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Experimental study to determine the optimal tensile force of non-open cut tunnels using concrete modular roof method

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Abstract. In this study, a model experiment and field experiment was conducted to introduce the optimal tensile force when constructing a non-open cut tunnel according to the ground conditions of sandy soil. CMR (Concrete Modular Roof) method is economical because of the high precision and excellent durability, and corrosion resistance, and the inserted parts can be used as the main structure of a tunnel. In addition the CMR method has a stable advantage in interconnection because the concrete beam is press-fitted compared to the NTR (New Tubular Roof) method, and the need for quality control can be minimized. The ground conditions were corrected by adjusting the relative density of sandy soil during the construction of non-open cut tunnels, and after introducing various tensile forces, the surface settlement according to excavation was measured, and the optimal tensile force was derived. As a result of the experiment, the amount of settlement according to the relative density was found to be minor. Furthermore, analysis of each tensile force based on loose ground conditions resulted in an average decrease of approximately 22% in maximum settlement when the force was increased by 0.8 kN per segment. Considering these results, it is indicated that more than 2.0 kN tensile force per segment is recommended for settlement of the upper ground.

Keywords: CMR (Concrete Modular Roof) method; ground condition; non-open cut tunnel; surface settlement; tensile force

1. Introduction

The open cut method of tunnel in metropolitan cities is difficult to solve the problem of Traffic congestion due to population concentration and the limited land (Nam *et al.* 2020); thus, non-open cut methods that can be safely employed for construction without affecting existing road and railway operations are gaining attention. Non-open cut methods include the structure towing method, steel pipe propulsion method, element towing and propulsion method, and panel propulsion method. To select the optimal non-open cut method, various conditions such as depth of ground and application site should be considered (Kang *et al.* 2015). Existing non-open-cut methods require high construction costs and detailed quality control, and the construction process is complicated. In addition, the TBM method is excellent among the existing tunnel construction methods, but there is a fear that it may be difficult to apply in the case of poor ground conditions (Abbas and Ali 2019). However, the CMR method can minimize equipment and quality control.

The CMR method is non-open cut method of constructing structures on the lower part of a common road or railway, and CMR beams are promoted in parallel at the lower part. In addition, as it is composed of concrete beams, it has excellent durability and can redeem for the weak interconnection problems raised by the steel pipe press-in method such as the NTR method. Therefore, in this study, after the completion of an excavation, a model experiment was conducted to determine the optimal tensile force to minimize the amount of settlement by analyzing the ground condition and the surface settlement that occurs according to the tensile force by using CMR method. In addition, to confirm the displacement that appears when the tensile force is introduced in the actual field, a field experiment was conducted.

2. Theoretical background

2.1 Literature review

Currently, during the construction of a tunnel using a non-open cut method in a metropolitan city, settlement occurs on the ground, affecting the surrounding structures. To prevent this problem, research on identifying the causes and establishing countermeasures has been conducted as outlined below.

The limit analysis of safety factors and failure mechanisms for a series of construction stages during drilling have been examined in previous studies (Shengbing 2018). A specific

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section of Beijing Metro Line 7 was considered for the analysis, the focus was on the effect of multiple soil layers and construction sequence of the double tunnel. The results of the study suggested that stair excavation technique was effective in obtaining a higher safety factor when excavating a tunnel than excavating the entire section at once.

Similarly, another previous study was investigated the effects of a dip-slip fault movement on a segment tunnel that transversely crosses either faults (Milad *et al.* 2020). It was observed that by increasing the depth of the tunnel, displacements and ground surface settlements were generated to enhance the quality of design.

In Kim *et al.* (2020), a database from a construction section of the Hong Kong subway was used to analyze the correlation between settlement-inducing factors and surface settlements monitored at different locations of a transverse trough. Pearson correlation analysis revealed a correlation between the factors in consideration. Factors, such as face pressure, advance speed, thrust force, cutter torque, twin tunnel distance, and ground water level presented a modest correlation with the surface settlement, while no significant trends were observed between the other factors and surface settlements. It was concluded that the integrated effect of the settlement-inducing factors should be related to the magnitude of surface settlement.

Lee *et al.* (2013) conducted a study to prevent stress relaxation from occurring in the ground around which the press-fitting of steel pipes was realized during the construction of underground structures using a non-open cut method. The support stiffness of the ground increased when pipe roofing grouting was realized.

Jung and Lee (2015) proposed a method for surface settlement prediction during the indentation of steel pipes in the non-open cut method, and conducted a comparison analysis of the gap parameter and volume loss prediction methods. Consequently, it was confirmed that the volume loss prediction method exhibited the most similarity in the maximum settlement amount and settlement tendency.

These studies demonstrate that surface settlement and deformation are observed in the application of the existing non-open cut method due to the TBM method and the indentation of the steel pipe. However, surface sedimentation and deformation that occur during internal excavation after press-fitting of the non-open cut method are also problems to be solved before construction of the structure. Currently, in Korea, studies on surface settlement and deformation occurring when various tensile forces are applied during excavation inside the structure after the press-fitting of non-open cut method is completed are insufficient. Therefore, it is necessary to analyze the settlement due to the excavation of non-open cut tunnels.

2.2 Ground settlement during tunnel excavation

Peck (1969) confirmed that the shape of the ground settlement that occurs during tunnel excavation is similar to the normal distribution, as shown in Fig. 1 Eq. (1) shows the settlement of the surface

$$S(x) = S_{max}\exp(\frac{x^2}{2i^2}) \tag{1}$$

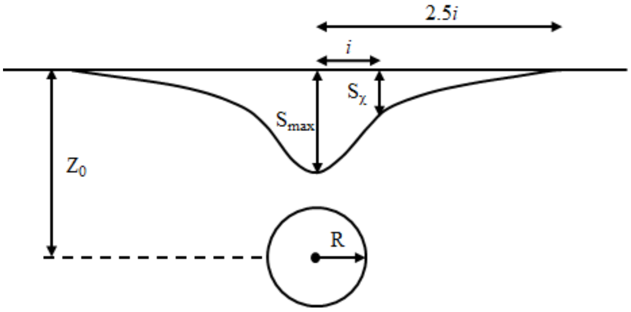


Fig. 1 Definition of settlement (Peck 1969)

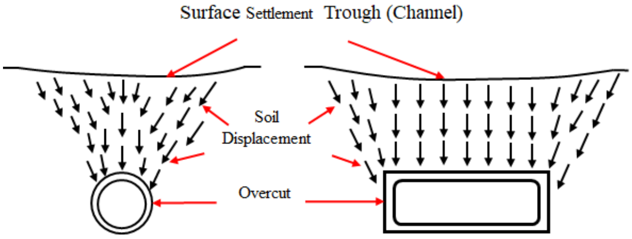


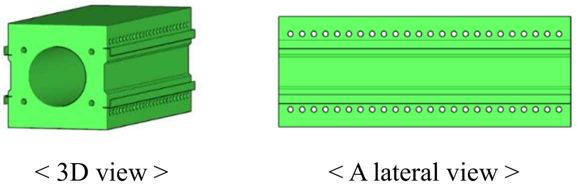
Fig. 2 Settlement behaviors for cross-sectional shape (Mamaqani 2014)

Table 1 Advanced research of relationship between depth and inflection

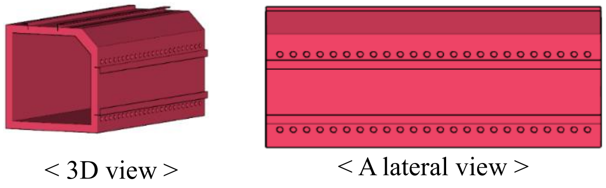
Division	Point of inflection	Research method
Peck (1969)	$\frac{i}{R} = K_a\left(\frac{Z_0}{2R}\right)^n$	Field observations
Cording and Hansmire (1972)	$\frac{i}{R} = 0.8tan\beta \times \frac{Z_0}{D} + 0.4$	-
Attewell and Farmer (1974)	$\frac{i}{R} = K_a\left(\frac{Z_0}{2R}\right)^n$	Field observations of UK tunnels
Atkinson and Potts (1977)	$i = 0.25(H + D)$	Field observations and model tests
Mair et al. (1979)	$i = 0.5Z_0$	Field observations and model tests
Clough and Schmidt (1981)	$i = R\left(\frac{Z_0}{D}\right)^{0.8}$	Field observations of UK tunnels
O'Reilly and New (1982)	$i = 0.28Z_0 - 0.1$	Field observations of UK tunnels

Where i is represents the width variable of the settlement shape and S_x is the inflection point. The results of previous studies have demonstrated that the ground settlement curve is similar to that of a normal distribution. The relationship between the inflection point i and depth Z_0 is summarized in Table 1.

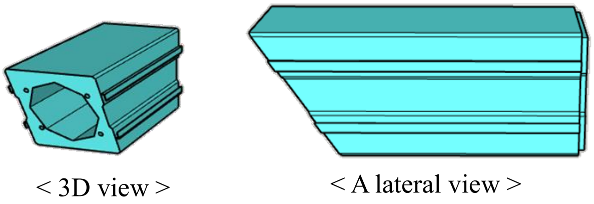
Mamaqani (2014) analyzed the settlement behavior from the excavation of a rectangular box-shaped tunnel instead of a conventional circular tunnel using numerical analysis and



(a) CMR beam sectional



(b) CMR corner sectional-1



(c) CMR corner sectional-2

Fig. 3 CMR construction materials

artificial neural networks. Owing to the effect of stress concentration on excavating a rectangular box-type tunnel, changes in the relaxation zone, and increase in the excavation area to secure the same inner industrial complex, a larger settlement occurred in the box-type tunnel. The settlement shapes are shown in Fig. 2.

3. CMR method

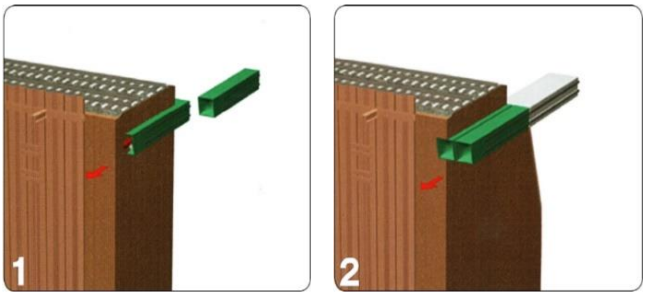
The CMR method, first patented and constructed in Japan in 1980 (Um 2000), is a non-open cut method wherein an element of the shape shown in Fig. 3 is propelled to the lower part without affecting the upper structure.

The construction method is shown in Fig. 4; after propulsion of the square steel pipe shoe, replacement and rear side excavation are conducted by attaching a CMR beam. Completing the propulsion and replacement process of the beam, insert PC steel and repeat the process of tensioning the connection part in the longitudinal direction. After all propulsion is completed, the steel material is insert in the transverse direction to make it tensioned. Finally inside excavation are conduct to complete the tunnel.

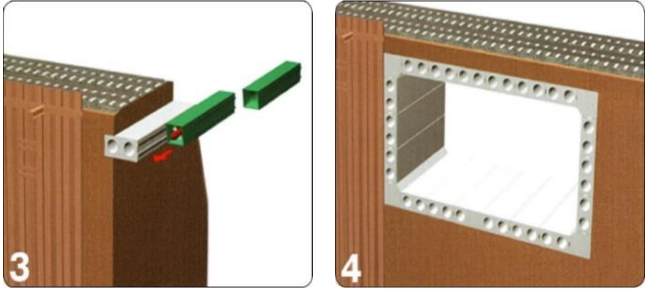
4. Laboratory model experiment of CMR method

4.1 Equipment

To analyze the settlement and tensile force of the tunnel using the CMR method, a model chamber with dimensions 2 m (width) × 1 m (height) × 0.75 m (length) was constructed, as shown in Fig. 5, to conduct a model experiment.



(a) Steel pipe propulsion (b) Jointing and excavation propulsion



(c) Parallel propulsion and excavation (d) Construction completed

Fig. 4 Double element replacement propulsion construction cycle

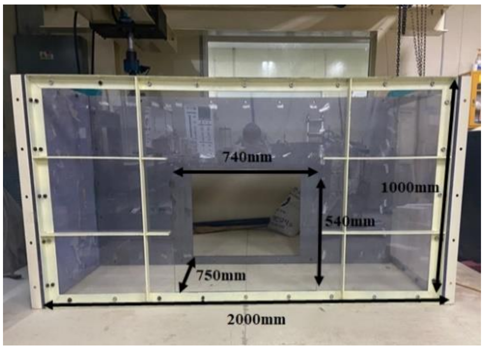
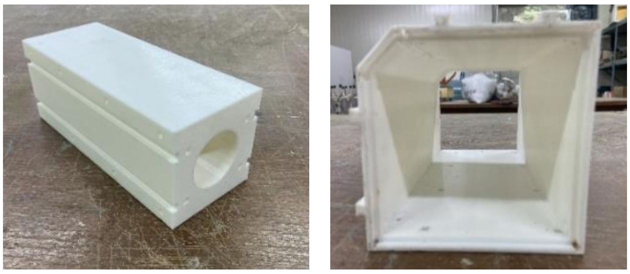
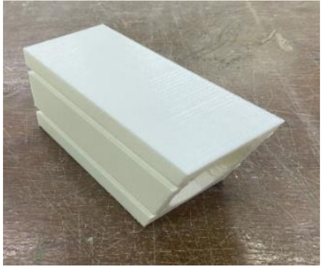


Fig. 5 Chamber

Model CMR structures were produced using a 3D printer. In addition, for the size of the model structure, approximately 1/10 of the geometrical similarity was applied to the CMR structures used in the actual field. To prevent the loss of sand from the small gaps in the structures during the model experiment, the model CMR structures were simplified to a concave-convex coupling type, as shown in Fig. 6. In addition, the model experiment was limited by the working space and difficult to insert actual reinforcement bars. Therefore, steel wires were inserted into the model structure instead of reinforcement bars, and the tensile force was verified by attaching a load cell after introducing a tension force. This was realized by hanging a weight, and the pre-stress was realized by pressing the steel wire and a sleeve that served as a wedge between the wires. Furthermore, owing to the lack of viscosity due to the nature of the sand soil during excavation, it was difficult to construct the inside of the tunnel densely; Therefore, the experiment was conducted by making a pedestal with a length of 125 mm to simulate a total excavation of 750 mm over six steps.



(a) Model CMR beam (b) Model CMR corner

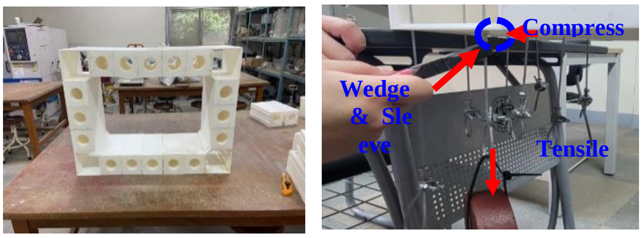


(c) Model CMR steel pipe

Fig. 6 3D printed model structures

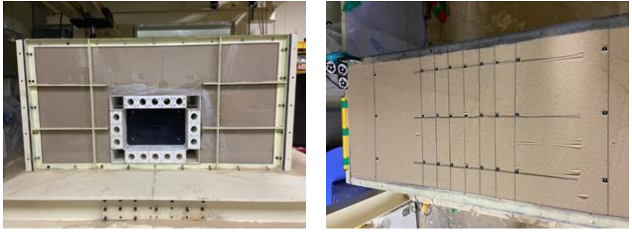
4.2 Method

The construction flowchart for tunnel measurement using the model CMR method is shown in Fig. 7. ① Constructing a model structure; ② Inserting a steel wire and introducing prestress to the structure; ③ Forming the tunnel lower ground and inserting the structure; ④ Using a sand-raining device based on the relative density test results; ⑤ Forming the ground; ⑥ Installing the target to be used for photographic measurement on the upper ground; ⑦ Analyzing the measurement data; ⑧ Performing the excavation and photo measurement sequentially. To confirm the settlement due to the increase or decrease in the tensile force, each segment was divided into 0.4, 0.8, 1.2, 1.6, and 2.0 kN tensile forces. The experiment was conducted using Jumunjin standard sand (KSL ISO 679), which is a domestic standard sand. In addition, to simulate the ground state, a relative density experiment was conducted to construct loose, middle, and dense ground (Das 2010), and a total of 15 experimental cases were implemented. The measurement points of the surface settlement were located at the center of each upper structure of the model structure, as shown in Fig. 8, and measured via photogrammetry up to a diameter of the tunnel in the range of 0.5D.

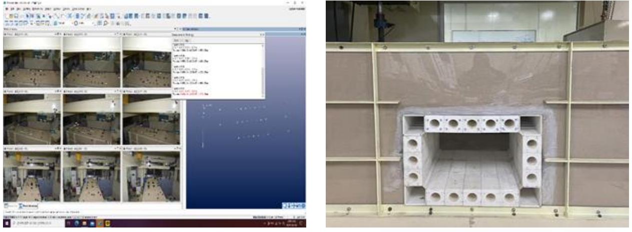


(a) Model CMR beam (b) Model CMR corner

(c) Model CMR steel pipe (d) Sand Curtaining



(e) Upper ground formation (f) Install targeting



(g) Analysis data (h) Sequential excavation

Fig. 7 Experimental process

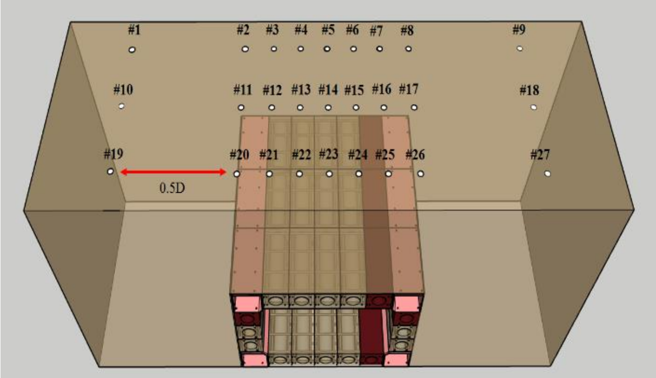
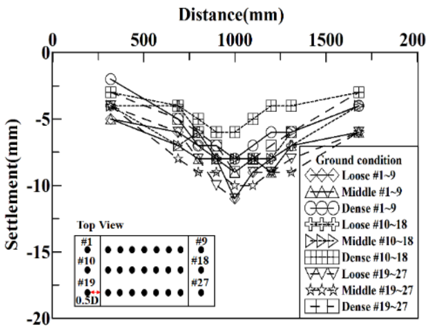


Fig. 8 Target layout

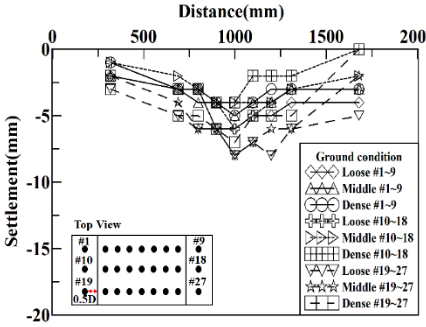
5. Experiment result of CMR method

5.1 Analysis result of settlement amount according to ground condition

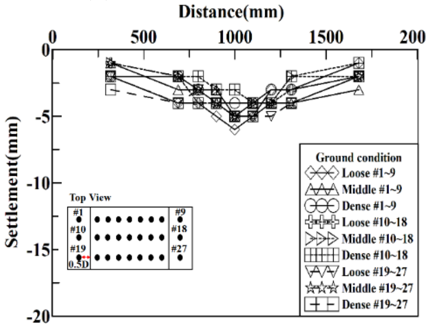
The purpose of this study was to analyze the surface settlement according to the change in relative density and tensile force during excavation, not settlement caused by indentation. Therefore, in all cases before excavation, it was assumed that no settlement occurred as the initial condition. The result of experiment, surface settlement measurement according to the excavation length in the model structure internal excavation experiment demonstrated that most of the maximum settlement occurred at the center of the CMR tunnel. In addition, as shown in Fig. 9, when the tensile force per segment area was 0.4 kN during the final excavation, a maximum settlement of 11 mm in the loose ground, 10 mm in the middle ground, and 9 mm in the dense ground was observed. Furthermore, the better the ground conditions, the lower the settlement by approximately 9–10%. In contrast, when the tensile force



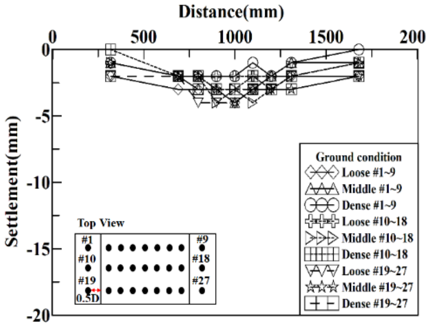
(a) Tensile force _0.4 kN



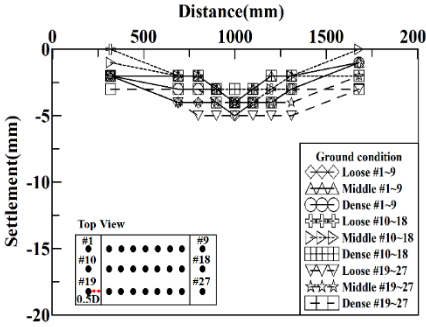
(b) Tensile force _0.8 kN



(c) Tensile force _1.2 kN

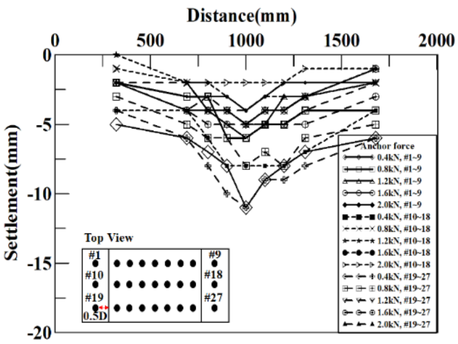


(d) Tensile force _1.6 kN

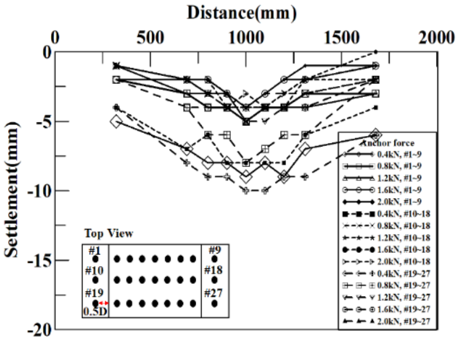


(e) Tensile force_2.0 kN

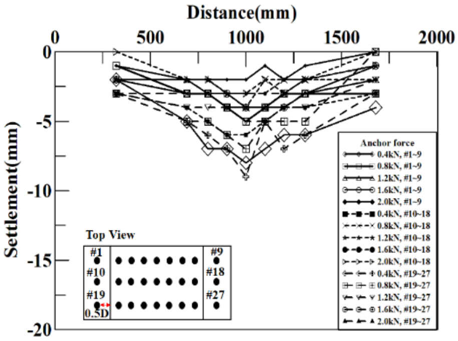
Fig. 9 Amount of settlement according to ground conditions



(a) Loose condition



(b) Middle condition



(c) Dense condition

Fig. 10 Amount of settlement according to tensile force

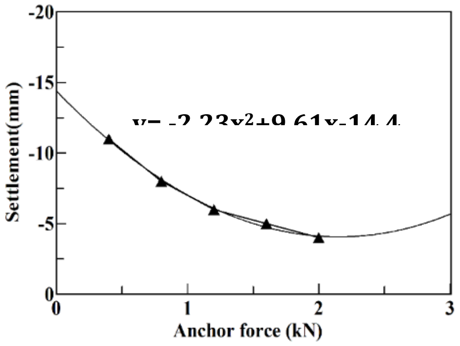
was 0.8 kN, the maximum settlement was 8 mm in the loose and middle grounds, and 7 mm in the dense ground. The comparative analysis of the middle and loose grounds demonstrated that no additional settlement occurred, and in the dense ground, the settlement amount decreased by approximately 13% that of the normal ground. At tensile force of 1.2 kN, maximum settlements of 6, 5, and 5 mm for the loose, middle, and dense grounds, respectively, were observed. The amount of settlement was reduced by approximately 17% in the middle ground than in the loose ground, while the comparative analysis between the dense and middle grounds demonstrated that no additional settlement occurred. When the tensile force was 1.6 kN, maximum settlements of 5, 4, and 4 mm for the loose, middle, and dense grounds, respectively, were observed. Although the settlement amount was reduced by approximately 20% in the normal ground than in the loose ground, no additional settlement occurred as demonstrated by the comparative analysis of the normal and dense grounds. Finally, for tensile force of 2.0 kN, the maximum settlements of 4, 4, and 3 mm occurred in the loose, middle, and dense grounds, respectively. The comparative analysis of the middle and loose grounds revealed that no additional settlement occurred, and the settlement amount of the dense and middle grounds was reduced by approximately 25%. Based on the results of this analysis, the extent of the decrease in settlement due to the ground conditions was rather insufficient; however, the better the ground conditions, the lower the settlement amount.

5.2 Analysis result of settlement amount according to tensile force

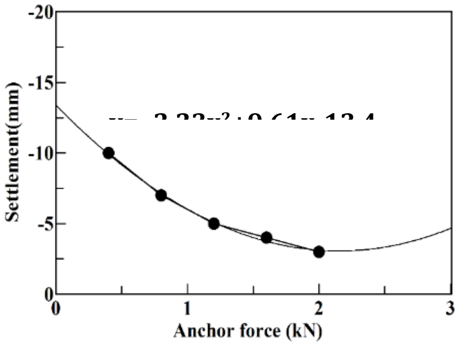
Analyzing the tensile force per segment area, as shown in Fig. 10, helped determine that, when the tensile force was increased from 0.4 to 0.8 kN, the maximum settlement on the loose, middle, and dense grounds decreased by 27, 20, and 22% from 11, 10, and 9 mm to 8, 8 and 7 mm, respectively. Furthermore, when the tensile force was increased from 0.8 to 1.2 kN, the maximum settlement was 6, 5, 5 mm, respectively, indicating a decrease of 25, 38, and 29%, respectively. When the tensile force was increased from 1.2 to 1.6 kN, the maximum settlement was 5, 4 and 4 mm, respectively, decreasing by approximately 17% in the loose ground and 20% in the middle and dense grounds. Finally, when the tensile force was increased from 1.6 to 2.0 kN, the maximum settlement decreased by 20% in the loose ground to 4 mm, and by 25% in the middle and dense grounds to 3 and 3 mm, respectively. Thus, when the CMR method was applied to sandy soil, the maximum settlement according to the tensile force decreased by approximately 22% on average when the tensile force per segment area increased by 0.4 kN.

5.3 Predictive formula for determining the optimal tensile force based on the ground condition

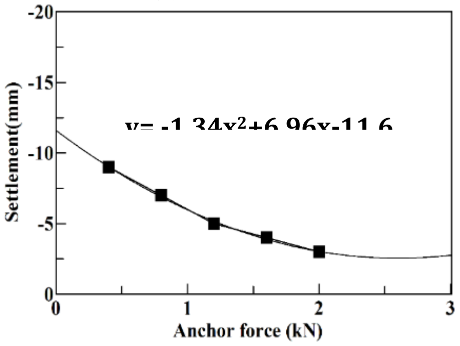
The maximum settlement according to the ground conditions and the tensile force per segment area were analyzed, as shown in Fig. 11, and a prediction formula for selecting the optimal tensile force according to the ground conditions was derived. A minimum settlement of 4 mm occurred when the tensile force per segment was 2 kN on loose ground, whereas a minimum settlement of 3 mm occurred when the tensile force was 2.2 kN on normal ground. In addition, a minimum settlement of 2.5 mm occurred at a 2.7 kN tensile force on dense ground.



(a) Dr_Loose



(b) Dr_Middle



(c) Dr_Dense

Fig. 11 Predictive formula for determining the optimal tensile force

6. Field experiment of CMR method

In this study, field experiments were conducted using concrete modular roof (CMR) method to confirm the displacement occurring at the actual site during the construction of a non-open cut tunnel. The size of each beam was 1 m (width) × 1 m (length) × 1 m (height). After the CMR beam was manufactured, a steel element (right leg part) and concrete beam were assembled in the shape of a tunnel. A prestress Concrete strand with a diameter of 12.7 mm was inserted into a total of 18 perforations, and a prestress force of 50 kN per hole was introduced. Next, to simulate the load, a 12.7 mm diameter steel line was inserted into the center of the CMR beam, and the tensile force was increased by 25 kN to measure the load using an LVDT. The process of the field experiment is shown in Fig. 12. In addition, As shown in Fig. 12(f), 5 beams from the left were set to 1 to 5 to analyze the displacement using the CMR beam.

7. Analysis of field experiment

Fig. 13, shows the results of measuring the displacement occurring in the upper structure when the tensile force is introduced through field experiment. It was observed that, when the tensile force is 50 kN, the displacement of the concrete structure increases with an increase in the applied load. When a load with a maximum tensile force of 130 kN is induced, maximum displacements of 0.27, 0.32, 0.64, and 0.58 mm are generated in the first, second, fourth, and last concrete structures, respectively. Displacement was induced

(a) View of CMR beam assembly (b) Introduce tensile force

(c) Insert steel wire to load introduction (d) Load introduction

(e) Measuremet of displacement (f) View of field experiment

Fig. 12 Process of the field experiment

by artificially inducing a load to simulate the settlement; however, a fairly insufficient amount of displacement occurred. Accordingly, it is expected that the settlement of the ground above the tunnel during the internal excavation stage of the CMR method will be minimal.

8. Conclusions

In this study, the CMR method was applied to determine the optimal tensile force based on the surface settlement caused by a excavation. Additionally, a model experiment was conducted to analyze the surface settlement that occurred when an tensile force was introduced according to the changes of relative density in the sandy soil. The conclusions of the experiment are as follows:

1. For the CMR tunnel construction in sandy soil, the settlement according to the ground conditions is rather minor; thus, the ground conditions are not a crucial decisive factor of surface settlement. However, it is desirable to realize construction on a ground with good conditions because there is a risk of heavy damage due to the settlement, which in turn is caused by various factors.

2. The amount of surface settlement due to the increase in tensile force decreases at a rather high rate compared to the change in relative density, which has a great influence on the amount of ground settlement during tunnel excavation. In addition, as a result of analysis on the increase in tensile force, the optimal tensile force is calculated to be at least 1.2 kN. When an tensile force greater than 1.2 kN, the difference of settlements was so samll that can not be compared the adavantage.

3. A prediction formula was proposed to select the optimal tensile force according to the ground conditions. The introduction of tensile force of 2.0–2.7 kN per segment depending on the ground state would be advantageous for minimizing surface settlement.

4. The results of the field experiment indicated that, the displacement was minor despite the artificial load applied to induce settlement. Additionally, the amount of settlement of the upper ground during the internal excavation stage of CMR construction was minimal. Thus, even if the ground conditions are unfavorable, it is possible to cope with an increase in the tensile force.

5. In this study, the model experiment was performed only on sandy soil; therefore, it is hardly to conclude the adaptability of the proposed method in the field with various types of ground conditions. Thus, further studies on settlement analysis and tensile force estimation based on various ground conditions are required.

6. This study has a limitation in that it was not possible to conduct an experiment by applying chambers of various sizes due to various restrictions such as time and space, so analysis according to various scales couldn't be performed. Thus, additional studies is need to improve reliability through scale analysis using various chambers in the future.

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