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Effects of Lubricants in Over-cutting Area of Pipe Roof Method on Reducing Surface Settlement

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Abstract

The pipe roof method, one of tunneling technique, has been used over the last few decades to reduce the influence on the surrounding construction. The function of pipe roof method is to minimize ground surface settlement and promote tunnel stability. In this method, several steel pipes are jacked around the main tunnel by using slurry pipe jacking before main tunnel excavation. Ground displacement is an unavoidable problem in the construction of a tunnel and underground spaces near the earth surface. When the steel pipe is jacked, over-cutting area must be formed to be lower the friction between the ground and the pipe, and this void is immediately filled with lubricants. Due to the low stiffness lubricants in the void space, it causes displacement above the steel pipe and leads to the surface settlement. Therefore, stiffness or Young's modulus of lubricants are significant to minimize the effects on the surface settlement. To study the effects of lubricants on reducing the settlement, FLAC3D was used for numerical modeling by introducing different strength of lubricants in the tail-void. The results showed that by increasing Young's modulus of lubricant, the surface displacement is effectively reduced. Additionally, the simulation results are agreed with field measurement data.

Keywords: FLAC3D, Pipe Jacking, Shell Structural Element, Tail-void, Trenchless Technology

1. Introduction

Ground surface displacement caused by tunneling in soft ground is the greatest concern in all aspects of tunnel design. In urban areas, this displacement affects the surface and sub-surface construction. Therefore, it is essential that tunnel operations are done with minimal impact on urban transportation and construction. To avoid this problem, the slurry pipe jacking with pipe roof method is adopted. The purpose of using slurry pipe jacking with pipe roof method is to extend tunneling operation into urban areas in the most demanding conditions, such as working in the presence of groundwater, limitation in the surface settlement. Moreover, during the pushing process of each pipe roof, the natural ground is always excavated about 20-60 mm greater than the diameter of the pushing pipe (Shimada et al., 2015). Each pipe installation induces ground deformation (Ahuja and Sterling, 2008). Hence, a lubricant is injected into the tail-void to prevent the ground from deformation due to stress release caused by the formation of the tail-void in the ground.

The pipe roof method has been used primarily in Japan for the construction of underground rail stations (Satoh et al., 1996). The pipe roof which is installed by pipe jacking (before excavation) creates an advance roof support system. Some large steel or concrete pipes are installed longitudinally, on the top of the tunnel section (Ahuja and Sterling, 2008) as shown in Fig 1. To enhance the strength of the pipe roof, concrete is injected into the hollow pipes. After the pipe roof is all constructed, the main tunnel is excavated. Thus, a mechanism of supporting the overburden load partially by the longitudinal beam action of the pipe roof is developed. It can be seen as ground reinforcement for excavation which supports the overburden and helps to stabilize the face and reduces ground movement (Ahuja and Sterling, 2008).

Each pipe is installed by using slurry pipe-jacking. Fig. 2 shows a slurry pipe-jacking system scheme. Slurry pipe-jacking is one of the trenchless technology for installing the underground pipelines through a bore created by a shield-type drivage machine. Firstly, pushing machine is installed and the drivage machine is set. Next, the drivage machine is pushed into the ground. Then, the pipe is installed and pushed after the drivage machine. The mud slurry and lubricant are injected into the face and the over-cutting area between the steel pipe and the soil during the pushing process. By repeating this process, all pipes are installed and the drivage machine is retrieved from the arriving pit. This system is particularly suited to both cohesive and sandy soil conditions and can be used to construct pipe tunnels up to 2,500 mm in diameter (Shimada et al., 2006).

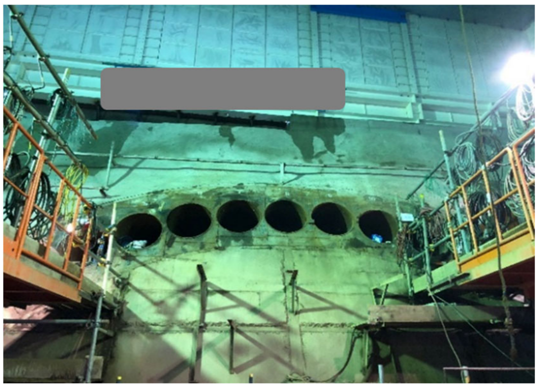


Fig. 1. Pipe roof method.

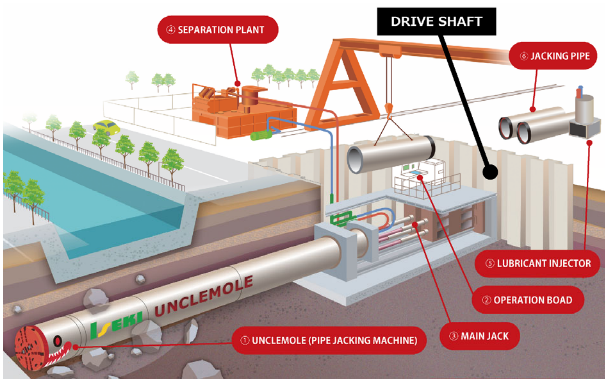
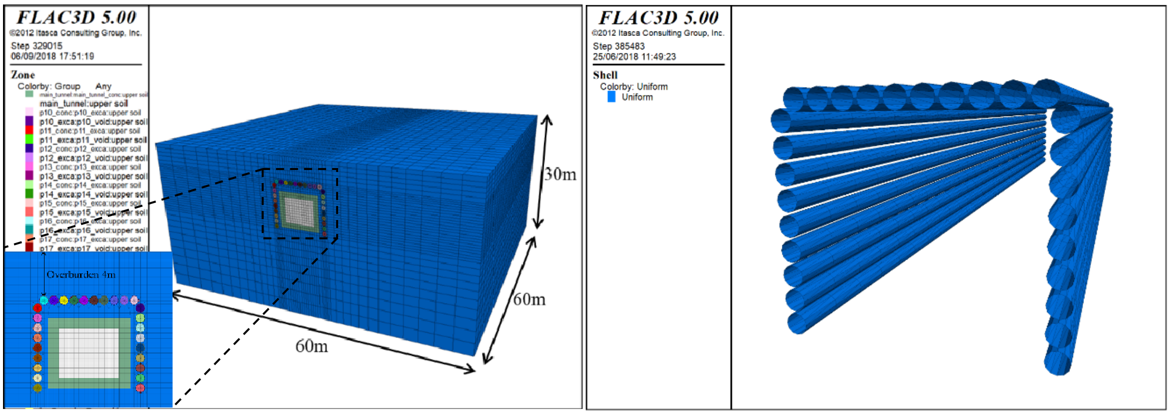


Fig. 2. Slurry pipe-jacking system scheme.

2. Numerical Simulation

To study the effect of lubricants injecting in tail-void by pipe roof method, the model has been developed by using the software FLAC3D. FLAC3D software is one of the most powerful software for analyzing in soil environments and based on the finite different method (Itasca Consulting Group Inc., 2005). The numerical model as shown in Fig. 3 is 60 m in width, 60 m in length, and 30 m in height. Both sides were set to be fixed horizontally, and the bottom of the model was fixed in a vertical direction. The surface of the model was a free boundary in all directions. The model consists of 28 steel pipes which form a gate shape around the main tunnel. The tunnel dimension is 8.4 m in height and 7.4 m in width. The pipe roof was positioned at the depth of 4 m. The diameter of the steel pipe is 0.8 m and the spacing is 0.9 m. The tunnel is constructed in gravelly clay. The Mohr-coulomb constitutive model was used for the soil and their parameters were listed in Table 1. The initial stress state corresponds to gravitational loading. The steel pipes of the pipe roof are modeled with shell structural element as shown in Fig. 4, and its properties were listed in Table 2.

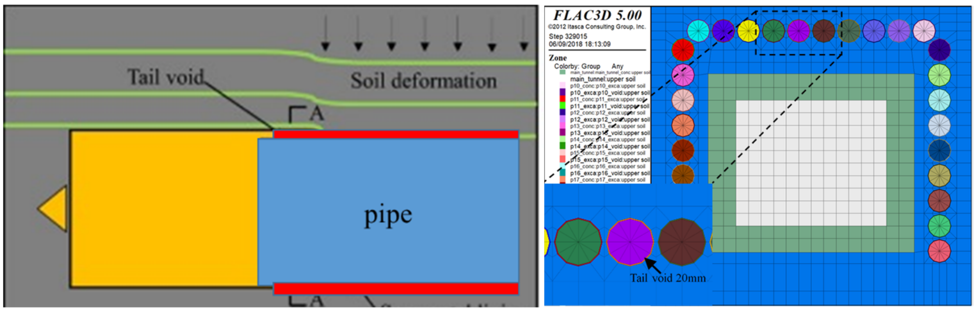


(a) Whole model (b) Steel pipe by using shell structural element

Fig. 3. Numerical model for slurry pipe-jacking system scheme.

Table 1 Mechanical properties of soil and concrete used in analysis.

Type	Young's modulus (MPa)	Poisson's ratio	Friction angle (°)	Cohesion (MPa)	Density (kg/m^3)
Gravelly clay	19.4	0.4	20.7	0.05796	2,000
Concrete	22,000	0.2	-	-	2,400



(a) Concept of tail-void (b) Tail-void 20 mm model

Fig. 4. Numerical model for tail-void.

Table 2 Mechanical properties of steel pipe.

Parameters	Values
Young's modulus (MPa)	210,000
Poisson's ratio	0.25
Thickness (mm)	12

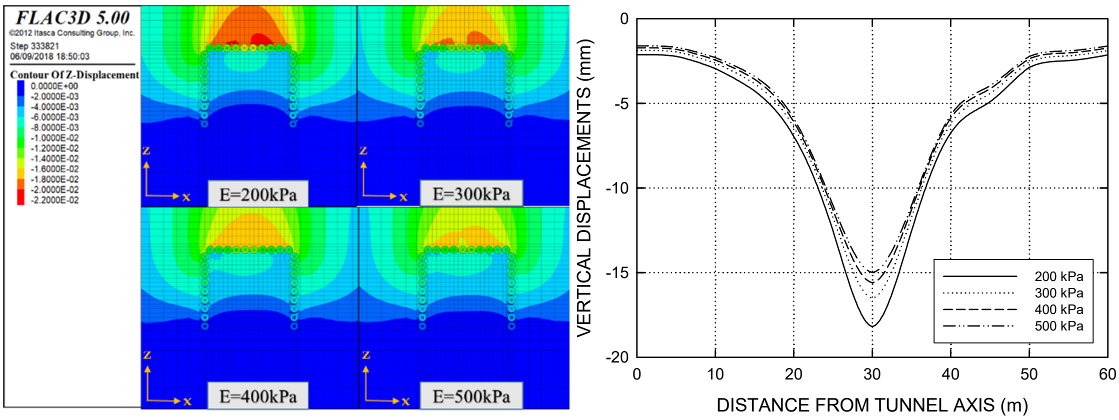
Table 3 Mechanical properties of lubricant.

Parameters	Values
Young's modulus (kPa)	200, 300, 400, 500
Poisson's ratio	0.4
Density (kg/m^3)	2,100

3. Results and Discussions

3.1 Effect of the stiffness of lubricant on the surface settlement

Fig. 5 (a), (b) shows the vertical displacement under different stiffness of the lubricant injected in tail-void. The results were obtained after 28 steel pipes were completely installed. It can be seen that an increase of the lubricants stiffness induces a decrease of the surface and sub-surface settlement just above the pipe roof location. The smaller the stiffness of lubricants is, the larger the subsidence will occur.



(a) Contour of vertical displacement (b) Graph of vertical displacement

Fig. 5. Vertical displacement distribution curve of pipe roof.

From Fig. 5 (b), it showed that the lower lubricant stiffness causes higher surface settlement. The maximum value developed directly at the center of the pipe roof's location. The maximum vertical displacement of 200 kPa lubricant is approximately 18 mm. The vertical displacement generated by using different strength of lubricants also showed the difference of approximately 3 mm by increasing the stiffness from 200 kPa to 500 kPa corresponding to 16% reduction of the displacement. The analysis also illustrates that by increasing the stiffness of lubricant from 200 kPa to 300 kPa, the maximum displacement decreases to around 16 mm which is 9% reduction. However, once the stiffness was increased from 300 kPa to 400 kPa, it reduced 5%. In the case of increasing from 400 kPa to 500 kPa, it reduced only 4 %. Therefore, it indicated that the lubricant has only little effect when we keep increasing the stiffness of lubricants. This result suggests that lubricant which is used in pipe roof method has sufficient effect for the deformation control.

3.2 Field study confirmation

This construction newly established a box culvert next to the existing box culvert on the riverside intersecting the national highway in Naha City, Okinawa Prefecture. The pipe roof construction method using the pipe jacking was adopted at that time. Due to the lack of drainage capacity of the existing box culvert during the typhoon and heavy rain, a large amount of water overflows from the river. Thus, flooding occurs frequently. In order to mitigate this problem, it is necessary to construct new box culverts adjacent to existing box culvert crossing the national highway. However, since the national highway in this area is the main road, construction by an open-cut method is impossible. Therefore, the box culvert was set up after the pipe roof jacking construction. Fig. 6 illustrates the arrangement of the pipe roof and box culvert. L-shaped pipe roof was constructed before setting up the new box culvert. Fig. 7 shows the 3D numerical model for the case. Table 4 and Fig. 8 describes the mechanical properties of void-keeper which is a lubricant to be used in this construction and filled in the over-cutting area with elapsed time.

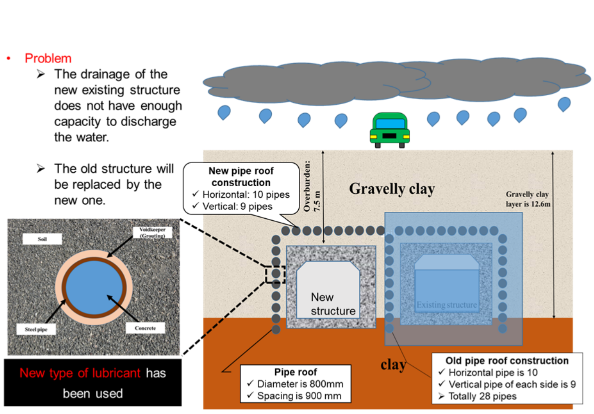


Fig. 6. Overview of study area.

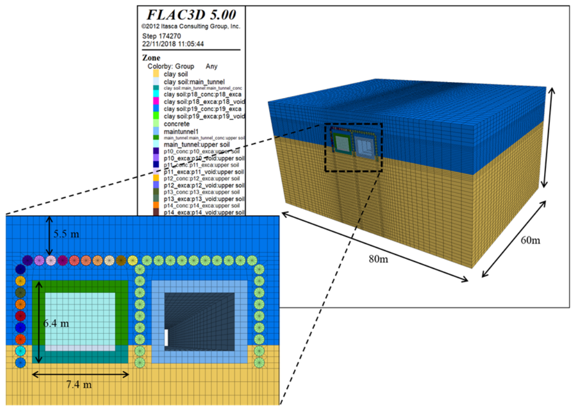


Fig. 7. 3D numerical model for the case.

Table 4 Mechanical properties of lubricant

(so called void-keeper) of elapsed time.

Lubricants	Young's modulus (MPa)	Poisson's ratio	Density (kg/m^3)
After injection	0.1	0.43	2,100
7 days	0.23	0.4	2,100
14 days	0.32	0.4	2,100
21 days	0.37	0.4	2,100
28 days	0.40	0.4	2,100

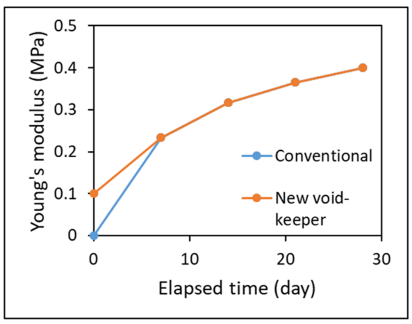


Fig. 8. Young's modulus with elapsed time.

To validate the results, the surface settlement obtained by the numerical simulation is compared with the field measurement data. Fig. 9 shows a comparison between numerical simulation and field measurement data of vertical displacement of cross-section and Fig. 10 illustrates a comparison between numerical simulation and field measurement data of vertical displacement of the longitudinal section. These two results were obtained after the completion of the pipe roof. It can be seen that the ground behavior of pipe roof construction was well simulated. The simulated results are in good agreement with the field measurement data. Fig. 11 shows the maximum surface subsidence (S_{max}) of each pipe after completion.

As can be seen from Fig. 11, the results of numerical simulation adopting new lubricant material are in good conformity with the field measurement data. Traditional lubricant injected into the over-cutting area yields higher maximum surface settlements than the new lubricant materials. This means that the new type of lubricant material provides a great effect on minimizing surface subsidence. The rapid increase in hardness and strength of void-keeper causes reduction of ground deformation.

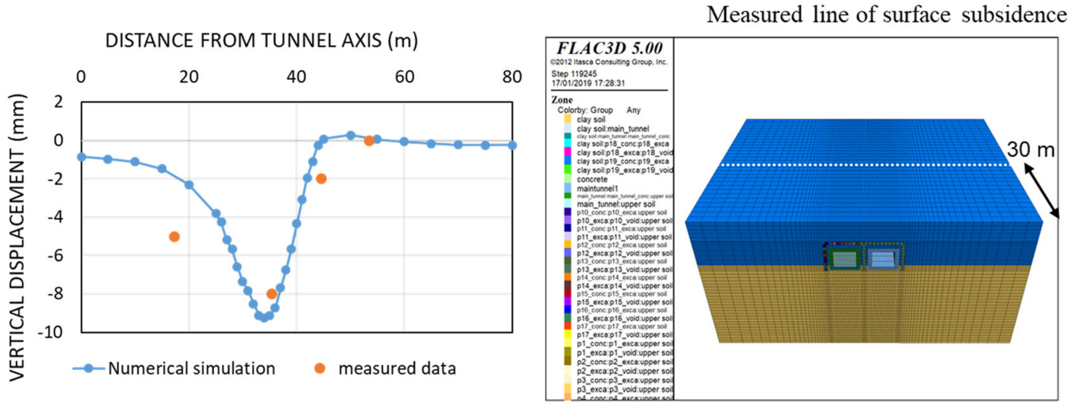


Fig. 9. Numerical simulation vs measured vertical displacements of ground surface in the cross section.

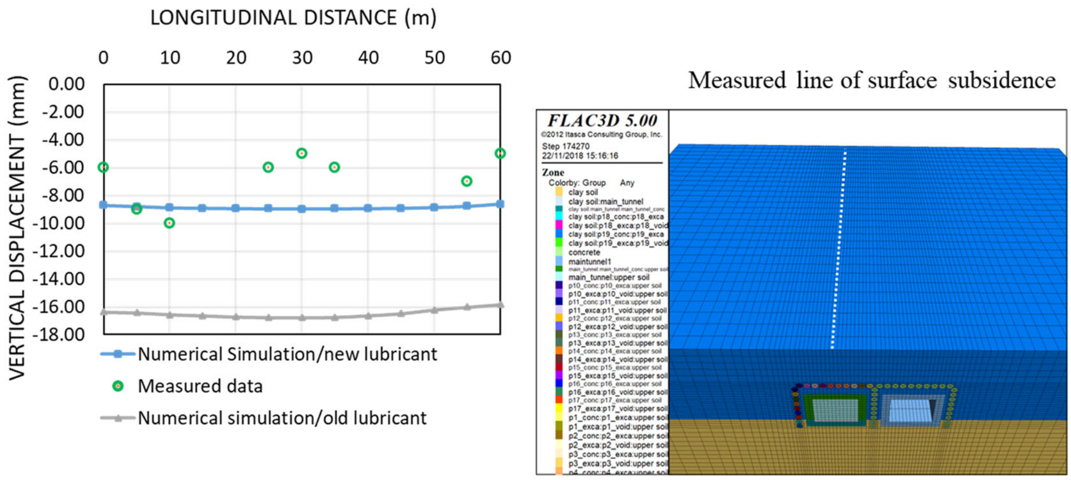


Fig. 10. Numerical simulation vs measured vertical displacements of ground surface in the longitudinal section.

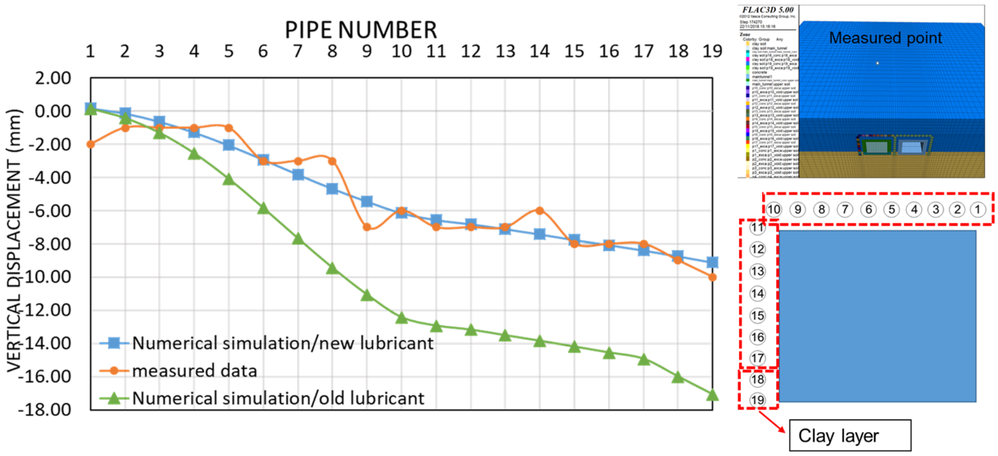


Fig. 11. The maximum vertical displacement of each pipe.

4. Conclusions

This paper presents the effect of Young's modulus of lubricants on the surface settlement for the pipe roof method by using three dimensional finite difference methods (FLAC3D). The simulated results revealed that an increase in the stiffness of lubricant in the over-cutting area of each steel pipe was very effective to minimize the surface displacement. Therefore, it is necessary to minimize the thickness of tail-void and to increase the stiffness of lubricant. Next simulation results are compared with field measurement data for verification. The results show that the surface settlement at field construction effectively reduced by adopting the new lubricant material.

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