Tunnel foot reinforcement using micropiles

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1. Introduction

In the excavation of a large-section tunnel or a tunnel in ground whose bearing capacity or rigidity is insufficient, tunnel supports might settle considerably, causing expansion of a loosened zone along the arch of the tunnel. In the case of a tunnel with a very large cross section or a flat cross section, a tendency like this could pose a serious tunnel stability problem. Long (10 to 12 m) forepiling, such as grout injection forepiling and jet injection forepiling, has been used successfully in recent years. These preliminary supports, however, cause stresses to concentrate in the lower part of the upper half of the tunnel. Particularly for earth tunnels in urban areas, therefore, it is becoming increasingly important to develop methods of foot reinforcement as a means of increasing the bearing capacity of the bottom of the top heading and preventing settlement. Figure 1 compares loads carried by long forepoling and conventional forepoling.

Focusing primarily on micropiles widely used for the foot reinforcement of mountain tunnels, this paper outlines various methods of foot reinforcement during tunnel excavation and reports some recent examples.

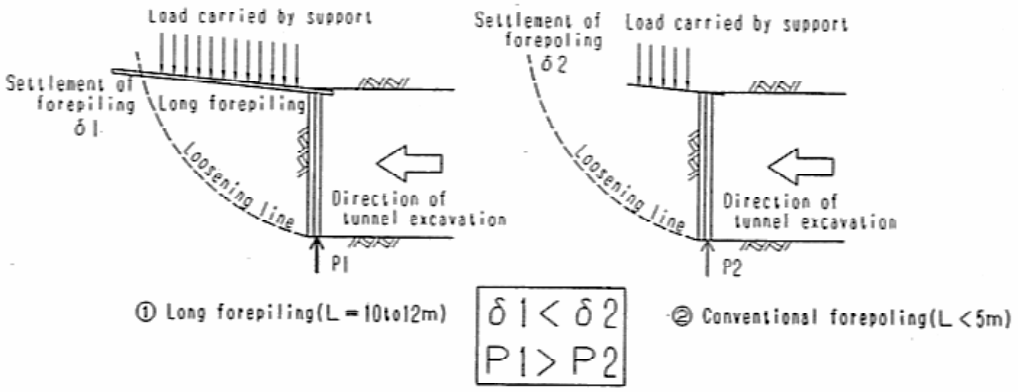


Figure .1 Comparison of loads carried by different types of forepiling

2. Overview of foot reinforcement

(1) Classification of foot reinforcement

Common practice in excavating a tunnel in soft ground is to make the cross section of a heading or drift smaller and advance such a heading or drift by using various auxiliary methods of construction. From the viewpoint of tunnel structure stabilization, however, it is advantageous to complete the lining as soon as possible, particularly in poor ground. In addition, it is rational to improve and reinforce the surrounding ground by various methods so as to excavate the tunnel without changing the tunnel cross section and shorten the time required for excavation.

In cases where control of ground surface settlement, prevention of deformation of adjacent structures or stabilization of the tunnel structure is a goal to be attained, a highly reliable auxiliary method of construction, instead of countermeasures taken only after a problem has arisen or of stopgap measures, needs to be adopted. Therefore, the umbrella arch method combining such techniques as micropiling and jet grouting has been developed and used. Figures 2 and 3 show a classification of foot reinforcement methods. Figure 4 illustrates the concept of the umbrella arch method.

The umbrella arch method is a method of reinforcing the ground ahead of the tunnel face by forming

a soil-cement arch along the tunnel circumference before tunnel excavation. The objectives of the umbrella arch method include the control of prior deformation, prevention of loosening of ground, and the maintenance of safety during construction. The umbrella arch method includes foot reinforcement works aimed at preventing the settlement of the lower part of the upper half of the tunnel and the prevention of sidewall squeezing.

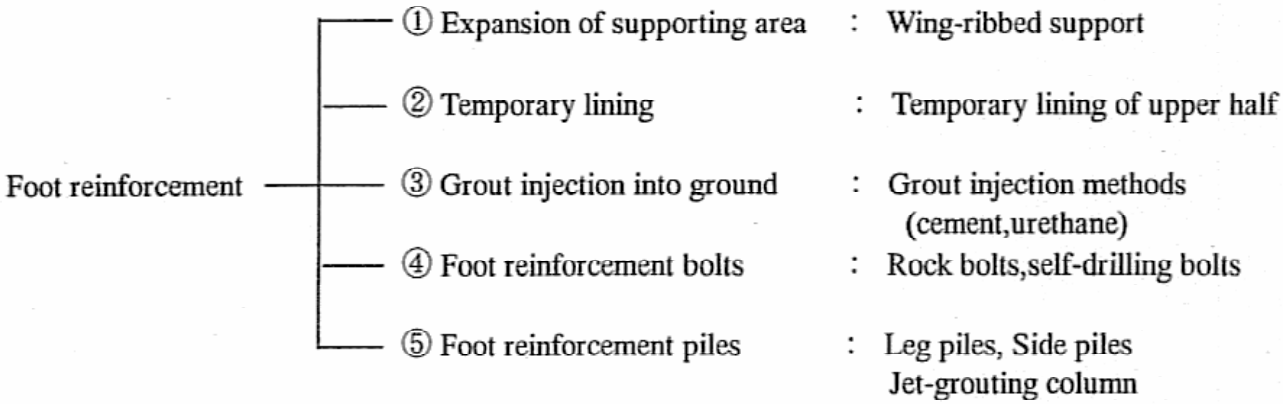


Figure .2 Types of foot reinforcement

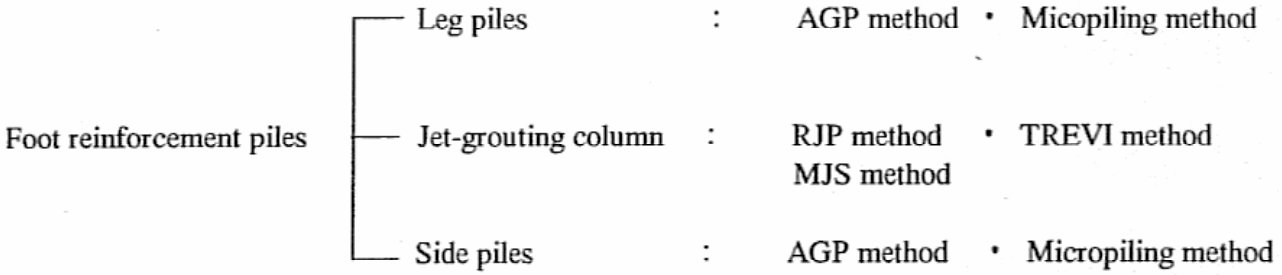
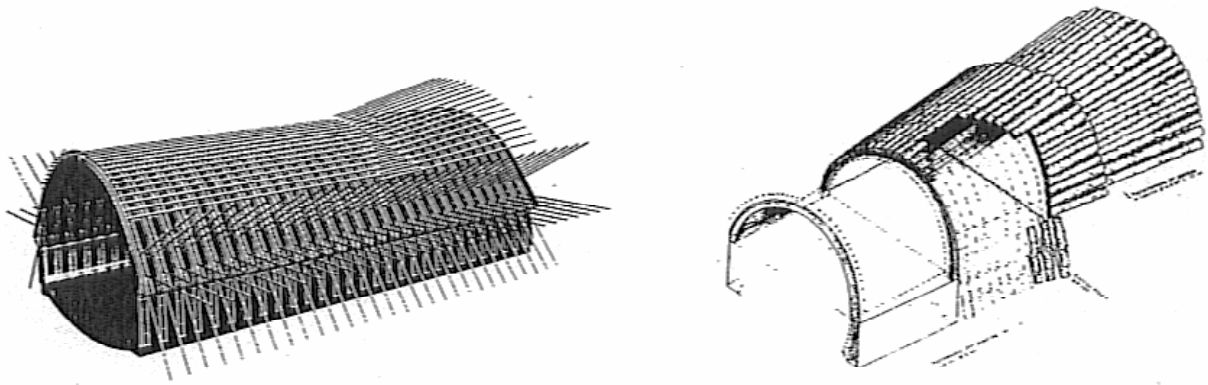


Figure .3 Classification of foot reinforcement piles



1) Micropiling 2) Jet grouting

Figure. 4 Umbrella arch method

(2) Foot reinforcement using micropiles

Micropiles are piles whose tip diameter is about 100 to 300 mm. A micropile is placed by inserting a steel pipe or other reinforcement into a drilled hole and injecting cement slurry or cement mortar into

the hole. As shown in Figure 5, major components of a micropile are a reinforcement (steel pipe) and a soil-cement column. A major characteristic of micropiles is its ability to ensure bonding with the ground by hole wall stabilization measures during drilling and local pressure grouting.

In the field of tunnel excavation, micropiling is in use as an auxiliary construction method for supporting a tunnel structure consisting of shotcrete and steel supports and stabilizing the tunnel face and the surrounding ground in poor ground where rock bolting is not possible.

In the ground composed primarily of accumulations of unconsolidated material deposited by glaciers (called "moraines") in the Alps area in northern Italy, rock bolting is difficult to carry out because there are many boulders. As an alternative to NATM, therefore, the so-called umbrella arch method consisting of tunnel face and ground stabilization measures based mainly on micropiles is used. The umbrella arch method is not thought of as an auxiliary construction method or a special construction method for maintaining the stability of the tunnel face or ground. Instead, it is now regarded as an important independent construction method for ensuring safety and economy of tunnel construction and has proved successful in many projects through the development and improvement of construction equipment. Photo 1 shows an umbrella arch under construction.

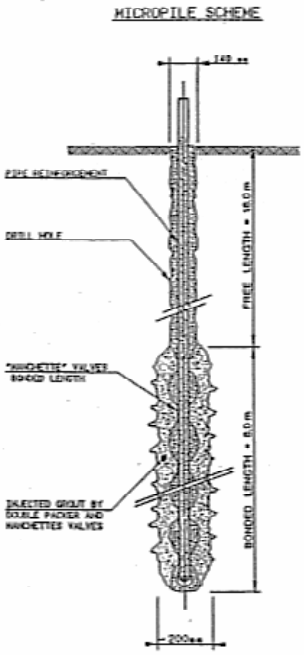


Figure.5 Example of a completed micropile

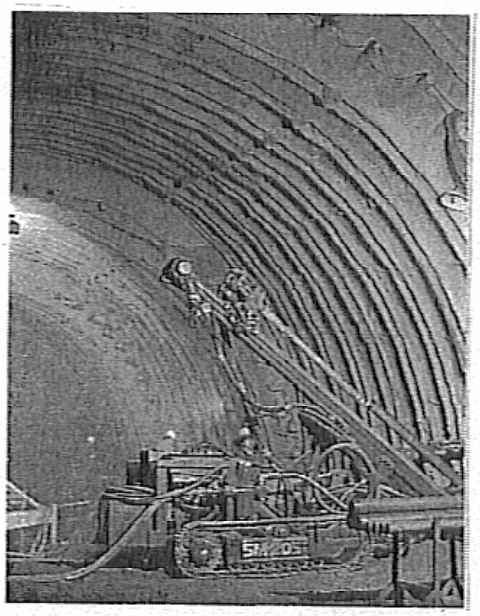


Photo.1 Micropiling operation

Micropiling as a means of foot reinforcement is a construction method involving the placement of steel pipes serving as grout casing in the tunnel foot zone, in order to stabilize the tunnel structure by preventing tunnel foot settlement, increasing the bearing capacity of ground, and reinforcing the support structure. Figure 6 shows the basic concept of a foot reinforcement method using micropiles. The explanation that follows focuses on the improvement of the bearing capacity of the bottom of the top heading.

As shown in Figure 6(a), if typical support construction is used, the vertical component of ground loads acting on the tunnel is carried by the lower part of the support alone. Consequently, stresses concentrate in the zone near the lower part of the support. If the ground has low bearing capacity or low rigidity, local collapse or large deformation of the ground near the lower part of the support will result, causing settlement of the support.

An increase in settlement of the support not only causes encroachment into the internal profile, but also promotes the loosening of the ground zone along the tunnel crown and thereby destabilizes the tunnel face and the ground as a whole. The objective of foot reinforcement is to support loads

concentrating at the lower part of the support, control support settlement, and stabilize the tunnel structure by increasing the strength and bearing capacity of the ground beneath the support or by forming load-bearing piles. In the micropiling method shown in Figure 6(b), micropiles, which are functioning as friction piles, carry the ground loads concentrating at the lower part of the support so as to distribute the loads widely in the surrounding ground. In this particular example, the micropiles placed under the tunnel act as compression members to carry vertical ground loads, and those placed at the sides of the tunnel act as tension members to resist horizontal ground loads.

Figure 7 shows an example of foot reinforcement for an urban tunnel, and Figure 8 shows an example of foot reinforcement for a tunnel built in a hilly or mountainous region.

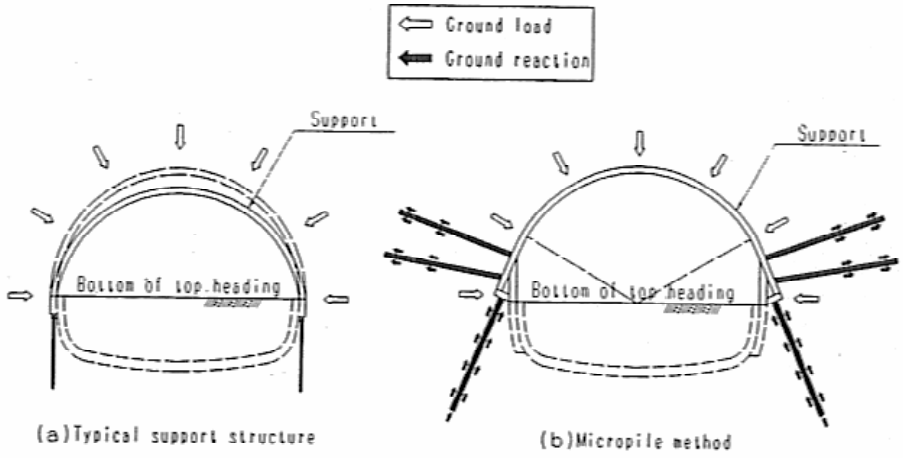
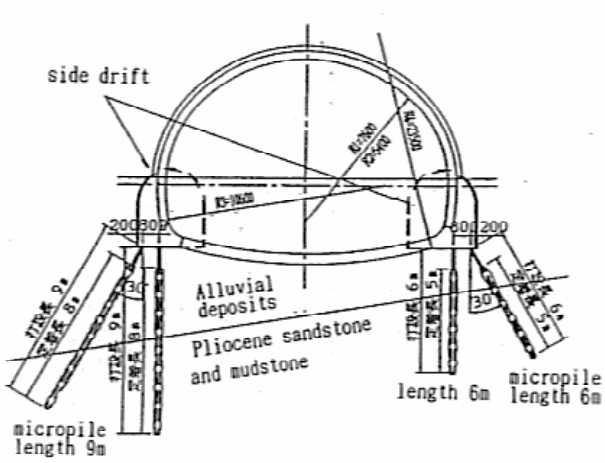
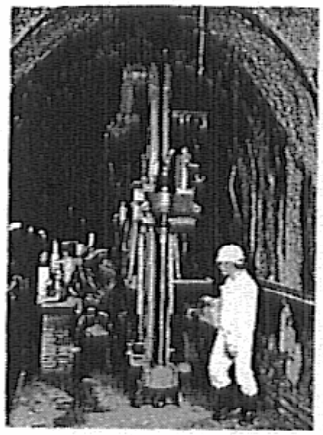
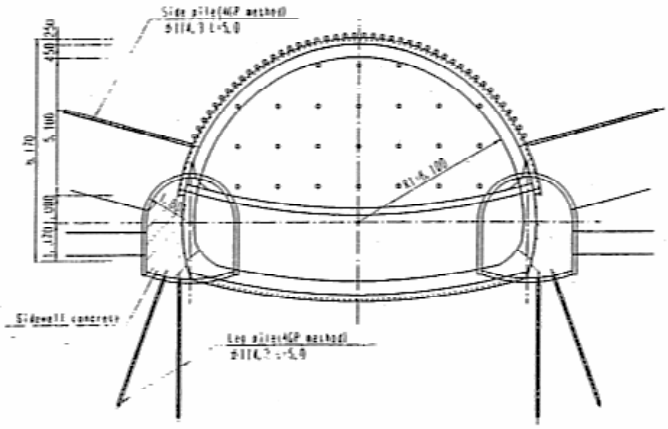


Figure. 6 Foot reinforcement with micropiles







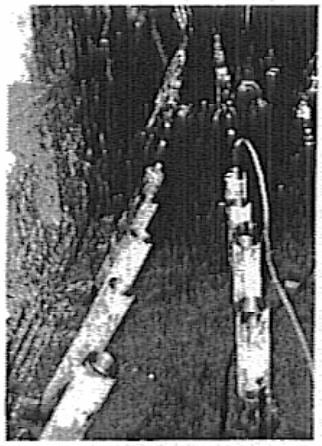


Figure. 7 Example of foot reinforcement for an urban tunnel

3. Design of foot reinforcement

(1) Design parameters

If the bearing capacity or settlement of the lower part of tunnel support during tunnel excavation poses a problem requiring foot reinforcement as a way to ensure construction safety and minimize adverse effects on the surroundings, it is necessary to conduct a design study on foot reinforcement as an auxiliary construction method. Design parameters for foot reinforcement piling are listed in Table 1. These parameters must be determined, after giving careful consideration to factors such as ground conditions, load conditions, constructibility, and economy and by making informed predictions based on data concerning past similar projects or on numerical analysis or conducting test construction, in such a manner that the purpose of the control works is attained and quality requirements satisfied.

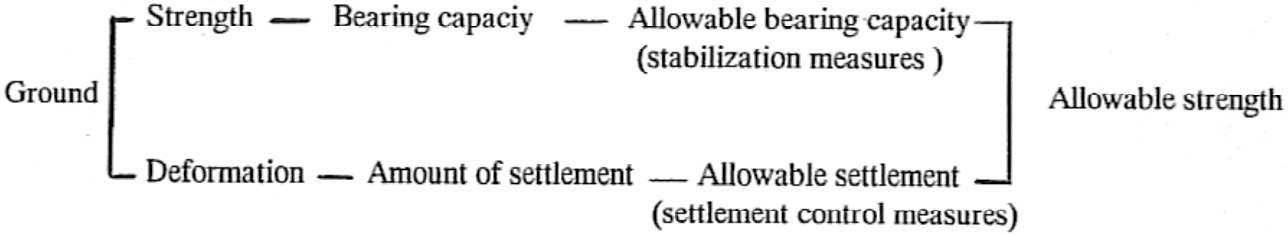
Bearing capacity requirements for micropiles acting as friction piles vary depending on the ground conditions and the methods of drilling and grouting used. Common practice is to adopt a method of ultimate bearing capacity calculation based on past project data or full-scale model test results. In the design of micropile-based tunnel foot reinforcement, usually the grouted-micropile design method based on data on the results of past projects and test construction carried out in Europe (mainly Italy) is adopted. This method is applied to micropiles placed by pressurized injection consisting solely of primary grouting or by staged-pressurization injection using steel pipes equipped with non-return valves.

Table .1 Design parameters

Construction method	Grouting details	Pile detais
Micropile & AGP	・Selection of grout ・Grout volume (grouting ratio) ・Grouting method Step／casing ・Grouting pressure	・Dreill hole diameter ・Steel pipe (diameter,wall thickness,length,material) ・Piling pattern (spacing,number of piles) ・Pile angle ・Pile head treatment
High-pressure jet-grouting pile	・Diameter of soil-cement column (jet pressure,discharge rate,extraction speed) ・Strength of soil-cement column (type of hardener,hard ener content) ・Pile length,Piling pattern (spacing,number of piles),pile angle	

(2) Design considerations

In designing a tunnel foundation, it is necessary to take into consideration both the strength and deformation of ground. The ability of ground to carry loads viewed from the standpoint of strength, which is called "bearing capacity," and the ability viewed from the standpoint of deformation, or settlement, as well as strength, which is called "strength," need to be distinguished. Just as there is such a thing as "allowable bearing capacity," which takes into account a factor of safety in addition to bearing capacity, there is "allowable strength," which is based on an allowable amount of settlement. The relationships among these are shown below.



Study for the determination of foot reinforcement as a means of increasing the bearing capacity of the bottom of the top heading or of preventing settlement requires estimation of the magnitude of loads acting on the lower part of the tunnel support, the bearing capacity of ground, the amount of settlement, and the like. Since the type of load acting on the lower part of the support varies depending on such factors as the ground conditions, the shape of tunnel cross section, and the tunnel excavation method, it is extremely difficult to make accurate predictions. Therefore, there is as yet no established optimal design method, and there are many cases where an empirical design method based mainly on data on past construction carried out under similar conditions is adopted. In cases where the validity of design and construction methods is evaluated according to field measurement results, it is necessary to measure not only crown settlement and the interior profile but also settlement of the lower part of the upper half of the tunnel and stresses in support members. For environmental measures, such as measures to control ground surface settlement at a tunnel site with shallow overburden or measures to prevent adverse effects on adjacent structures, field measurement control paying attention to the relationships among surface settlement, crown settlement, and settlement of the bottom of the top heading is important. Figure 8 shows the concept of the design of foot reinforcement.

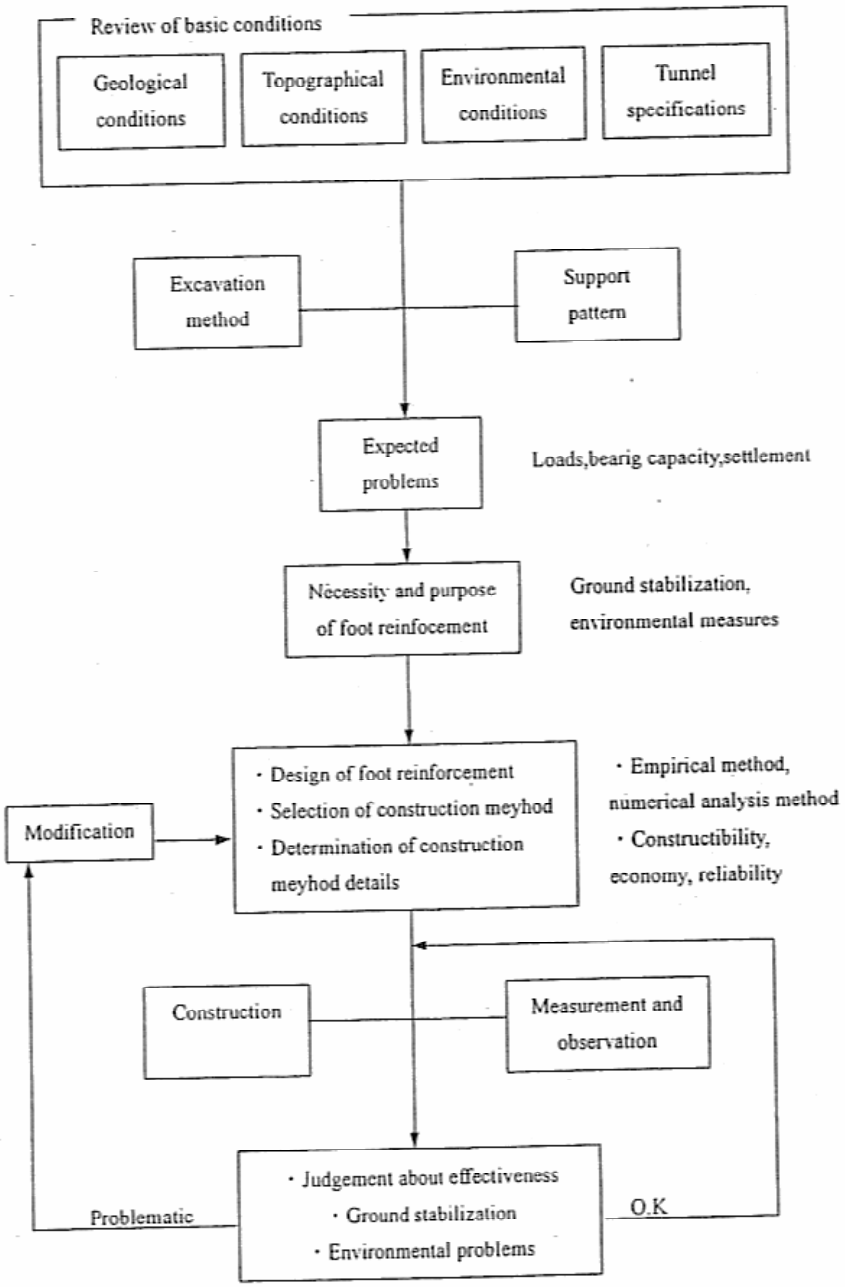


Figure. 8 Concept of foot reinforcement design

4. Micropiling

(1) Drilling

To execute micropiling, it is necessary to select appropriate methods of drilling and steel pipe insertion suitable for the ground conditions and the working environment. Figure 9 shows a classification of drilling methods.Drilling methods are usually classed either as rotary percussion or rotary. Depending on how they are combined with different kinds of drive systems, these drilling methods are classified into the down-the-hole hammer method, the top hammer method, the rotary method, and the double rotary method. Drilling muck is removed by using a drilling fluid (e.g., water, slurry), foam, air, auger, etc.

For drilling from inside a tunnel, a method of slurry treatment needs to be determined according to the amount of the drilling fluid used. It is also necessary to take into consideration such factors as reduction in the drilling speed due to an escape of drilling fluid, as well as pile angle, piling procedure, and construction cycles.

In the micropiling method for foot reinforcement, an air or auger method is used as a standard drilling and mucking method, mainly in order to prevent ground deterioration due to the drilling fluid. Other drilling and mucking methods, such as cement slurry or other grouting materials and drilling and mug methods which use foam, have been developed in recent years.

Double-pipe drilling methods which use a combination of a hole-enlarging bit and a down-the-hole hammer or a top hammer is now in wide use. The down-the-hole hammer method is a rotary percussion type drilling method. In this method, a hammer installed directly over the drill bit at the hole bottom is driven by compressed air supplied through the drill rod, and the reciprocating hammer piston hit the drill bit directly.

This method makes large-diameter deep drilling possible, and even difficult-to-drill ground, such as boulder strata and gravel strata, can be drilled efficiently. Photo 3 shows a drilling tool. Figure 10 shows the procedure for down-the-hole hammer drilling.

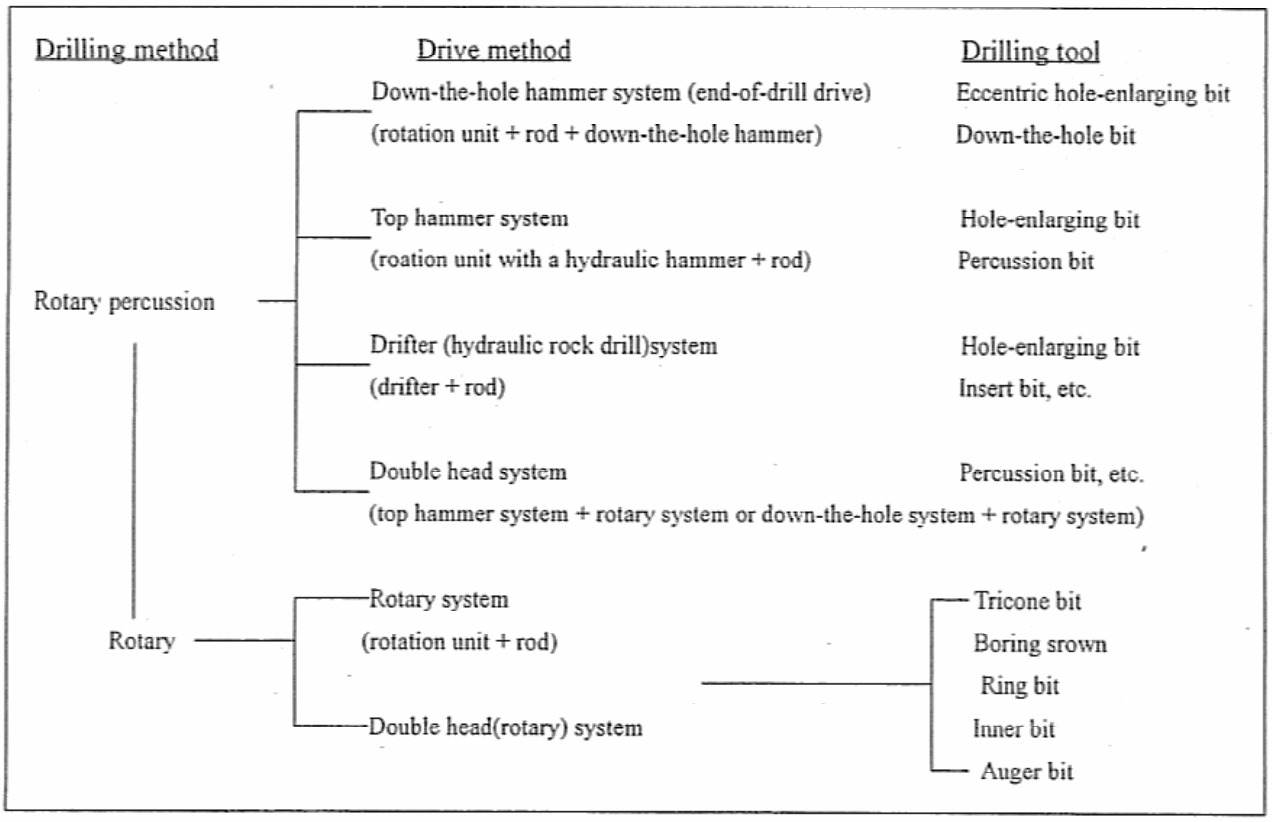


Figure. 9 Classificasion of drilling methods

Stage 1

Drilling(using double pipe used)

Stage 2

Etraction of drill rod

Stage 3 Primary grouting

Grouting of gorund zone around reinforcement pipe
Grouting pressure: 0 to 10kgf/cm²
(using double packer)

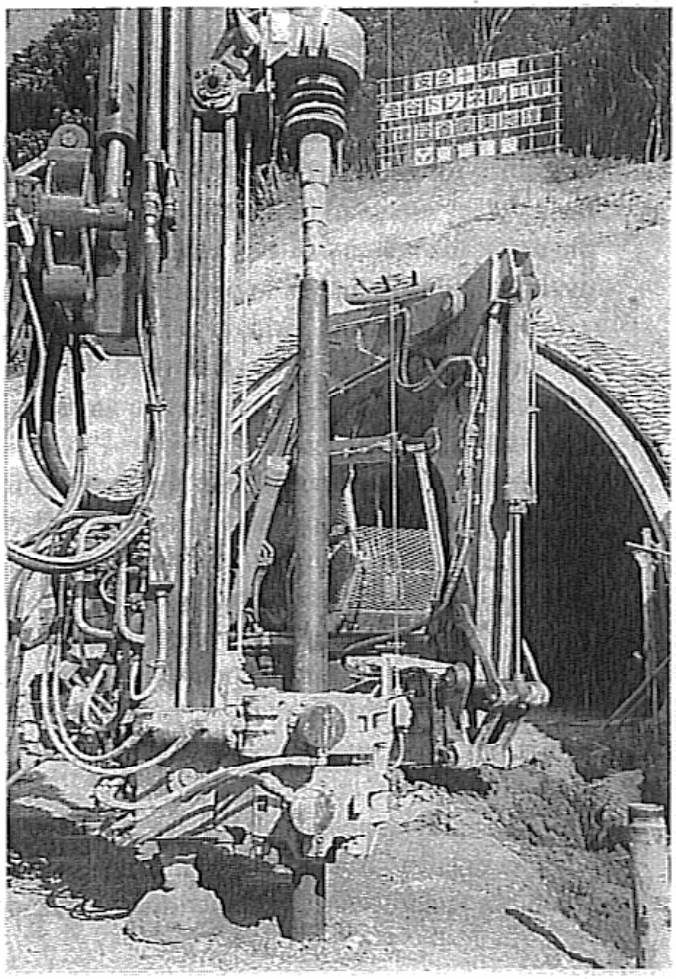
Stage 4 Secondary grouting

Grouting of anchor zone
Grouting pressure: 20 to 30kgf/cm²
(using double packer)

Stage 5

Filling reinforcement pipw with grout

Pile head treatment



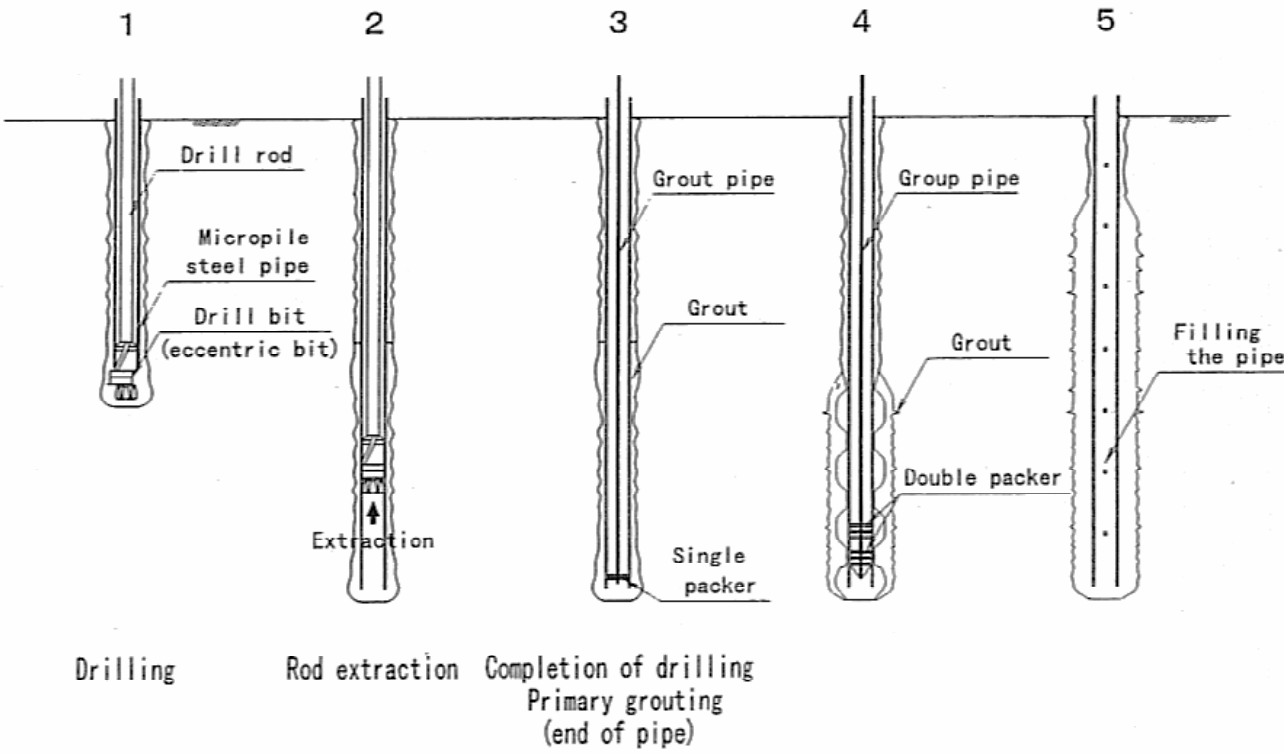


Figure. 10 Procedure for micropiling using the down-the-hole hammer method

(2) Grout injection

For grouting, appropriate grout injection methods and grouting materials (cement slurry, mortar) need to be selected according to the ground conditions. In foot reinforcement using micropiles, usually local pressure grouting (post-grouting) with packers is adopted. To make effective pressure grouting, non-return valves to prevent the backflow of the grout are installed in the bond zone at 30 to 100 cm intervals. Photo 2 shows some of the steel pipes used. Photo 3 shows examples of grout packers.

Primary grouting is performed mainly for the purpose of filling out the gap between the hole wall and the steel pipe surface and large cracks in the ground. In secondary grouting, a grout is injected under pressure by the step-up method using a double-packer system immediately after the primary grout has begun to harden (usually 2 or 3 hours after completion of primary grouting). The pressure used in the secondary grouting is usually around 2 MPa and not greater than 5 MPa.

The grouting material used is a cement slurry with a water/cement ratio (W/C) of 40 to 50%. Cement mortar may be used in cases where the groundwater level is high or the ground is cracky.

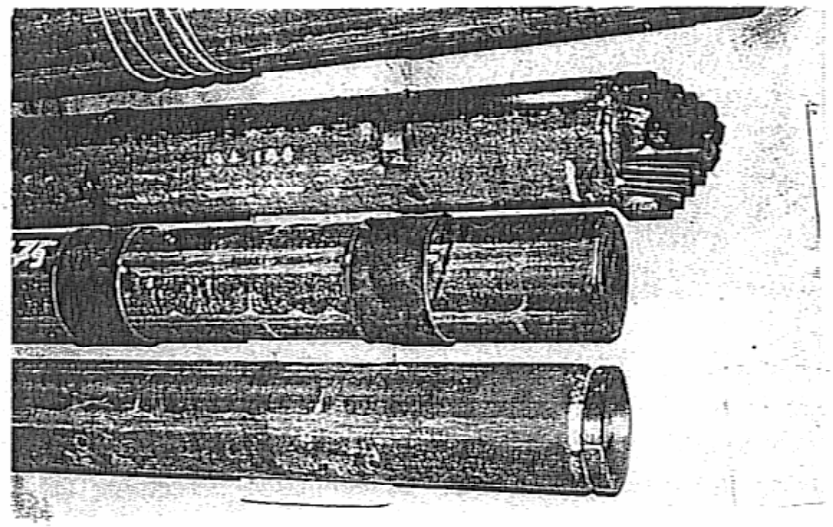


Photo. 2 Steel pipes used (for different drilling methods)

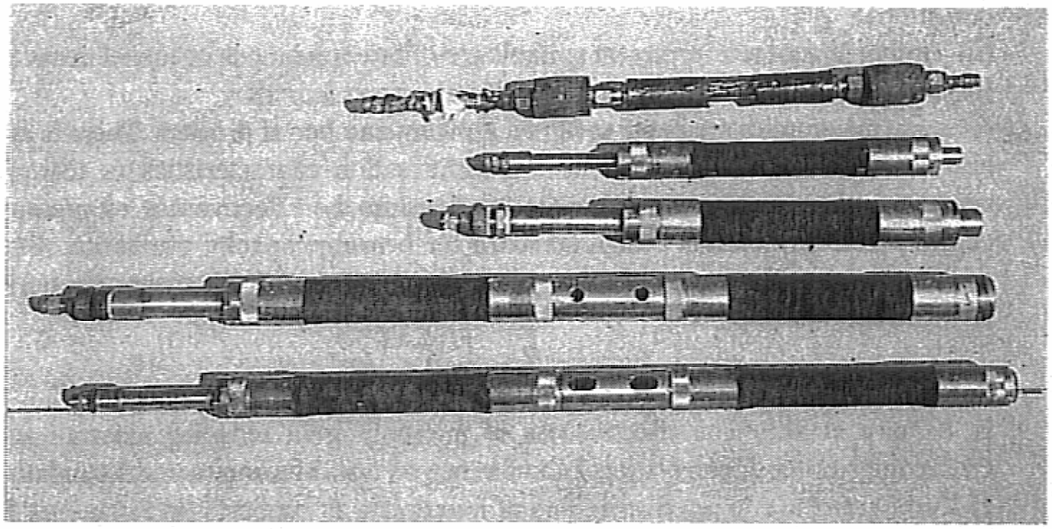


Photo. 3 Pckers

(3) Drilling machine

Micropiling can be performed in a limited space. General-purpose hydraulic drilling machines, which permit the use of different drilling methods and drill hole diameters (100 to 200 mm) according to the ground conditions and the working environment, are used. In-tunnel work tends to be inefficient because of disturbance of ground and muddiness of the ground surface on which to work caused by the use of a large amount of drilling fluid. By using a drilling machine equipped with a high-torque rotary head, therefore, a dry (air) drilling method, such as the auger drilling method or the down-the-hole hammer method, is often adopted. For this reason, drilling machines that are capable of dry drilling are often selected. Photos 4 and 5 show typical drilling machines.

Photo. 4 Drilling machine (SM103)

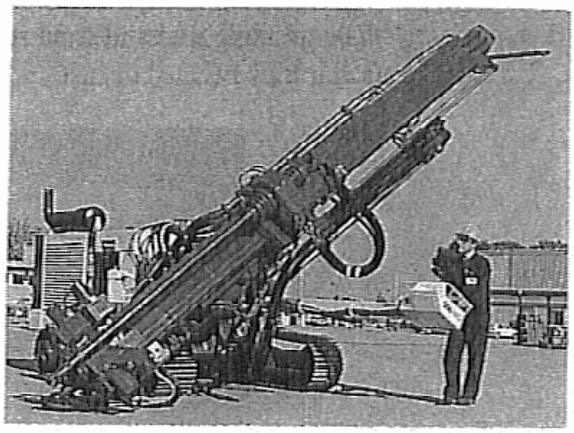


Photo. 5 Drilling machine (SM400)

5. Conclusions

There are many problems yet be addressed concerning the prediction of the behavior of the surrounding ground during tunnel excavation and methods for quantitative evaluation of auxiliary construction methods. The next step should be numerical analyses and field measurement data evaluation by which to be establish even more rational design and construction methods. The tasks ahead in the area of foot reinforcement during tunnel excavation can be summarized as follows:

(i) Methods for selecting foot reinforcement methods according to ground conditions and working conditions

(ii) Timing of foot reinforcement suitable for different methods of tunnel excavation

(iii) Establishment of simpler design and evaluation methods

Micropiles are being used in a growing number of projects. There is as yet no uniform standard, however, for the bearing capacity and deformation characteristics of for small-diameter piles. It is necessary, therefore, to elucidate the relationship the effectiveness of pressure grouting and bearing capacity and formulate a design standard for bearing capacity evaluation. Further study is needed, in addition, on the cost aspect of micropiling, including the procurement of materials and the improvement of construction equipment.

References

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