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Prevention of the ground subsidence by using the foot reinforcement side pile during the shallow overburden tunnel excavation in unconsolidated ground

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ABSTRACT

Large settlements of the ground surface, crown and foot of a tunnel have been measured at a construction field that an NATM tunnel has been excavated under shallow overburden and unconsolidated ground conditions. For these settlements, it was assumed that if the settlement at the foot of the tunnel had been prevented, the ground subsidence can be controlled effectively. Based on this idea, Foot Reinforcement Side Pile (FRSP) has been utilized to prevent the ground settlement. It was reported that the FRSP could effectively prevent the settlements of ground surface and tunnel during the construction period. However, the mechanism of how the FRSP prevents the settlements of tunnel and surrounding ground has not been clearly understood. In practice, several parameters of the FRSP, such as the length, the spacing and the diameter of the pile, have been determined through the practical construction works.

In this paper, three dimensional trapdoor model experiments and the corresponding numerical analyses, and numerical analyses for the actual tunnel excavation are carried out to examine the effect of FRSP on preventing settlements of ground surface and crown and foot of tunnel, and to discuss its mechanism. As a result, it was observed that the FRSP can prevent settlements of the ground surface and tunnel effectively, and these effects of the FRSP are connected with the distance from the tunnel lining to the slip line. When the FRSP is long enough to cross the shear line, it can exert the effect of the shear reinforcement, load redistribution and internal pressure to prevent the settlements of the tunnel and surrounding ground effectively.

1. Introduction

Up to now, cut and cover method has been widely used as the main tunneling method for excavating a shallow overburden tunnel in soft ground. Recently, due to the development of the construction and measurement techniques, the construction of the shallow overburden tunnel in soft ground using New Austrian Tunneling Method (NATM) have been increasing (Yokoyama et al., 1987; Kitagawa et al., 2004; Irshad and Heflin, 1988; Akutagawa et al., 2006; Pinto et al., 2013). However, since the unconsolidated ground has the low stiffness and the ground arch action is not effective enough due to the shallow overburden, large ground subsidence frequently occurs in the construction field (Fukushima et al., 1989; Adachi et al., 1986). For example, due to the topography and route conditions, a shallow overburden tunnel on unconsolidated ground using NATM was excavated during the construction of a new bullet train line in Japan and various auxiliary tunneling methods were applied in order to ensure the safety of the construction (Miwa and Ogasawara, 2005). In this construction field, the large settlements of the ground surface, crown and foot of the tunnel have been measured as shown in Fig. 1(a) (Kitagawa et al., 2009), and these settlements show almost the same value. This phenomenon was called an accompanied settlement, and the prevention of ground, crown and face of tunnel has become an important issue.

For the phenomenon of the accompanied settlement, it was assumed that the ground subsidence can be effectively prevented, if the settlement at the foot of tunnel had been prevented. Based on this idea, Foot Reinforcement Side Piles (FRSP) had been utilized in the construction site as shown in Fig. 2. The FRSP is one of the foot reinforcement methods, which is performed by inserting a steel

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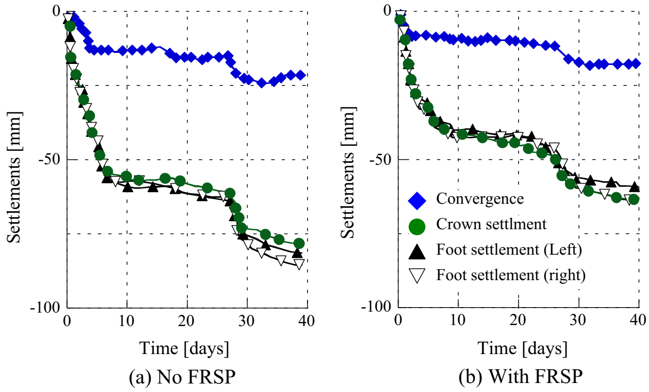

Fig. 1. Temporal change in the settlements of the tunnel and the convergence (Ushikagi Tunnel).

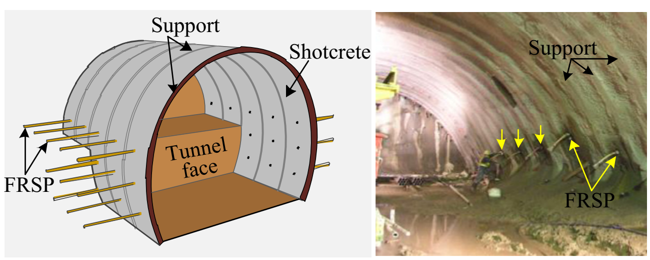

Fig. 2. Foot reinforcement side pile.

pile into the ground from the inside of the tunnel, and it was reported that the FRSP can effectively prevent the settlement in the shallow overburden and unconsolidated construction conditions. The temporal changes in the settlements of the abovementioned tunnel and the convergence, which were measured in the mentioned field are shown in Fig. 1. The settlements measured in the field without FRSP and with FRSP installed are shown in Fig. 1(a) and (b) respectively (Kitagawa et al., 2009). The comparison of these figures indicates that the settlements of both crown and foot of the tunnel became smaller by installing the FRSP. However, even though the effects of the FRSP have been reported in the field, the mechanism of how the FRSP preventing the settlements is still not clearly understood. In practice, several parameters of the FRSP, such as the length, the spacing, the diameter and the position of the pile, has been determined through the practical construction works. Therefore, there is a need for the clarification of the applying method of the FRSP.

On the other hand, several auxiliary methods have been developed with the increasing of the construction fields of tunnels under shallow overburden and unconsolidated conditions, and many researches have been carried out for the shallow tunnels and auxiliary methods. A variety of model experiments and numerical analyses were performed to investigate the mechanical behavior of shallow tunnels, which were excavated under unconsolidated ground conditions. Shimada (1980) carried out a series of model experiments to investigate the mechanism of the surface settlement during shallow tunnel excavation. Moreover, Finite Element (FE) simulations have been performed by Akutagawa et al. (2006) to predict the ground movement caused by tunneling of a shallow NATM tunnel in unconsolidated soil. On the other hand, some auxiliary methods, such as forepoling (Fukushima et al., 1989), umbrella arch method (Ocak, 2008; Yoo and Shin, 2003), footing reinforcement bolt and pile (Fang et al., 2012) and pipe roof (Okawa et al., 1985; Fang et al., 2012) are widely used when excavating a shallow tunnel under unconsolidated constructions, and the effect of these methods have been described in the literature.

For the effect of the FRSP, Kitagawa et al. (2009, 2010) carried out a series of model experiments (Kitagawa et al., 2009) and corresponding rigid-plastic FE analysis (Kitagawa et al., 2010) to concerning the effects of the FRSP on preventing surface settlement. The experimental and numerical results showed that, the FRSP were effective on preventing ground settlement when they were long enough to intersect with the slip line, and the effects increased with the FRSP became longer. Moreover, the FRSP became more effective, when (i) it was fixed to the tunnel tightly, (ii) the ground had large internal friction angle, and (iii) it was installed at the lower part of the tunnel. In this research, the footing of the tunnel was modeled as a T shaped model and the lining model are rotating with the descending of the trapdoor. However, the T shaped section is different with the shape of the real tunnel footing; furthermore, the rotation of the tunnel footing has not been measured in the field. Therefore, it is thought that the T shaped footing model cannot represent the mechanical behavior of the real tunnel lining appropriately. On the other hand, the rigid plastic finite method can only be used to discuss the limit state of the soil, and it cannot consider the mechanical behavior of the ground and the FRSP during the tunnel excavation process. Moreover, the influence of the parameters such as the length of the FRSP, and the mechanism of the FRSP's effect were not discussed in detail.

Hence, in this study, three dimensional trapdoor experiments, corresponding numerical analyses and the numerical analyses for actual tunnel work are performed in order to discuss the mechanism of the effect of the FRSP. First of all, the model of the tunnel footing is improved based on the abovementioned literature (Kitagawa et al., 2009), and a series of three dimensional trapdoor model experiments and corresponding elasto-plasticity FE analyses are carried out to define the effect of the FRSP more clearly. Moreover, the tunnel excavation processes in the real field are simulated by using the elasto-plasticity FE method, to investigate the mechanical behavior of the ground and the FRSP during the tunnel excavation process for clearly defining the mechanism of the effect of the FRSP.

2. Layout of model experiments and analyses

2.1. Three-dimensional trapdoor model experiments

In order to consider the effect of the FRSP for the phenomenon of accompanied settlement and the influence of the length of FRSP, a series of model experiments were carried out with different length of the FRSP. Fig. 3 shows the schematic diagram of the experiment apparatus used in the model experiments, namely three dimensional (3D) trapdoor apparatus. The tunnel excavation process was simulated with lowering a supporting plate, which is called a trapdoor. The trapdoor experiment apparatus are adopted to investigate the mechanism of tunnel excavation problems by many researchers in the past (e.g. Murayama and Matsuoka, 1971; Nakai et al., 1997; Adachi et al., 2003).

The displacement of the trapdoor and the vertical load acting on the bottom of the chamber have been measured in all of the lowering processes. Displacement of the trapdoor was measured by a contact displacement transducer which installed in the lower part of the trapdoor. The measuring range of this displacement transducer is 25 mm and its sensitivity is 500 μ strain/mm. Moreover, Three pieces of load measurement plates (Trapdoor, Panel A and Panel B) were installed at the bottom of the chamber to measure the load that was acting on these plates. The measuring range of