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Research article

Numerical Investigation of Effective Parameters on the Tunnel-Canal Interaction (A Case Study: Tabriz Line 2 Urban Subway)

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Abstract

Tunneling in urban areas is more prone to vulnerable problems that may threaten life safety or cause urban infrastructure disasters. Tunneling parameters, such as face pressure, are important controlling aspects that can avoid disasters or cause some, like high amounts of settlements or different collapse forms. Tunnel line intersection with other underground spaces like pre-bored tunnels, shallow canals, or deep underground structures can cause high amounts of stresses and disasters on them, which will result in high amounts of displacements, fractures, and/or failure. Numerical modelling of the tunnelling process effects on the existing underground structures is a valuable method of investigating the stability of important structures. Since numerical models are accessible, studying effective parameters of the tunnelling process on the existing structure can be considered. In this paper, the effective parameters on the stability of an intersected canal are numerically investigated. Face pressure, canal cross-section geometry, canal's wall material, and canal–tunnel distance are the main parameters that have been investigated in this study. As a case study, the Tabriz line 2 urban subway intersection with Shah-Chalaby canal has been investigated. Numerical models result that the tunnel–canal distance has the maximum effect on the stability of canal structure, with 60% effectiveness of the total investigated parameters. In order to keep canal's stability, controlling the distance parameter as the most important one should be done. Face pressure is the second effective parameter of the modeled ones. The share of face pressure is 25% effective. Canal's wall material and its geometry are the following effective parameters, respectively. These two have not been examined thoroughly or sufficiently in the last decades. Geometry changes of existed canal have 15% effectiveness on the concluded numerical results. The results of this paper can be used in tunnelling operations of different projects.

1. INTRODUCTION

Tunnelling process will change the ground stress distribution and can cause critical effects on the existing structures. Ground surface settlements are one of the most important aspects that should be monitored during and after excavation. Much research has been done on the subject of surface settlements resulting from the tunnelling process. Existing underground structures such as tunnels, canals, deep foundations, and underground spaces will make the settlement issue more critical and important. Tunnelling beneath an existing structure will change the ground's initial stress condition and apply some extra induced stresses on the existing structure above the tunneling line. In some cases, these induced stresses can cause high amounts of settlements, and the conclusion of these stresses may be failure of the existing structure above [18].

In order to investigate the effect of tunnelling on the available structures, numerical modelling will be profitable. Numerical modelling can determine the resulting displacement and induced stresses, failure probability, and effective parameters. Regarding the field process, identifying and controlling the effective parameters can increase the structure's safety. In the last decades, various investigations have been done on the tunnel-canal interaction subject. References such as Standing et al. 2015, wang and Sun 2024, and He et al. 2023 are some of the nouvelle investigations. Since most of the cities all over the world have underground tunnel networks, it is necessary to excavate the new ones beneath the previous ones [24]. The new Crossrail tunnels in central London need more attention since the induced forces and stresses should not exceed the proper limits. As a critical operation using monitoring instruments in Hyde Park, numerical modelling and experimental investigation of cast iron segment response to possible stress distribution has been studied in this research [24]. As mentioned in the research, numerical modelling's pre-studies with 3-D ICFEP, show good converged results with the results of field monitoring.

Tunnelling effects on the infrastructure stability is a main topic that has not been appropriately covered in the last decades. Franza in 2016 estimated the tunnel effects on the deep foundations or underground infrastructures like piles which is a subject that needs to be considered [9]. To obtain the interaction mechanism of Tunnel-Pile-Structure-Interaction, geotechnical centrifuge test has been used for greenfield tunnelling in sands and tunnel excavations beneath piles and pile buildings. Based on experiments, tunnelling-induced pile displacements are affected by (i) pile-soil stress distribution and condition (ii) pile foundation design and safety (iii) superstructure stiffness and configuration [9]. (As concluded the superstructure stiffness and self-weight is a controlling important parameter in induced displacement investigation).

In some cases, the excessive settlements of excavation become so critical that soil improvement or reinforcement will be necessary. Hohhot subway construction resulted in many possible deformations that obligated the use of interlayer soil grouting and steel support reinforcement. He et al. in 2023 stated that, this method of construction can increase the safety of pedestrian passages. These results show that using soil improvement methods may sometimes be necessary [11].

Analyzing the excessive displacements of piles has been studied in other research too. (Face pressure has been determined as one of the most effective parameters on the induced settlements by Devriendt and Williamson in 2011). Analytical and numerical investigation methods are two ways of tunnel examining and pre-studying. Using analytical methods can lead to more exact results, while numerical ones are more rapid and more straightforward to use [7].

Using FLAC3D, Chakeri et al. in 2011 determined Tohid twin tunnel's effects on the line 4 urban subway of Tehran city. As resulted from the models, effects of tunnelling in the intersection area are more than the other parts; in other words, when new tunnel's construction reaches the existing one, the induced stresses and displacement will be critical [3].

Although many research studies have been conducted on surface and underground structure displacement investigation [10, 16, 26, 15, 30, 27]; determining the most effective parameters and numerically investigating the effects of these parameters has not been studied. In this paper, the effective parameters such as face pressure, tunnel-canal distance, canal geometry and the canals wall material have been determined using FLAC3D modelling and Tabriz line 2 urban subway intersection with Shah-Chalaby canal has been studied. In-order to investigate the wall material effects, ABAQUS modelling package is decided to be profitable due to its ability in modelling four nodal elements with applied proper material sciences.

Numerical modelling the construction stages and problems of the tunnel line is usually referenced. Rapid solvation, exact response and parametric investigation availability are the main advantages of using numerical models instead of experimental methods. FLAC3D is a 3D numerical modelling package that can provide needed simulation of the TCI problem. FLAC3D is a three-dimensional 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 [12].

Modelling in this program is based on defining nodes and fixing grids and grid-lines via related X, Y and Z parameters. Mesh elements are in polyhedral shape, which gives more freedom to the user while modelling complex geometries like the ones with angular nodes, intersections or surfaces. Defining boundary conditions, applied stresses, mechanical properties, theorical behaviors and valid response laws, are the options and advantages of this program. Materials movement/displacement, yield, and flow or grids and elements deformation are the other aspects of using FLAC3D. Using the explicit, Lagrangian calculation scheme and the mixed-discretization zoning technique ensures the suitable use of FLAC3D for plastic collapse and flow modelling accurately [12].

Akbari et al. 2020, Used finite difference analysis to investigate the interaction of a newly-driven large tunnel with twin tunnels [1]. In this investigation, the effect of a new boring tunnel on the existing one and the influence of horizontal distance is discussed. (Based on results, effects of newly boring tunnel are negligible in a distance more than three times the existing tunnel's diameter). Wang et al. in 2014 Studied the effects of tunneling on the pile-groups which have not been adequately covered. Conducting research, there are three critical locations in this interaction which are namely near the mid-depth of pile shaft (Test SS), next to (Test TT) and below the tow of the pile group test (Test BB). Among the three tests, twin tunneling below the pile toe (Test BB) caused the largest settlement to the pile group [25].

In another study, Simic-silva et al. in 2020 tried numerical modelling the tunneling operation caused cutting the existed piles in the tunnel's face and modelling the TBM advancement effect on adjacent pile. Using numerical modelling results, tunnel excavation influences an area in span of one tunnel diameter in advance of the excavation face, one tunnel diameter behind the excavation face and transversally, five times the tunnel diameter either side from the center point [21].

Numerical investigating the tunnelling operation effects on other structures and ground settlements have been studied in various researches [6, 29, 19, 13, 14]. These papers conclude the numerical and experimental results of investigating the effects of new boring tunnel on the existing piles or tunnels. Studying these papers show that, although different investigations have been done on the subject of interactions, influence of the effective parameters must be considered.

Chen et al. in 2024 proposed the results of numerical studying the construction of a double line tunnel effects on structures above the surface have been considered [5]. The results show that in constructing step, each tunnel of the double line, has a different effect on ground and structures around. As an important conclusion of this numerical research, constructing the first tunnel will have a "blocking effect" that can change settlement curves and distribution of the disturbance area [5]. Distance parameter counts important in cross tunnels too. Subway development causes constructing the crossing tunnels which are directly affected by parameters such as crossing angle and axis-to-axis distance [8]. Based on numerical results, constructing the cross angle over 45^{o} will reduce the stress on the lining. Sherizadeh and Dehghan in 2017 stated that parameters like tunnelling continuation, excavation method and tunnelling parameters, segment thickness, distance between two underground structures and soil parameters are some of the effective points that influence the intersection results [31].

Different research shows that various excavation parameters do affect the concluded results. Using various parameters like EPB face pressure, intersection distances, geotechnical profile and the stiffness of existed infrastructure, effect the obtained results.

In this paper using numerical modelling, some of the effective parameters have been investigated. As a pioneer investigation article, effects of tunnelling face pressure, existed canal's geometry, canal-tunnel vertical distance and canal's wall material property are determined. These parameters investigation combined with the real project data, obtained from Tabriz line 2 urban tunnel project make the results more valuable and nouvelle. Tabriz line 2 tunnel construction is an important project which faces different challenges; crossing various soil types causes cutter abrasion [nickjou], tunnel-fault intersection, construction beneath surface structures and tunnel-canal interaction are some of these challenges. The stated results of this paper are referenced as line 2 construction guidance.

2. TUNNEL-CANAL INTERACTION

Tunneling in urban areas faces various challenges, such as excavating beneath urban worn texture, crossing fault zones, excavating in different mixed ground layers, high underground water levels, problematic soils, beneath infrastructures, etc. All these cases need some preparations in order to cross the area safely. These challenges can cause high-ground settlements and stresses that may result in structure failure or other important critical problems. To avoid such happenings, pre-studies should be done in-order to estimate the possible results of construction. Studies via numerical modeling can show the possible events.

Tunnel-Canal Interaction (TCI) is one of the most critical conditions that should be considered before construction. Based on material science, high stress amounts can cause plastic strains, which will result in cracks, fractures or material failure. Tunnelling via TBM causes excessive induced stresses which can directly affect the existing structures' strength and stability. If the induced stresses exceed the strength parameters, vulnerable strains will occur on the canal structure. As a conclusion, tunnelling beneath underground structures needs pre-studies that should investigate the structure stability. TCI is critical mainly because of the initial existing structure. As a case of study, (Tabriz line 2 intersection with Shah-Chalaby canal in Abbasi area of Tabriz city is investigated in this paper. Fig. 1, shows the intersection location of current TCI study. Shah-Chalaby canal is valuable because of its important role in controlling surface water floods, gathering surface water in its area, avoiding waste accumulation and directing sewage.

Existence of canal will change the normal stress condition of the ground. Construction beneath Shah-Chalaby needs some extra studies. As seen on Fig. 1, this canal starts from Seylab area till Mehranrood which includes an approximate surface of 1.5 km^2).

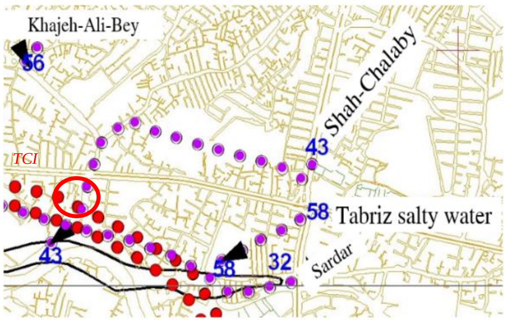

Fig. 1. Shah-Chalaby canal location.

TBM operation is mainly based on face pressure that will guarantee ground stability; so, applying a suitable face pressure in construction step is important. In conditions like crossing beneath canals, using a proper face pressure will be more important.

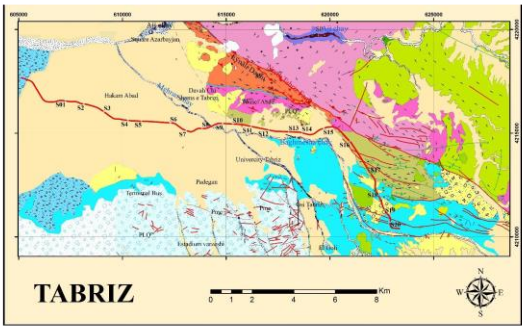

Fig. 2. Geological map of the Tabriz region (adapted map from the geological survey of Iran 2009).

Fig. 2 shows the geological map of the area. As seen on the map, Tabriz consists of various ground types and fault zones. Mountainous belt, fault zones and various land frontiers are shown in the figure above.

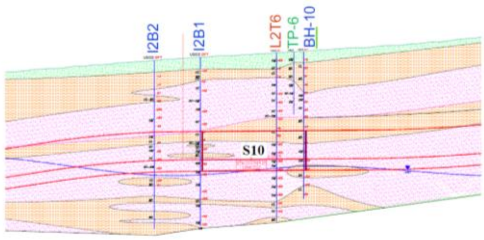

Fig. 3. geotechnical profile of area.

As seen on the Fig. 3 above, geotechnical profile in the intersection area, mostly consists of four layers which have various soil properties based on initial ground research and geotechnical reports [barzegari]. The information is gained from different log data in the tunnelling path. In the intersection zone, TBM machine is located in a layer consists of approximately 90% coarse mass and 10% fine mass, while, canal exists in a layer of approximately 100% fine mass.

3. TCI MODELLING

The initial modelling of TCI is shown in Fig. 2. Shah-Chalaby is a rectangular-shaped tunnel with a dimension of 2.3 m. Buried depth of canal is 3.65 m and the mechanical properties of canal's wall are reported in Table 1.

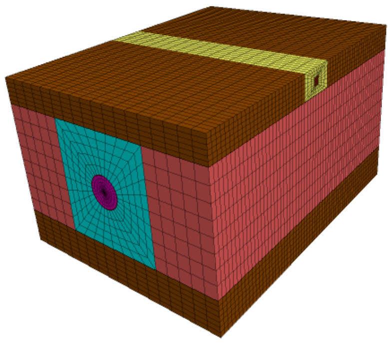

Fig. 4. TCI initial modelling.

As seen on Fig. 2, modelled zone contains tunnel structure, canal and surrounding ground. The angle of TCI is 90 degrees to tunnel line direction and the vertical distance till tunnels center of origin is 20.075 m. Based on gathered information from construction and monitoring teams, canal's wall had made of concrete, wall condition (fractures, cracks and etc.) is proper and the performance is normally running.

Table 1. Canal modelling properties

Property	Magnitude
Dimension (m)	2.3
Modelled Length (m)	90
Depth (m)	3.65
Young's modulus (Pa)	3e10
Poisson's ratio	0.1
Density (Kg/m^3)	2600

Ground is defined in four layers with properties described in Table 2 and Fig. 3 /geotechnical report/. The ground layers' properties are the same as Tabriz line 2 urban subway geotechnical reports in the TCI area. To investigate the effective zone of TCI, model area contains a volume equal to 317.961 m^3. Effective zone is an area in which the tunnelling process influences on the ground. Modelling 90 meter of TCI area in longitudinal (Y) direction, will adequately show the effect of TBM advancing on the canal structure. The stability of the canal highly depends on the canal-base strength and quality. Field investigations highly recommend assuming the canal-base in suitable condition. Any failure occurrence in the canal base will directly affect water leakage, pore pressure increasement and more settlement by time passes. In order to reduce the running water effect on the displacement and canal's possible failure, modelling effective parameters is important.

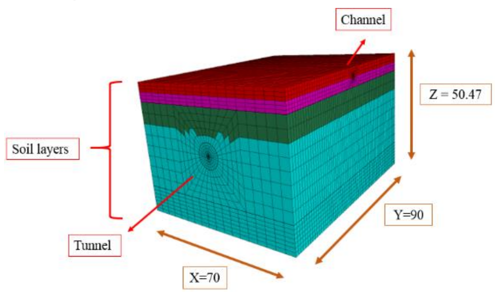

Fig. 3. TCI ground layer property identification.

After exerting ground properties, applying boundary conditions with fixing displacement and velocity in all faces except Z+ is necessary. To model the effect of surface structures in the range of TCI, loading the model surface in Z+ should be considered. The modelling process should be done in three steps: reaching the equilibrium state in the initial model, the canal model, and the tunnel model. In tunnel boring model, segments must be modeled with concrete properties. Tunnelling operation should be modeled in 83 steps which describes the position of TBM and segment in each advance rate. As seen on the Fig. 4, segment installation should be considered with grout injection for each 1.5 meters of advancement. Concrete segments should be modeled with elastic modulus equal to 3e10 (pa) and 0.35 (m) thickness. These are the real data of segments that are being used in Tabriz line 2 project. Base on literature and experiment in tunnelling subject, there are practical parameters in TCI area that can provide the induced results which are count critical. Face pressure, canal cross-section geometry, canal's wall material and canal – tunnel distance are considered as the critical effective aspects.

Table 2. Ground layers properties

Ground Layer	1	2	3	4
Thickness (m)	4	4	8	34.47
Bulk Modulus (MPa)	29.17	37.50	34.60	51.04
Shear Modulus (MPa)	9.0	9.9	15.0	18.3
Cohesion (KPa)	5.0	10.0	7.0	25.0
Friction (degree)	28.0	24.0	28.0	31.0
Density (Kg/m3)	2060	2060	2120	2120

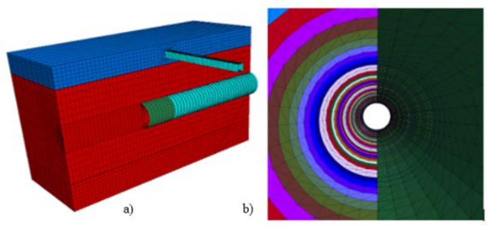

Fig. 4. Modelling in FLAC3D: a) Excavating process b) Segmental lining.

Face pressure is an important tunnelling parameter which should be determined in pre-process and pre-advance step. Using the proper face pressure can guarantee the ground and face stability. High amounts of face pressure can make the advancement process hard and the low amounts of it, will increase the failing, collapsing and settlement possibilities. The results of face pressure changes and the proper amount will be discussed more.

The canal's shape will affect the critical points in which higher amounts of stress will happen. Constructing a rectangular, circular or horse-shoe geometry will decide the induced results of tunnelling process on the canal structure. The differences of reaction in arch and angle and the theory of stress distribution in corner and surface, will change the effected section surface and this will be concluded in results. To compare the results of shape effects on the displacement magnitudes, canal's volume should be the same for all three forms.

Wall material and its mechanical properties are the other effective parameter. Different materials like stone or concrete, which are used for construction, show different strains and reactions that will affect the total results of TCI. Density of material will affect the displacement and strength parameters will determine the stability of whole structure.

Distance between canal and the tunnel can judge the amount of effecting stress on canal structure; in other words, when canal is closer to the tunnel line, the percentage of effective stress will be more and more distance will absorb more stress.

3.1. Face Pressure Effect On Canal Structure

According to the literature, applying proper pressure is one of the most important parameters in excavating process. TBM process operates mainly based on face pressure which decides the ground to stay firm and stable or collapse. Changes in the pressure cause various amounts of ground stresses. Face pressure effect on the ground settlement has been studied in the last decades [2, 4, 8]. All of these studies agree on the using a proper face pressure to control different effected results.

In this study, using numerical modeling, face pressure effects on the existed canal have been identified. The applied pressure magnitudes are 0.7, 0.8, 0.9, 1.0 and 1.2 bars. Since the shape of Shah-Chalaby is rectangular, identifying proper face pressure is modeled in the base shape. Results of TCI modelling are shown in Table 3 and Fig. 6 below.

Table 3. Results of modelling TCI with various face pressures

Face Pressure (bars)	Max Canal displacement (mm)	Max Surface Settlement (mm)	Axial Induced Stress on Canal (Pa)
0.7	9.05	8.7	3.52E6
0.8	7.8	7	3.57E6
0.9	6.7	5	3.70E6
1.0	5.89	5	3.82E6
1.2	5.13	5	3.86E6

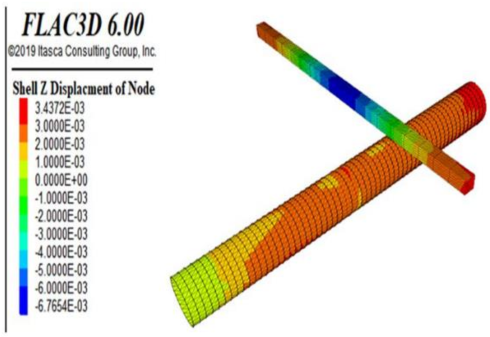

Fig. 6. Results of modelling TCI with 0.9 bars face pressure.

Results indicate that increasing face pressure from 0.7 to 1.2 bars increases canal stability and reduces its displacement. As mentioned previously, a proper magnitude of pressure is an amount in which, although the stability will be secured, it will not make the excavation process difficult. Resulted maximum canal displacements are 8.9, 7.8, 6.7, 5.8 and 5.13 mm in different pressures respectively. Results show that increasing pressure from 0.7 to 0.8 bars has a more significant effect on the stability than increasing it from 1.0 to 1.2 bars. This means that after a critical pressure amount, its magnitude has low effects on the stability and increasing pressure parameter beyond that will be waste of energy and machine performance. Fig. 7 shows the pressure-displacement curve in which the proper pressure magnitude is identified.

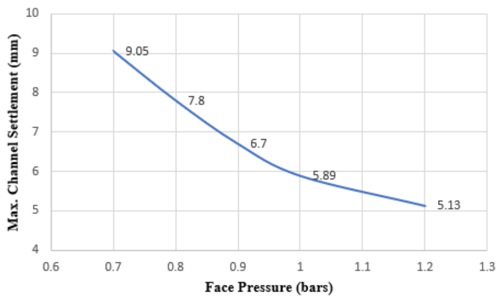

Fig. 7. Face pressure - Max. canal vertical displacement curve.

Based on the results, increasing face pressure from 0.7 to 0.8 bar increases Max. canal vertical displacement by 13.4%, from 0.8 to 0.9 bar by 14.1%, from 0.9 to 1.0 bar by 11.9% and from 1 to 1.2 bar by 12.9%. This shows that after 0.9 bar the effect of face pressure reduces. Advancing the excavation process with 0.9 bars in Shah-Chalaby area is advised.

3.2. Canal's Geometry Effect On Canal Structure

The shape and geometry of the excavated tunnel is another important effective parameter that has been studied in this research. Other geometrical base investigations have studied effects of diameter, cover/diameter, height/width, etc., in different circular or horse-shoe shaped tunnels, but studying displacement differences in three usual construction shapes of square, circle, or horse-shoe canals have not been investigated. In-order to apply this parameter and study the effects, using three-dimensional modeling, three shapes of tunnels are modeled.

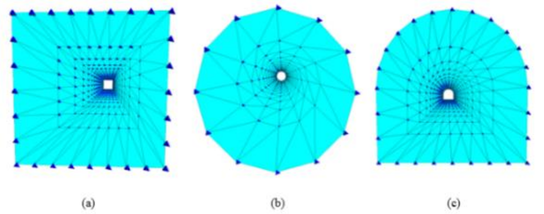

Fig. 8. Three modeled shapes of canal.

Different modelled shapes are shown in Fig. 8 above. Applied diameter in modelling these three shaped is 2.3 m and the approximate volume of all three is 330 m^3. Since FLAC3D is a user-defined program, we can easily model various geometries that are needed. Table 4 below shows the results of displacement investigations with various geometries. As mentioned in the previous section, 0.9 bar is an acceptable face pressure for the excavation process.

These results show that displacement in the circular shape is more than both square and horse-shoe geometries. Although the differences between these three are not very much, this difference in magnitude is considerable. The displacement order of geometries is Square < Horse-shoe < Circle. Experimental investigation of this result should be considered in future studies.

Table 4. Modelling results for different canal shapes

Canal Shapes	Square	Circle	Horse-Shoe
Canal displacement (mm)	6.76	7.56	7.12
Surface settlement (mm)	4.37	4.36	4.37
Axial stress (Pa)	3.70e6	3.71e6	3.69e6

3.3. Canal – Tunnel Distance Effect On Canal Structure

Distance effects have been attended in various researches numerically and experimentally. All of these papers conclude that the inter-tunnel distance in double line tunnels or the horizontal/vertical distance between tunnel and a surface structure is an important effective parameter. It is evident that the buried depth of a tunnel will directly affect the displacement and induced stresses on an existing structure.

Based on referenced literature the effect of distance in TCI zone has been mentioned as an effective parameter. Studied distance in this article is the vertical distance, which refers to the depth of both canal and tunnel structures. The distance changes of canal to tunnel are reduced to half of the previous initial one and the changes in magnitudes are determined.

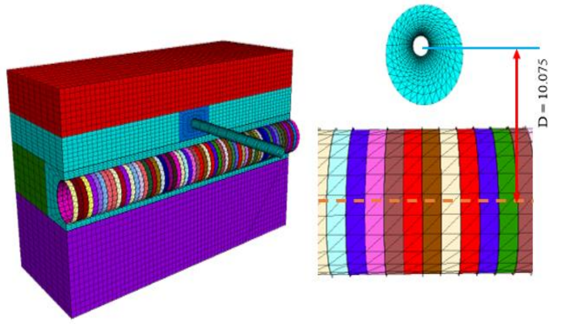

Fig. 9. Reduced vertical distance of TCI.

Numerical models are simulated with a tunnel-canal distance equal to 10.075 m which is half of the initial one with a distance of 20.075 m. Excavating with face pressure equal to 0.9 bar and a lower distance of 10.075 m, Maximum induced canal displacement will be 9.5 mm. comparing the results of initial distance 20.075 m and approximately half distance of 10.075 m, shows that canal displacement increases from 6.7 mm to 9.5 mm. As a conclusion of vertical distance affect, 50% reduction of vertical distance between tunnel and canal structure results in 41.8% increasement in the canal displacement. Since canal is closer to the boring tunnel, induced stresses will have higher amounts. 50% reduction of vertical distance will have 16% increasement effects on the canal's axial stress. Fig. 10 shows the Maximum settlement magnitudes in both canal and ground contours. The left contour relates to ground displacement and the right one is for canal structure.

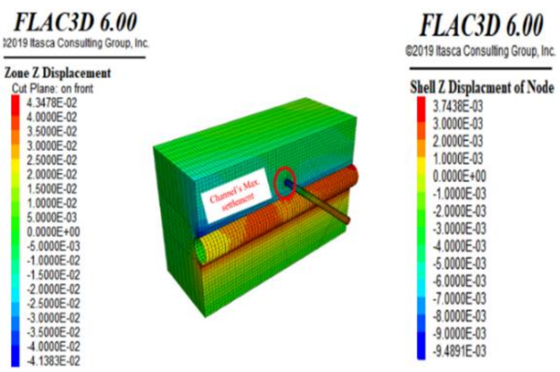

Fig. 10. Canal's Max. settlement with a closer distance to the boring tunnel.

4. CANAL'S WALL MATERIAL STABILITY

Results of numerical modelling show significant induced stresses on canal's wall. The stability of canal relates to the strength of its wall material. Obtaining TCI induced stress effects on wall stability is an important aspect which should be considered. In this paper the stability of canal wall is investigated via ABAQUS program.

ABAQUS/Standard is a general-purpose finite-element solver that simulates actual static and structural dynamic events. Its applications include thermal stress analysis, sealing evaluations, steady-state rolling simulation, fracture mechanics studies, heat transfer modeling, acoustics, pore pressure, etc.[22]. Elastic theory of materials indicates that applied loads on thin shells, surfaces and membranes can lead to bending and buckling of elements. When the length parameter of an element is larger than its thickness, applied load in inter-plane direction of element will cause larger deflections and reactions in the middle part in comparison to edge zones of the element.

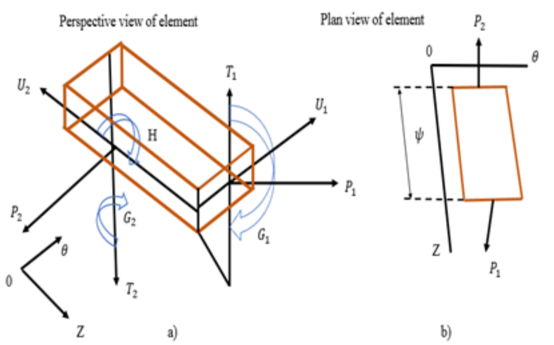

Fig. 11. A membrane element stress-tensors: a) Perspective view of element b) Plan view of element [30].

On the schematic view (a) of Fig. 11, if the applied coupled loads T_1 and T_2 are combined and changed to load T and displaced to the middle of the element, bending will occur in the shell element above. Wall element modelling in different numerical programs are defined as shells, surfaces or membranes. Regarding wall material effects modelling in numerical simulation of TCI needs applying this part of elastic-theory to the modelling steps.

Using ABAQUS program, wall modelling with concrete properties have been done. Modelling programs simulating via mesh element models, highly depend on mesh size and element type. FLAC3D models the shell element with three nodal triangular elements, while ABAQUS uses four nodal square and rectangular elements for plane stress/strain models. Square-shaped elements are more sufficient for numerical modellings than the other shapes; they can reduce possible errors of solving route. Due to the reliability of reasons, reducing errors and gaining time advantage, this modelling step is done via ABAQUS program. Applied parameters are subscribed in Table 5 below. Assuming the canal's wall as a 2D shell element obligates calculating inter-plane applied load on the walls. Applied loads in all three directions are calculated via the FLAC3D program. Applying these loads to ABAQUS modelling and investigating wall's mechanical parameters effects on the concluded dislocations, is the calculation method used in this paper. Since modellings are made in element scale, applied load should fit the geometry dimensions.

Table 5. Applied wall parameters

No.	1	2	3
Wall Material	Concrete	Stone	Wood
Elastic Modulus (Pa)	3e10	0.1	26.0e5
Poisson's Ratio	2e10	0.3	22.5e5
Density (Kg/cm3)	1.1e10	0.4	4.0e5

Applying these parameters to the modelled element will show deformation shape, induced moments and local stress on each mesh element. Changing material properties based on the possible construction material can show the stability parameters of the wall in various materials. Using un-suitable material No. 3, shows large amounts of deformations. To reduce element dislocations, proper material should be used during construction of canal's wall. Fig. 12, shows: a) applied load – boundary condition, b) mesh elements, c) deformed shape of modelled canal's wall and d) Displacement contour legends in inter-plane direction of wall elements. Results of each modelled material is reported in Table 6.

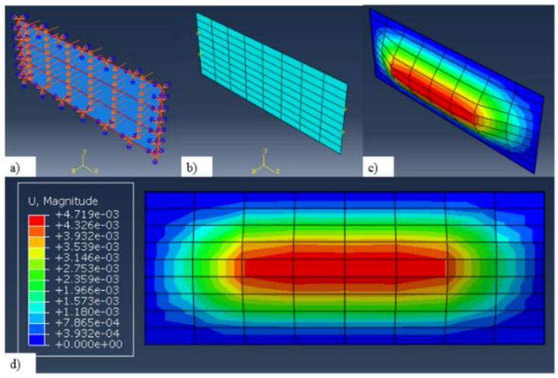

Fig. 12. Wall material effects modelling: a) Applied loads and boundary condition b) Mesh elements c) Inter-plane displacement Result d) Displacement contour legends

5. WEIGHTING THE EFFECTIVE PARAMETERS

Based on numerical models and their results, weighting the effective parameters show that tunnel-canal distance is considered as the most effective parameter of induced ground and structural reactions. Designing the proper path of TBM advance and tunnel line needs considering the possible vulnerable effects on the existed structures.

Table 6. Wall stress and displacement

No.	1	2	3
Wall Material	Concrete	Stone	Wood
Max. Center induced stress (Pa)	1.6e6	1.2e6	1.3e6
Max. Induced displacement (m)	4.7e-3	6.5e-3	1.09e-2

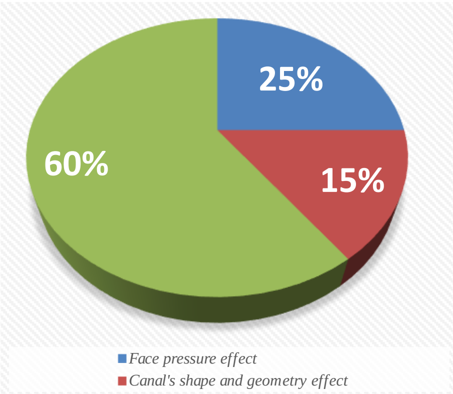

Fig. 13. TCI effective parameter's magnitudes

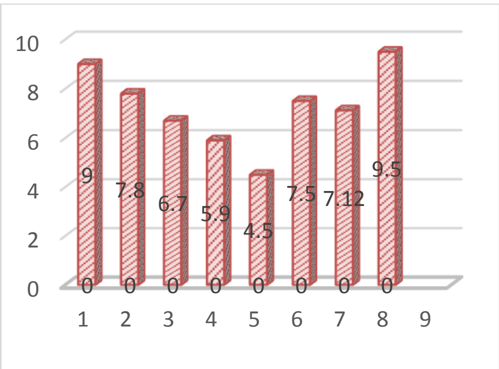

Fig. 14. Displacement magnitudes based on various defined conditions.

Table 7. Displacement magnitudes based on various defined conditions

No.	Face Pressure (bars)	Canal's Shape	Tunnel – Canal Distance (m)	displacement (mm)
1	0.7	Square	20.075	9
2	0.8	Square	20.075	7.8
3	0.9	Square	20.075	6.7
4	1	Square	20.075	5.9
5	1.2	Square	20.075	4.5
6	0.9	Circle	20.075	7.56
7	0.9	Horse-shoe	20.075	7.12
8	0.9	Circle	10.075	9.5

6. CONCLUSION

Large scale urban projects like metro construction, faces various challenges that can directly affect safety of structures in the excavation effective area. Crossing existing tunnels and canals are one of the most critical cases that needs pre-studies in-order to investigate the stability of the underground installation. Investigating effective parameters on the stability of existing underground structures utilizing numerical modelling, shows that the excavating face pressure, canal's shape and geometry, canal – tunnel distance and canal's wall material have a considerable effect on the stability and displacement of the canal.

Modelling the first three parameters via FLAC3D declare that Tunnel – Canal distance is the most effective parameter on the canal's displacement magnitude with average 60% effectiveness. Excavating face pressure and canal's shape have average 25% and 15% effectiveness respectively.

Wall material is another parameter that shows canal's stability. Various materials have different strengths and reactions facing applied loads. Using the ABAQUS program, modeling results in:

- Concrete wall has almost the least inter-plane displacement in comparison with the other three wall materials. Concrete-wall Maximum induced displacement in the middle zone of wall element is 4.7e-3.
- Stone wall with Max. displacement of 6.5e-3 has the mean displacement and induced stress amounts.
- Wooden wall has the maximum inter-plane displacement with the magnitude of 1.02e-2.

These results indicate that wall material can provide stability of the canal structure during excavation process. Using concrete, stone or wood can provide the needed canal strength to stand or fail against induced moments and stresses. Based on numerical investigation results, modeling eight different combinations of shape, pressure, and distance show that displacement magnitude in a combination of 0.9 bars pressure – circle shape – TCI distance 10.075 (Case 8), has the most displacement magnitude while the condition of 1.2 bars – square shape – TCI distance 20.075 (Case 5) has the least displacement amount. Controlling these effective parameters, the TBM process will be less vulnerable to existing underground structures.

For future studies, investigating the existed canal's shape and geometry effect in an ideal and same condition of tunnelling is suggested. Experimental investigation of this topic can gain more knowledge and detailed results about this subject. Furthermore, determining the effects of injected grout /Rahmati/, horizontal distance between the existed canal and boring tunnel, intersection angle, underground water effect and ground property effects can be processed.

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