
DEVELOPMENT AND PROSPECT OF ROOT PILES IN TUNNEL FOUNDATION REINFORCEMENT

Hao Ding, Linjian Su, Jinxing Lai, Yuanhang Zhang*

School of Highway, Chang'an University, Xi'an 710064, China, laijinxing@chd.edu.cn

ABSTRACT

Over the past couple of decades, root piles as the new tool for addressing a number of tough problems have been gaining a continually increasing interest in tunnel, especially for complex geological conditions. Therefore, in order to promote the development and application of root piles in tunnel engineering, this paper systematically sorts out the research status and development prospect of root piles from the application in foundation underpinning to reinforcement of tunnel foundation. Firstly, the type and development process of root piles are discussed. Secondly, the reinforcement mechanism of the root piles in the tunnel base is refined and combed: the reinforcement mechanism analysis focuses on frictional resistance of soil around pile, soil among piles, and piles. Thirdly, the calculation method of reinforced tunnel foundation is studied from the bearing of vertical load, horizontal load and pile reinforcement design. And through the engineering case, the paper illustrates the reinforcement effect of the root pile in ensuring the stability of the tunnel and the concrete process of the root piles in the tunnel construction. Finally, the problem and development prospect of root piles are discussed, so as to provide new perspectives and fundamental data for the research on tunnel engineering.

KEYWORDS

Tunnel engineering, Root piles, Foundation bottom consolidation, Construction

INTRODUCTION

Owing to socio-economic development and increasing demand in quality of life, the scale and quantity of transportation and engineering construction have exhibited a growing trend. Tunnels, which are underground constructions, provide incomparable advantages; as such, it has also shown a markedly increasing trend. In mountainous areas, tunnels can be used to address problems related to terrain or elevation, improve alignment, shorten mileage, save time, and reduce the destruction of vegetation. In urban areas, they can reduce the land on ground and actively take part in traffic dispersion; in rivers, straits, harbours, and other areas, tunnels exert no influence on waterway navigation, improve comfort, increase concealment, and are not affected by climate [1-2]. With the development of tunnel and subway shield engineering, the foundation treatment becomes an essential aspect of any project. Given the variation in geological conditions, complexity of the construction environment, and structure of stress characteristics, both economical and practical foundation treatment must be considered to effectively shorten the construction period, reduce costs, and increase project benefits [3–6]. Under complex geological conditions, adopting a traditional foundation treatment can lead to poor engineering performance. Thus, root piles are gradually applied to reinforce a tunnel foundation while being used for foundation underpinning of historical buildings. Root piles have become a significant and indispensable technology in underground engineering because they can ensure tunnel stability and increase the bearing capacity of the tunnel foundation [7]. They are characterized by a small diameter, simple construction technology, light construction equipment, and flexible arrangement. Vertical root piles provide vertical resistance, whereas slanted root piles provide lateral resistance. They can be used flexibly, and with a small investment, that can play a greater role [8]. By sorting out information, the types of root piles reinforcement are shown in Figures 1 and 2.

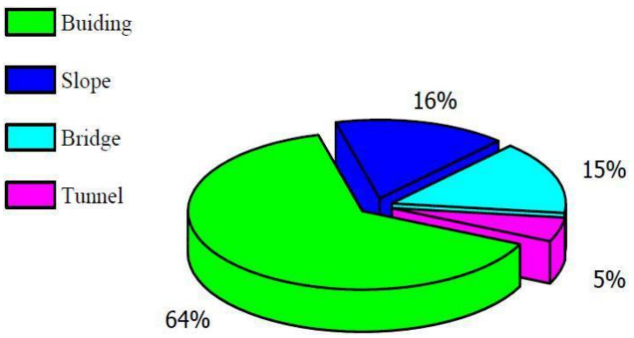

Fig.1 - Reinforcement type of root piles before 2000

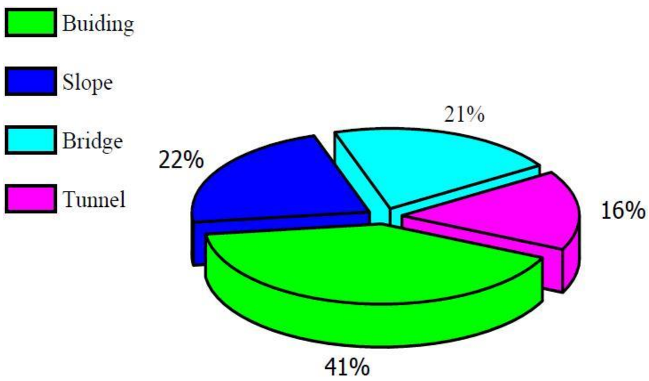

Fig.2 - Reinforcement type of root piles after 2000

Root piles reinforcement has gradually been applied in tunnel engineering and has obtained desirable engineering results [9-10]. When the tunnel foundation is reinforced by root piles, the settlement of the foundation is efficiently reduced, the bearing capacity is improved, and the normal and safe operation of the tunnel is ensured. In addition, the construction of root piles does not require a large site and is applicable in small tunnels. This research systematically elaborates on the development of root piles. Root piles are expounded from the perspectives of reinforcement mechanism, calculation method, tunnel construction, and so on presenting a summary, and discussing the development directions of root piles in the future.

DEVELOPMENT OF ROOT PILES

Category of root piles

Root piles, also known as micropiles, are bored piles with diameters typically ranging from 70 mm to 300 mm and a slenderness ratio of over 30, achieved by drilling, strong reinforcement, and pressure grouting [11–12]. Considered as a new reinforcement structure, its design is inspired by trees in a mountain ridge or jungle [13]. Root piles have different categories in various places. The small diameter of root piles provides more reinforcement, and its construction is similar to that of

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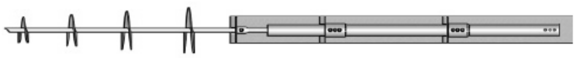
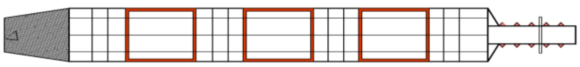
the anchor; it is also referred to as a large anchor rod in engineering. Steel bars, steel pipes, or steel-reinforced materials can be added according to the force needed [14–16]. Table 1 presents the classification and types of root piles. Pressure grouting in root pile construction efficiently ensures the close integration of grout and foundation soil [17–18]. Meanwhile, pressure cement grouting can also be extended in the soil around root piles, thereby improving the bearing capacity of a single pile and enhancing the mechanical property of the soil around the pile. After hardening and moulding, grout can bear tensile stress (pressure) [19–21].

Tab. 1 - The classification and types of root piles

The type of root piles	Characteristic	Picture
Pressed of root piles	A press-in sleeve is used, a reinforcement material is placed in the casing, and then a grout is formed to form a pile	
Suspension root piles	The whole length of high-pressure jet grouting to form a spiral-sprayed column reinforcement, interpolating suspended root pile	
End-bearing root piles	The bearing capacity of single pile is much higher than that of other types of root piles	

Development of root piles

Root piles were first developed by Fondedile, and their application was initially restricted by construction technology. They often have a diameter of 100 mm and a bearing capacity of 400 kN and used to be applied as foundation reinforcement of ancient buildings and underpinning engineering [22]. The first engineering case is the reinforcement of a school building in Naples; the root pile adopted was 13 m long and 100 mm wide, made by drilling and grouting. Grouting is made of coarse sand, cement, and water. From Italy, root pile reinforcement subsequently spread to Europe, America, and Japan. Its role is not limited to rehabilitation; it has gradually expanded to subway engineering and rock slope stability reinforcement. In 1993, France cooperated with the Federal Highway Administration (FHWA) to examine root piles. The results indicated that root piles exhibit potential and superior development prospect in addressing difficult problems related to foundation and slope stability. Several related organizations were formed to conduct studies and compile technical specifications and manuals. FHWA compiled a guide for the design and construction of root piles. After the Hyogoken–Nanbu earthquake in 1995, root piles technology was introduced to Japan with the support of International Workshop on Micropiles; subsequently, Japanese Association of High Capacity Micropiles was established for the research and development of root piles. *Design Manual for Root Piles with High Bearing Capacity for Seismic Reinforcement of Existing Pile Foundation* was compiled in 2002.

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Since then, root piles have been widely used for underpinning, adding a building layer, loading of factory building foundation and equipment foundation, remediation of dilapidated buildings, tunnel crossing, and foundation pit excavation, among others. With the improvement of root pile technology, the scope of application has extended to tunnel engineering, particularly loess tunnel. For instance, root piles have been adopted for the foundation reinforcement of The Luotuochang Tunnel in the section of the eolian sand stratum because of the desirable reinforcement effects of root piles and the construction quality of engineering ensured by the technique.

REINFORCEMENT MECHANISMS FOR TUNNEL

A hole is created in the foundation by using several techniques. The reinforcement cage and grouting pipe, as required by the design, are inserted into the hole. After the hole is cleaned, stones or fine stone silicon of certain specifications are placed into the hole, and the water in the hole is replaced by cement grout to form pressure grouting (this process is not suitable for putting fine stone silicon), thereby forming a grouting pile with diameters of similar or varying sizes. Owing to the permeation of grout, soil among the piles will be improved in root pile reinforcement; the foundation is referred to as the “composite foundation” of improved soil and root piles [23–24].

Improvement of frictional resistance and tip resistance for soil around piles

According to the construction technology for grouting and pile foundation, static pressure grouting needs to be conducted before the pile is formed, with pressure ranging from 0.3 Mpa to 0.8 Mpa. To permeate the soil around the pile and at the bottom of the pile, construction activities are conducted, such as surface layer sealing, node length control, time control, secondary grouting, and pressure stabilization. The physicochemical properties of soil are improved by compaction, filling, consolidation, replacement, and so on; thus, the space between the pile lining and the surrounding soil is filled with press-in cement grout, and the soil around the piles is in close contact, thereby increasing the contact area for the pile and soil [25–26]. Meanwhile, with hydrolysis and hydration of cement grout, as well as hydration and carbonization of clay particles and cement, the cementation between the root piles and the surrounding soil is enhanced. The frictional resistance between the root piles and the surrounding soil around is considerably improved, and the tip resistance is increased because the soil at the bottom of the pile is improved. The sketch map for grouting is shown in Figure 3.

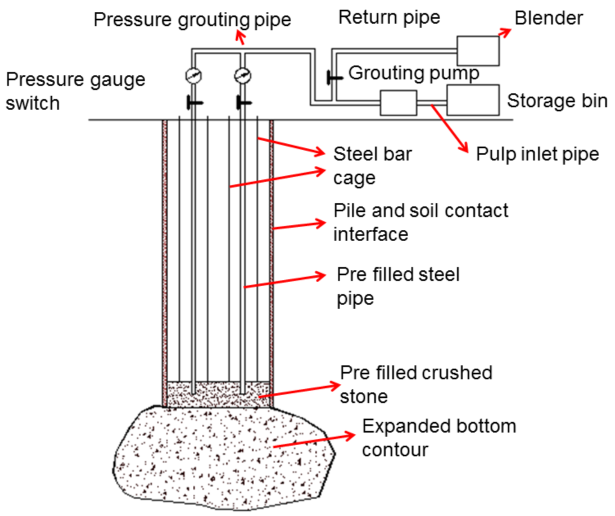

Fig.3 - The sketch map for grouting

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(1) Hydrolysis and hydration of cement grout

Ordinary Portland cement is composed of CaO, SiO_2, and Al_2O_3; thus, the combination of cement minerals are identified as Ca_3SiO_3, Ca_2SiO_3, Ca_3AlO_3, $4CaO·Al_2O_3·Fe_2O_3$, and $CaSO_4$. A chemical reaction occurs when cement is mixed in water. When the cement mortar is forcibly pressed into the soil, $Ca(OH)_2$, $CaO·SiO_2·H_2O$, and $CaO·Al_2O_3·H_2O$ are quickly produced. Over time, cement becomes solid stone, with its strength increased after setting and hardening [27].

$3CaO·Al_2O_3+6H_2O \rightarrow 3CaO·Al_2O_3·6H_2O$

$3CaO·Al_2O_3+Ca(OH)_2+mH_2O \rightarrow 4CaO·Al_2O_3·nH_2O$

$3CaO·SiO_2+nH_2O \rightarrow 2CaO·SiO_2·(n-1)H_2O+Ca(OH)_2$

$2CaO·SiO_2+mH_2O \rightarrow CaO·SiO_2·nH_2O+Ca(OH)_2$

Owing to the coagulability of cement, Ca(OH)2 is separated from a saturated solution of Ca(OH)2 as an amorphous body and becomes viscoid, containing cement particles. The binding force of particles is enhanced; thus, Ca(OH)2 becomes acicular crystals, penetrates the amorphous bodies of CaSiO3, and integrates with them, thereby increasing the mechanical strength of cement [28–29].

(2) Function of clay particles and cement hydrates

After formation, some cement hydrates continue to harden, resulting in a cement skeleton; some react with surrounding active particles.

① *Function of ion exchange and granulation*

SiO_2 (free) abundant in soil becomes silicate colloidal particles in water. Its chemical equation is written as follows:

$$SiO_2+H_2O=H_2SiO_3$$

The Na^+ or K^+ on the surface of silicate colloidal particles can exchange with Ca^+ in cement hydrate for the small soil particles to grow. In addition, cement combines with the soil mass and becomes cemented soil, sealing the space between soil masses, thus maintaining a satisfactory bearing capacity for an extended time. The specific surface area of colloidal particles generated from cement hydrate is 1,000 times that of original cement particles, thus generating great surface energy. Grouting is used not only to seal the voids in the soil mass but to close weathered cracks as well, improving the strength of cement soil at the macro level [30–32].

② *Hard condensation reaction*

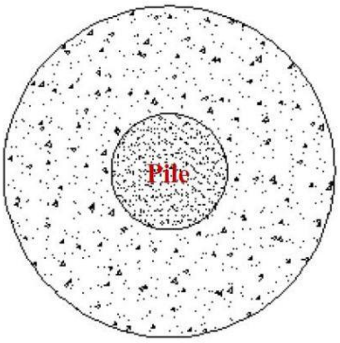
With the continuous development of cement hydration, a large quantity of Ca^+ is separated from the solution. When the quantity of Ca^+ exceeds the quantity for ion exchange, some or most of the SiO_2 and Al_2O_3 of clay minerals react with Ca^+ and gradually generate stable crystal compounds insoluble in water, considerably enhancing the strength of cemented soil.

(3) Function of carbonation

The free $Ca(OH)_2$ in cement hydrate can absorb CO_2 in water and air; carbonization then occurs, generating $CaCO_3$ insoluble in water. This reaction can increase the strength of cemented soil; however, the process occurs slowly, and the strength increases only slightly. As static pressure grouting is adopted, grout can only be pressed into the void in the soil around the pile. Soil mass covered by cement grout occurs frequently, and particles in soil mass can gradually change its performance caused by the permeation of cement hydrolysate [33–34].

Improvement of soil among the pile

After static grouting, most of the slurry will be squeezed into the holes and seams in the soil among the pile. Under specific pressure, the slurry permeates into the surrounding soil layer in the direction of least resistance, turning the pile body and the surrounding soil layer into an irregular round mixing layer wrapped in cement paste under high pressure, greatly increasing the frictional resistance and horizontal loading competence of piles. Meanwhile, the structure of the adjacent soil is improved, and the density and bearing capacity of the foundation soil are increased. This effect is particularly evident for sand and artificial filled soil. Analysis of the existing practical materials for the project indicates that the strength of the foundation soil among the pile may increase by 10% to 30% after the tree–root pile treatment [35]. After grouting, a slurry diffusing zone, which has undergone variations in materials and physical mechanical properties at the pile–soil interface, can form. The slurry diffusing zone then exhibits an annular distribution around the pile body, as shown in Figures 4 and 5.



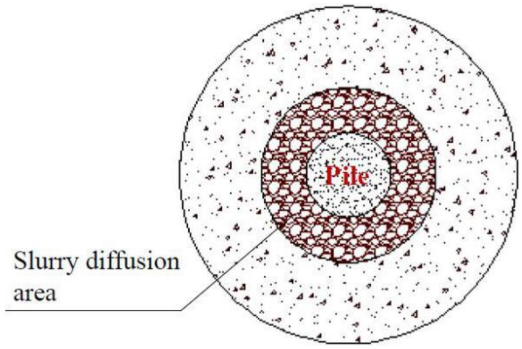


Fig.4 - General rigid pile of composite foundation   Fig.5 - Root pile of composite foundation

As illustrated, the generally rigid pile of composite foundation consists of pile and natural soil, which combine and carry the load. The grouting pile composite foundation consists of 3 components: pile, grout diffusion area, and natural soil. These components act together to provide the bearing capacity of the composite foundation. After the cementation of grout at the interface between the pile and the soil, the grouting pile can exert friction on the pile side in full length; the load is transferred to a deeper soil layer, and the load between the piles is reduced accordingly. Meanwhile, the properties of the natural soil within a certain range of the pile are enhanced, and the average modulus of the soil between the piles is increased, thereby improving the composite modulus and reducing the settlement of the composite foundation.

Role of piles in tunnels

As grouting root piles are semi-rigid or rigid, the deformation moduli of the piles are far greater than that of the soil among the piles. When the upper load is carried by the grouting root pile and the surrounding soil, the load of the basement concentrates on the root pile. Static load testing shows that the root piles (occupying about 10% of bearing plate) bear 50% to 60% of total loading, whereas the soil among the piles (occupying about 90% of the bearing plate) only carry 40% to 50 % of the total loading. Therefore, the root piles reduce the stress in the soil layer within a certain depth of the tunnel basement, and decrease the large compression deformation in the bearing layer. After piling, the root piles exert a lateral restraining effect on the soil between piles [36–37], and lateral displacement of the soil between piles is limited. Given the surrounding constraints, the deformation of the soil between the piles is limited, and the settlement of the soil is reduced under the same loading [38–41]. As shown in Figure 6, the tunnel foundation is reinforced by root piles.

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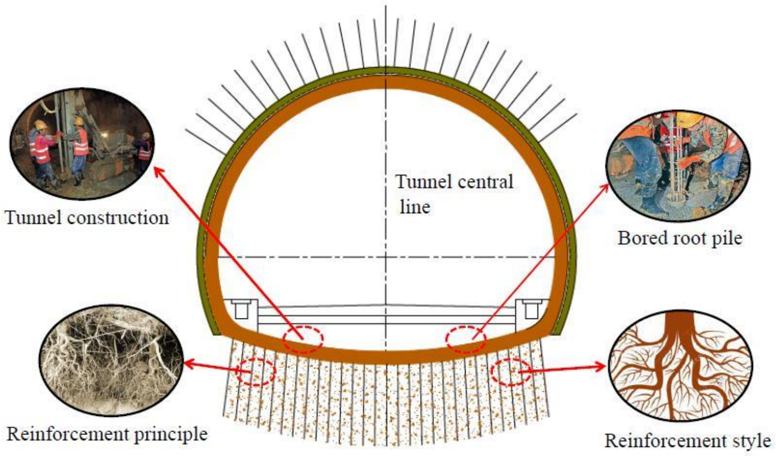

Fig.6 - The tunnel foundation is reinforced by root piles

CALCULATION METHOD STUDY

Vertical load bearing

The tip resistance of the root pile is generally ignored, whereas the frictional resistance is considered in calculating the vertical bearing capacity of a single root pile because of its small diameter. However, when the pile tip is supported on the rock, the pile tip resistance should be considered, and the bearing capacity of the pile is mainly controlled by the material strength of the pile mass [42–46]. Australian engineers have proposed a semi-empirical and semi-theoretical root pile design theory. The vertical bearing capacity of a single pile is mainly provided by friction resistance, without considering the pile tip resistance. Vertical compression of root piles was proposed by Bruce [22] as follows (1): mined by load testing and ultimate bearing

$$P_{C-allow}=\left[\frac{f'_{c-grout}}{FS_{grout}}A_{grout}+\frac{F_{y-steel}}{FS_{y-steel}}(A_{bar}+A_{casing})\right]\frac{F_a}{\frac{F_{y-steel}}{FS_{y-steel}}} \quad (1)$$

where $f'_{c\text{-}grout}$ is the uniaxial tensile strength of grouting (MPa); FS_{grout} is the grouting strength safety factor; A_{grout} is the net area of the grouting section (m^2); $F_{y\text{-}steel}$ is the minimum yield stress of the reinforced steel (MPa); $FS_{y\text{-}steel}$ is the safety factor of the reinforced steel; A_{bar} is the section area of the reinforced steel (m^2); A_{casing} is the casing section area (m^2); and F_a is the allowed axial stress (MPa) [47–53].

When the bearing capacity of a single pile is determined by the soil, the pile load is transferred to the soil through lateral resistance. The resistance of root piles is mainly determined by the grouting–soil interface. As shown in (2):

$$Q_{su}=\sum_{i=1}^{n}u_i q_{sui} \quad (2)$$

where u_i is the thickness of the ith layer of the soil around the pile (m); q_{sui} is the ultimate lateral friction of the ith layer of the soil around the pile.

The pile group effect should be considered when calculating the load-bearing capacity of the root pile group. The pile group effect is influenced by the following factors: ratio of the central distance between two adjacent piles and pile diameter; embedded depth of the pile; connection between the pile tip and the hat beam; pile-group size, and soil properties. The two hypotheses below can be used to confirm the allowable load for the pile–soil complex of which the root pile bears a considerable concentrated loading:

(1) The stability of a single pile should be considered after the pile group effect.

(2) The safety of the whole pile cylinder should be considered.

Horizontal load bearing

To calculate the horizontal load-bearing capacity of a single root pile [54–56], if the reinforcement ratio is less than 0.65%, the horizontal load-bearing capacity eigenvalue of a single root pile can be calculated according to the following formula (3):

$$R_{ha} = \left(\frac{0.75\alpha\gamma_m f_t W_o}{\gamma_M} \right) \times (1.25 + 22\rho_g) \quad (3)$$

where α is the horizontal deformation coefficient; γ_m is the plasticity coefficient of the pile section modulus; f_t is the designed tensile strength value of the pile concrete; γ_M is the maximum of the bending moment coefficient; ρ_g is the reinforcement ratio of the pile; W_o is the section modulus of the tension edge of pile conversion sections [57–62].

Pile reinforcement design

(1) The horizontal force of the top of the pile should meet the requirements of the following formula (4), configured with the pile connected to the top of the structural bar; the depth of the pile into the pile diameter is 3 to 5 times.

$$F_1 \leq Ud^2 \sqrt[5]{1.5d^2 + 0.5d}\,(1 + \frac{0.9N_1}{rR_1 A}) \quad (4)$$

where F_1 is the horizontal force of the single pile top; U is the comprehensive coefficient; d is the diameter of the pile; N_1 is the axial pressure of the pile top; R_1 is the designed strength of the pile; r is the plasticity coefficient of the pile section of the modulus; and A is the pile section area.

(2) For the pile with small horizontal force, the reinforcement ratio can be adjusted from 0.40% to 0.65%.

APPLICATION AND CONSTRUCTION IN TUNNELS

Application in tunnel construction

The Application and Construction are shown in Table 2.

Table 2 - Engineering Example of Reinforcing Tunnel by Tree Root Piles

Number	Name	Reasons of usage	Reinforcement effect
1	Lan Yu railway tunnel [39]	Basement cracking, damage, subsidence, squeezing to both sides and the mud pumping phenomenon is more serious	Monitoring data show that all aspects of the indicators have reached the design and specification requirements
2	Luo Tuochang Tunnel [63]	The geologic condition is very poor, and the aeolian sand has poor self - stability ability	The bearing capacity of composite foundation reaches the design requirements
3	Fan Jingshang Tunnel [64]	The vaults have irregular subsidence and peripheral convergence	The bearing capacity of the root pile fully reaches the design requirements
4	Chang Liangshang Tunnel [65]	Poor condition of the surrounding rock, erosion of groundwater, and defects at the bottom of the tunnel	Invert function is restored, the whole structure stress of the tunnel and the surrounding rock condition is improved
5	Nan Jing Tunnel [66]	Engineering geological and hydrogeological conditions are poor,construction is difficult	The surface settlement is small and the root pile tip displacement is small
6	Liu Yong tunnel [67]	The opencut tunnel is serious settlement, cracking, instability	The settlement, instability and cracking of opencut tunnel have been obviously controlled

Application in soil with a loose structure and high water content

Lanyu Railway is a single-hole double-track tunnel with a total length of 715 m for the Lanyu Railway crossing the debris flow area. The total length of the tunnel is 263 m, and the shallowest depth is only 14 m. The debris flow deposits are composed of round gravel, breccia, and phyllite with different diameters and partially saturated sandy loess. The structure is loose, highly porous, water-saturated, and fluid.

The results indicate that the maximum compressive stress of the support is decreased after root piles are used to reinforce the bottom of the tunnel. The maximum settlement is 4.52 mm, and the maximum vibration velocity of the filling surface of the inverted arch is 62.9 mm/s without using root piles as reinforcement. With root piles, the maximum settlement is 3.16 mm, and the maximum vibration velocity is 24.8 mm/s; without root piles, the maximum settlement is reduced by 30.1%, and the maximum vibration velocity is reduced by 60.6%. The settlement of the filling arch was controlled by the root piles reinforcement; thus, the vibration velocity is markedly reduced and the stability of the tunnel is improved [39].

Application in eolian sand

Luotuochang Tunnel is located in the contact area between the Liangmao area of Loess Plateau in Northern Shaanxi and the Mu Us Desert. Quaternary loess and the sand cover layer are thinner, and the sand is semi-fixed. Eolian sand is formed by blowing, moving, and accumulating under wind action in the arid area, characterized by loose sand, layered distribution, and poor stability. The tunnel crossing the eolian sand stratum belongs to grade-VI rock. The eolian sand surface at the exit of the tunnel is shown in Figures 7.

Fig.7 - Surface sandy land in tunnel exit section

According to load testing mentioned in Reference [35], the impacts of a single root pile on the reinforcement of a tunnel settlement can be obtained by varying the aggregates, lengths, and diameters of the pile, as shown in Figures. 8, 9, and 10. The effects of the root pile group on tunnel settlement are shown in Figures 11.

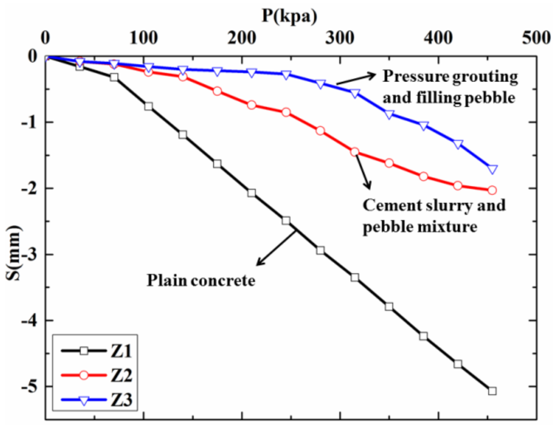

Fig.8 - Different pile aggregates[30]

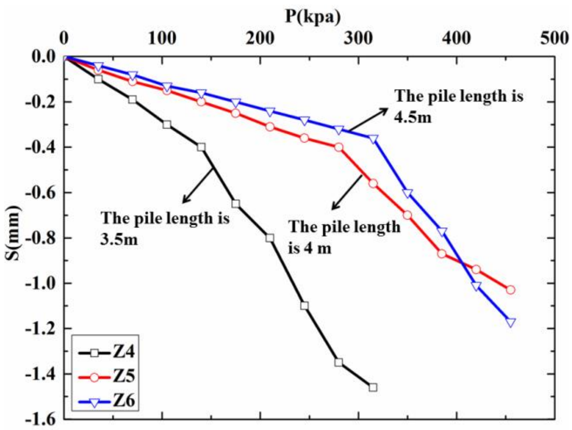

Fig.9 - Different pile lengths[30]

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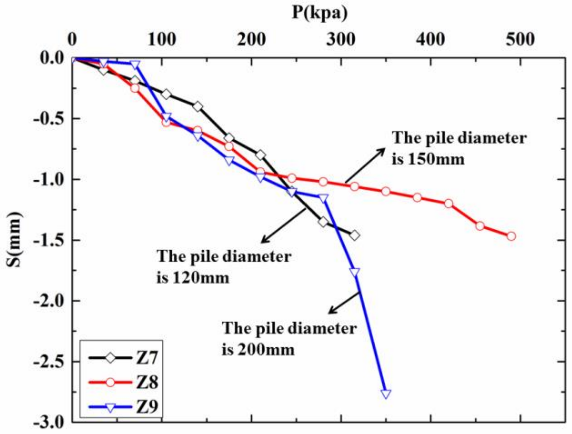

Fig.10 - Different pile diameters[30]

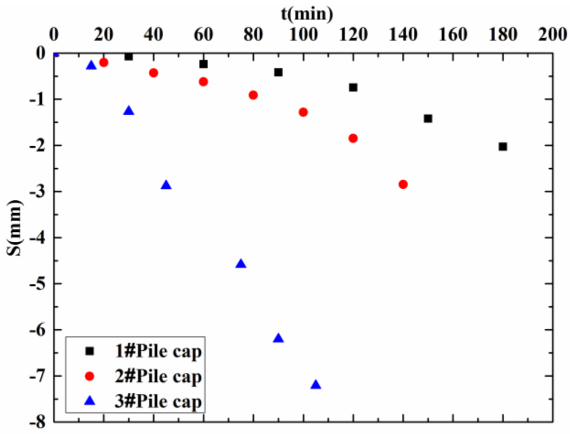

Fig.11 - Tunnel subsidence [30]

(1) Compared with the Z1 pile, the Z2/Z3 bearing capacities were improved by 86.7% and 226.7%, respectively. Among the 3 pile aggregates, the pile formation process, which first fills the pebble, followed by pressure grouting, can obtain the maximum single pile bearing capacity. In addition, the reinforcement of the tunnel bottom is remarkable.

(2) The bearing capacity of a single pile markedly increases with an increase in pile length; beyond a certain extent, the single pile bearing capacity increases slowly.

(3) In the case of a pile forming material, an increase in pile diameter leads to an increase in the bearing capacity of a single pile. If the pile diameter is increased by 25% from 120 mm to 150 mm, the single pile bearing capacity is increased by 67% from 70 kPa to 105 kPa. If the pile diameter increases by 66.7%, the single pile bearing capacity is increased to 135 kPa, reflecting a 92.8% increase. This result indicates a significant improvement for the single pile, and it enhances the stability of the tunnel [30].

(4) The bearing capacity of the composite foundation of the pile group is markedly improved compared with that of the single pile. For the composite foundation with 3 piles, the bearing capacity of the composite foundation is 3 times higher than that of the single root pile. However, composite foundation formed using 8 piles has a bearing capacity lower than that of a single pile [35].

Constructing root piles in the tunnel

The construction flow chart for root piles is shown in Figure 12.

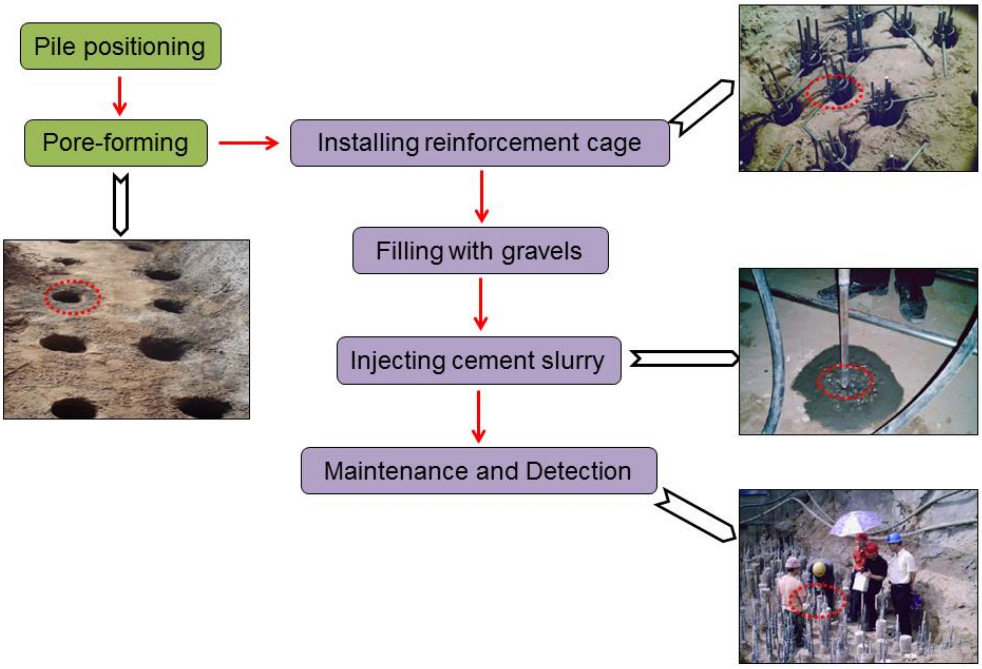

Fig.12 - Layout chart

(1) Pile positioning: Pile deviation should be controlled within 20 mm, the vertical deviation of a straight pile should not exceed 1%, and the inclination of the inclined pile should be adjusted according to the design requirements [68–71].

(2) Pore-forming: An engineering geological drilling machine or the Luoyang shovel can be used to make holes. The Luoyang shovel as the archaeological tool is widely used in Chinese geotechnical engineering, as shown in Figure 13. Water or natural cement slurry are used in drilling, and generally, the casing is not used. A one-section casing is placed near the hole; after the designed elevation is reached, the hole is cleaned until water purification occurs.

(3) Installing reinforcement cage: When the reinforcement cage is placed, it cannot be forced down under the pressure; thus, it should be placed at the same time to ensure the stability of the hole wall. Two reinforcement cages must be vertical, and the elevation must meet the design requirements.

(4) Filling with gravel: The gravel should be rinsed with water, and the filled volume shall be controlled 1.15 times as much as the calculated volume. To ensure a uniform backfill of gravel, about 0.2 m^2 pebble is filled. The shaking reinforcement cage and grouting pipe are shaken for gravel to reach the bottom of the hole [72–74].

(5) Injecting cement slurry: Grouting pump is used for both cement mortar and mortar. In grouting, the grouting pressure has to be controlled so that slurry can emerge evenly until the holes overflow. Grouting should be continuous; if interrupted, it should be disposed immediately.

Fig.13 - Luoyang shovel

SUMMARY AND PERSPECTIVES

New technologies and methods have been identified since the application of root piles in engineering, and these techniques can be investigated further and used continuously. In addition, the application of root piles in tunnel construction is becoming increasingly prominent, providing reliable measures for the stability of the tunnel foundation. Although root piles have only been recently used in tunnels, such application has developed rapidly. Root piles have their own distinct advantages. In some specific cases, root piles are likely to be the only effective solution; however, some problems still need to be discussed related to their research and application, as follows:

(1) Root piles generally use filling pile calculation methods; however, the principal method of bearing the root pile is by the lateral friction of pile, and the designed calculation method remains defective. More calculation methods exist for root piles; however, the geological conditions under different methods and the determination of suitable design techniques for specific conditions need further investigation.

(2) Given that root piles exhibit distinct characteristics, under different combinations, the working performance, load transfer, and failure modes of root pile groups obviously vary from other types of piles. Thus, the failure modes of root piles need to be examined further to improve the pile bearing capacity and ensure the stability of the tunnel bottom.

(3) Under the influence of an earthquake or a mechanical vibration, root piles have to bear horizontal dynamic loading. Research on the lateral cyclic loading of root piles is currently inadequate, and the design theory remains imperfect. Therefore, China (an earthquake-prone country) should fully evaluate root piles working mechanisms under dynamic loading.

OMPETING INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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