International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 07, NCIRTAI - 2026

Development And Prospect of Root Piles in Tunnel Foundation Reinforcement

M. Ramya
[1]Assistant Professor, Department of Civil Engineering, Sri Bharathi Engineering College for Women, Pudukkottai, India.
ramya89.me@gmail.com

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, Rootpiles, 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 educe 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 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.

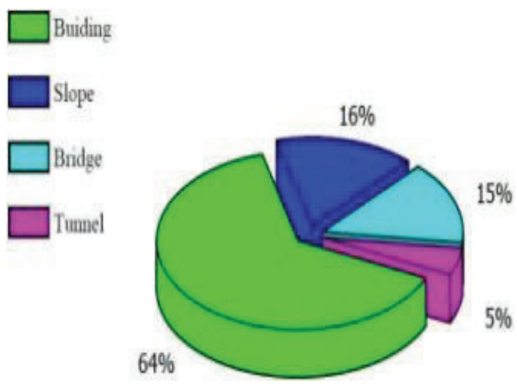


Fig 1: piles reinforcement

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 was introduced to Japan with the support

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 07, NCIRTAI - 2026

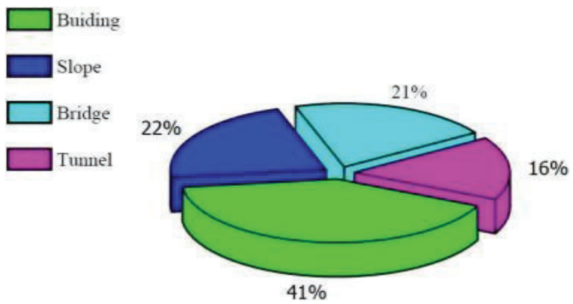


Fig 2: Surface area of colloidal particles

of International Workshop on Micro piles; subsequently, Japanese Association of High Capacity Micro piles 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 2020

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, $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$, and $CaSO_4$. A chemical reaction occurs when cement is mixed in water. When the cement mortar is forcibly pressed into the soil, $Ca(OH)_2$, $CaO \cdot SiO_2 \cdot H_2O$, and $CaO \cdot Al_2O_3 \cdot H_2O$ are quickly produced. Over time, cement becomes solid stone, with its strength increased after setting and hardening [27].

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

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

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

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

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 $CaSiO_3$, and integrates with them, thereby increasing the mechanical strength of cement [28–29].

(1) 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*

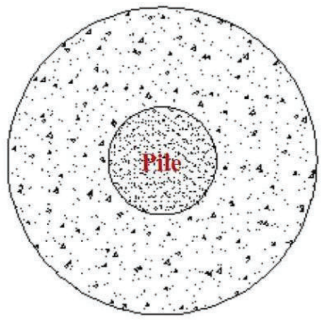
With the continuous development of cement hydration, a large quantity of Ca^+ is separated from the solution. When the quantity of Ca^+ exceeds the quantity for ion exchange, some or mostof the SiO_2 and $Al_2O_3$of clay minerals react with Ca^+ and gradually generate stable crystal compounds insoluble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

(2) Function of carbonation

The free $Ca(OH)_2$ in cement hydrate can absorb CO_2in 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 3 and 4.



International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 07, NCIRTAI - 2026

Fig.3-General rigid pile of composite foundation

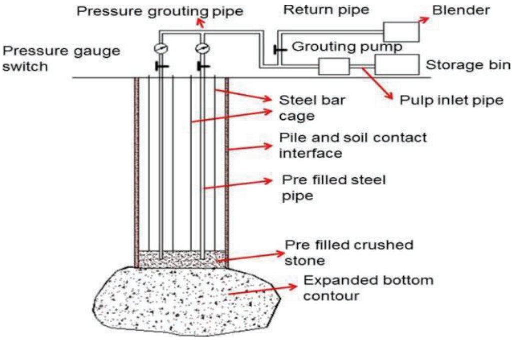


Fig.4-Rootpile of composite foundation

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, andthe 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 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.

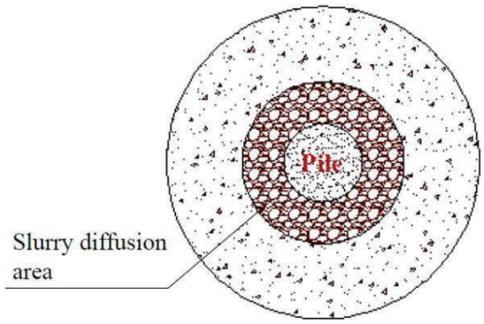


Fig 5: Role of piles in tunnels

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

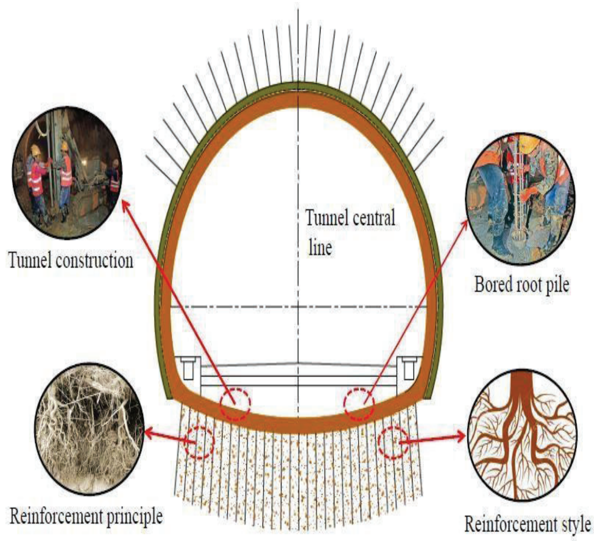
As grouting root piles are semi-rigid or

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 eigen value of a single root pile can be calculated according to the following formula (3):

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.



International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 07, NCIRTAI - 2026

Fig 6 : The tunnel foundation is reinforced by root piles

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 is3.16mm,andthemaximum vibration velocity is 24.8 mm/s; without root piles, the maximum settlement is reduced by 30.1 Pile reinforcement design. 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 ti

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

SUMMARYAND 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.

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

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:

(4) 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.

(5) 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.

(6) Under the influence of an earthquake or a mechanical vibration, root piles have to bear horizontal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 07, NCIRTAI - 2026

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.

REFERENCES

[1] J.X.Lai,K.Y.Wang,J.L.Qiuetal.,“Vibrationresponsecharacteristicsofthecrosstunnelstructure,”*Shock&Vibration*,vol.2016,ArticleID9524206,2016.doi:10.1155/2016/9524206.

[2] M.N. Vu, W. Borer, and J. Bosch, "The impact of shallow cover on stability when tunneling in soft soils,"*Tunnelling & Underground Space Technology*, vol.50, pp. 507-515,2015

[3] H. Xing, F. Xing, and J. Wu, “Effects of Pit Excavation on an Existing Subway Station and Preventive Measures,”. *Journal of Performance of Constructed Facilities*, vol. 30, no.6, pp. 2016 ;

[4] A. Chepurnova, "Assessing the influence of jet-grouting underpinning on the nearby buildings, *“Journal of Rock Mechanics and Geotechnical Engineering*, vol.6, no.2, pp.105-112,2014

[5] M. Cardu, and J. Seccatore, "Quantifying the difficulty of tunnelling by drilling and blasting,"*Tunnelling & Underground Space Technology*, vol.60, pp.178-182,2016

[6] D. Wang, and W. Sui, "Grout diffusion characteristics during chemical grouting in a deep water-bearing sand layer,"*International Journal of Mining Science and Technology*,vol.22, no.4, pp.573-577, 2012

[7] G. Meschke, J. Ninic. J. Stascheit, and A. Alsahly, "Parallelized computational modeling of pile–soil interactions in mechanized tunneling,"*Engineering Structures*,vol.47,no.1,pp.35-44,2013.

[8] Jiang Qingwei .Research on Stability at high digging root pile slope protection[D]. Xi’an: Chang’an University, 2014.(in chinese)

[9] S. Seki, S. Kaise, Y. Morisaki et al., "Model experiments for examining heaving phenomenon in tunnels,"*Tunnelling & Underground Space Technology Incorporating Trenchless Technology Research*, vol.23, no.2, pp.128-138,2008.

[10] C.J. Lee, B.R.Wu, H.T. Chen, and K.H. Chiang, "Tunnel stability and arching effects during tunneling in soft clayey soil,"*Tunnelling & Underground Space Technology*,vol.21, no. 2, pp. 119-132,2006.

[11] LiZhan,TengYanjingLiQingruietal.Micro-piletechniquesforimprovementprojectofexisting buildings[J]. China Civil Engineering Journal, 2015(S2):197-201.(in chinese).

[12] WANGHui, CHENGjianping, QUEjinsheng.Researchondesignandapplicationofrootpilesto Strengthening foundations[J]. Rock and Soil Mechanics,2006(s2):1290-1294.(in chinese)

[13] S.W. Sun, B.Z. Zhu, and J.C.Wang, "Design method for stabilization of earth slopes with micro piles,"Soils & Foundations, vol.53, no.4, pp.487-497,2013.

[14] A.E. Elsaied, "Performance of footing with single side micro-piles adjacent to slopes,"*AEJ - Alexandria Engineering Journal*,vol.54,no.4, pp. 903-910,2014.

[15] C.Zanuy,P.D.L.Luente,andM.Pinilla,"Bendingstrengthofthreadedconnectionsformicropiles,"*Journal of Constructional Steel Research*,vol.78, pp.68-78,2012.