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تأثير استخدام نظام التدعيم الخرساني بالطريقة النمساوية الجديدة لحفر الأنفاق (NATM) فى بناء المحطات تحت سطح الأرض

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الخلاصــة

غالبا ما تكون التربة فى جمهورية مصر العربية وخاصة فى مدينة القاهرة من نوعية التربة الناعمة ما بين التربة الطينية والتربة الرملية. إن حفر المحطات تحت سطح الأرض بعرض كبير (أكبر من عشرة أمتار) فى هذه النوعيات من التربة من الممكن أن يتسبب فى حدوث هبوط أرضى كبير (أكبر من ثلاثين ملليمتر) والذى بدوره يسبب أضراراً خطيرة بالمبانى المجاورة لعمليات الحفر والتى غالبا ما تقع داخل مسافة من منتصف المحطة تساوى مرة ونصف كامل عرض المحطة. ولذلك فان عمليات حفر محطات تحت سطح الأرض وذات عرض كبير تحتاج الى نظام تدعيم يجب عمله قبل الحفر ليمكن التربة من اعادة توزيع الاجهادات حول الفراغ الناتج بعد عملية الحفر وكذلك يعمل على تجنب حدوث هبوط أرضى غير مرغوب فيه. إن هذا البحث يوضح كيف يمكن استخدام نظام التدعيم الخرسانى فى السيطرة والتحكم فى الفراغ الناتج من عمليات الحفر أسفل سطح الأرض وفى أى هبوط أرضى. ولقد تم استخدام نموذج عددى لتمثيل مراحل الحفر أثناء التنفيذ ولتحليل وتصور سلوك التربة خلال عمليات الحفر. أظهرت نتائج تحليل النماذج العددية المختلفة أنه يمكن استخدام النظام التدعيمى الخرسانى بنجاح فى تقليل الهبوط الأرضى الناتج من عمليات الحفر وكذلك فى تعزيز استقرار التربة.

Effects of using Concrete Pre-Supporting Systems with NATM in construction of Underground Stations

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ABSTRACT

The soil in Egypt and especially in Cairo city is mostly soft soil varying between clay and sand layers. Excavation of large span (more than 10 meter) underground station in such soil layers can cause large displacements (more than 30 mm) which may result in harmful effects for the nearby buildings which are often located within distance from the center line of station equal to 1.5 times of total width of station. Therefore, the excavation process of large span underground stations needs a supporting system to enable redistribution of the loads and stresses around the excavation opening to the surrounding soil mass to avoid undesirable excessive displacements. This paper shows how the concrete pre-supporting system can be used to control the stability of the underground space and the ground settlement. Numerical modeling is used to simulate all the construction stages and to analyze the ground behavior. Analysis results from different models show that pre-supporting systems can be used successfully to reduce the ground surface settlement and to enhance ground stability.

Keywords: NATM; pre-supporting system; soft soil; tunnels; underground stations.

INTRODUCTION

Tunneling in urban areas by Tunneling Boring Machine (TBM) has become the most popular method as it is fast in construction, more safe and has fewer settlement effects on ground surfaces. However, the main disadvantage is its limited span (up to 10 meters). The stations, which generally have large spans compared to usual tunnel sizes, are generally constructed by Cut and Cover method instead of TBM. In some special urban areas, cut and cover method cannot be used because it makes a lot of disturbance to surface activities. Therefore, the New Austrian Tunneling Method (NATM) can be used for large span (more than 10 meters) cave construction. NATM is a popular method of tunnel design and construction and refers to the old Austrian tunneling method which was developed in Austria between 1957 to 1965 and explained by Rabcewicz (Rabcewicz, 1964). NATM and machine methods can be used together for excavations which can lead to less deformation with large spans. The main problem in NATM appears in large spans and small overburdens. Overburden is the distance between the surface of the soil and crown of the station. Small overburden in NATM does not enable the arch action in the soil mass to be formed well. The stress redistribution caused by excavation induces movements in soil media and ground surface (Sauer, 1990). Movements in soil media may cause damage to nearby structures and underground utilities. Some aides and improvements are needed for NATM to control those movements and to be safer. Pre-supporting system is usually used to overcome NATM problems with large spans. This technique can distribute part of the stresses around tunnel opening during the excavation period with shotcrete until final lining is activated.

PRE-SUPPORTING SYSTEM

In case of soft ground with low overburden, concrete pre-supporting system is the most practical and preferred technique in controlling ground surface displacements (FHWA, 2009). Pre-supporting system is used for controlling sub-surface soil movement and ground surface displacement to control damage to nearby structures and underground utilities. Techniques of pre-supporting system are various and their applicability depends on many factors such as water ground level, type of soil layers, overburden, section of the tunnel opening and the allowable surface settlement limits. After studying the factors related to excavation operations such as water table, type of the soil, unsupported length, type of surface area, … etc., an optimal pre-supporting system technique can be determined like grouting, freezing, canopy arch, soil nail and concrete pre-supporting system. The main advantages of the pre-supporting system can be summarized as follows (Sadaghiani & Taheri, 2008) (Volkmann, G. and W. Schubert. 2006) (Evert Hoek, 1998) (Carrieri, G. et al. 1991):

1- The soil arc continuity is preserved around the opening.

2- It reduces the displacements and, thus, the disturbed zone around the opening affected by the excavation.

3- Moreover, it ensures that the soil mass remains undisturbed due to which the main strength parameters of soil are not changed.

In grouting technique, holes are drilled into the ground, grout pipes are inserted in holes and finally pressurized grout is injected into the ground through those pipes. Observed benefits of grouting can be summarized as follows (FHWA, 2009):

1. Strength of grouted zone is increased.
2. Grouted soil tends to produce good material.
3. Permeability of grouted zone is decreased.

CONCRETE PRE-SUPPORTING SYSTEM (CPS)

Concrete pre-supporting system (CPS) is a concrete system constructed initially around the proposed underground space to enhance soil stability during the excavation stage. The main advantage of concrete pre-supporting system in large underground spaces is to reduce soil deformation and, thus, increase the stability of the large excavation with low overburden in soft ground. Another advantage is that it reduces the construction time (Sadaghiani & Dadizadeh, 2010) (Sadaghiani & Taheri, 2008) (Volkmann, G. and W. Schubert. 2006) (Evert Hoek, 1998) (Carrieri, G. et al., 1991). After CPS construction, the station construction is carried out by the multi-stage excavation and initial supporting of the main space. The main excavation proceeds in large sections followed by installing very light initial supporting system such as shotcrete and welded wire mesh over the excavated surface. Construction stages mainly depend on type of element used in concrete pre-supporting system, opening span and overburden. Arch and piles (Frame) are the most common concrete elements that are used in pre-supporting system.

A. Concrete arch pre-supporting system (CAPS)

This technique is inspired by the construction method of old Iranian small water tunnels and qanats (Paul, 1968) (Wulff, 1968) and consists of concrete piles and arch beams constructed around a proposed underground space. This method has been utilized in several underground stations in Tehran Metro since 2002 (Sadaghiani & Dadizadeh 2010). Repeated traverse in-between distance and properties of pre-support frame has to be determined along the station length depending on the allowable displacement requirement. Construction stages of CAPS, as shown in Figure 1, can be summarized as follows:

1) Machines establish lining of tunnels and then small horseshoe section arc galleries (a,b) are excavated along the station length, Figure 1-"1".
2) Small traverse horse shoe sections arc (c) are to be excavated many times with the interval repeated distances, Figure 1-"1".
3) Using excavated small access galleries, piles (d) is excavated, reinforced and then concreted, Figure 1-"2,3".
4) Finally, using excavated small access galleries; arch frame (e) is excavated, reinforced and then concreted, Figure 1-"4,5".

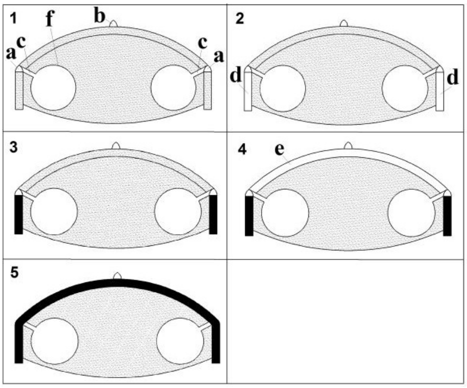

Fig. 1. Construction stages of CAPS (Sadaghiani, Dadizadeh, 2010) (a,b: arc galleries; c: traverse horse shoe arc; d: piles; e: arch frame; f: TBM lining)

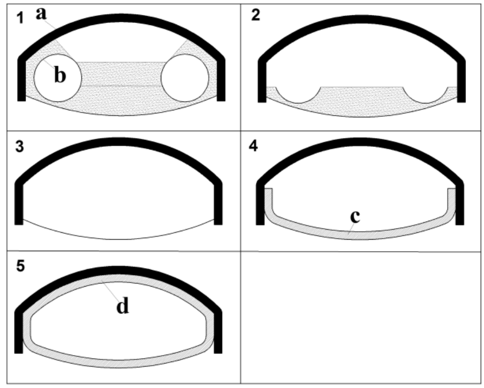

Fig. 2. Construction stages of main underground space (Sadaghiani, Dadizadeh, 2010) (a: arch frame; b: TBM lining; c: invert part of final Lining; d: crown part of final concrete lining)

After construction of CAPS, excavation of the main section is started. Construction stages of the main section, shown in Figure 2, can be summarized as follows:

1) Excavate the crown part by applying the shotcrete lining, Figure 2-”1”.

2) Excavate the side-drift parts by applying the shotcrete lining, Figure 2-”2”.

3) Excavate the invert part by applying the shotcrete lining, Figure 2-”3”.

4) Cast the invert and side parts of final concrete lining, Figure 2-”4”.

5) Cast the crown part of final concrete lining, Figure 2-”5”.

B. Concrete modified arch pre-supporting system (CMAPS)

CMAPS is suggested here and can be considered as a modification of CAPS. In CMAPS, one middle column is added in the middle span of the frame that increases its efficiency as the clear span between the piles is decreased by 50%. The results of the analysis presented later in the paper show that the displacement produced by CMAPS is less than that of CAPS. Construction stages of CMAPS are similar to those of CAPS with the addition of one middle concrete column as shown in Figure 3.

After construction of CMAPS, excavation of main section is started and it is similar to the excavation stages of main underground space using CAPS as shown in Figure 4.

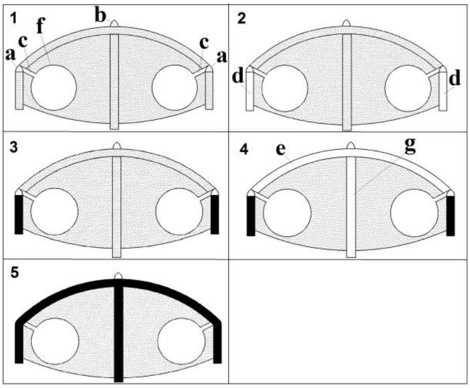

Fig. 3. Construction stages of CMAPS (a,b: arc galleries; c: traverse horse shoe arc; d: piles; e: arch frame; f: TBM lining; g: additional middle column)

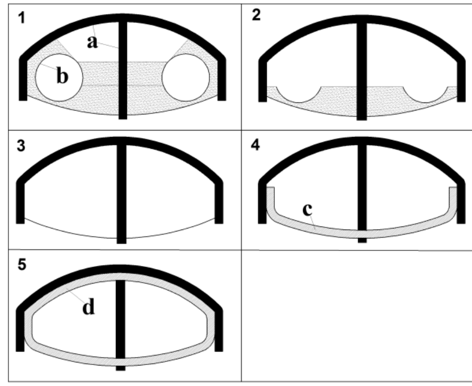

Fig. 4. Construction stages of main underground space (a: arch frame with additional middle column; b: TBM lining; c: invert part of final lining; d: crown part of final concrete lining)

C. Concrete pile pre-supporting system (CPPS)

After machines activate lining of tunnels as shown in Figure 5-"1", concrete piles can be established through tunnels openings as shown in Figure 5-"2".

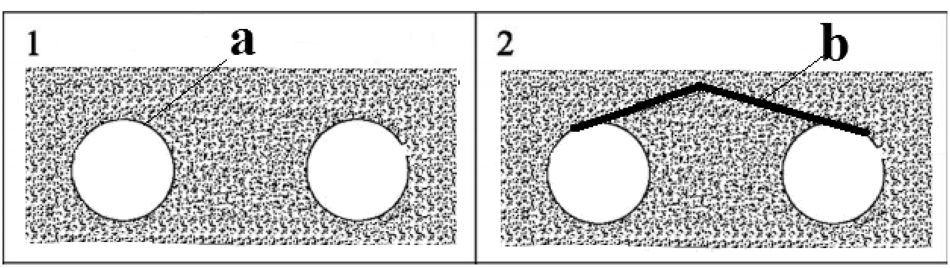

Fig. 5. Construction stages of CPPS (a: TBM lining; b: piles)

After construction of Concrete Pile Pre-supporting (CPPS), excavation of main section would be started as shown in Figure 6 which can be summarized as follows:

1) Excavate part of the crown by applying shotcrete, Figure 6-"1".
2) Excavate the rest of the crown by applying shotcrete, Figure 6-"2".
3) Excavate bench part by applying shotcrete, Figure 6-"3".
4) Excavate the invert part by applying shotcrete, Figure 6-"4".
5) Cast the invert and side parts of final concrete lining, Figure 6-"5".
6) Cast the crown part of final concrete lining, Figure 6-"6".

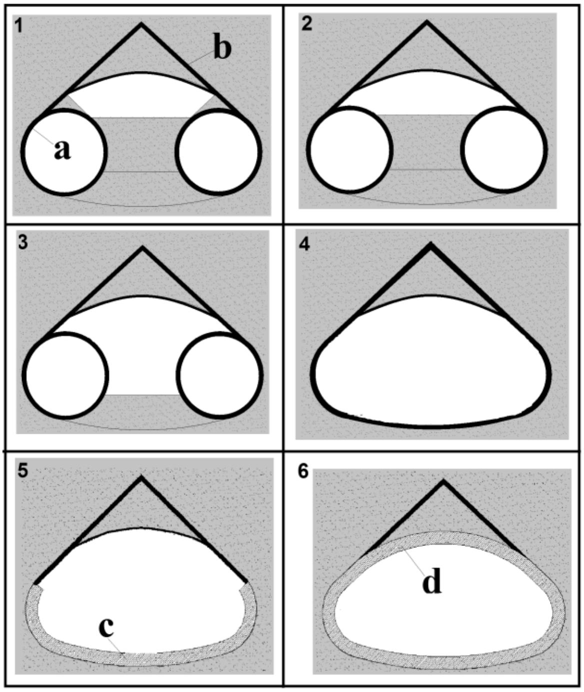

Fig. 6. Construction stages of main underground space (a: TBM lining; b: piles; c: invert part of final lining; d: crown part of final concrete lining)

D. Enlargement concrete pile pre-supporting system in enlargements of tunnel (ECPPS)

This system is used in case of enlargement of tunnels. After machines activate lining of tunnels as shown in Figure 7-"1", concrete piles can be established through tunnels openings as shown in Figure 7-"2".

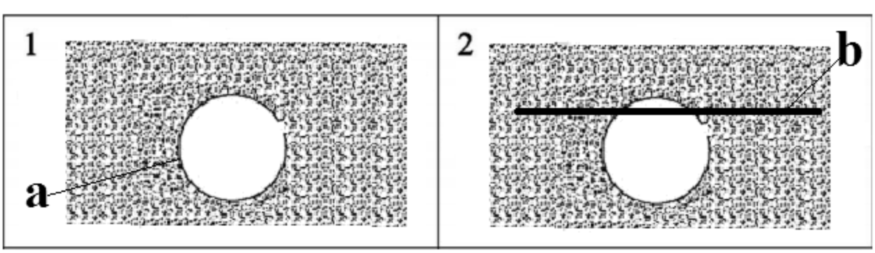

Fig. 7. Construction stages of ECPPS (a: TBM lining; b: piles)

Figure 8(a) shows how the main section of the station is divided into many parts. After construction of the concrete piles of ECPPS, excavation of main section would be started as shown in Figure 8(b) which can be summarized as follows:

1) Excavate the crown inside parts by applying shotcrete, Figure 8(b)-”1”.
2) Excavate the crown outer parts by applying shotcrete, Figure 8(b)-”2”.
3) Excavate the bench outer parts by applying shotcrete, Figure 8(b)-”3”.
4) Excavate the bench inside parts, Figure 8(b)-”4”.
5) Excavate the invert outer parts by applying shotcrete, Figure 8(b)-”5”.
6) Excavate the invert inside parts by applying shotcrete, Figure 8(b)-”6”.
7) Cast the invert and sides part of final concrete lining, Figure 8(b)-”7”.
8) Cast the crown part of final concrete lining, Figure 8(b)-”8”.

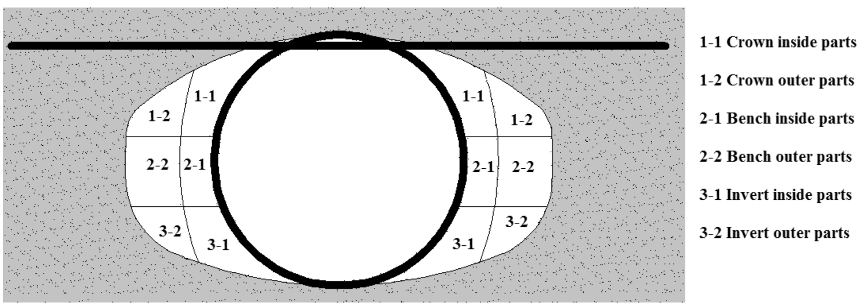

Fig. 8(a). Divisions of the main section

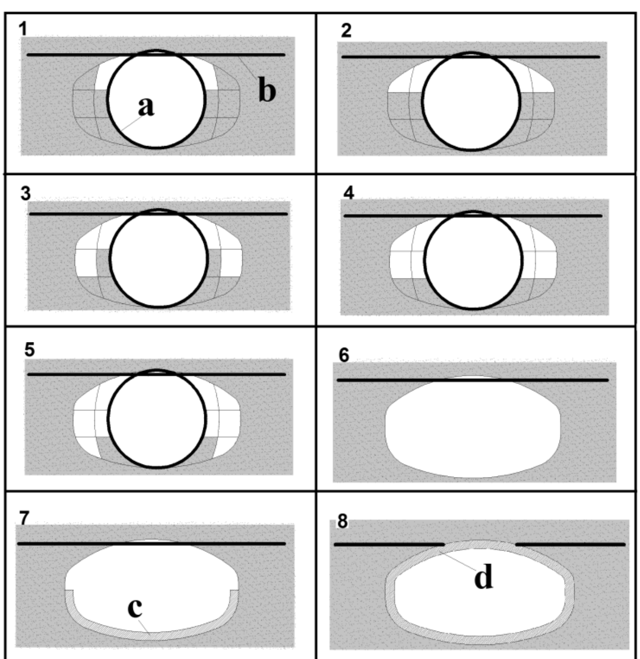

Fig. 8(b). Construction stages of main underground space (a: TBM lining; b: piles; c: invert part of final Lining; d: crown part of final concrete lining)

NUMERICAL MODELLING OF LARGE SPAN UNDERGROUND OPENING

A. General construction sequence of station

Numerical modeling using finite element method by MIDAS software (MIDAS Manual) is employed to study the behavior of surrounding media through tunneling using different pre supporting systems. The common construction stages used in the models can be summarized as follows:

1- Excavate and activate lining of the tunnels before excavation of main section of station

2- Establish pre-supporting system

3- Excavate large spans with suitable sequences that can produce fewer displacements

4- Activate main lining of the stations

B. Parameters used

The soil layers in Egypt and especially in Cairo city are almost soft soil between clay and sand layers (Said, 1962) (Shata, 1988). Table 1 illustrates properties of soil layers used in different models.

Table 1. Properties of soil layers used in the models

Soil Layer	**Modulus of Elasticity** E kN/m^2	**Poisson's Ratio** υ	**Unit Weight** γ kN/m^3	**Cohesion** c kN/m^2	**Friction Angle** Ø degree	**Lateral Pressure Factor** K_0
Fill	1000	0.45	18.00	-	30	0.48
Sand	75000	0.30	19.50	-	38	0.50
Grouted zone in case of Sand layer	750000	0.30	19.50	-	38	0.50
Clay	60000	0.45	20.00	200.00	-	0.33
Grouted zone in case of Clay layer	600000	0.45	20.00	200.00	-	0.33

Every model is considered having two layers as shown in Figure 9(a). The first layer always is fill layer. The second layer is either sand or clay exhibiting properties shown in Table 1. Grouted zone (if used) is created before excavation work is started. Grouting zone width is extended over station width by distance 5.0 m on all sides as shown in Figure 9(b).

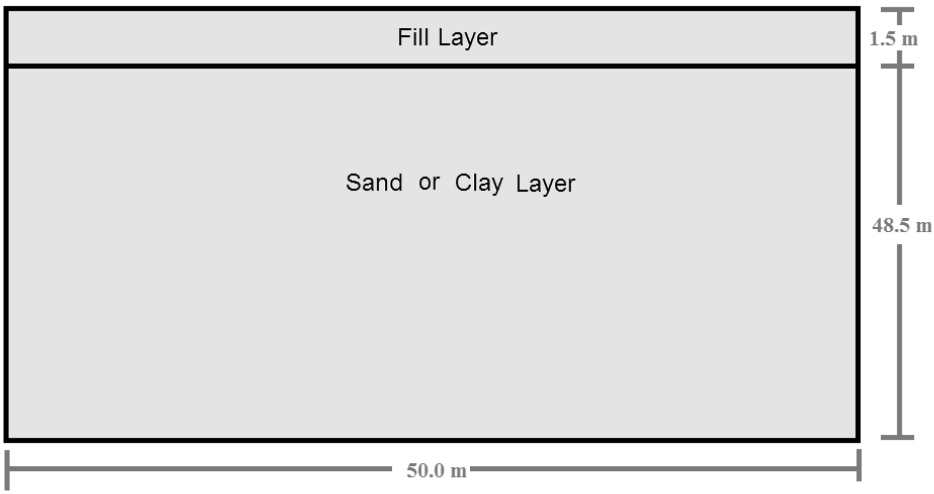

Fig. 9(a). Soil layers used in different models without grouting zone

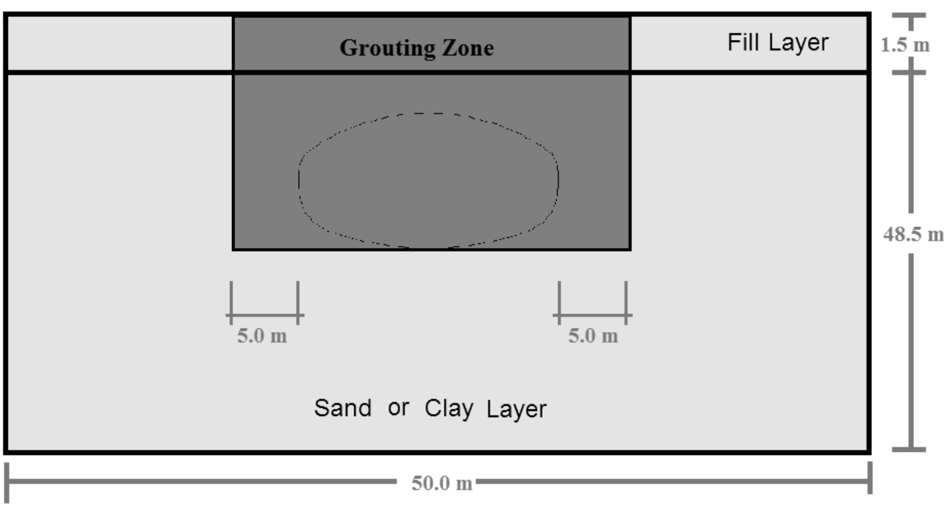

Fig. 9(b). Soil layers used in different models with grouting zone

C. Model description

After some test trials, best dimensions are chosen for models (Augarde, et al., 1998) (Chong, et al., 2009) to use on three sections for the analysis where different conditions are determined. Concrete elements used in different models have modulus of elacticity

E=20000000 kN/m², Poisson's ratio υ=0.20 and unit weight γ=25 kN/m³. Properties of concrete elements sections used are as follows:

- Section "1" using CAPS or CMAPS with larger curvature, Figure 10.

  (Pile diameter = 1.0 m, Frame section = 1.0x1.3 m, Repeated distance = 3.0 m, surface loads = 20 kN/m², Depth of concrete station section = 0.9 m)

- Section "2" using CPPS, Figure 11.

  (Pile diameter = 0.4 m, Repeated distance = 0.8 m, surface loads = 20 kN/m², Depth of concrete station section = 0.8 m)

- Section "3" using ECPPS in large enlargement section, Figure 12.

  (Pile diameter = 0.60 m, Repeated distance = 0.9 m, surface loads = 20 kN/m², Depth of concrete station section = 1.2 m)

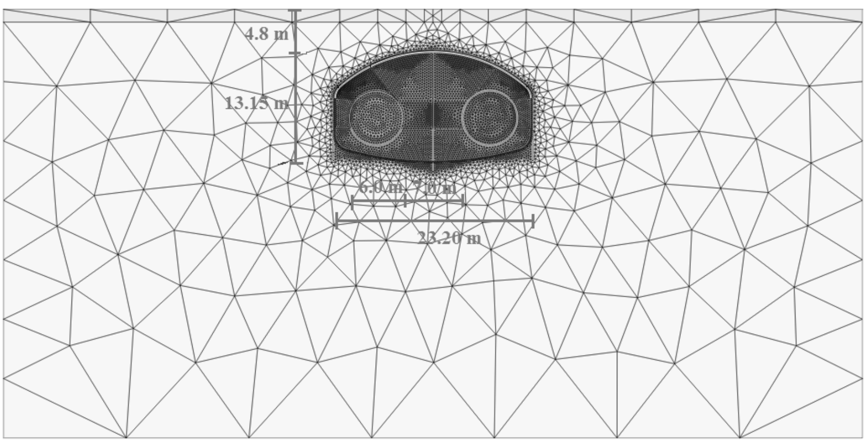

Fig. 10. Section "1" for model using CAPS or CMAPS

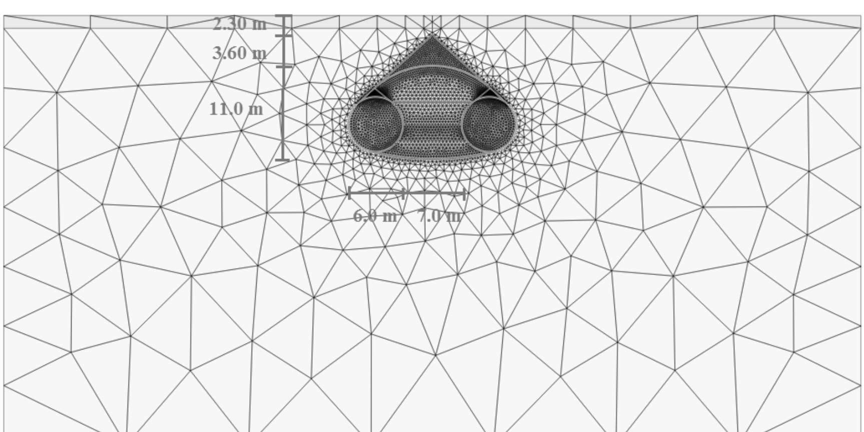

Fig. 11. Section "2" for model use CPPS

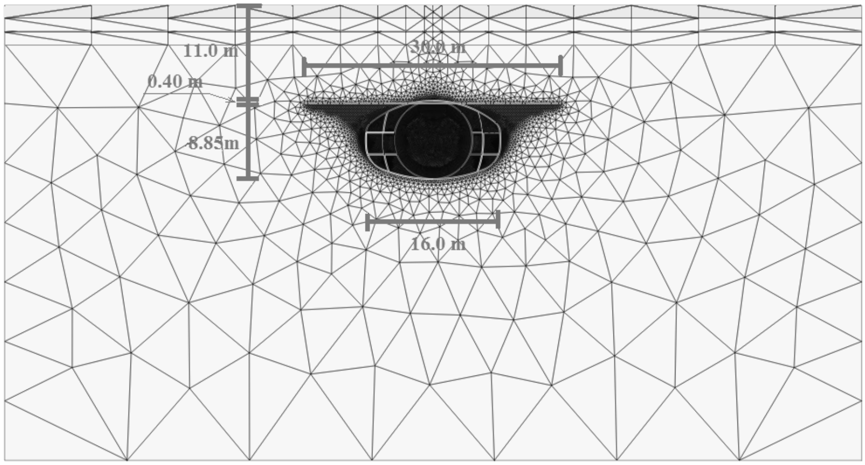

Fig. 12. Section "3" for model use ECPPS

D. Effect of using pre-Supporting systems with NATM

D.1 Section "1"

a) Sand layer

In case of sand layer, the results are shown in Figures 13 and 14. The results show that by using CAPS only, the displacements reduced approximately to 51% of its value in a model without any pre-supporting system and the maximum surface settlement could be reduced to 47mm. By using CAPS and grouting systems together, the displacements reduced approximately to 33% of the displacements in model without any pre-supporting system and the maximum surface settlement could be reduced to 29 mm. By using CMAPS only the displacements reduced approximately to 10% of displacement in model not using any pre-supporting system and the maximum surface settlement could be reduced to 7 mm.

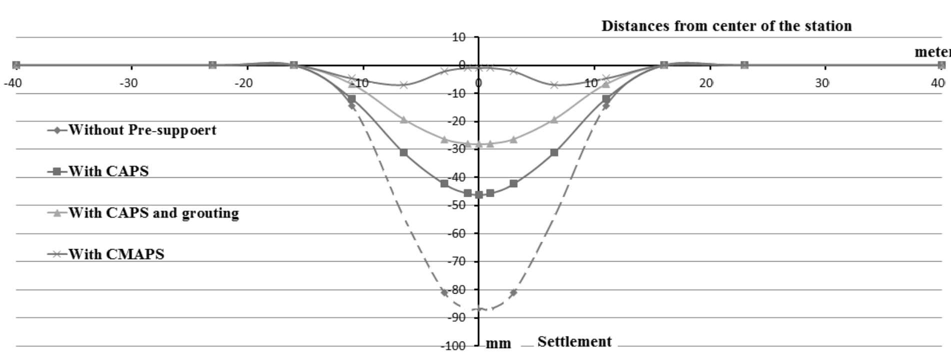

Fig. 13. Surface settlements for different techniques – Section 1 (Sand Layer)

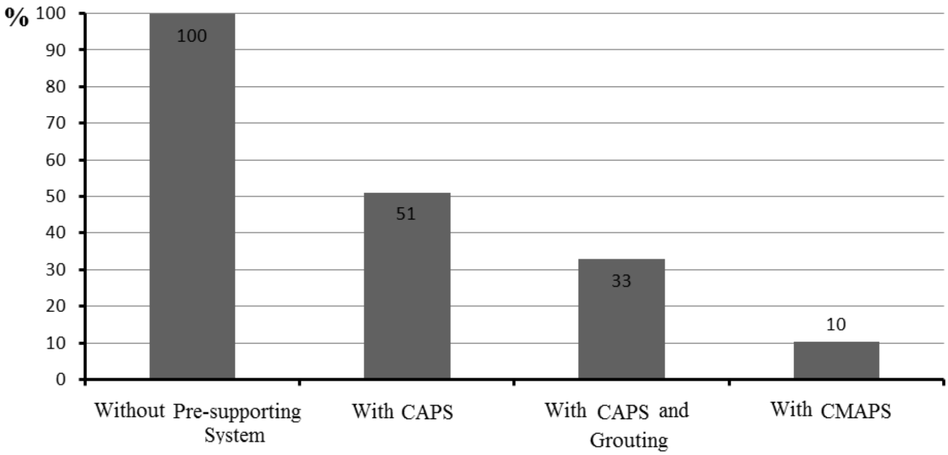

Fig. 14. Average percentage of vertical settlements for different techniques compared to the case of no pre-supporting technique – Section 1(Sand Layer) (vertical settlements of many points in the soil are compared with their vertical settlements without using pre-support system and the average is considered)

b) Clay layer

In case of clay layer, the results are shown in Figures 15 and 16. The results show that by using CAPS only, the displacement reduced approximately to 63% of its value in a model not using any pre-supporting system and the maximum surface settlement could be reduced to 54 mm. Using CAPS and grouting systems together, the displacement reduced approximately to 32% of the displacement in model without any pre-supporting system and the maximum surface settlement could be reduced to 29 mm. By using CMAPS only, the displacement reduced approximately to 13% of displacement in model without any pre-supporting system and the maximum surface settlement could be reduced to 9 mm.

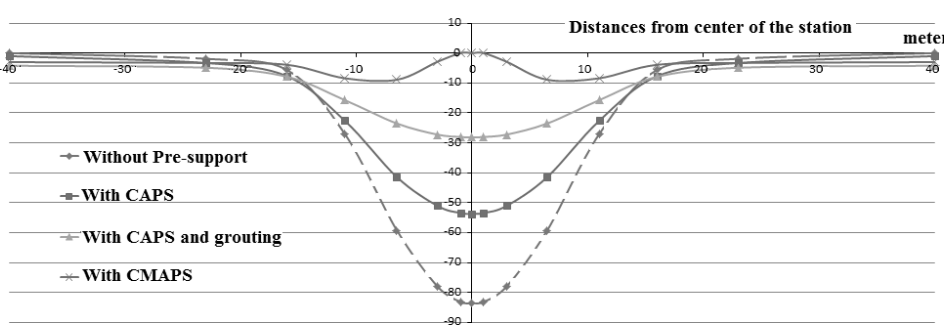

Fig. 15. Surface settlements for different techniques – Section 1 (Clay Layer)

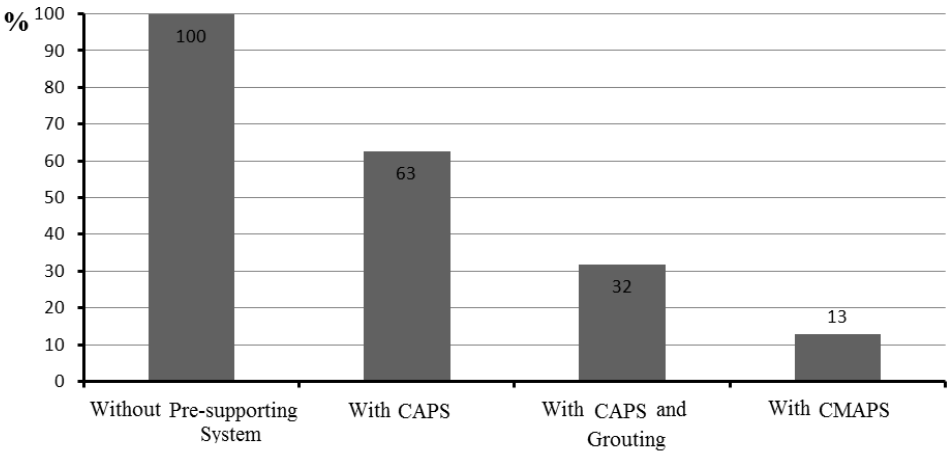

Fig. 16. Average Percentage of vertical settlements for different techniques compared to the case of no pre-supporting technique – Section 1 (Clay Layer) (vertical settlements of many points in the soil are compared with their vertical settlements without using pre-support system and the average is considered)

D.2 Section "2"

a) Sand layer

In case of sand layer, the results are shown in Figures 17 and 18. The results show that by using pre-supporting system only, the displacement reduced approximately to 16% of its value in a model without any pre-supporting system and the maximum surface settlement could be reduced to 21 mm. By using pre-supporting and grouting systems together, the displacement reduced approximately to 9% of the displacement in model without any pre-supporting system and the maximum surface settlement could be reduced to 12 mm.

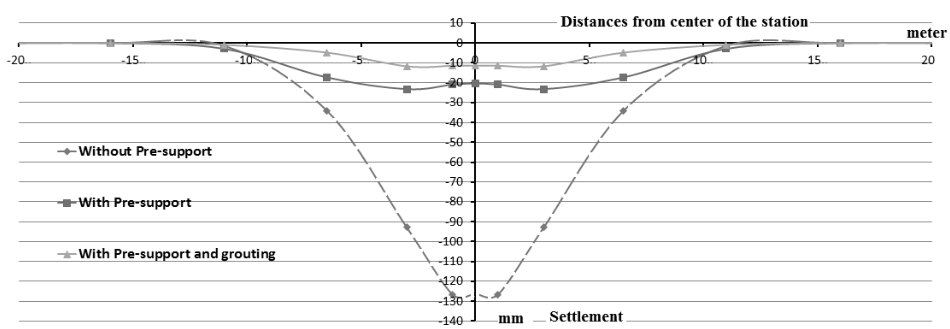

Fig. 17. Surface settlements for different techniques – Section 2 (Sand Layer)

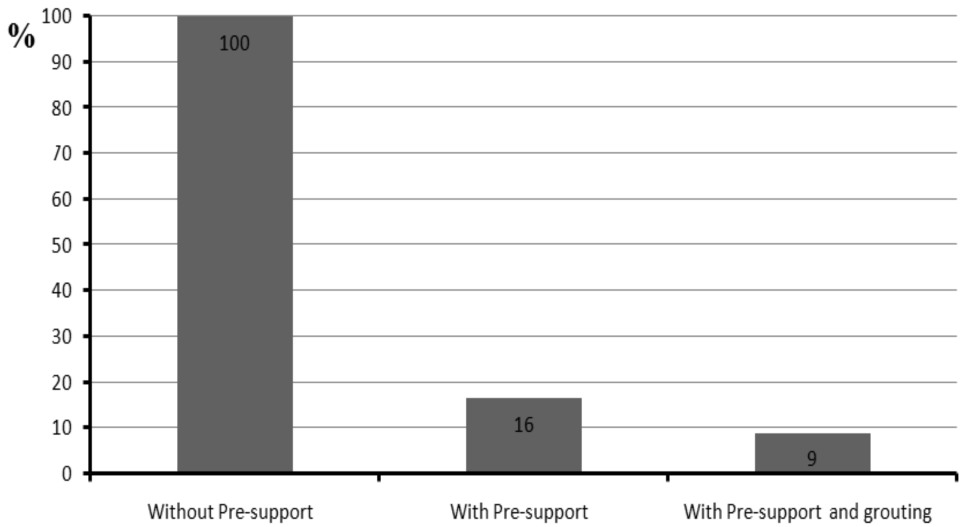

Fig. 18. Average percentage of vertical settlements for different techniques compared to the case of no pre-supporting technique – Section 2 (Sand Layer) (vertical settlements of many points in the soil are compared with their vertical settlements without using pre-support system and the average is considered)

b) Clay layer

In case of clay layer, the results are shown in Figures 19 and 20. The results show that by using pre-supporting system only, the displacement reduced approximately to 36% of its value in a model without any pre-supporting system and the maximum surface settlement could be reduced to 25 mm. By using pre-supporting and grouting systems together, the displacement reduced approximately to 14% of the displacements in model without any pre-supporting system and the maximum surface settlement could be reduced to 13 mm.

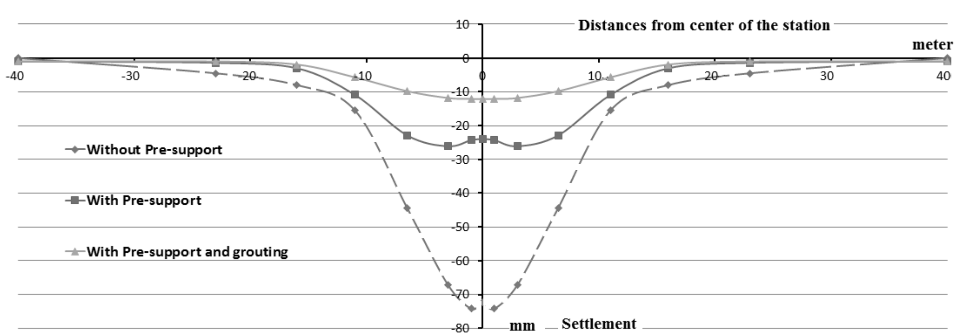

Fig. 19. Surface settlements for different techniques – Section 2 (Clay Layer)

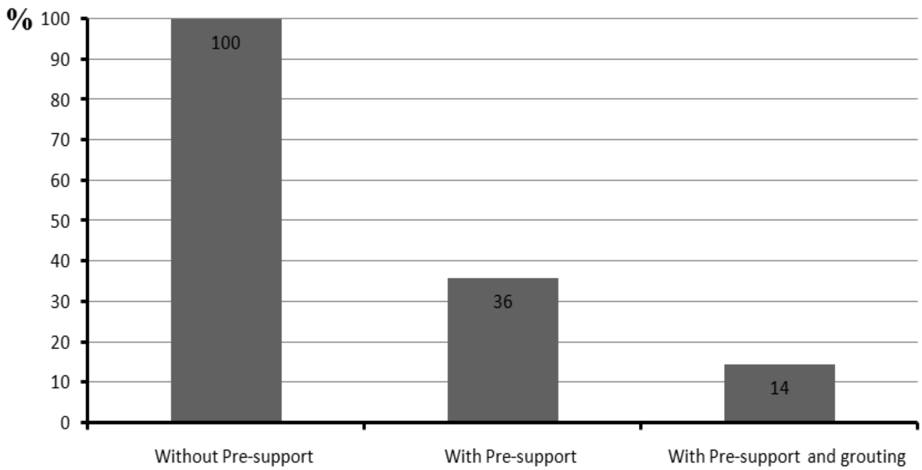

Fig. 20. Average percentage of vertical settlements for different techniques compared to the case of without pre-supporting technique – Section 2 (Clay Layer) (vertical settlements of many points in the soil are compared with their vertical settlements without using pre-support system and the average is considered)

D.3 Section "3"

a) Sand layer

In case of sand layer, the results are shown in Figures 21 and 22. It is evident that by using pre-supporting system only, the displacement reduced approximately to 54% of its value in a model without any pre-supporting system and the maximum surface settlement could be reduced to 22 mm. By using pre-supporting and grouting systems together, the displacement reduced approximately to 16% of the displacement in model without any pre-supporting system and the maximum surface settlement could be reduced to 6 mm.

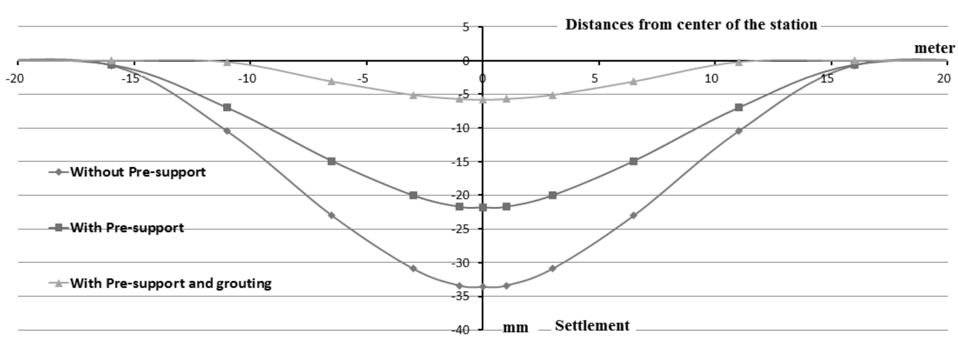

Fig. 21. Surface settlements for different techniques – Section 3 (Sand Layer)

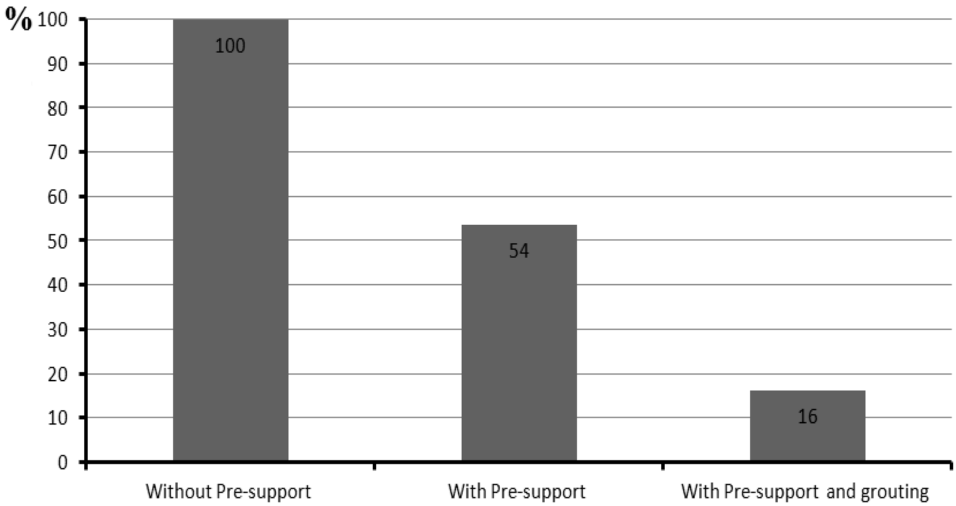

Fig. 22. Average percentage of vertical settlements for different techniques compared to the case of without pre-supporting technique – Section 3 (Sand Layer) (vertical settlements of many points in the soil are compared with their vertical settlements without using pre-support system and the average is considered)

b) Clay layer

In case of clay layer, the results are shown in Figures 23 and 24. The results show that by using pre-supporting system only, the displacement reduced to approximately 76% of the displacement in model without any pre-supporting system and the maximum surface settlement could be reduced to 30 mm. By using pre-supporting and grouting systems together, the displacement reduced approximately to 29% of the displacement in model without any pre-supporting system and the maximum surface settlement could be reduced to 12 mm.

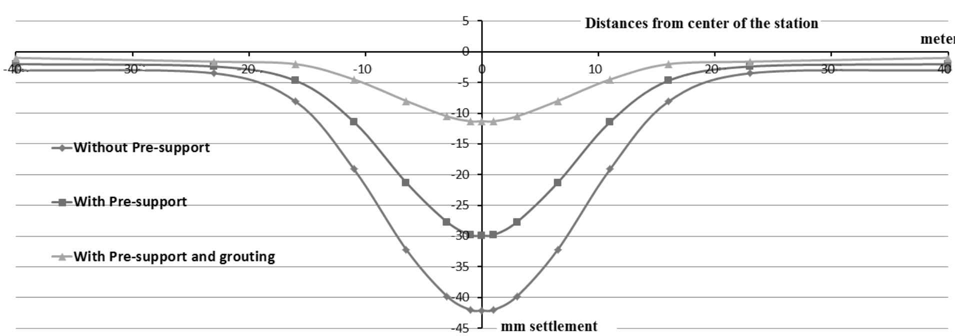

Fig. 23. Surface settlements for different techniques – Section 3 (Clay Layer)

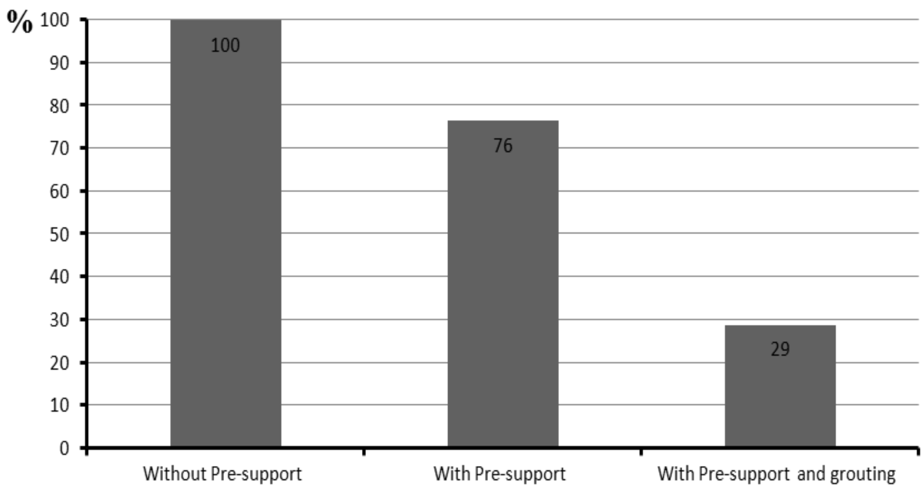

Fig. 24. Average percentage of vertical settlements for different techniques compared to the case of without pre-supporting technique – Section 3 (Clay Layer) (vertical settlements of many points in the soil are compared with their vertical settlements without using pre-support system and the average is considered)

DISCUSSION AND COMMENTS

NATM with underground large span openings (Stations) especially in soft soil needs some aids to be safer and economic. Pre-supporting systems are able to control the displacements and disturbance due to excavation process. After construction of Pre-supporting system, the main underground station is constructed in stages with minimal initial supporting system. Results produced by analyzing the models which do not have any pre-supporting system have unfavorable larger displacements. These displacements may lead to damage of the nearby structures. Less displacement could be found in the models using CPS as shown in the results of different models. The displacements could be reduced by using grouting technique with CPS. CPS and grouting are used only when the displacements of using CPS separately are more than allowable values.

CMAPS could reduce the settlements to very small values. The engineering value gained from this modification is visible with regards to the deformation reduction results. Vertical displacements can be reduced by CMAPS to approximately 10% of displacements without using any pre-supporting system in sand layers and up to 13% of displacements without using any pre-supporting system in clay layers. Increasing radius of the arch could further reduce the displacement. This technique is preferred for underground opening with very large widths.

CPPS could reduce the settlements to allowable values without need to use grouting. However, the settlements will be reduced more if grouting technique is used along with CPPS. Vertical displacements can be reduced by CPPS to approximately

9% of displacements without using any pre-supporting system in sand layers and up to 14% of displacements without using any pre-supporting system in clay layers. This technique is preferred for underground opening with large width and two tube tunnels.

If the tunnel is executed by using one machine, enlargement method may be easier and less cost effective for excavation of underground opening. There are small enlargement and large enlargement techniques. Small enlargement is the enlargement with small distance from 1.0 m to 2.0 m approximately in Egyptian soil conditions. Large enlargement are those with a distance varying from 2.0 m to 6.0 m approximately in Egyptian soil conditions. Small enlargement in the tunnel section may not need a pre-supporting system but large enlargement in tunnel section surely requires some supporting means such as CPPS to control the values of settlements. Vertical displacements can be reduced to approximately 16% of displacements without using any pre-supporting system in sand layers and up to 29% of displacements without using any pre-supporting system in clay layers. This technique is preferred for underground opening with one tube tunnel and with widths equal or less than 16.0 m.

In case of using NATM only in large spans, the size of concrete section needed for the final lining of station will be increased compared to small spans. If CPS is used beside NATM in large spans, the final lining size will be decreased as the CPS will participate in supporting some of the loadings.

CONCLUSIONS

NATM with underground large span openings especially in soft soil needs some aids to be safer. Concrete pre-supporting system (CPS) is able to control the displacements and disturbances due to excavation process. Both techniques (CPS and Grouting) are able to control well the displacements and they can be used together when the CPS induced displacements are more than the allowable values. The proposed modified technique CMAPS could reduce the values of settlements more than CAPS. High curvature of the arch curve is recommended for reducing the settlement. CPPS also could reduce the settlements to favorable values. Large enlargement in tunnel section needs some additional support like CPPS to control the settlements' values. The choice of the optimal technique is case dependent and depends on site conditions and preferred construction method, as well.

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