Numerical Modelling of TBM Segmental Lining at Accidental Cases

Prof. Dr. Mostafa Zaki [1], Dr. Ahmed Hassan[1], Eng. Mostafa Asaad [2]

[1.] Civil Engineering Department, Faculty of Engineering, Minia University, Minia 61111, Egypt
[2.] Technical Department (TD), National Authority for Tunnels (NAT), Cairo, Egypt
Mostafa_asaad08@yahoo.com

Abstract: Thanks to the high safety degree and the high speed rate of work, mechanized tunneling have speedily spread worldwide for tunnels excavation. These factors make mechanized tunneling preferable for decision makers all over the world. In some cases when the safety limits for one or more of the parameters which control the stability of lining is exceeded, the excavation work may collapse. If an accidental case happened during construction, the consequences for time, cost and sometimes human losses is so high that make tunnelling engineers do their best to avoid such accidental cases. To achieve the previous aim, the interaction between lining components with grout and surrounding soil in addition to the appropriate value for face support should be comprehensively understood. The aim of this research is to study the behaviour of segmental lining at accidental cases. To achieve this goal, first a short study will be performed for making appropriate model for simulating segmental lining components. Consequently better understanding will be possible for the interaction between different segmental lining components and the annular grout. Then a comprehensive study will be introduced for the effect of parameters which may lead to excavation failure. Hence, safety limits could be set for these parameters. Consequently it will be possible to avoid accidental cases which may happened due to the exceeding of the limits of these parameters.
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1. Introduction

The aim of studying the nonlinear behavior of TBM segmental lining is to predict its behavior in accidental cases. Furthermore to predict its behavior due to any change of the conditions of different parameters subjected to the concrete section. Generally the structural design model should yield criteria related to failure cases, against which the tunnel should be designed safely [6].

This paper focuses on studying and investigating the behavior of segmental lining, in order to avoid any possible failure of the lining. Furthermore if the previous goal wouldn't be possible in some cases, at least it will be possible to reduce the time of the delay consumed to investigate the reasons of the failure and to overcome it.

Firstly a suggested technique will be developed to simulate the TBM segmental lining. In this technique the important components of TBM segmental lining (Segments, Joints, Bolts and Gaskets) will be simulated by its own properties.

Two possible cases for failure will be studied in this paper. First case focused on studying the effect of not installing some or all bolts on the stability of the ring during construction. The second accidental case which will be studied is the effect of excessive grout concentrated in certain segments on the stability of the model.

2. Soil Modelling

During the construction of the lining and before the hardening of the grout, there is no direct interaction between the lining and the soil. To date and to the knowledge of the authors, this case is the more critical case during tunnel construction. Most failure cases happen during this stage. Hence, it will be reasonable to model the confinement provided by the soil by means of springs. Since the focus in this paper is to study the local behaviour of the lining during construction, so modelling the soil with springs will help to more focus on this aim. The more sophisticated modelling of the whole soil layers with shell elements will make the model too large to illustrate the local behaviour of the lining components.

2.1 Stiffness of springs

The confinement provided by the soil has been modelled using spring elements. These types of support resist lining movement in direct bearing and tangential shear across the grouted layer surrounding the lining. The springs' stiffness was calculated using linear load deformation relationship according to Duddeck and Erdman [1], [2], [7] and [8].

$$E_c = \frac{E\,(1-\nu)}{(1+\nu)\,(1-2\nu)}$$

$$C_r = \frac{Ec}{R}$$

$$K = Cr\ X\ A$$

Where:
E, ν = Young's Modulus and Poisson's Ratio of the ground
R = equivalent tunnel radius
A = area of soil that is to be represented by the equivalent radial spring. This is the distance between adjacent radial springs multiplied by unit length.

2.2 Spring Constants calculations

Spring constants can be determined based on tributary projections on the x and y axis of each joint. If the analysis software being used supports the use of radial springs, then all spring constants will be the same. The following formulas can be used to determine spring constants [12]:

Spring constant in Y direction = $K_s\ (X_n + X_{n+1})/2$ Where:

$X_n = |\ (x_n - x_{n+1})|$

$X_{n+1} = |\ (x_{n+1} - x_{n+2})|$

Spring constant in X direction = $K_s\ (Y_n + Y_{n+1})/2$ Where:

$Y_n = |\ (y_n - y_{n+1})|$

$Y_{n+1} = |\ (y_{n+1} - y_{n+2})|$

Figures 1 and 2 illustrate the method for calculating orthogonal springs:

In the above equations:

The coordinates for joint N = (x_n, y_n)

The coordinates for joint N+1 = (x_{n+1}, y_{n+1})

The coordinates for joint N+2 = (x_{n+2}, y_{n+2})

Ground behaviour in tangential direction is generally ignored in beam spring model method. Although this leads to frictionless sliding of the lining against the ground, it has a negligible effect on member forces [3]. For that reason, ground springs stiffness are only considered in radial direction.

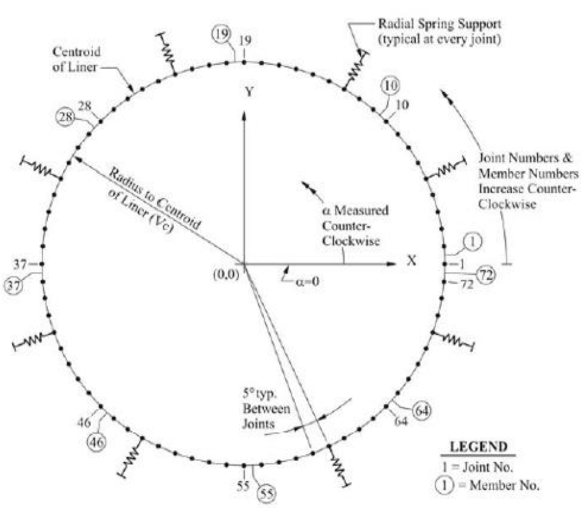


Figure 1. Joints and members – computer model

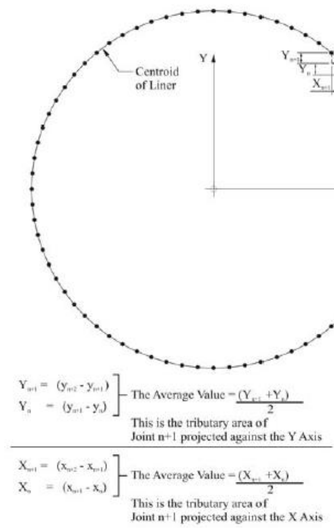


Figure 2. Spring constant computation

3. FEM Software

The FEM software used in this study is Midas GTS [9]. It is a comprehensive finite element analysis software package that is equipped to handle the entire range of geotechnical design applications including deep foundations, excavations, complex tunnel systems, seepage analysis, consolidation analysis, and embankment design, dynamic and slope stability analysis. Midas GTS also has an advanced user friendly modelling platform that enables unmatched levels of precision and efficiency [9].

4. Data Used in the modelling

The data for the model which will be considered in this paper is taken from the accident of Cairo metro line 3 phase 1, at tunnel section between Bab El-Sharia and El-Giesh stations [10] (Figure 3) (Tables 1, 2).

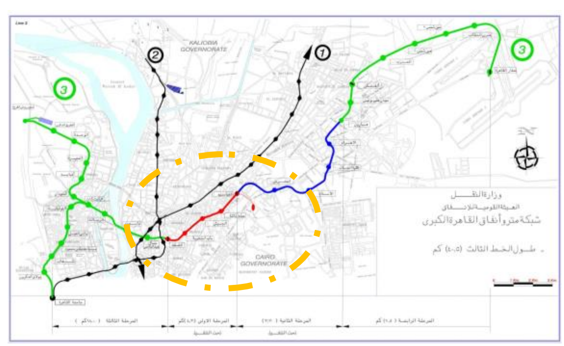


Figure 3. Map showing the route of Cairo metro line 3

- ➢ The zone of failure is the red line at the clouded zone.

Table 1. Data of lining used in the modelling.

Segment				Joint		Bolt		
Inner Diameter (m)	Thickness of Segments (m)	Length of Segments (m)	No. of Segment	Thickness of Joint Gap (mm)	Thickness of Gasket (mm)	Length of Bolt (cm)	Diameter of Bolt (cm)	Angle of Bolt circumferential axis
8	0.4	1.5	7+1 Key Segment	7	7	30	2.8	25°

Table 2. Parameters of different materials used in the analysis.

Parameter	Segments (Concrete)	Grout	Bolts	EPDM Gasket	Plywood packing
Initial Tangent Elastic Modulus (E) MPa	30000	0.1 to 20 E3	210000	see Fig. 4	3650
Poisson's Ratio (ν)	0.2	0.4	0.3	0.4	0.18
Density kg/m^3	2600	-	8030	-	-
Unconfined Compressive Strength(fcu) Mpa	60	-	-	-	-
Initial Yield Stress (σy) Mpa	48	-	350	-	10
Tensile failure stress Mpa	4	-	800	-	14
Type of Selected Element	Solid Element	Solid Elem	Solid Elem	Solid Element	Solid Element
Model Behavior	Drucker Prager	Mohr Coulomb	Von Mises	Elastic	Elastic

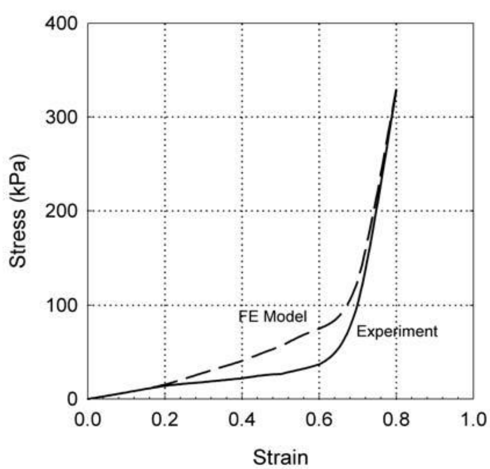


Figure 4. Stress-strain response of the EPDM gasket [4]

5. Segmental Lining FE Simulation

In this section the suggested approach used to model the segmental lining components will be presented. Since the purpose of this paper is to study the local behaviour of segmental lining, 3-D simulation will be used. Consequently it will be possible to accurately simulate and study the behaviour of each component of TBM segmental lining. In this approach, all elements of segmental lining are modelled with solid elements. Properties of each element have been considered by two parameters:

a) The actual properties of each material.

b) The model behaviour type used to represent the actual behaviour of this material.

Table 2 illustrates the elements and model behaviour type used to simulate each component material. It should be noted that all lining components (segments, longitudinal bolts, radial bolts, gasket, and grout layer) have been simulated using solid elements.

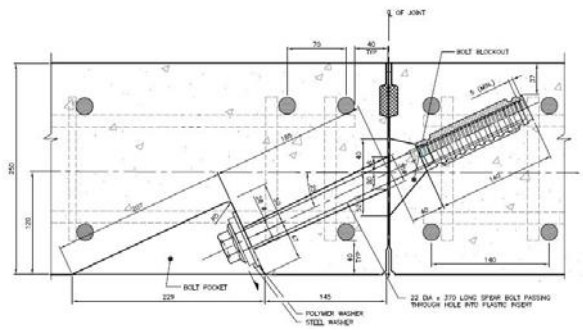


Figure 5. Details of modern liner joints

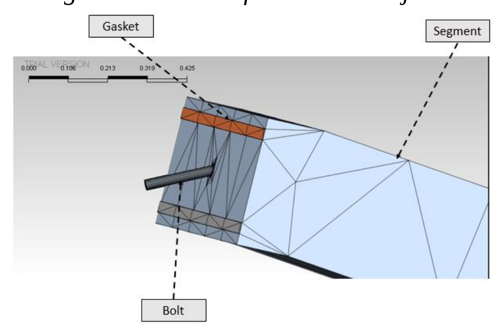


Figure 6. Simulation of modern linear joint

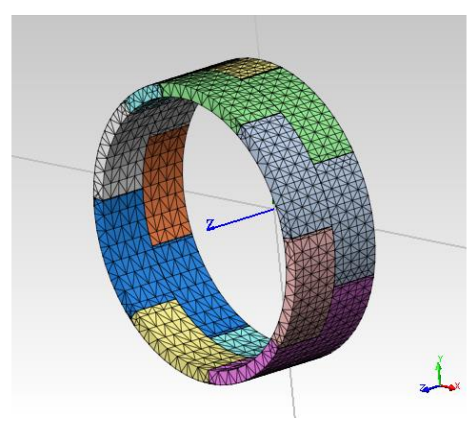


Figure 7. Numerical simulation of segmental lining (case study)

6. Normal Construction Case

First considered case is for normal construction condition, where no accidental cases occurred during construction. This model is used to check the value of deflection and to check any local plastic points occurred in the modelling in ordinary cases.

6.1 Load Cases

Load Case 1: Activation of lining + Activation of grout (E: 100 kN/m^2).

In this case, lining is activated and grout layer also activated but the modules of elasticity of the grout is very small. This situation doesn't allow direct contact between the lining and the soil. In this case also springs represent the soil is activated.

Load Case 2: Grout pressure (250 kN/m^2).

In this case, only the load of the grout and the own weight of lining + grout are activated. The soil load is not applied because there is still a gap between the lining and the soil. The gap is filled with grout but in this case the grout is too week to transfer the loads.

Load Case 3: Removing Bolts.

In this case the modules of elasticity of the grout is increased to 20 E3 MPa which is the final value after hardening. In the same time the connecting bolts are removed from the ring. This case aims to study the possibility of removing the connecting bolts after the hardening of the grout around the ring.

6.2 Analysis Results

Referring to the results shown in the figures below (Figures 8-11), the following points can be concluded:

1- The deflection at crown of tunnel after construction of ring 2 is 2.1cm

2- After ring construction, where the bolts are installed also, no plastic zones generated around the segments except a very local plastic zones generated around bolts.

3- Due to the high tensile forces in bolts, bolts got deformed and plastic zones generated on the bolts.

4- The settlement slightly increases if bolts removed after hardening of grout, the increase is very small. Whereas, no plastic concentration occurs after removing bolts.

➢ As a conclusion, after the hardening of grout there is no need for bolts and can be safely removed from the ring.

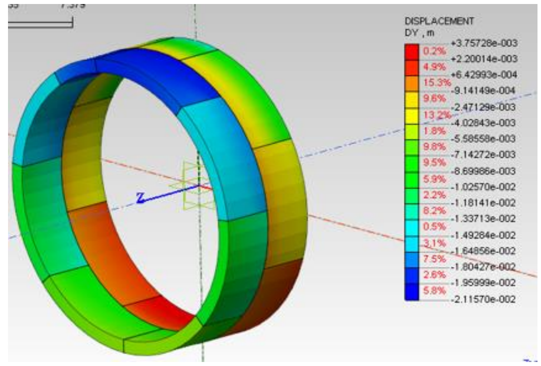


Figure 8. Vertical deformation after construction of ring

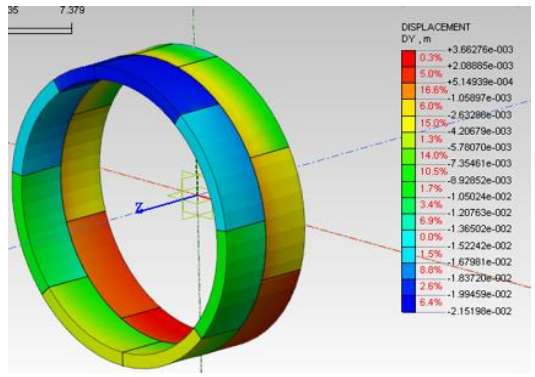


Figure 9. Vertical deformation after hardening of grout and removing bolts

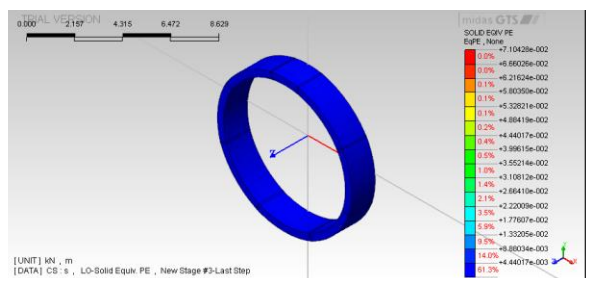


Figure 10. Distribution of plastic zones after hardening of grout and removing bolts

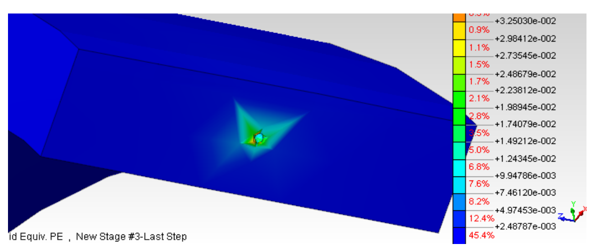


Figure 11. Plastic zones in the area of segment around connecting bolt

7. Effect of Connecting Bolts – A Parametric Study

During the erection of rings, sometimes TBM machine crew does not erect some or all bolts between the segments. This could happen by mistake or intentionally (to reduce the consuming time or cost). Erection of bolts has great effect on the stability of rings during construction of rings until the hardening of the surrounding grout layer. In the following section, this case will comprehensively studied. The aim of this study is to investigate the effect of not installing some or all bolts during construction of the ring, and to which extent this case could lead to collapse of the ring.

7.1 Analysis Procedure

The procedure used in this study will be as follows:

- The same load cases used in the previous section will be followed (The normal construction case section).
- Number of bolts in the ring are 8 bolts, bolt for each joint. Instead of activating all bolts in the model, some bolts won't be activated. This case aims to simulate the case in which the crew didn't erect some bolts between segments of the ring.
- Several cases have been studied, in every one, certain number of bolts are not activated starting from one bolt until all bolts of the ring are not activated.
- In each case the value of deformation and the distribution of plastic zones are recorded. Then a schematic graph is drawn to illustrate the change in the behaviour of the ring versus the increase of number of bolts which were not activated in the model.

7.2 Load Cases

Load Case 1: Activation of lining + Activation of grout (E: 100 kN/m^2).

In this case Segments component (Segments and Gaskets) are activated and grout layer also activated. All bolts are activated except certain bolts start from 1 bolt to all bolts. In each model one case only studied. The following numbering of joint shown in Figure 12, will be used for each model. In order to illustrate the number and location of bolts which won't be activated in the model. First bolt which won't be activated in model, will be bolt No. 1 in Figure 12 for the following models, the number and location of bolts which won't be activated have been randomly chosen to simulate the actual situations.

Load Case 2: Grout pressure (250 kN/m^2).

In this case the load of the grout and the own weight of lining + grout are added to the model.

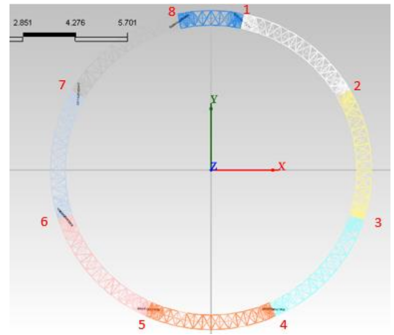


Figure 12. Numbering and orientation of bolts/joints

7.3 Analysis Results

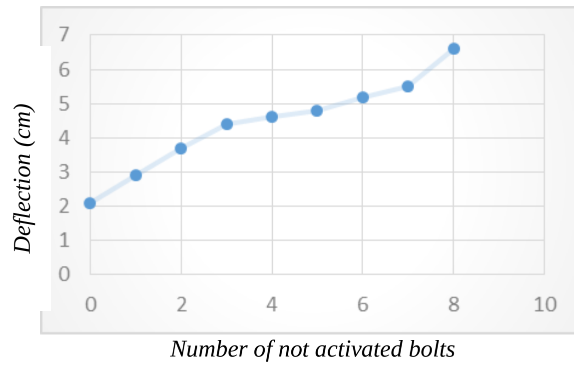


Figure 13. Value of crown deformation versus the number of not activated bolts

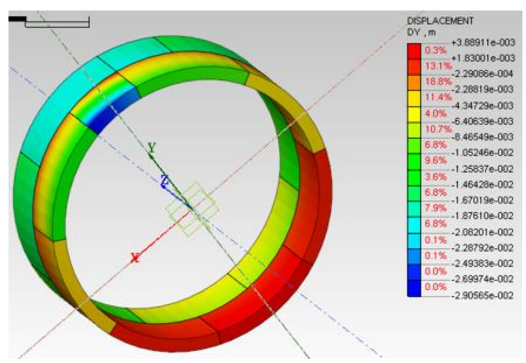


Figure 14. Vertical settlement for not installing 1 bolt case

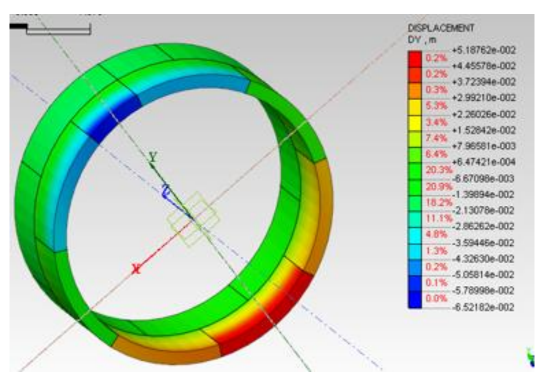


Figure 15. Vertical settlement for No-bolt case

Table 3. Value of crown deformation versus the number of not activated bolts.

Model No.	No. of not activated Bolts	Deformation (cm)	% Increase of original	% of Increase of the previous model
Normal Case	0	-2.1	--	--
1	1	-2.91	39%	39%
2	2	-3.7	76%	27%
3	3	-4.4	110%	19%
4	4	-4.6	119%	5%
5	5	-4.8	129%	4%
6	6	-5.2	148%	8%
7	7	-5.5	162%	6%
8	8	-6.6	214%	20%

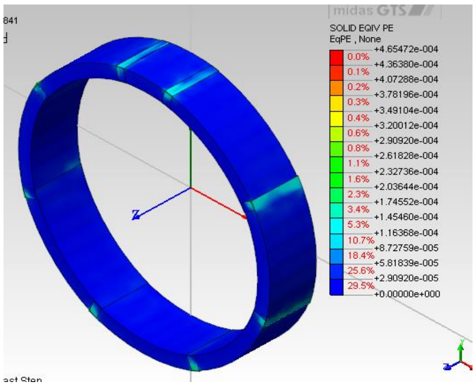


Figure 16. Distribution of plastic zones for No-bolt case

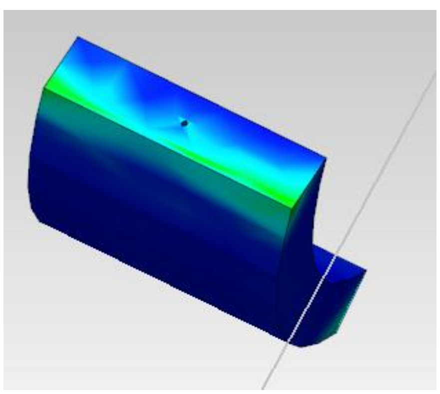


Figure 17. Distrubtion of plastic zones around the edges of segments

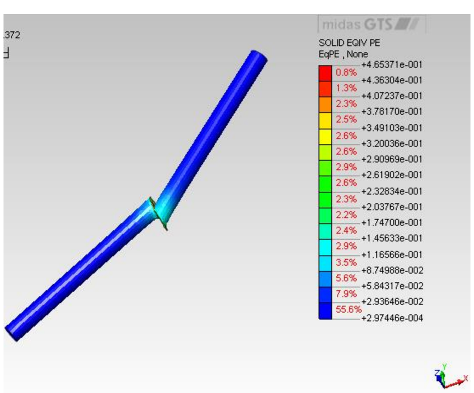


Figure 18. Distribution of plastic zones at bolt No. 8 for not activating 1 bolt case

From the Results shown in table 3 and Figures (13-18) the following points can be noticed:

- Longitudinal bolts have great effect in the stability of the segmental lining during construction.
- Even if one bolt only is not activated, the value of crown deflection increases by percentage of 39% of the normal case.
- The current study concluded that not installing more than one bolt during construction may cause the ring collapse.
- Erection of bolts has great effect in the stability of the ring during construction. Installation of bolts should be carefully handled.

8. Effect of Excessive Grout on Ring Stability

Backfill grouting are basically used to fill the annular void between the segmental lining and the surrounding ground (tail void), by grout injection. The interaction between machine, lining and the grout is very important. Attention should be paid to avoid excessive grout which causes destructive effect on lining (see Figures 19, 20). Excessive grout could be generated from two possible ways:

- After grouting the lining, grouting volume will settle, opining a gap on the upper part of cross section. In this case more grouting is required to fill this gap, this grouting called secondary grouting. Secondary grouting is usually undertaken within 20m of the last ring built. Secondary grouting may cause destructive effect if its value overestimated, which makes the secondary grout concentrated by large value in certain segments [11].
- The other possible source of excessive grout comes from the fact that grout pushed into the annular void between lining and ground through nozzle. If some nozzles got clogged the grout around lining will be redistributed and will be concentrated around certain segments.

Figure 19. Key segment is pushed out by excessive grouting pressure [11]

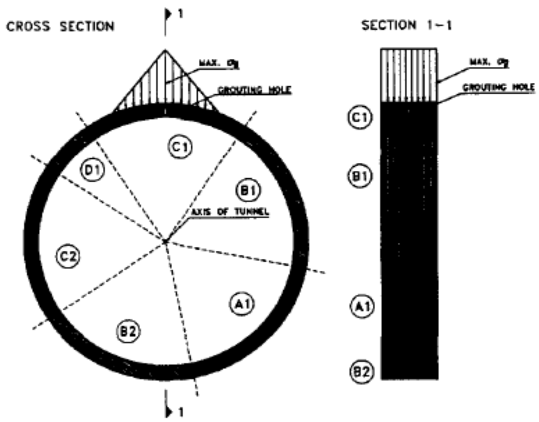


Figure 20. Applying of Grout Pressure [5]

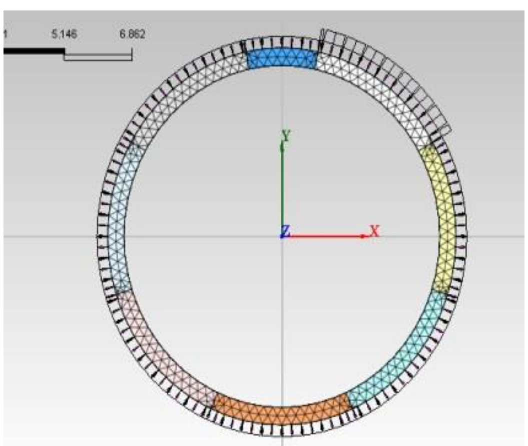


Figure 21. Simulation of excessive grout load

This part focuses on the effect of excessive grout in the stability of lining. Two cases will be studied as follows:

1- Uniform excessive grout around the whole ring.
2- Excessive grout in some segments.

The study will consider increasing in grout by value start from 10% of the original value to 100% of the original value.

8.1 Analysis Procedure

The procedure used in this study will be as follows:

- Modelling of the lining components, grout layer and soil springs.
- Simulation of construction process of the segments and the surrounding grout layer.
- Applying of the grout load on the ring and the own weight of the lining.
- An additional value of the grout load representing the excessive grout is added to the model. The two cases mentioned earlier will be studied as follows:

1) Firstly the excessive grout is applied to one segment only as indicated in Figure 21, in order to represent the case of concentration of excessive grout in certain local segments. The value of excessive grout is increased gradually.

2) In the second case, a uniform excessive grout is applied to the whole ring to compare its effect in the stability of the lining with the effect of concentration of excessive grout in certain segments.

8.2 Load Cases

Load Case 1: Activation of lining + Activation of grout (E: 100 kN/m^2).

In this case Segments component (Segments, Bolts and Gaskets) are activated and grout layer is also activated.

Load Case 2: Grout pressure (250 kN/m^2).

In this case the main load of the grout and the own weight of lining + grout are applied to the model.

Load Cases 3 to n: Excessive grout load (25 to 250 kN/m^2).

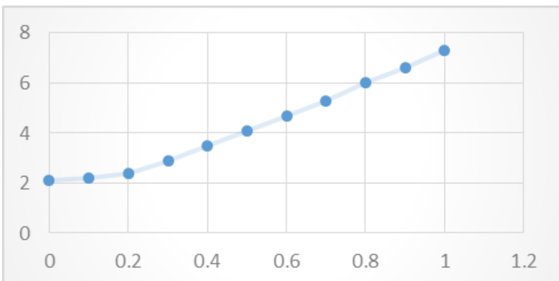
In this case the excessive grout will be applied to the model. The value of excessive grout load starts from 25KN/m^2 which represents 25% of the original value at load case (3). The maximum applied excessive grout will be 250KN/m^2.

8.3 Analysis Results (Table 4)

Table 4. Value of crown deformation via the value of excessive grout.

percentage of Original	Excessive grout Value	Deformation (cm)	% of Increase of the original	% of Increase of the previous load case
-	**0**	**-2.1**		
10%	25	-2.2	5%	5%
20%	50	-2.4	14%	9%
30%	75	-2.9	38%	21%
40%	100	-3.5	67%	21%
50%	125	-4.1	95%	17%
60%	150	-4.7	124%	15%
70%	175	-5.3	152%	13%
80%	200	-6	186%	13%
90%	225	-6.6	214%	10%
100%	250	-7.3	248%	11%
Increase by 100% at all segments	250	-2.77		

Deflection (cm)



Percentage increase of excessive grout

Figure 22. Value of crown deformation versus the value of excessive grout

From the Results shown in Table 4 and Figures (22-26) the following points can be noticed:

- For the uniform excessive grout around the whole segments, the deformation at crown is -2.77 cm.
- For the excessive grout at one segment by value 10%, the deflection at crown is -2.2 cm, meanwhile for excessive grout by value 100%, the deflection at crown is -7.3 cm.
- The above results mean that the main damage effect on ring from excessive grout will happened in case of some segments only have excessive grout. As long as the excessive grout value increases the deflection will increase until the failure case.

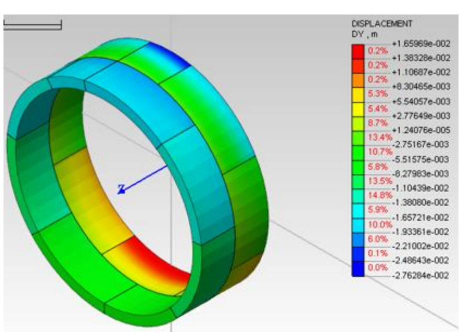


Figure 23. Vertical settlement for uniform excessive grout by 100% value at the whole ring

- From the distribution of plastic zones shown in Figures (25 - 26), it is noticed that in all accidental cases any failure or plasticity zones generated first in bolts at the joint between segments until failure. This notice lead to the following suggestions:

1- Using nonlinear criteria for modelling concrete segmental lining have small importance, since most of expected failure will occur at joints.

2- It is better to use 2 bolts between each 2 segments to face any unexpected accidental cases, and reduce the risk of accidental cases on segments.

- Effect of excessive grout in certain segments is very destructive and one of major reasons which could cause failure.
- The required grout pressure value should be carefully calculated and grout injection process should be carefully performed under careful supervision to prevent any excessive pressure generated on segments.

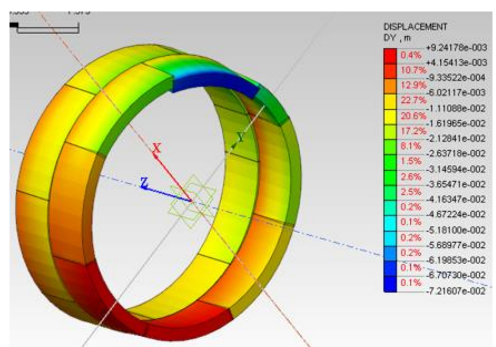
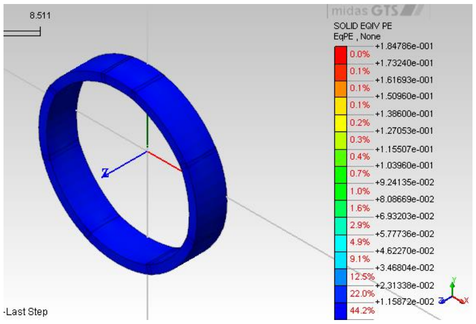
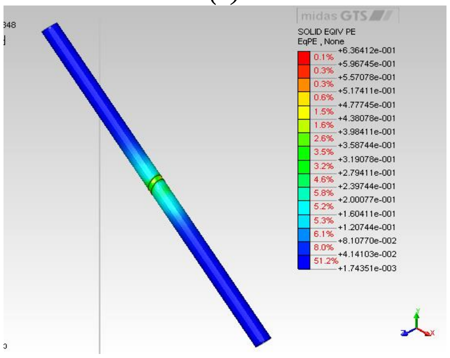


Figure 24. Vertical settlement for excessive grout by 100% value at one segment

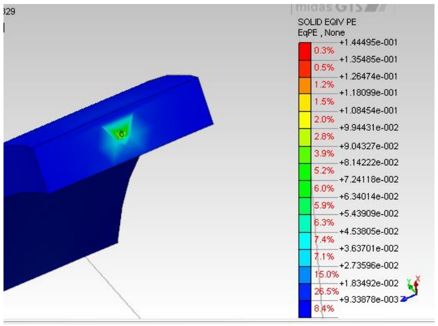


(a)

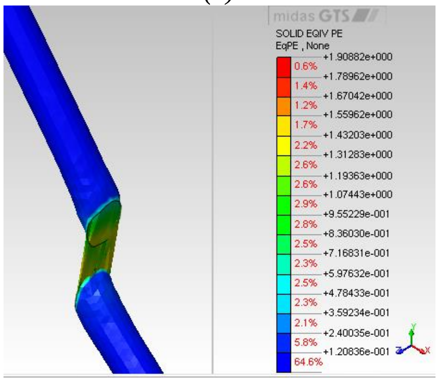


(b)

Figure 25. Distribution of plastic zones for uniform excessive grout at all segments by 100% value, at segments (a) and bolts (b)



(a)



(b)

Figure 26. Distribution of plastic zones for excessive grout by 100% value at one segment,
(a) *At the edges of segments*, (b) At bolt

9. Conclusions

Several cases have been investigated for studying the behaviour of TBM segmental lining at accidental cases during construction. From these cases the following points can be concluded:

- After ring construction, where the bolts installed also, no plastic zones generated around the segments except a very local plastic zones generated around bolts.
- In normal cases and due to the tensile forces in bolts, bolts got deformed and plastic zones generated on the bolts.
- The settlement slightly increases if bolts removed after hardening of grout, the increase is very small. Whereas, no plastic concentration occurs after removing bolts.
- After the hardening of grout there is no need for bolts and it can be safely removed from ring.
- Installation of bolts is very important during the construction of lining and should be carefully handled.
- If more than one bolt isn't installed during the construction of the ring, this could lead to ring failure.
- Excessive grout concentrated at some rings has destructive effect on the ring. This situation could lead to collapse of ring. Consequently this situation should be totally avoided during the construction of TBM segmental lining.
- Uniform excessive grout around the whole ring have small effect on the stability of ring. Especially in cases where the value of excessive grout is small. Noting that, the case of uniform excessive grout is rarely happened and normally the excessive grout concentrated in certain segments.
- From the distribution of plastic zones shown earlier, it is noticed that in all accidental cases, any failure or plasticity zones generated first in bolts at the joint between segments until failure. Consequently it is better to use 2 bolts between each successive segments to minimize any unexpected accidental cases.

Corresponding Author:
Eng. Mostafa Asaad
Technical Department (TD)
National Authority for Tunnels (NAT)
Cairo, Egypt
E-mail: mostafa_asaad08@yahoo.com

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