Effect of pre-ground improvement method during shallow NATM tunnel excavations under unconsolidated conditions

Effets de la méthode d'amélioration préalable des sols durant l'excavation de tunnel peu profond utilisant la nouvelle méthode autrichienne (NATM) dans un sol non-consolidé

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ABSTRACT: During the construction of the Bullet Train lines in Japan, several shallow tunnels were excavated in unconsolidated ground using the New Austrian Tunnelling Method (NATM). However, ground and tunnel settlements frequently occurred due to the low stiffness of the ground and the shallow overburdens. In order to prevent such settlements and to ensure the stabilization of the cutting face of the tunnels, a pr-ground improvement method was adopted in the above fields. Various combinations of improved areas and levels of strength were tried in the fields, and the tunnels were excavated successfully. However, the mechanism of the effect of the pre-ground improvement method, the influence of the strengh of the improved ground, and the influence of the depth and the width of the improved areas are not clearly understood. Therefore, 2D elasto-plastic FE analyses are carried out here to clarify the effect of the pre-ground improvement method on the prevention of ground and tunnel settlements.

RÉSUMÉ : Durant la construction des lignes du train rapide japonais, plusieurs tunnels peu profonds ont été excavés dans des sols non-consolidés en utilisant la nouvelle méthode autrichienne (NATM). Cependant, à cause de la faible cohésion du sol et du mort-terrain peu profond, des affaissements du sol et du tunnel arrivaient fréquemment. Dans le but de prévenir ces affaissements, et pour s'assurer de la stabilité des parois du tunnel, une méthode supplémentaire d amélioration préalable du sol a été adoptée dans les terrains mentionnes ci-dessus. Divers combinaisons des surfaces améliorées et des niveaux de résistance ont été essayées sur place, et les tunnels ont été creusés avec succès. Cependant, l'effet de la méthode d'amélioration préalable des sols et l'influence de la résistance des terrains améliorés, de leur profondeur et de leur largeur n'est pas clairement comprise. Dans cette étude, des analyses 2D par éléments finis élasto-plastique sont effectuées afin de clarifier l'effet de la méthode d'amélioration préalable des sols sur la prévention des affaissements du sol et du tunnel.

KEYWORDS: shallow tunnel, unconsolidated ground, NATM, pre-ground improvement method, surface settlement

1 INTRODUCTION

Up to now, the open-cut method has been the main tunneling method when excavating shallow tunnels in unconsolidated ground. And, the New Austrian Tunnelling Method (NATM) has been thought to be suitable when excavating tunnels in mountainous areas. Recently, however, not only because of advances in construction and measurement techniques, but also because it is more economical than either the shield tunneling method or the open-cut method, NATM has also become popular for shallow tunnel excavations. For example, during the construction of the Bullet Train lines in Japan, several shallow tunnels were excavated in unconsolidated ground using NATM (Kitagawa et al., 2005, 2009). However, ground and tunnel settlements frequently occurred due to the low stiffness of the unconsolidated ground and the significant reduction in the arching effect arising from the shallow overburdens. In order to prevent such settlements and to ensure the stabilization of the cutting face of the tunnels, a pre-ground improvement method was adopted in the above-mentioned fields.

Figure 1 shows the construction process of the pre-ground improvement method. First of all, the ground is excavated to the upper part of the tunnel crown. Then, cement is mixed with the natural ground around the side wall of the tunnel using the shallow or deep mixing stabilization method. Thereafter, spreading and rolling compaction of the premixed soils are performed over the tunnel crown area. Finally, backfilling and rolling compaction of the excavated soils are performed to the ground surface. Thereafter, the tunnel is excavated using NATM. Various combinations of improved areas and levels of strength of the improved ground were tried in the fields, and the tunnels were excavated successfully. Morover, the effect of the pre-ground improvement method was confirmed in a previous analytical study (Cui et al., 2012). However, the mechanical behavior of the ground and the tunnel during the tunnel excavation process has not been discussed sufficiently. The strength of the improved ground, and the depth and the width of the improved areas, have been determined through practical construction works .

In this study, therefore, 2D elasto-plastic finite element analyses, that simulate the tunnel excavation process, are carried out to clarify the effect of the pre-ground improvement method.

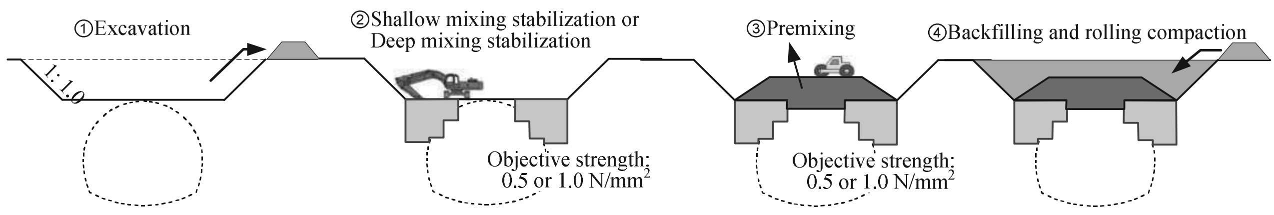


Figure 1. Construction process of pre-ground improvement method

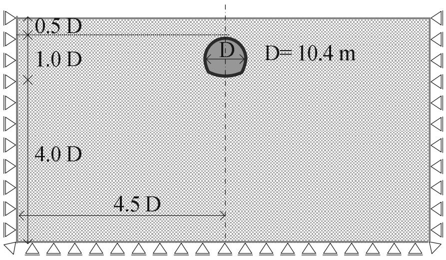


Figure 2. Analysis area and boundary conditions

STAGE	Construction process	Image
STAGE1	Initial conditions (initial stress)	
STAGE2	Equivalent *in situ* stress of top heading	
STAGE3	Before installing supports and shotcrete in top heading	40 %
STAGE4	Supports & shotcrete Top heading excavation complete	60 %
STAGE5	Equivalent *in situ* stress of bottom section	
STAGE6	Before installing supports and shotcrete in bottom section	40 %
STAGE7	Supports & shotcrete Tunnel excavation complete	60 %

Figure 3. Analysis procedure

2 OUTLINE OF NUMERICAL ANALYSIS

2.1 *Modeling of ground, lining and tunnel excavation process*

Figure 2 shows the analysis area and the boundary conditions. The object of the analysis was determined based on the construction field data. The overburdens were varied between 2.0 m and 5.25 m (0.5 D).

The subloading t_{ij} model (Nakai & Hinokio, 2004) was used to simulate the ground material. The properties of the model ground are given in Table 1. Density ρ and void ratio e were measured by *in situ* tests, while the other parameters were referred to certain references (Iizuka & Ohta, 1987; Nakai & Hinokio, 2004).

Table 1. Properties of natural ground

Density ρ ($\times 10^3$ kg/m^3)	1.50
Poisson's ratio ν	0.36
Void ratio (e_0)	1.27
Coefficient of earth pressure at rest k_0	0.56
Principal stress ratio at critical state	2.60
Compression index λ	0.1154
Swelling index κ	0.02

The improved ground was modeled as an elastic material. Young's modulus was calculated based on compressive strength q_u (N=8 q_u /100, E=2800 N). The values used in this analysis were 2.24×10^5 kN/m^2 (q_u=1.0×10^3 kN/m^2).

The tunnel lining was modeled as a composite elastic beam unifying the tunnel supports and the shotcrete. Flexural rigidity EI and axial rigidity EA of the composite beam were made to be equal to the sum of the corresponding values of the supports and the shotcrete. The Young's modulus of the composite beam was taken as 1.23×10^7 kN/m^2 (Cui et al., 2010).

The tunnel excavating process was simulated by the release of an equivalent force to excavation. The analysis included seven steps, as shown in Figure 3.

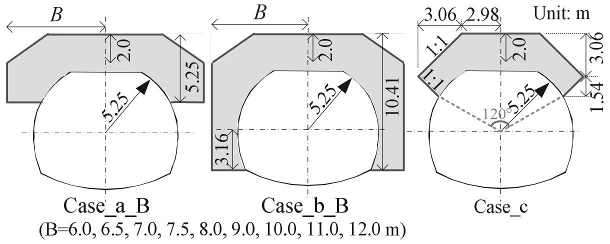


Figure 4. Analytical patterns for different improved areas

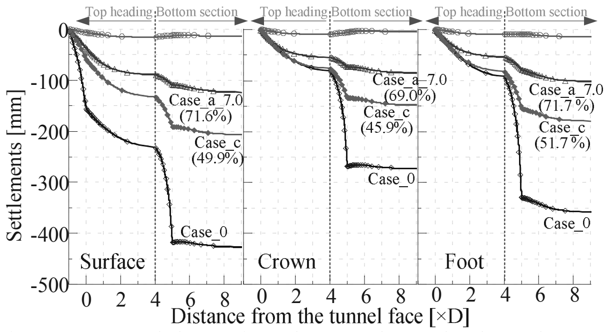


Figure 5. Temporal changes in settlements of ground and tunnel

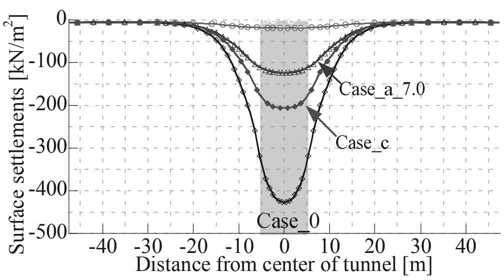


Figure 6. Surface settlement when tunnel excavation completed

2.2 *Analysis patterns*

Figure 4 shows the analytical patterns for different widths of the improved areas. The ground was improved around the crown of the tunnel and the top section in the Case_a_B series. The Case_b_B series is for the ground which was improved around all cross sections of the tunnel. B represents the width of each improved area, varied between 6.0 m and 12.0 m. Only the area around the crown of the tunnel was improved in Case_c.

The improved area of Case_a_7.0 was adopted in the Ushikagi Tunnel (Tohoku Bullet Train line), that of Case_b_6.5 was adopted in the Kamikita and Akabira Tunnels (Tohoku Bullet Train line), and that of Case_c was adopted in the Dainiuozu and Uozukaminakazima Tunnels (Hokuriku Bullet Train line). These three cases represent the basic patterns when determining the areas for the pre-ground improved method.

The mechanical behavior of the ground and the tunnel for the above three cases is investigated in this study, and the influence of the width and the height of the improved areas is discussed.

3 EFFECT OF PRE-GROUND IMPROVEMENT METHOD

3.1 *Mechanical behavior of the natural ground*

Figure 5 shows the temporal changes in the settlements of the ground surface, the crown and the foot of the tunnel. Case_0 is the analysis pattern for the excavated tunnel without ground improvement. The ground surface and the tunnel sink with large values in Case_0. They become smaller with the improvement of the ground, and the effect is seen to increase in the order of the improved areas (Case_b_6.5 > Case_a_7.0 > Case_c). These values in parentheses are the reduction ratios for each settlement value from the Case_0.

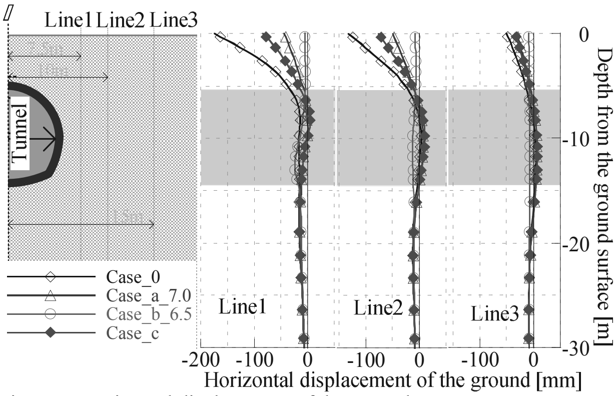


Figure 7. Horizontal displacement of the ground

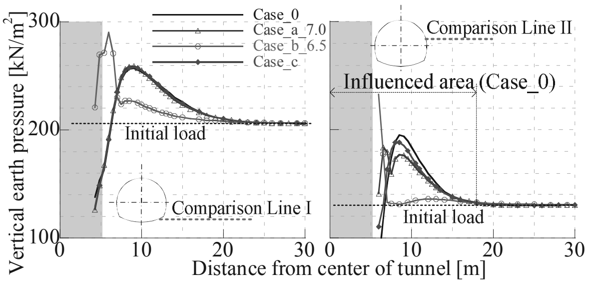
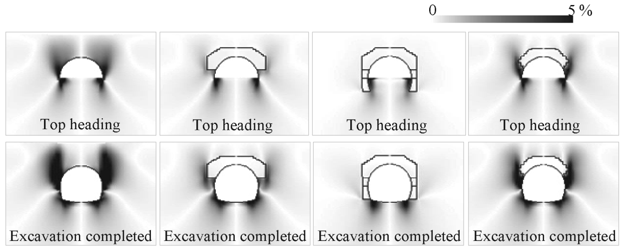
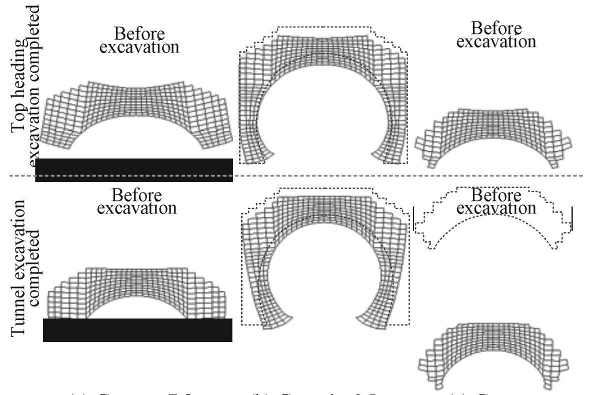


Figure 8. Vertical earth pressure distribution (Excavation completed)



(a) Case_0 (b) Case_a_7.0 (c) Case_b_6.5 (d) Case_c

Figure 9. Shear strain distribution



(a) Case_a_7.0 (b) Case_b_6.5 (c) Case_c

Figure 10. Deformation of improved ground

Figure 6 shows the surface settlement curves after the tunnel excavations have been completed. The figure indicates that surface settlements can be prevented by adopting the pre-ground improvement method, and that the method becomes more effective as the improved area becomes larger.

The horizontal displacement occurring in the marked ground areas (Lines 1, 2 and 3) are shown in Figure 7. The distance between the center of the tunnel lining and Lines 1~3 are 7.5 m, 10.0 m and 15.0 m, respectively. The ground is displaced toward the tunnel lining, due to the tunnel excavation, and the largest horizontal displacements are seen on the ground surface in all of the cases and all of the examination positions. The horizontal displacements become smaller as the areas of the improved ground increase. In particular, there is almost no displacement seen in Case_b_6.5, for which all cross sections of the tunnel were improved.

Figure 8 shows the vertical earth pressure distribution on the marked positions after the tunnel excavations have been completed. The straight dotted lines show the initial vertical earth pressure distribution before the excavation. The full black lines, without markers, show the vertical earth pressure distribution for Case_0 where the tunnel was excavated without ground improvement. The figure shows that the vertical earth pressure, acting on both sides of the tunnel, increases due to the tunnel excavation, in a certain area. This area is called an influenced area due to the tunnel excavation. The vertical earth pressure acting on comparison Lines I and II is concentrated in the improved area, and the influenced area becomes narrow in Case_b_6.5. This effect is called an earth pressure redistribution effect. However, there is almost no change in the influenced area for Case_a_7.0 and Case_c.

The shear strain distributions for the two analysis stages, namely, when the top heading has been completed and when all of the tunnel excavation has been completed, are shown in Figure 9. In Case_0, for a tunnel excavated in a natural ground, large shear strain is generated from the foot of the tunnel and develops to the ground surface. When ground improvement has been performed, the development of shear strain is intercepted by the improved area. As a result, the shear strain becomes smaller due to the improved ground. This effect is called a shear reinforcement effect, and it becomes more effective as the improved area becomes larger. On the other hand, the improved area is surrounded by relatively large shear strain, as in Case_a_7.0 and Case_c. The skimpiness of the width of the improved ground is thought to be the reason for this phenomenon. The large shear strain is generated over a large area when the ground has not been improved, and the improved area is not wide enough to intercept all of the large shear strain area, as in Case_a_7.0 and Case_c. As a result, the large shear strain is remaining around the improved area. When all the cross sections of the tunnel have been improved, as in Case_b_6.5, the improved ground can intercept the large shear strain from the foot of the tunnel, despite the width of the improved ground. However, the pre-ground improvement method has almost no influence on the shear strain that occurs from both edges of the invert of the tunnel lining.

3.2 *Mechanical behavior of improved ground*

Figure 10 shows the deformation of the improved ground. For easy understanding, the deformation is expanded to 50 times. The dotted lines represent the original position of the improved ground. The deformation of the improved ground becomes smaller when the improved areas become larger. The deformation of the improved ground shows the same shapes in Case_a_7.0 and Case_c; the upper part of the improved ground is compressed and both ends of the improved ground are moving away from the tunnel. On the other hand, both ends of the improved ground are moving towards the center of the tunnel in Case_b_6.5. This deformation shape is the same as the deformation of the tunnel lining, indicating that the improved ground can restrain the deformation of the tunnel lining.

4 INFLUENCE OF WIDTH AND HEIGHT OF THE IMPROVED AREA

The reduced ratios of the settlements of the ground surface and the tunnel for different widths of the improved area are shown in Figure 11. The analytical results indicate that the settlement-preventing effect increases when the width of the improved area

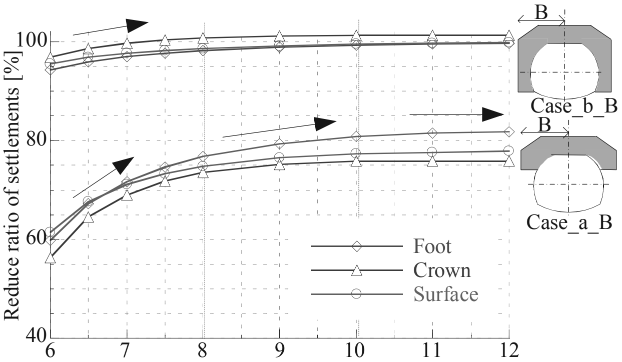


Figure 11. Influence of width of improved ground

becomes larger. For the Case_a_B series, the reduced ratios of the settlements increase rapidly when the widths are smaller than 8 m; they reach a peak of 90% when the widths are larger than 10.5 m. For the Case_b_B series, the reduced ratio of the settlements of the tunnel and the ground are larger than 95% in all of the cases.

A series of numerical analyses, that changed the height of the improved area, was carried out in this research work. Figure 12 shows the reduced ratios of the settlements of the ground surface and the tunnel for different heights of the improved area. The analytical results indicate that the settlement-preventing effect increases when the height of the improved area becomes larger, linearly.

5 CONCLUSIONS

The mechanical behaviors of the ground and tunnels have been discussed in this research work in order to clarify the effect of the pre-ground improvement method. The effect of the pre-ground improvement method and the influence of the width and the height of the improved area are shown in the following.

(1) The ground improvement method can prevent the settlement of the ground and the tunnel, and this effect becomes more effective as the width and the height of the improved area increases.
(2) The influenced area due to the tunnel excavation becomes narrow when improved the ground around all cross section of the tunnel lining.
(3) The height of the improved ground has a more significant influence than the width of the improved ground on the effect of the prevention of settlements.

Moreover, from the above analytical results, the advantage of the effect of the pre-ground improvement method is presented as the three matters as shown in Figure 13.

The first one is the effect of strength increase. The strength of the ground increases due to the ground improvement. As a result, the deformation of the ground has been prevented by the pre-ground improvement method. Moreover, the deformation of the tunnel lining can be prevented by the restriction of the improved grounds.

The second one is the effect of shear reinforcement. Large shear strain is generated from the foot of the tunnel and develops to the ground surface, as shown in Figure 13(b), during the tunnel excavation process. When the improved areas are deep enough or wide enough to cover the large shear strain area, the development of the shear strain will be intercepted by the improved ground. As a result, the settlement of the ground can be prevented. For the cases in which all the cross sections of the tunnel were improved, as in Case_b_B, the effect of shear reinforcement has been obtained, independent of the width of the improved ground. On the other hand, the pre-ground improvement method exerts the effect of shear reinforcement when the width of the improved ground is wider than a certain value, in series Case_a_B.

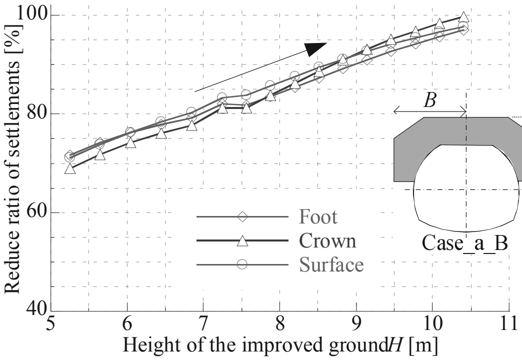


Figure 12. Influence of height of improved ground

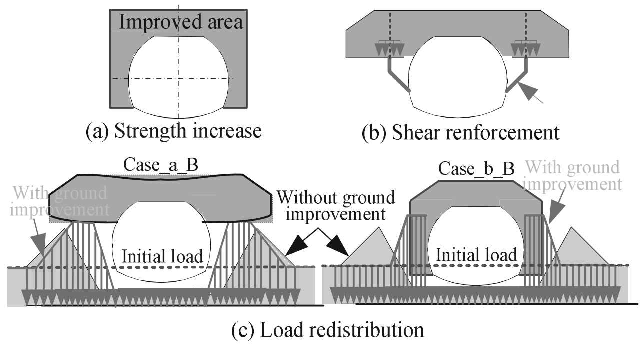


Figure 13. Mechanism of effect of pre-ground improvement method

The third one is the effect of earth pressure redistribution. The vertical earth pressure is concentrated in the lower part of the improved area, and the earth pressure acting on the other area becomes smaller, as shown in Figure 13(c). Moreover, the influenced area becomes smaller when all the cross sections of the tunnel are improved as series Case_b_B, although there is almost no change when only the area around the top section is improved as series Case_a_B.

In addition, these three kinds of effects become even more effective as the width and the height of the improved ground increase.

6 ACKNOWLEDGEMENTS

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