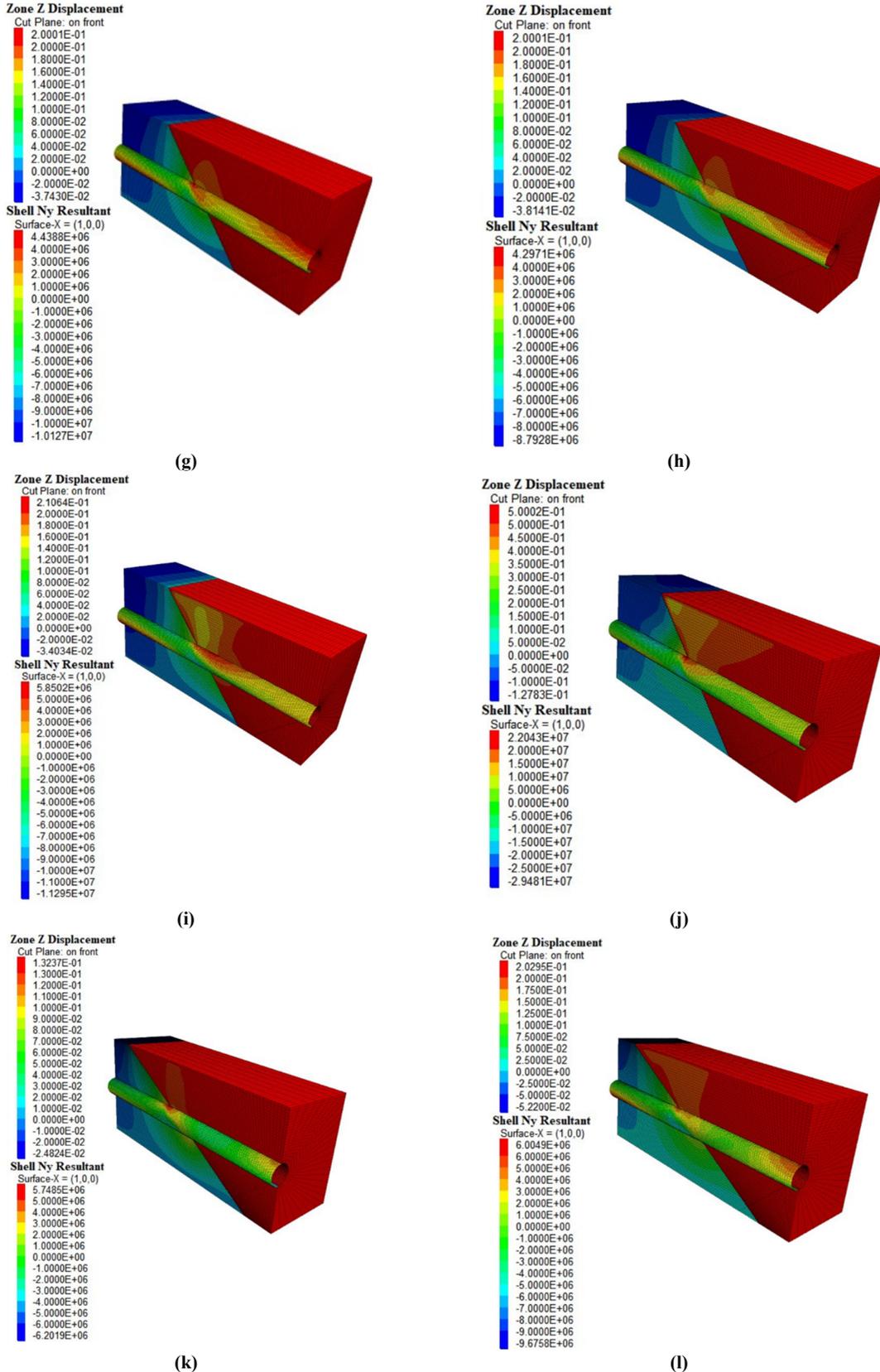


Figure 5. Numerical modelling results: (a) A=55, D=13, G=0.15| (b) A=55, D=20, G=0.3| (c) A=55, D=20, G=0.5| (d) A=55, D=20, G=0.15| (e) A=55, D=50, G=0.15| (f) A=45, D=13, G=0.15| (g) A=45, D=20, G=0.3| (h) A=45, D=20, G=0.5| (i) A=45, D=20, G=0.15| (j) A=45, D=50, G=0.15| (k) A=30, D=13, G=0.15| (l) A=30, D=20, G=0.3| (m) A=30, D=20, G=0.5| (n) A=30, D=20, G=0.15| (p) A=30, D=50, G=0.15

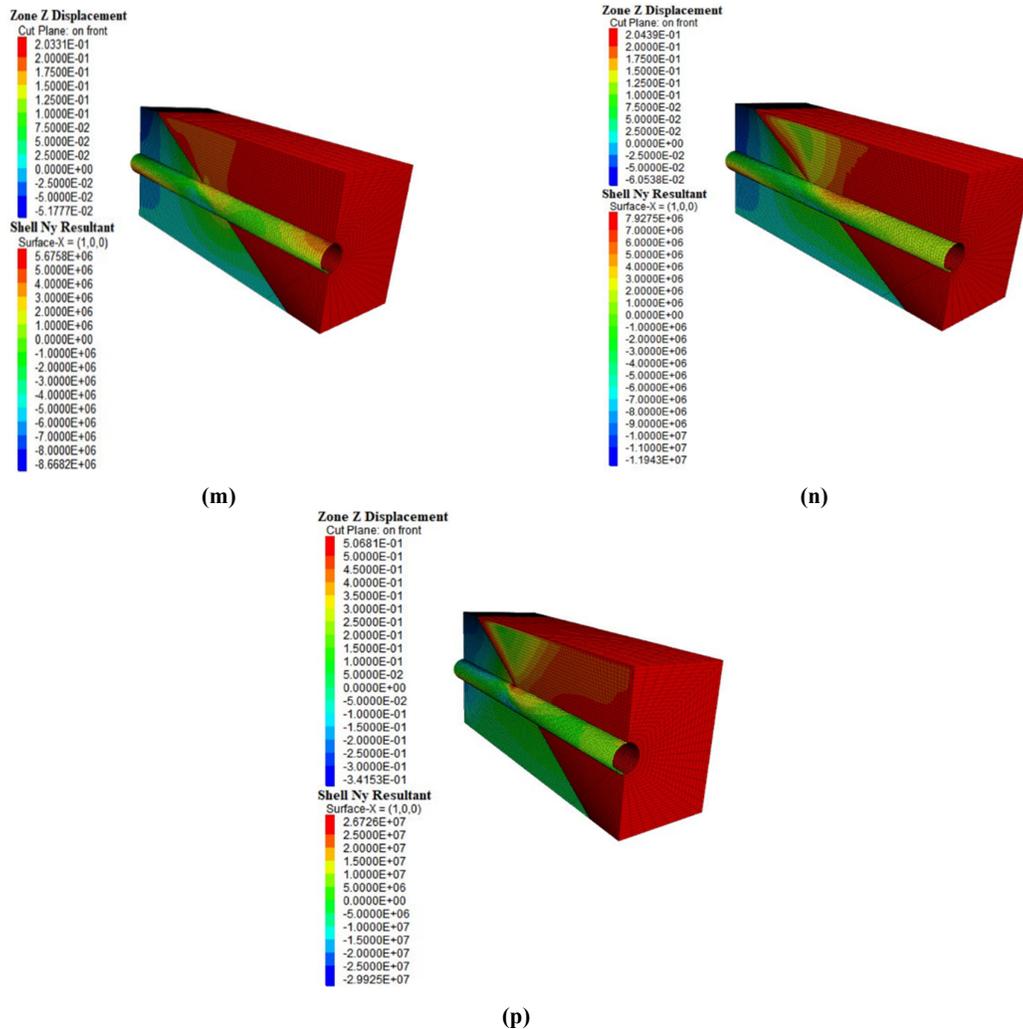


Figure 5. Numerical modelling results: (a) A=55, D=13, G=0.15| (b) A=55, D=20, G=0.3| (c) A=55, D=20, G=0.5| (d) A=55, D=20, G=0.15| (e) A=55, D=50, G=0.15| (f) A=45, D=13, G=0.15| (g) A=45, D=20, G=0.3| (h) A=45, D=20, G=0.5| (i) A=45, D=20, G=0.15| (j) A=45, D=50, G=0.15| (k) A=30, D=13, G=0.15| (l) A=30, D=20, G=0.3| (m) A=30, D=20, G=0.5| (n) A=30, D=20, G=0.15| (p) A=30, D=50, G=0.15

Based on obtained results of numerical modelling, all the three parameters of fault plane angle, grout layer thickness and fault zone displacement, effect the induced magnitudes of normal force in the tunnelling direction. Table 3, shows the results of diverse parameters effects on induced normal force of lining structure.

Comparison of magnitudes show that ground displacement is the most effective variable of the

three parameters. Figure 6, shows the effectiveness of diverse parameters on the linings induced normal force. Comparing in 100% change of the referenced parameters, ground displacement increases the induced normal force by 60.67%, fault plane angle decreases the normal force by 34.52% and the grout layer thickness decreases the normal force by 32.9%.

Table 3. Variable parameters effect on induced normal force magnitudes of lining construction

Modelling Cases	Variable	Induced Normal Force Change
1 4, 5	Changing fault zone's displacement from 13 to 20 and 50 cm (+53.8 %, +284.6%)	+53.5%, +356.23% increase
4 2, 3	Changing grout layer thickness from 0.15 to 0.3 and 0.5 m (+100%, +233.34%)	-57.82%, -66.89% decrease
14 9, 4	Changing fault plane angle from 30 to 45 and 55 degrees (+50%, 83.34%)	-35.38%, -9.09% decrease

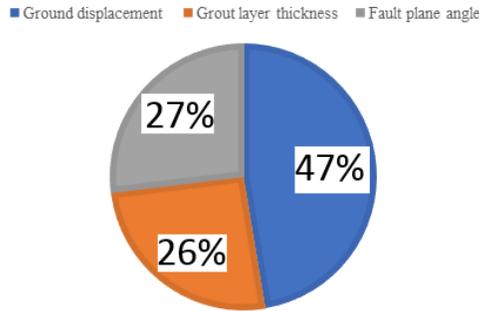


Figure 6. Parameter effectiveness

Induced moment magnitude on linings structure, is the other effective parameter in tunnel lining construction. Analyzing the induced moments effect in various tunnelling conditions, show that moment magnitude changes in different conditions. Table 4, shows the induced moment magnitudes in different modelled conditions. Based on results, modelling case 15, with fault plane angle 30 degrees, grout layer thickness 0.15 m and ground zone movement of 50 cm, has the largest moment magnitude comparing to all cases.

Modeling results depict several important reactions in both normal force and maximum moment calculations of diverse conditions. Fault zone displacement is the most influential parameter on the induced normal force. This indicates that in-order to reduce fault zone effectiveness and damage propagation on segmental lining, fault zone movement magnitude must be identified prior to any designs.

Considering induced moment magnitudes, grout layer thickness can control moment influences on lining structure. As deduced in table 4, increasing grout layer thickness from 0.15 to 0.3 and 0.5 meters (100% and 233.34% increase),

causes 50.57% and 114.52% reduction in moment magnitudes respectively.

As depicted on figure 7, diverse effective parameters have considerable influences on fault plane character. Increasing fault zone displacement magnitude, rises both maximum effected normal force and induced moment magnitudes. Larger grout layer thickness causes less induced force and moment which is more effective on moment magnitude in comparison to normal force. Fault plane angle shows a considerable effectiveness; increasing plane angle from 30 to 45 degrees reduces applied normal force value while increasing the angle from 45 to 55 degrees, increases the induced force magnitude. These reactions show that the grout layer thickness which changes ground properties around the circular tunnel section, such as its modulus of elasticity, governs the induced reactions with a considerable influential rate.

Table 4. Maximum moment magnitudes

Layer	Bulk Modulus (Pa)
1	5.4e5
2	5.2e5
3	3.65e5
4	7.83e5
5	14.8e5
6	6.09e5
7	5.5e5
8	3.63e5
9	8.4e5
10	16e5
11	6.3e5
12	5.5e5
13	4.76e5
14	8.8e5
15	16.9e5

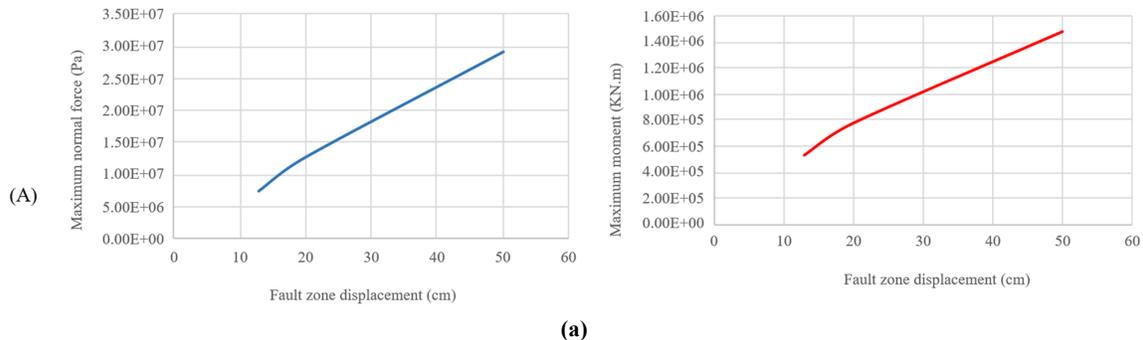
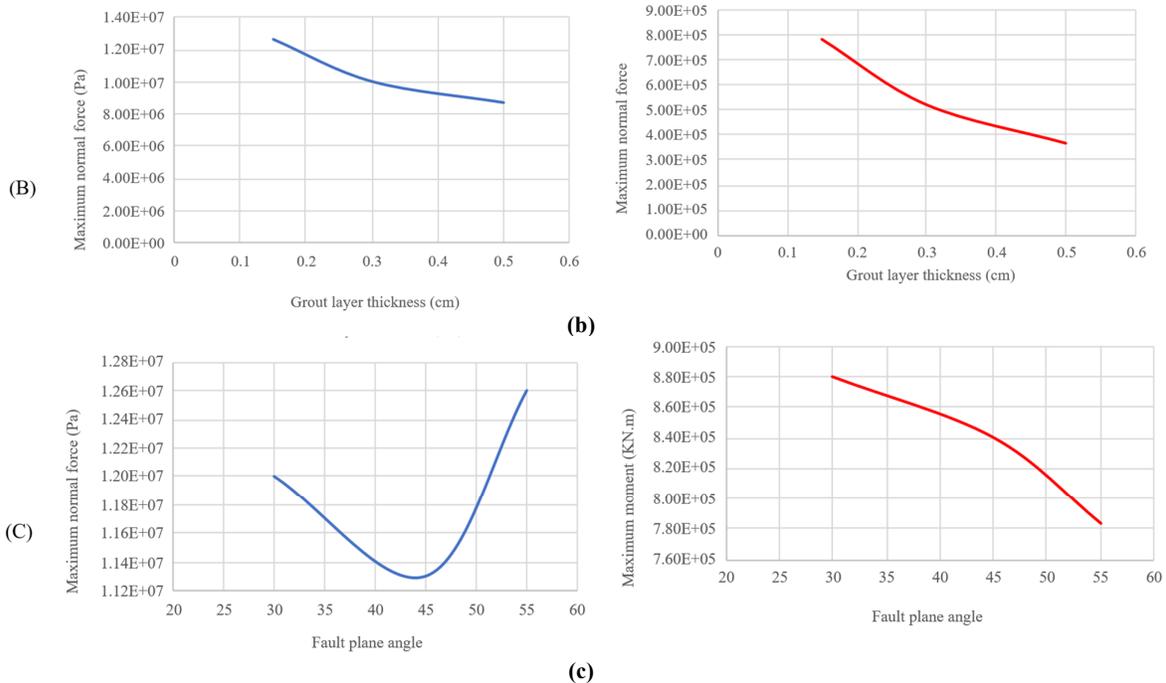


Figure 7. Parametric overview of influenced variables with diverse effective characteristics of fault plane; (a) force and moment changes in plane angle = 55 degrees, grout layer thickness = 0.15 m and various fault zone displacements (b) force and moment changes in plane angle = 55 degrees, fault zone displacement = 20 cm and various grout layer thickness (c) force and moment changes in fault zone displacement = 20 cm, grout layer thickness = 0.15 m and various fault plane angles



Continuation of Figure 7. Parametric overview of influenced variables with diverse effective characteristics of fault plane; (a) force and moment changes in plane angle = 55 degrees, grout layer thickness = 0.15 m and various fault zone displacements (b) force and moment changes in plane angle = 55 degrees, fault zone displacement = 20 cm and various grout layer thickness (c) force and moment changes in fault zone displacement = 20 cm, grout layer thickness = 0.15 m and various fault plane angles

5. Conclusions

Tunnel-fault intersection is a challenging issue in urban mechanized tunnelling process. Ground movement can cause high amounts of stresses and moments in tunnel lining structure which will cause considerable damages in the lining structure. There are diverse parameters that affect the lining structure which should be considered before constructing step.

Based on literature, fault plane angle, grout layer thickness and ground's displacement magnitude are three main effective parameters which influences the lining's efficiency. In this paper, the normal force and moment magnitudes are numerically modelled using FLAC3D package. Investigating induced normal force magnitude, which is considered as the most effective applied stress in segmental lining analysis, show that, ground displacement magnitude is the most effective parameter in stress analysis. Based on results, changing 100% the ground displacement magnitude results in 60.67% increase of applied normal force magnitude. Changing 100% the fault plane's angle results in 34.52% decrease of normal force and changing 100% the grout layer thickness results in 32.9% decrease of induced normal force magnitude.

As the other considerable parameter, induced moment magnitude increases 111.5% while increasing the ground displacement magnitude; grout layer thickness, decreases it by 113% and fault plane angle decreases the induced moment magnitude by 100%. Based on these obtained results, grout layer thickness is the most influential parameter on induced moment magnitudes.

Utilizing numerical modeling without any experimentally combined research can cause several assumptions in-order to reach the results. To reduce assumptions, we recommend experimental researches which can complete the lack of functional magnitudes and behavioral assurance. These results can be utilized in designing step of mechanized tunneling through fault zones to obtain the needed strength of structural elements.

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مطالعه عددی پارامترهای مؤثر بر تنش داخلی پوشش تونل در ناحیه تقاطع تونل-گسل

میلاذ منافی^۱، حامد ملاداودی^{۱*}، و حمید چاکری^۲

۱. دانشکده مهندسی معدن، دانشگاه صنعتیامیرکبیر، تهران، ایران
 ۲. دانشکده مهندسی معدن، دانشگاه صنعتی سهند، تبریز، ایران

چکیده	اطلاعات مقاله
<p>حفر تونل در مناطق شهری با چالش‌های متعددی همراه است که باید در مطالعات پیش از ساخت به دقت مورد ارزیابی قرار گیرند. در میان این چالش‌ها، عبور تونل از مناطق گسلی بسیار حائز اهمیت بوده و به طور گسترده‌ای مورد تحقیق قرار گرفته است. مطالعات گذشته عمدتاً بر جابجایی پوشش تونل تحت شرایط مختلف حرکت گسل متمرکز بوده‌اند. در پژوهش حاضر، اثرات سه پارامتر کلیدی شامل بزرگی جابجایی زمین، ضخامت لایه تزریق و زاویه صفحه گسل بر لنگرهای خمشی و نیروهای محوری القایی مورد بررسی قرار گرفته است. نتایج عددی نشان می‌دهد که بزرگی جابجایی زمین بیشترین تأثیر را بر تنش‌های القایی دارد، در حالی که ضخامت لایه تزریق و زاویه صفحه گسل تأثیرات مشابهی دارند. تحلیل‌ها همچنین نشان می‌دهند که افزایش ۱۰۰ درصدی در جابجایی زمین منجر به افزایش ۶۰/۶۷ درصدی در نیروی محوری القایی می‌شود. افزایش ضخامت لایه تزریق موجب کاهش نیروهای القایی به میزان ۳۲/۹ درصد می‌گردد، در حالی که افزایش زاویه صفحه گسل نیروی محوری را ۳۴/۵۲ درصد کاهش می‌دهد. نتایج مدل‌سازی همچنین نشان می‌دهد که ضخامت لایه تزریق مؤثرترین عامل تأثیرگذار بر لنگرهای خمشی القایی است. این یافته‌ها دیدگاه‌های ارزشمندی را جهت ارزیابی ظرفیت سازه‌ای و شکست احتمالی پوشش تونل در محل تقاطع با مناطق گسلی ارائه می‌دهند.</p>	<p>تاریخ ارسال: ۲۰۲۵/۱۱/۱۰ تاریخ داوری: ۲۰۲۵/۱۲/۰۵ تاریخ پذیرش: ۲۰۲۶/۰۲/۰۶</p> <p>DOI: 10.22044/jme.2026.17124.3382</p> <p>کلمات کلیدی</p> <p>پوشش سگمنت جابه جایی گسل Flac 3D گسل های شیب لغز</p>