Tunnelling and Underground Space Technology 42 (2014) 216–226

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Pre-nailing support for shallow soft-ground tunneling

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ARTICLE INFO

Article history:
Received 12 September 2013
Received in revised form 27 January 2014
Accepted 10 March 2014
Available online 1 April 2014

Keywords:
Shallow tunnel
Soft-ground tunnel
Nail
Pre-support
Reinforcement

ABSTRACT

In tunneling, supports are usually installed after excavation. Thus, the risk of tunnel collapse is highest immediately after excavation at the tunnel face. This is one of the main problems faced when constructing shallow tunnels in soft ground. In this paper, a pre-support tunneling method using a pre-nailing technique is proposed to improve face stability and reduce tunnel deformation. By driving nails into the ground before excavation, it is possible to achieve mechanical advantages such as restricting the deformation of the ground and preserving the arching of the ground. A theoretical governing equation for the pre-installed nails was formulated, and the mechanism whereby the deformation is reduced was investigated. The mechanical advantages of the method were validated in terms of the ground reaction behavior by carrying out small-scale model tests. A parametric study of the main design factors showed that the distance between the nails is the most important factor. Finally, a case study whereby the method was applied in the field was conducted; the pre-nailing technique was found to be particularly useful for reducing surface settlement and is appropriate for shallow, soft-ground tunneling.

1. Introduction

When a soft ground tunnel with a thin soil cover is excavated, special efforts are required to reduce the degree of tunnel deformation and to ensure stability. In the case of urban tunnels particularly, ensuring safety and controlling settlement are the most important engineering problems (Peck, 1969). To overcome these problems, not only the ground reinforcement must be provided before the tunnel is excavated but longitudinal tunnel reinforcements such as multi-step steel pipe grouting must also be installed (Aksoy and Onargan, 2010; Juneja et al., 2010; Kamata and Mashimo, 2003). However, sometimes the structural advantages provided by these reinforcements cannot be attained because their support functions and installation time are limited.

Because tunnel supports can be installed only after considerable deformation has occurred, it is not possible to use these supports as a means of preventing deformation before or immediately after the excavation. Furthermore, additional ground disruption caused by the installation of supports is unavoidable. Therefore, there are limitations to controlling the deformation of the ground with supports inside the tunnel. As shown in Fig. 1, the greatest risk of collapse is at the face.

If supports could be installed prior to the excavation of the tunnel, the risk of collapse can be significantly reduced, as indicated by the dotted line in Fig. 1. Korbin and Brekke (1976), through model testing, reported that pre-reinforcement of the ground not only limits the deformation of the tunnel and increases the length of time that it can support itself, but also increases the level of safety.

Bolts and nails are important reinforcing and/or supporting elements in tunneling (Ng and Lee, 2002; Oreste and Dias, 2012; Osgoui and Oreste, 2007). In this study, we investigated the pre-nailing technique, whereby nails that provide ground reinforcement and support are installed before the tunnel is excavated. In particular, we examined the technique from the viewpoints of mechanical principle, design factors, and field applicability. As shown in Fig. 2, pre-nailing refers to the insertion of steel bars or pipes by drilling from the ground surface to the peripheral-tunnel boundary before the start of excavation. By using pressure grouting to install nails, ground reinforcement and pre-support can be provided during excavation. Finally, the nails are connected to lattice girders and/or steel supports, which are installed immediately after the excavation; this allows the nails to act as part of a combined tunnel support system. Therefore, the nails function both as ground reinforcement and as support, similar to the rock bolts installed inside the tunnel. Because nailing is possible on the ground surface and can be performed before the tunnel is

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http://dx.doi.org/10.1016/j.tust.2014.03.010
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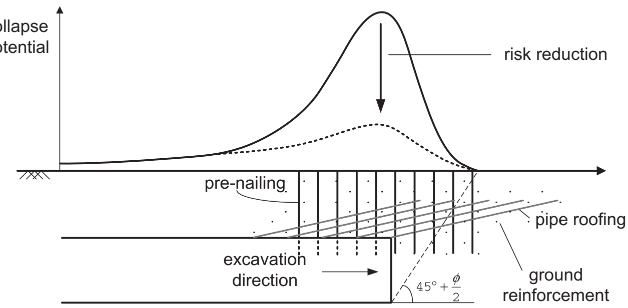

Fig. 1. Potential of collapse at the tunnel face.

excavated, it is referred to as "pre-nailing support." Thus, the development of the pre-nailing technique has been based on the concept of a pre-supported tunnel, which incorporates existing simple reinforcement into the support structure of the tunnel.

In this study, the mechanical principle of the pre-nailing method was investigated theoretically and the design factors were analyzed through model testing and numerical analysis. Finally, the technique's practical applicability was verified through an actual field project.

2. Theoretical background to nail behavior

2.1. Concept of pre-support

The principle of the pre-nailing technique can be understood by referring to the concept of convergence confinement. Fig. 3 shows the ground reaction curves for pre-nailing. Because pre-nailing provides ground reinforcement, the ground reaction curve is considerably lower than that before reinforcement, which results in a reduction in the convergence (Fig. 3(a)). Additionally, because nails are already installed before the excavation, they can share the tunnel bearing pressure even before the excavation by shifting the support characteristic curve to the origin (Fig. 3(b)). Therefore, pre-nailing suppresses the overall displacement $\Delta u_1 + \Delta u_2$, where the ground reinforcement effect reduces displacement Δu_1 and the pre-support function reduces displacement Δu_2. The reduction in convergence suppresses the settlement of the subsurface and surface. However, in practice it would not be easy to separate these effects, because both are achieved by taking advantage of the shear resistance between the nails and the soil.

2.2. Governing equation for nail movement

The principle whereby settlement is reduced through the use of pre-nailing can be examined by studying the behavior of a single nail installed at the center of a tunnel. Fig. 4(a) shows how tunneling affects the movement of the ground into which a nail has been installed. To derive the governing equation for the nail, it is assumed that the ground is homogeneous, isotropic, and elastic, and that there is no slippage between the nail and the ground. The nail is installed prior to the excavation and is in a "0" stress state. As the excavation face approaches the nail, however, the settlement of the ground causes the nail to go into tension.

According to Fleming et al. (1985), the shear stress (τ) at the boundary of the pile (nail) and ground is proportional to the ground displacement (S):

$$\tau \approx \frac{GS}{4r_0} \tag{1}$$

where G, S, and r_0 are the shear modulus of the ground, displacement at the boundary, and radius of the nail, respectively. The load P applied to the nail is transferred to the skin friction of the nail. If the equilibrium condition for an infinitesimal element of the nail is considered as shown in Fig. 4(b), the equilibrium equation is obtained as

$$P = P - dP + 2\pi r_0 \tau dz \tag{2}$$

If Eq. (1) is then added to Eq. (2),

$$\frac{dP}{dz} = \frac{\pi}{2} GS \tag{3}$$

If the elastic modulus of the nail is E^*, the constitutive equation for the nail can be formulated as

$$\varepsilon_a = \frac{dS}{dz} = \frac{1}{E^*}\frac{P}{\pi r_0^2} \tag{4}$$

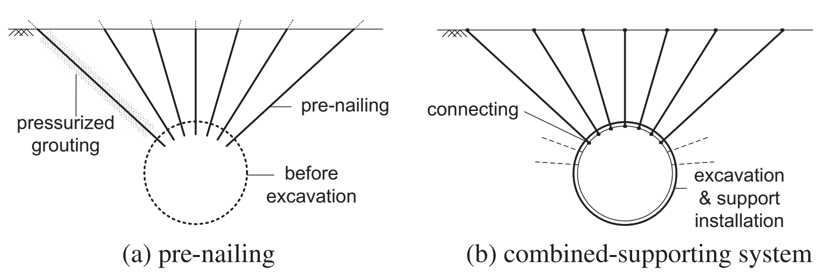

Fig. 2. Construction sequence of pre-nailing method.

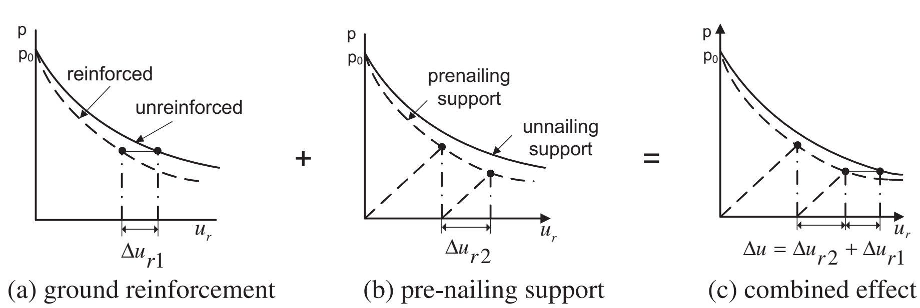

Fig. 3. Principle of pre-nailing support.