https://doi.org/10.37420/j.epbt.2025.003

Review of Bearing Capacity Enhancement Performance of Post-Grouting Piles in Railway Bridge

Liangjian Yuan [1,2] Huang Hui [1,2]

[1] Jiangsu Railway Group Co., Ltd., Nanjing, Jiangsu, China

[2]Jiangsu Province Engineering Research Center of Intelligent and Green Railway, Nanjing, Jiangsu, China

Abstract

This review comprehensively examines post-grouting technology for enhancing bearing capacity of railway bridge pile foundations. It elucidates three core mechanisms: grout diffusion/penetration in soil matrices (influenced by soil tortuosity and grout viscosity), soil property improvement through void filling and crack sealing, and altered pile-soil interaction via grout bulb formation. Key influencing factors include soil grain size/permeability, pile geometry/installation methods, and grouting parameters (pressure/volume/material properties). Experimental analyses reveal that optimized grout control can increase pile-soil interface cohesion (5.8-18.8) and shear strength (1.16-2.91), with field tests showing 133% bearing capacity improvement using geopolymer grouts. Numerical modeling confirms up to 51% lateral load enhancement. The review emphasizes the need for site-specific parameter optimization considering geological conditions (e.g., karst formations) and groundwater dynamics, providing practical guidance for infrastructure rehabilitation projects.

Keywords: Bearing Capacity, Post-Grouting Piles, Enhancement Performance, Railway Bridge

© By the author(s); licensee Mason Publish Group (MPG), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (https://masonpublish.org/licenses/by/4.0/)

1 Introduction

Railway bridges are critical components of transportation infrastructure, and the stability and safety of these structures heavily rely on the integrity of their pile foundations. These foundations are often subjected to significant loads from train traffic and environmental factors, making them vulnerable to bearing capacity issues over time. Insufficient bearing capacity can lead to excessive settlement, structural damage, and ultimately, compromise the safety of railway operations. To address these challenges, post-grouting technology has emerged as a promising method for enhancing the bearing capacity of existing pile foundations. This technology involves injecting grout into the soil surrounding the pile after its initial installation, aiming to improve soil properties and increase the pile-soil interaction, thereby boosting the overall load-bearing capacity.

This review aims to provide a comprehensive overview of the bearing capacity enhancement performance of post-grouting piles in railway bridge applications. It will explore the underlying mechanisms of bearing capacity improvement achieved through post-grouting, examine the factors influencing its effectiveness, and analyze experimental and field studies conducted on post-grouted piles. Specifically, the review is structured around three central themes. First, it will delve into the mechanism of bearing capacity enhancement by post-grouting, analyzing grout diffusion and penetration characteristics, the impact of grout material properties, the effect of grouting pressure and volume, and the application of numerical simulation and theoretical modeling. Understanding these mechanisms is crucial for optimizing grouting procedures and predicting the resulting bearing capacity improvements. Second, the review will explore the factors influencing the effectiveness of post-grouting, including soil properties, pile geometry and installation method, grouting parameters, and geological conditions. Identifying these factors is essential for tailoring post-grouting strategies to specific site conditions and maximizing their impact. Finally, the review will examine experimental and field studies on post-grouting pile bearing capacity, focusing on laboratory model tests, field load tests in railway bridge projects, and comparative analyses of different post-grouting techniques. By analyzing these studies, the review aims to provide a practical perspective on the application of post-grouting in railway engineering and assess its effectiveness in real-world scenarios. Through this structured approach, this review seeks to provide a valuable resource for engineers and researchers involved in the design, maintenance, and rehabilitation of railway bridge pile foundations.

2 Mechanism of Bearing Capacity Enhancement by Post-Grouting

The mechanism by which post-grouting enhances the bearing capacity of piles is a complex interplay of grout diffusion, soil improvement, and altered pile-soil interaction. The process hinges on the effective delivery and distribution of grout within the soil surrounding the pile .

The effectiveness of post-grouting is fundamentally tied to the grout's ability to permeate the soil matrix, a process significantly influenced by soil type. In granular soils like loose sands and gravels, cement-based grouts are frequently employed to create a composite material exhibiting enhanced strength and reduced permeability. Research by Xie et al. highlights the crucial role of soil tortuosity and grout viscosity in penetration grouting applications. Furthermore, innovative techniques such as high-frequency pulsed grouting, as explored by Li et al. , demonstrate improved penetration compared to traditional steady-pressure methods. The success of grout diffusion directly impacts the subsequent soil improvement and the overall bearing capacity enhancement.

The properties of the grout material itself are paramount in dictating the extent of soil improvement and the resulting modification of pile-soil interaction. Grout acts as a binding agent, effectively sealing cracks, pores, and voids within the soil, thereby improving its mechanical properties and reducing permeability. Crucially, the selected grout must possess sufficient fluidity and fineness to penetrate discontinuities and adequately fill voids . Studies have shown a direct correlation between grout volume and interface shear strength, with increased grout volume generally leading to improved shear resistance under constant normal

© By the author(s); licensee Mason Publish Group (MPG), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (https://masonpublish.org/licenses/by/4.0/)

stress and grouting pressure. Similarly, augmenting grouting pressure, while maintaining constant normal stress and grout volume, also enhances interface shear strength. Numerical investigations, such as that conducted by Qaddoory et al. , have demonstrated that grouting can substantially increase the load-bearing capacity of single piles, with improvements of up to 27% under vertical loads and 51% under lateral loads. This enhancement is attributed to the grout's ability to fill voids and improve the soil-pile interface. However, the selection of grout materials necessitates careful consideration of environmental factors. The toxicity and potential environmental harm associated with traditional chemical grouts have spurred the search for and adoption of more sustainable grouting materials and injection techniques. The volume of grout used also influences the load bearing capacity of the pile. In fact, precise control of grouting parameters can significantly increase cohesion and shear strength at the pile-soil interface. Si-Si Shi et al. demonstrated increases of 5.8–18.8 times in cohesion and 1.16–2.91 times in shear strength through optimized grout parameter control.

The application of appropriate grouting pressure and volume is a critical factor influencing the formation of grout bulbs and the degree of soil compaction around the pile, ultimately impacting the effectiveness of post-grouting. Higher grouting pressures, carefully managed to avoid soil fracturing, typically result in larger grout bulbs and increased soil compaction. The increased grout volume expands the zone of influence, densifying the surrounding soil and enhancing its resistance to deformation. However, excessive pressure can lead to undesirable consequences, such as ground heaving or damage to nearby structures. Therefore, meticulous control and monitoring of grouting pressure and volume are essential for optimizing the post-grouting process, achieving the desired bearing capacity enhancement while safeguarding the integrity of the surrounding environment.

Numerical simulation and theoretical modeling are indispensable tools for understanding and predicting the bearing capacity enhancement achieved through post-grouting. These approaches enable the investigation of intricate pile-soil interaction mechanisms and the optimization of grouting parameters, reducing the reliance on extensive and costly physical experiments. While the provided references lack specific examples related to railway bridge piles, the application of numerical methods to post-grouting is well-established. Techniques like finite element analysis (FEA) and computational fluid dynamics (CFD) are frequently used to simulate grout propagation, soil deformation, and stress distribution around the pile following grouting. These models can incorporate factors such as grout material properties, soil characteristics, and grouting pressure to predict the resulting increase in pile bearing capacity.

3 Factors Influencing the Effectiveness of Post-Grouting

The effectiveness of post-grouting as a technique for enhancing the bearing capacity of pile foundations in railway bridges is contingent upon a complex interplay of factors. These factors can be broadly categorized into soil properties, pile geometry and installation methods, grouting parameters, and geological conditions, including groundwater levels. Understanding and carefully considering each of these aspects is paramount to achieving optimal results.

The properties of the surrounding soil, particularly grain size distribution and permeability, exert a significant influence on grouting performance. Soil grain size distribution dictates the grout's capacity to permeate the soil matrix. Finer-grained soils, characterized by smaller pore spaces, present a greater challenge to grout penetration compared to coarser-grained soils. Similarly, soil permeability, which governs the ease with which fluids flow through the soil, directly impacts grout diffusion. High permeability facilitates wider grout distribution, leading to a more extensive zone of soil improvement and a more substantial increase in pile bearing capacity. Conversely, low permeability restricts grout flow, potentially resulting in localized grout bulbs and uneven soil compaction. Therefore, a comprehensive geotechnical investigation is essential to characterize the soil profile and inform the selection of appropriate grout mixes and injection strategies.

Beyond soil characteristics, the geometry of the pile and the installation method play a crucial role in

© By the author(s); licensee Mason Publish Group (MPG), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (https://masonpublish.org/licenses/by/4.0/)

determining post-grouting efficiency. The pile's surface area and shape dictate the potential contact area for grout injection and subsequent soil improvement. Piles with larger surface areas offer more opportunities for grout to penetrate the surrounding soil. Furthermore, the installation method significantly affects the soil's initial state around the pile. Driven piles, for example, compact the surrounding soil, potentially hindering grout penetration compared to bored piles, which may leave a looser soil structure. Consequently, the choice of pile type and installation technique must be considered in conjunction with the post-grouting strategy.

The optimization of grouting parameters, including grouting pressure, grouting time, and grout composition, is also crucial for maximizing the effectiveness of post-grouting. The interplay between these parameters dictates the extent of grout penetration, soil compaction, and ultimately, the improvement in pile-soil interaction. Careful consideration must be given to these parameters to avoid issues such as soil fracturing due to excessive pressure or inadequate grout penetration due to insufficient pressure or time. The selection of grout composition, including cement type, water-cement ratio, and the addition of admixtures, significantly affects its flowability, setting time, and strength, all of which are critical for achieving the desired soil improvement. Further research is needed to develop comprehensive guidelines for optimizing these parameters based on specific soil conditions, pile geometry, and project requirements.

Finally, geological conditions and groundwater levels represent critical environmental factors influencing the outcome of post-grouting. The presence of geological features such as karst formations can significantly affect grout diffusion and soil improvement. For instance, Huang et al. found that bead-shaped karst caves are more unfavorable to the exertion of the load-bearing capacity of tubular piles than karst caves filled with plastic-hard plastic breccia silty clay to which the piles have direct access. The presence of karst, dominated by medium-weathered limestone and caves with various spatial features, can significantly affect grout diffusion and soil improvement. Groundwater levels also play a crucial role, with fluctuations potentially leading to erosion, flooding, or weakening of the foundation base. Therefore, a thorough understanding of the local geological context and groundwater conditions is essential for optimizing grouting parameters and ensuring the long-term performance of post-grouted piles.

4 Experimental and Field Studies on Post-Grouting Pile Bearing Capacity

Understanding the efficacy of post-grouting techniques in enhancing pile bearing capacity necessitates a multi-faceted approach, incorporating both controlled laboratory experiments and real-world field investigations. Laboratory model tests provide a fundamental understanding of the load-settlement behavior of post-grouted piles, allowing for the controlled manipulation of variables and detailed observation of grout's influence on soil-pile interaction. For instance, studies have demonstrated the relative effectiveness of different grouting locations. Zhang et al.found that pile-side grouting offered better settlement control compared to tip grouting, while a combined tip-side approach yielded the most significant reinforcement. Similarly, Zhao et al. utilized physical models to quantify the reduction in bearing capacity caused by voids in rock-socketed piles, highlighting the importance of addressing such defects through grouting. These scaled-down simulations, often employing simplified soil conditions, provide valuable insights into the fundamental mechanisms at play during post-grouting.

However, the transition from laboratory findings to practical application requires validation through field load tests, particularly in critical infrastructure projects such as railway bridges. Field load tests are essential for assessing the performance of post-grouted piles under realistic conditions, where complex soil profiles and environmental factors can significantly influence the outcome. These tests involve applying controlled loads to instrumented piles and meticulously monitoring their settlement response. The selection of appropriate grouting materials is also a key consideration, as demonstrated by Li et al., who compared geopolymer and ordinary Portland cement in silty fine sand. Their results indicated that geopolymer grouting led to a substantial increase in ultimate bearing capacity (133% with 8 kg of geopolymer) and improved pile side friction resistance, suggesting its potential for enhancing pile performance in such soil types. The results

© By the author(s); licensee Mason Publish Group (MPG), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (https://masonpublish.org/licenses/by/4.0/)

underscore the necessity of considering material properties and soil type when designing post-grouting strategies.

Ultimately, the selection of the most appropriate post-grouting technique hinges on a comparative analysis of their respective advantages and limitations in the context of specific railway engineering challenges. While direct comparisons of different techniques applied to railway bridge pile foundations are scarce in the provided references, the underlying principles of each method offer valuable insights. Sleeve grouting, for example, allows for targeted soil improvement at specific depths by injecting grout through pre-installed sleeves along the pile shaft. This is particularly beneficial in layered soil profiles, where certain strata may require more reinforcement than others. Conversely, tip grouting primarily focuses on enhancing end bearing capacity by injecting grout at the pile tip. The optimal choice, or a combination of techniques, depends on a comprehensive assessment of factors such as soil conditions, pile geometry, and the desired level of bearing capacity enhancement. Therefore, a holistic approach that integrates laboratory findings, field validation, and a thorough understanding of the available grouting techniques is crucial for maximizing the effectiveness of post-grouting in railway bridge applications.

5 Conclusions

In summary, this review has illuminated the multifaceted nature of bearing capacity enhancement in railway bridge pile foundations through post-grouting. The process hinges on the effective interplay of grout diffusion, soil improvement, and modified pile-soil interaction, all significantly influenced by soil properties, pile characteristics, and carefully optimized grouting parameters. Both laboratory experiments and field studies have demonstrated the potential of post-grouting to substantially improve pile performance, with the selection of appropriate techniques and materials being crucial for achieving optimal results in specific geological contexts.

Looking ahead, the future of post-grouting in railway bridge engineering holds immense promise. Continued research should focus on refining numerical models to better predict grout propagation and soil behavior, exploring innovative and sustainable grouting materials, and developing comprehensive guidelines for optimizing grouting parameters based on site-specific conditions. Furthermore, the integration of advanced monitoring technologies, such as distributed fiber optic sensors, could provide real-time feedback on grout distribution and pile performance, enabling adaptive and responsive grouting strategies. By embracing these advancements, the engineering community can unlock the full potential of post-grouting, ensuring the long-term stability, safety, and reliability of railway bridge infrastructure for generations to come.

References

Baozhi Xie, Hua-Rong Cheng, Xuesong Wang, Zhishu Yao, Chuan-xin Rong, R. Zhou, Liangliang Zhang, Long Guo, Hong Yu, W. Xiong, Xu Xiang, Theoretical Research on Diffusion Radius of Cement-Based Materials Considering the Pore Characteristics of Porous Media, Materials, 2022, 15.

Yongfeng Li, Xiaobin Chen, Jianzhong Li, Lubo Tang, Fantong Lin, Xinxin Zhang, A Numerical Study on the Cement Slurry Penetration Performance of the Cyclic Grouting Method with High-Frequency Pulsating Pressure, Applied Sciences, 2023.

V. Achal, S. Kawasaki, Biogrout: A Novel Binding Material for Soil Improvement and Concrete Repair, Frontiers in Microbiology, 2016, 7.

Si-Si Shi, Zhi-hui Wan, Tao Hu, Xiao-Nan Qian, Chang Duan, Kai Qi, Analysis of the effect of grouting parameters on pile-soil interaction of grouted piles, Frontiers in Earth Science, 2023.

Khalid I. Qaddoory, B. J. Noman, H. M. Saleh, Numerical Analysis of the Pile-Grout System in Soft Clay under Vertical and Lateral Load, E3S Web of Conferences, 2023.

Lingjun Huang, Rui Gao, Jingou Chi, Xiaocai Yan, Study on load-bearing behaviors of prestressed post-grouting tubular piles in the karst region of northern Fujian Province, China, Frontiers in Earth

© By the author(s); licensee Mason Publish Group (MPG), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (https://masonpublish.org/licenses/by/4.0/)

Science, 2024.

Rodolphe Many Ndinga, Geotechnical calculations in the design of building foundations and building foundations in central Africa, Bases and Foundations, 2024.

Jiaqi Zhang, Chunfeng Zhao, Yue Wu, Experimental Study on Post-Grouting Pile Vertical Bearing Performance Considering Different Grouting Methods and Parameters in Cohesive Soil, Applied Sciences, 2023.

Xiaolin Zhao, S. Melentijevic, Yupeng Shen, Zengkui Sun, Kaiyuan Wang, Jincui Xu, Zhiqiang Li, Experimental study of the effects of the void located at the pile tip on the load capacity of rock-socketed piles, Scientific Reports, 2024, 14.

Pan Li, Yangyang Xia, Xinhui Xie, Jing Wang, Chaojie Wang, Mingsheng Shi, Bo Wang, Haoye Wu, Study on Vertical Bearing Capacity of Pile Foundation with Distributed Geopolymer Post-Grouting on Pile Side, Materials, 2024, 17.

© By the author(s); licensee Mason Publish Group (MPG), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (https://masonpublish.org/licenses/by/4.0/)