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WIDENING OF EXISTING ROADWAY TUNNELS USING NATM

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Abstract

Roadway tunnels present a good solution for traffic problems in high-population cities. More difficulties exist in the development process, when traffic density exceeds the tunnels design capacity. The development process can be achieved either by widening of existing tunnels or by adding new tunnels. This research discusses the first alternative; by widening existing roadway tunnels.

Many of widening techniques projects are implemented for existing tunnels all over the world. Some widening techniques are implemented with the condition of stopping traffic flow while some other techniques allow traffic flow during implementation. The applied technique must ensures two issues: user safety during widening process and minimum disturbance to surrounding ground, especially in soft ground [1],[2]. In this research, widening of existing tunnel is performed with the New Austrian Tunnelling Method (NATM) which does not allow traffic flow during construction. The impact of the widening tunnels construction phases on induced stresses in surrounding ground and stability of the existing tunnel itself is investigated.

Key words: Widening Roadway tunnels, NATM, Numerical Modeling

1. Introduction

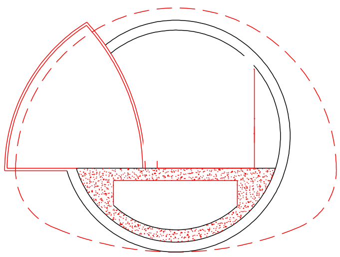
When roadway tunnel traffic capacities are insufficient and adding new tunnels has to be avoided, tunnel widening can be the choice to increase the number of lanes. Widening represents retrofitting of existing tunnel which realizes higher traffic capacity more than 25%.

Widening highway tunnels idea was first thought by Societa Autostrade engineers as early as the start of the 1980s when the need first arose to widen highways to three lanes and add an emergency hard shoulder [3]. Studies were undertaken in different media with the aim of producing a universal methodology to use widening in all types of rock and soft ground under all conditions[3]. Widening for existing tunnels has been implemented for different projects all over the world. One of the widening techniques has been conducted in Nazzano road tunnel in Italy using pre-cutting machine and the traffic was kept flow during widening stages [4]. Another widening project has been conducted using Pre-supporting System Arch (PSS-Arch) which wide the existing tunnel after supporting the surrounding soil using steel pipes [5]. Also, a project using New Austrian Tunneling Method (NATM) has been used for expanding a metro station underground in China [6].

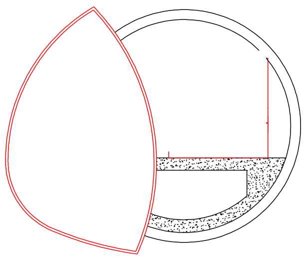
In this research, a widening for an existing tunnel using NATM is introduced. NATM is known as Sprayed Concrete Lining (SCL) or Sequential Excavation Method (SEM). The main idea is to use the geological stress of the surrounding soil mass to stabilize the tunnel itself. NATM involves the lining of the walls of an excavated tunnel with wire mesh, then spraying them with quick-drying concrete. A second concrete lining can be installed later[7]. A two dimensional modeling is performed for this technique. The study considers the induced deformations in ground and the existing tunnels and induced stress presented by plasticized zones in surrounding ground. In order to implement numerical modeling, widening construction phases using NATM should be defined logically and sequentially.

2. Widening Construction Phases

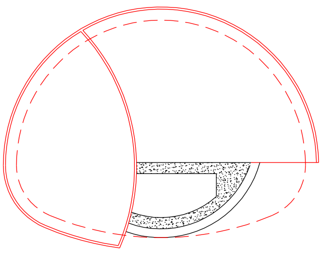
The construction phases of the widening are outlined as shown in Figure1. The NATM widening construction is conducted using upper and lower heading type and combined by side drift wall technique. Initial support is provided by application of a layer of shotcrete to achieve an interlocking support with the ground. Shotcrete is typically reinforced by steel fibers or welded wire fabric. A special construction shoring which permits to install the side drift sprayed shotcrete is required. The first stage is done by excavation of the top heading left side and initial shotcrete is applied. Then, the second stage is to excavate the lower part of tunnel left side and initial shotcrete is applied. After these stages, the shotcrete ring is closed and existing tunnel lining is supported using the temporary shoring. In the third stage, the excavation of the right upper side is formed and followed by application of initial shotcrete. Then, in the fourth stage, the invert is excavated and closed using initial shotcrete. Finally, in the fifth stage, the side drift is dismantled and the final lining installation is completed.
The adopted geometry for studied tunnels is similar to El-Azhar twin tunnels [8]. The existing and the widened cross sections are shown in Figure 2. Existing roadway tunnel diameter is 9.4m for external diameter which had been constructed using Tunneling Boring Machine (TBM). Widening phases, which are shown in Figure1, are implemented for the current case. The study is applied for cohesion-less sandy soil which is commonly exist in Egyptian ground. Soil grouting is applied for soil improvement before widening stages.



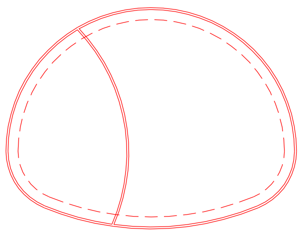
1st stage: Excavation of left upper part with initial shotcrete



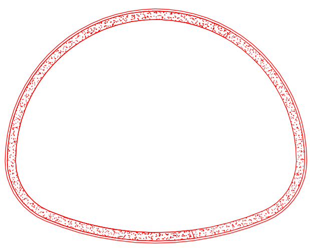
2nd stage: Excavation of left lower part with initial shotcrete



3ed stage: Excavation of Right upper part with initial shotcrete.



4th stage: Excavation of Right lower part with initial shotcrete.



5th stage: Final lining activation

Figure 1: Widening using NATM.

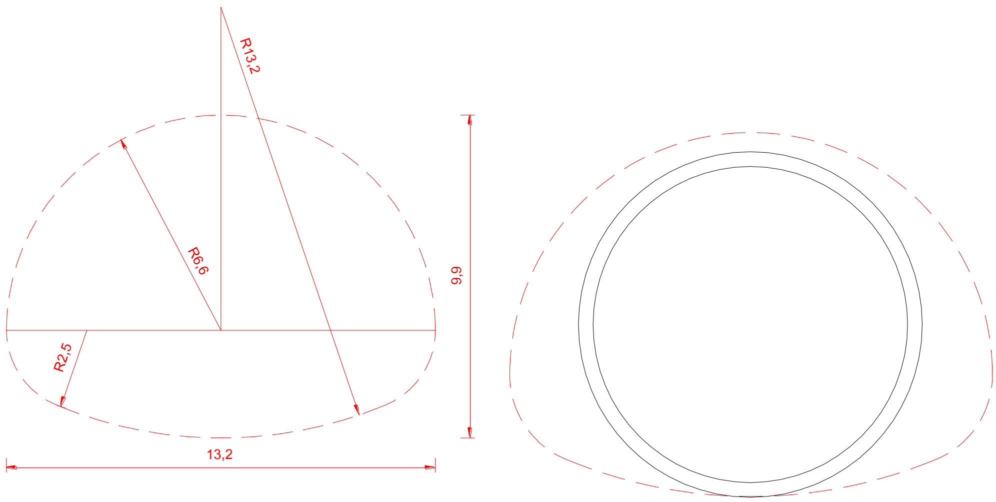


Figure 2: The NATM tunnel cross section relative to original existing tunnel.

3. Numerical Modeling

A two-dimensional FEM numerical model is developed to simulate the present study case. Due to symmetry assumption; the model represents one of the twin tunnels as shown in Figure 3. The segmental lining thickness is 0.4m and the tunnel current capacity is two lanes in one direction. Ground water level exists at 15.4m depth from the ground surface. Widening of the tunnels is planned to increase the traffic lanes to be three lanes.

In the study, 2-D plane strain analysis using elsto-plastic soil model based on Mohr-Coulomb failure criterion is performed. The Finite Element Analysis package, MIDAS-GTS, is used. In this model, the soil is represented with 3-node triangular elements and the tunnel lining is represented with 2-node elastic beam elements[9],[10]. The main construction stages considered in these models are:

1. Initial stresses calculation
2. Excavation of soil for existing tunnel
3. Installation of tunnel lining segments
4. Long term effect and the traffic load is considered
5. Grouting the area of enlargement tunnel cross section from the inside of the existing tunnel
6. Excavation of NATM 1st stage; left heading side followed by initial shotcrete
7. Excavation of NATM 2nd stage; left bench side followed by initial shotcrete to close the side drift ring
8. Excavation of NATM 3rd stage; right heading side followed by initial shotcrete
9. Excavation of NATM 4th stage; right bench side followed by initial shotcrete to close the other side drift ring
10. Remove of side drift wall and installation of the final lining

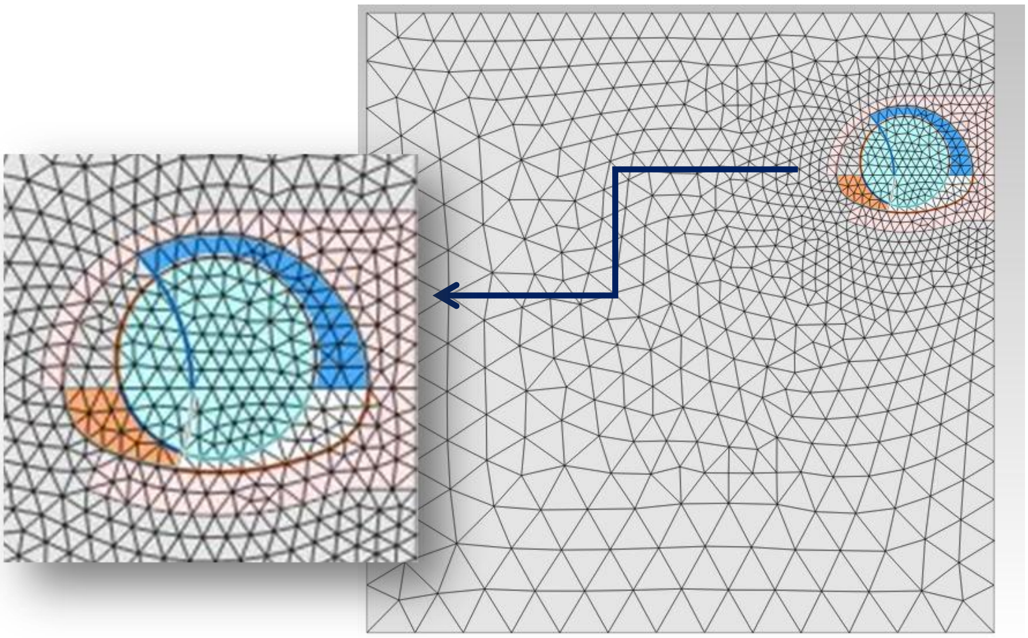


Figure 3: Mesh layout for two-dimensional numerical modeling

3.1. Material Properties

Tables1 and 2 show the characteristic material properties for existing tunnels lining, NATM lining, grout and ground soil respectively.

Table 1: Material properties of existing tunnels lining

Concrete properties	Thick (m)	γ kN/m^3	E_{ref} (MPa)	ν
Lining	0.4	25	28.5x10^3	0.2
Initial Shotcrete	0.2	25	25x10^3	0.25
Final Shotcrete	0.3	25	28x10^3	0.2
Invert slab	0.5	25	28x10^3	0.2
Grouting	-	21	300	0.2

Table 2: Material properties of soil parameters

Soft ground type	Sand	
Material Model	Mohr-Coulomb	_
Type of material behavior	Drained	_
Soil unit weight (γ)	20	kN/m^3
Young´s modulus (E)	40000	kN/m^2
Poisson's ratio (ν)	0.37	_
Cohesion (C)	0.0	kN/m^2
Friction angle (Φ)	39	_
Coefficient of Earth pressure at rest (Ko)	0.37	_

4. Analysis and Results

Results, from this model, are plotted to show the effect of widening construction stages on ground surface deformations, tunnel deformations and straining actions in existing tunnels lining.

4.1. Surface Deformation

As shown in Figures 4 and 5, it is illustrated that maximum surface deformation occurred at the final stage is 11.4 mm. The maximum percentage of surface deformation is 31% occurred in the first stage of widening excavation. This means that during the first widening stage, the excavation length (in longitudinal direction) reduction is recommended.

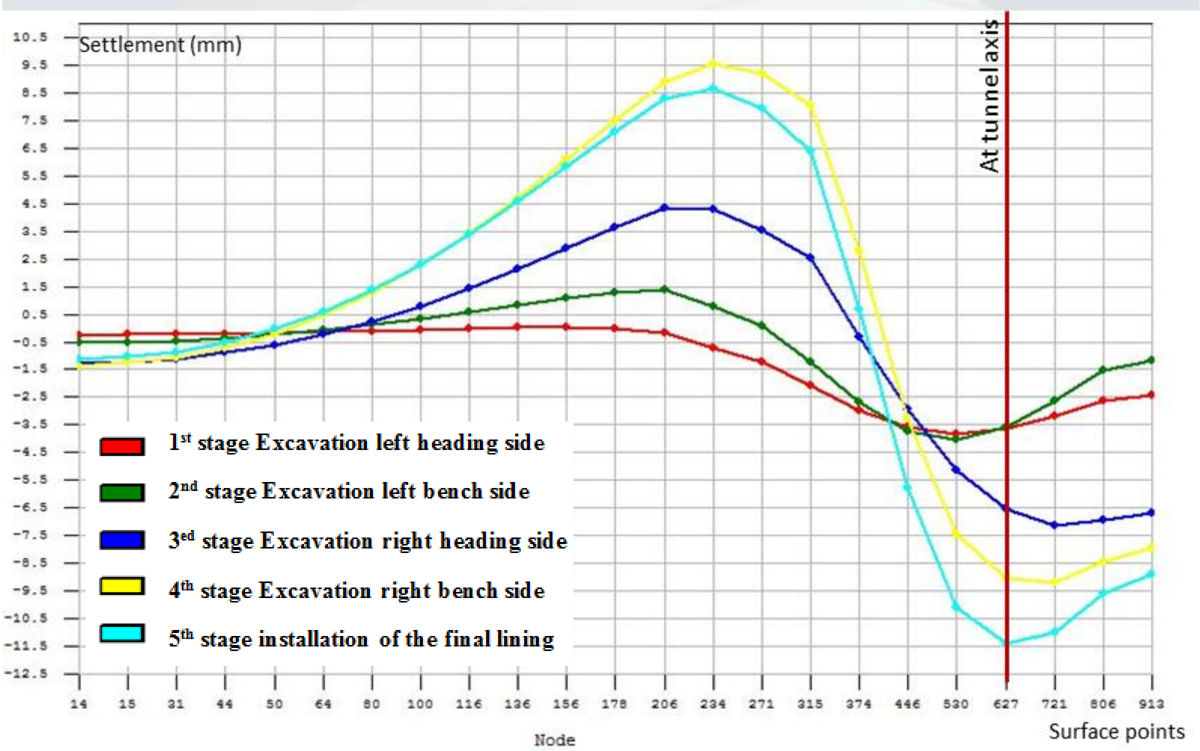


Figure 4: Surface deformation due to widening construction stages using NATM technique

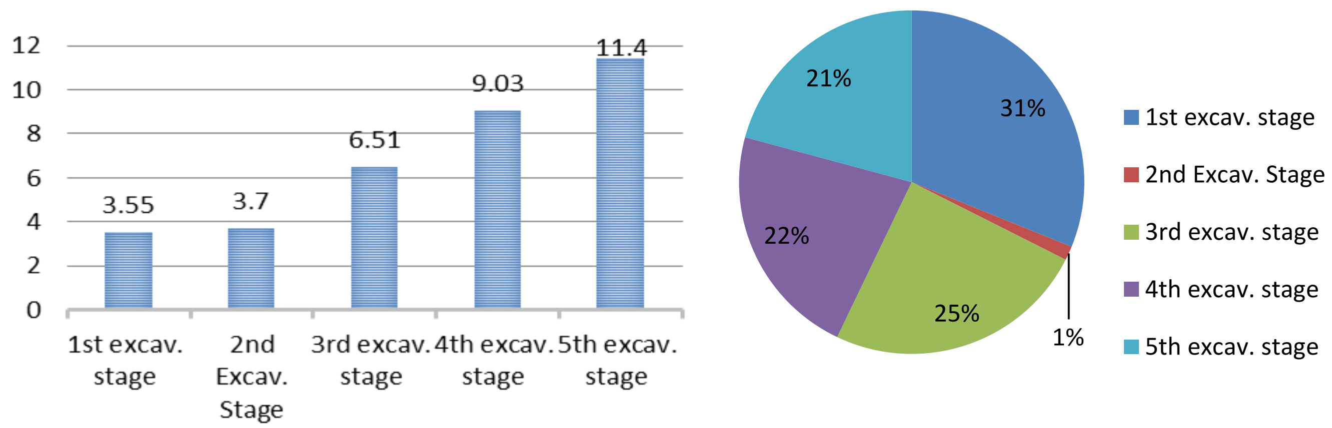
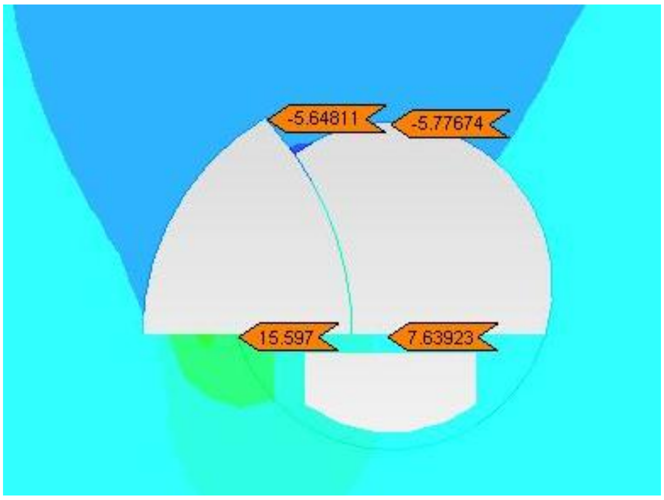


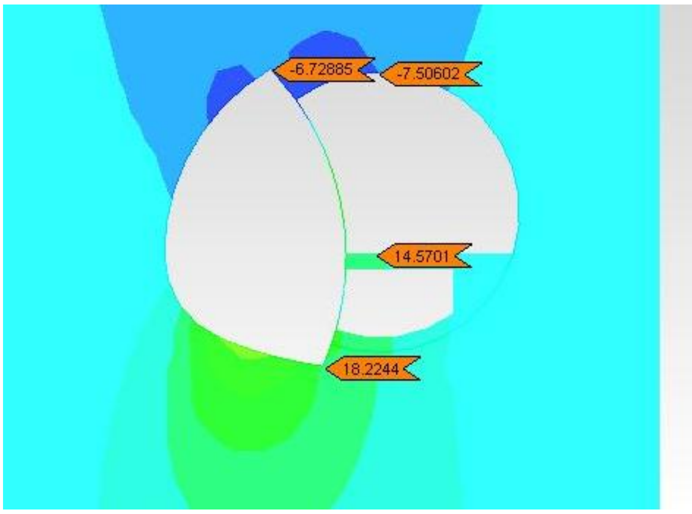
Figure 5: Maximum surface deformation values in each stage of widening and its percentage

4.2. Existing Tunnel Deformation

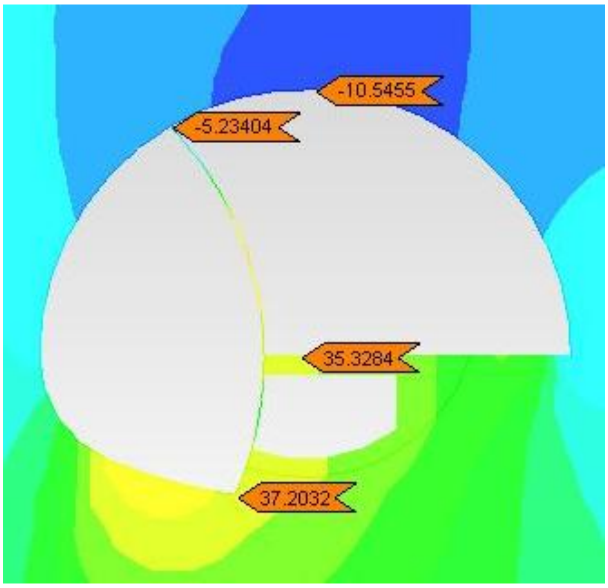
Crown and invert of existing tunnel are influenced by widening construction stages as shown in Figure 6. It is recognized that crown and invert deformation are increased during widening stages. The crown shows settlement with small values while the invert shows heave with much higher values.



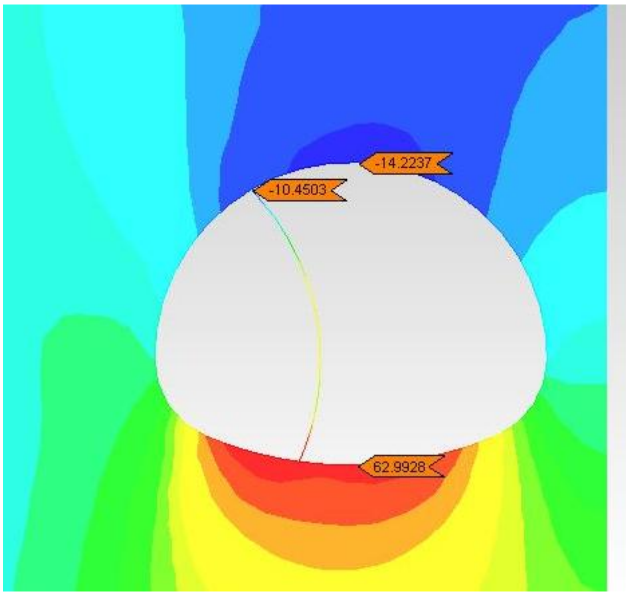
1st stage: Excavation of left upper side



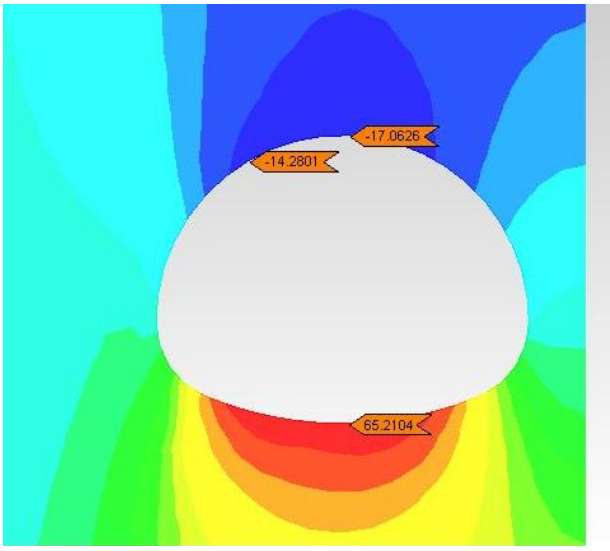
2nd stage: Excavation of left lower side



3rd stage: Excavation of right upper side



4th stage: Excavation of right lower side



5th stage: Final lining activation

Figure 6: Tunnel crown and invert deformation in (mm) due to widening stages.

4.3. Straining Actions

- **Normal forces variation**

The induced normal forces in the existing tunnel lining are influenced by widening stages. As shown in Table 3, it is recognized that normal force in the segmental lining varying during excavation processes. The normal force in the widening lining is described in Table 4.

Table 3: Normal forces in existing tunnel lining.

Load case/location	Crown Nx (ton)	Invert Nx (ton)	Left side Nx (ton)	Right side Nx (ton)
Traffic load case	-30.3	-37.2	-64.0	-64.2
Grouting stage	-33.8	-39.0	-63.4	-68.3
Excavation of NATM 1st stage	-24.6	-38.4	0.0	-73.3
Excavation of NATM 2nd stage	-17.0	-27.4	0.0	-78.3
Excavation of NATM 3rd stage	0.0	-27.4	0.0	0.0
Excavation of NATM 4th stage	0.0	0.0	0.0	0.0
Final lining 5th stage	0.0	0.0	0.0	0.0

Table 4: Normal forces in NATM lining.

Load case/location	Crown (ton)	Invert (ton)	Left side (ton)	Right side (ton)
Excavation of NATM 1st stage	-16.9	0.0	-39.6	-15.2
Excavation of NATM 2nd stage	-38.2	-30.1	-87.1	-29.4
Excavation of NATM 3rd stage	-10.1	-28.0	-96.6	-55.2
Excavation of NATM 4th stage	-33.5	-23.1	-113.2	-129.1
Final lining 5th stage	-36.5	-29.7	-117.0	-140.7

- **Bending moment variation**

The induced bending moment in existing tunnel lining are also influenced by the widening process. As shown in Table 5, it is recognized that bending moment in the segmental lining varying during excavation process. The bending moment in the widening lining is described in Table 6.

Table 5: Bending moment in existing tunnel lining.

Load case/location	Crown M_Y(ton.m)	Invert M_Y (ton.m)	Left side M_Y (ton.m)	Right side M_Y (ton.m)
Traffic load case	11.5	13.6	12.4	13.9
Grouting stage	12.7	13.6	12.9	17.5
Excavation of NATM 1st stage	12.8	13.5	0.0	18.9
Excavation of NATM 2nd stage	12.8	16.2	0.0	19.8
Excavation of NATM 3rd stage	0.0	16.3	0.0	0.0
Excavation of NATM 4th stage	0.0	0.0	0.0	0.0
Final lining 5th stage	0.0	0.0	0.0	0.0

Table 6: Bending moment in NATM lining.

Load case/location	Crown M_Y(ton.m)	Invert M_Y (ton.m)	Left side M_Y (ton.m)	Right side M_Y (ton.m)
Excavation of NATM 1st stage	1.4	0.0	0.4	3.1
Excavation of NATM 2nd stage	3.0	4.4	0.9	-5.0
Excavation of NATM 3rd stage	0.1	3.3	1.0	0.7
Excavation of NATM 4th stage	0.2	0.8	1.1	1.4
Final lining 5th stage	1.7	7.4	4.9	6.1

5. Conclusions

For the investigated study cases, defined with soil type, tunnelling depth and tunnels diameter, the following conclusions may be presented:

- Selecting soil improvement using grouting and side drift for NATM during construction stages help to achieve stability for existing tunnels and after widening phases.
- The surface deformation resulted during widening are sustainable and within allowable limit. The progress induced in the surface deformation during widening stages demonstrates that the first widening stage is the critical one, which represents 31% of total settlement occurred. Hence, shortening the excavation pitch during this stage is highly recommended.
- Internal stresses in old lining degraded during widening stages and the lining did not expose to over stresses. In addition internal stresses in NATM lining grow up gradually during widening stages.
- Widening in existing tunnel can be implemented using NATM, which represents one of the economic techniques in tunneling methods, in order to increase traffic capacity.

- The numerical methods especially the Finite Element Method has proven to be a powerful tool to check the applicability and safety of new construction methods.

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توسعة أنفاق الطرق القائمة باستخدام NATM

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أنفاق الطرق تمثل حلا جيدا لمشاكل المرور في المدن ذات الكثافة السكانية العالية. وعندما تتجاوز الكثافة المرورية الطاقة التصميمية للانفاق القائمة، تواجه تطوير الاتفاق القائمة كثيرا من الصعوبات. فتطوير الانفاق القائمة لا يمكن أن يتحقق الا عن طريق توسيع الأنفاق الموجودة أو إضافة أنفاق جديدة. يناقش هذا البحث توسيع أنفاق الطرق القائمة. قد تم تنفيذ العديد من المشاريع لتوسيعة الانفاق القائمة في شتى أنحاء العالم. يمكن ان تتم طرق التوسعة المختلفة اما اثناء توقف حركة المرور خلال التنفيذ او بالسماح لتدفق المرور اثناء التنفيذ. هناك اشتراطات سلامة يجب تأمينها لتطبيق عملية التوسيع مثل تحقيق سلامة حركة المرور اثناء التنفيذ و الحد من التشكلات الارضية الناتجة عن عملية التوسعة خصوصا اذا تمت في تربة غير متماسكة [١]، [٢]. ان هذا البحث يستعرض تنفيذ التوسعة بانفاق طرق قائمة باستخدام الطريقة النمساوية الحديثة لحفر الانفاق (NATM). ان التنفيذ باستخدام هذه الطريقة يستلزم عدم السماح لحركة المرور اثناء مراحل التفيذ المختلفة. يتم دراسة مراحل التنفيذ اللازمة لاتساع الانفاق باستخدام النماذج العددية وطريقة العناصر المحددة. واخيرا يتم استعراض نتائج الانفعالات الحادثة لسطح الارض و الانفعالات الحادثة للقطاع الخرساني اثناء مراحل التنفيذ المختلفة و الاجهادات الداخلية للقطاع الخرساني القائم والنهائي بعد التوسعة.