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Study on Settlement of Soft Soil Foundation and Intelligent Reinforcement Countermeasures in Rock and Soil Engineering

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Abstract: This paper investigates settlement issues in soft soil foundations and proposes intelligent reinforcement strategies, detailing their characteristics, settlement mechanisms, and existing assessment/control methodologies. Based on global research progress, it examines three primary intelligent reinforcement approaches for soft soil foundations: smart dynamic compaction, intelligent monitoring systems, and smart pile foundation reinforcement. Case studies from practical engineering projects demonstrate the critical role of these technologies in controlling settlement and enhancing foundation stability. The study further forecasts future development trends and application prospects for intelligent reinforcement techniques in soft soil engineering, while proposing practical solutions to accelerate widespread adoption of these innovative methods.

1. Introduction

Soft soil foundations pose significant challenges in engineering safety due to their low strength, high compressibility, and complex settlement behavior. As urbanization progresses, the increasing demands for construction projects on soft soil have made conventional reinforcement methods increasingly inadequate. Intelligent reinforcement technology, with its advantages of high efficiency and precision, has emerged as a novel solution for soft soil foundation settlement management. This paper focuses on the application of intelligent reinforcement techniques through integrated analysis and evaluation methods for soft soil foundation settlement. By introducing common intelligent reinforcement technologies and principles along with case studies, this research highlights the critical importance and promising future applications of intelligent reinforcement in soft soil foundation engineering[1].

2. Background and status of soft soil foundation settlement

2.1 Characteristics and settlement mechanism of soft soil foundation

Soft soil foundations typically consist of cohesive soils, silt, or loose sandy soils, which are prone to settlement under construction loads. These materials exhibit key characteristics including high water content, low strength, compressibility, and poor bearing capacity. The settlement mechanism primarily depends on soil compressibility and the interaction between soil and water. When external loads act on soft soil foundations, pore water pressure within the soil first increases, accompanied by processes like drainage and consolidation that gradually reduce the volume. The settlement behavior of soft soil foundations is closely related to factors such as soil layer thickness, density, moisture content, and load intensity[2]. In practical engineering, deep excavations, pile foundations, and soil reinforcement are commonly employed to mitigate settlement risks in soft soil foundations. Settlement characteristics can be quantitatively analyzed through methods such as settlement observation, field tests, and numerical simulations, which have been widely adopted in various construction projects. Conventional control measures like preloading, sand piles, and foundation improvement often serve as standard practices for managing soft soil foundation settlement, ensuring stable and load-bearing foundations during engineering implementation[3].

2.2 Research status of soft ground settlement at home and abroad

Research on soft soil foundation settlement in China started relatively late. However, with the acceleration of urbanization, demands for development and construction in soft soil areas have grown increasingly stringent, driving deeper academic exploration. Current research priorities focus on settlement mechanisms, calculation methodologies, reinforcement techniques, and engineering applications. Recent years have seen growing emphasis on real-time monitoring, data analysis, and predictive modeling as intelligent monitoring technologies advance. International research in this field has been more established, particularly in Europe, America, and Japan, where mature theoretical frameworks exist for predicting long-term soil settlement under various loads and optimizing engineering designs in soft soil regions. Foreign studies typically combine precise numerical simulations with physical model experiments and long-term observational data to address settlement challenges. As research progresses, international understanding of soft soil settlement has evolved into a comprehensive approach that considers multi-factor interactions during settlement processes. Through extensive experimentation and data accumulation, scholars worldwide have developed various analytical models tailored for soft soil foundation settlement studies, providing valuable references for practical engineering applications[4].

2.3 Influence of soft ground settlement on engineering safety

Soft soil foundation settlement directly impacts the stability and service life of engineering structures, particularly for high-rise buildings, bridges, and large public facilities. Excessive settlement can easily lead to uneven foundation subsidence, cracking, and severe structural deformation. Therefore, scientifically evaluating and controlling soft soil foundation settlement is crucial for ensuring project safety. In practice, construction period settlement monitoring typically employs methods such as settlement observation wells, laser scanning, and real-time data collection from ground settlement points to track settlement conditions. When exceeding permissible limits are detected, corresponding reinforcement measures-such as pile foundation reinforcement or ground improvement-are implemented to prevent settlement from compromising building stability. Meanwhile, detailed geological surveys and optimized foundation treatment plans during the design phase can effectively mitigate settlement impacts on project safety. Proper settlement control not only ensures structural integrity but also extends building longevity. In China's key engineering projects, settlement control technology has become an indispensable technical approach[5].

3. Settlement analysis and evaluation methods of soft soil foundation

3.1 Basic theory of sedimentation analysis

The fundamental theories of soft soil foundation settlement originate from consolidation and compression principles in soil mechanics. Consolidation theory posits that pore water discharge during loading causes soil compaction and settlement, with water pressure rapidly released in early stages followed by gradual pore water drainage in later phases, resulting in progressively increased settlement. Quantitative analysis of settlement processes can be conducted using soil physical-mechanical properties such as porosity, moisture content, and compressibility modulus. For highly compressible soft soils, the settlement process typically takes several years or even decades to stabilize. The core of settlement analysis lies in determining soil compressibility and consolidation characteristics, employing mathematical models integrated with practical engineering conditions to predict settlement under specific loads. Given the heterogeneous nature and complexity of soft soil layers, settlement analysis generally employs finite element analysis and three-dimensional numerical simulations for more accurate predictions. Theoretical analyses typically combine field test data with laboratory measurements to provide scientific foundations for engineering design.

3.2 Common methods and techniques for settlement assessment

Common settlement assessment methods include direct measurement techniques (primarily consolidation compaction tests), empirical formulas, and numerical simulations. Consolidation compaction tests, as a widely adopted evaluation technique in practical engineering, determine soil compression coefficients and consolidation characteristics by analyzing consolidated and compressive curves. For large-scale soft ground foundation projects, numerical simulation is typically employed for settlement analysis. Common numerical models like finite element method and finite difference method effectively simulate nonlinear and dynamic behaviors of soil under load, while accounting for multi-layered soil characteristics. These simulations comprehensively reflect complex soil responses and settlement processes, offering significant advantages for long-term settlement analysis. Empirical formulas and rules remain widely used, particularly when experimental data are insufficient, enabling rapid settlement estimation. By strategically combining different assessment methods with on-site monitoring data, effective scientific prediction and control of soft ground foundation settlement can be achieved.

3.3 Application and limitation of settlement prediction model

Settlement prediction models are extensively applied in soft soil foundation engineering, particularly for evaluating long-term settlement trends in large-scale construction projects, infrastructure, and transportation systems. Common models include one-dimensional consolidation theory, quadratic compression, and nonlinear models. These frameworks predict settlement magnitude and progression based on soil physical-mechanical parameters, load intensity, and construction methods. While providing crucial decision-making support during project design phases to optimize engineering solutions, existing models exhibit limitations-especially in regions with complex soil structures and variable groundwater conditions where conventional models often underperform. To address these shortcomings, machine learning and artificial intelligence-based settlement prediction models have emerged in recent years. These innovative approaches effectively handle large-scale, complex datasets and enhance prediction accuracy through self-learning mechanisms. However, as they remain experimental in nature, they haven't been widely adopted in practical engineering applications. Future improvements should focus on enhancing model adaptability and precision, particularly for those addressing complex geological scenarios.

4. Application of intelligent reinforcement technology in soft soil foundation

4.1 Overview of intelligent reinforcement technology

Intelligent reinforcement technology utilizes modern information systems, artificial intelligence, IoT, and big data to monitor, analyze, and control the reinforcement process of soft soil foundations in real time, thereby enhancing both reinforcement effectiveness and construction efficiency. Conventional methods like dynamic compaction, preloading, and pile foundation reinforcement typically rely on manual experience and on-site observations during soft soil foundation treatment, which often involve uncertainties and limitations. By implementing intelligent reinforcement technology, real-time data collection and analysis enable dynamic adjustments to reinforcement plans and optimized construction processes, ensuring that reinforcement outcomes meet predetermined objectives.

4.2 Common intelligent reinforcement technology and its principle

Micro-pile reinforcement technology is specifically designed for soft soil foundation improvement. By driving small-diameter piles into the ground to create composite foundations, it enhances both load-bearing capacity and stability. The system integrates construction phases with intelligent monitoring, enabling real-time tracking of pile parameters and ground responses while dynamically adjusting construction plans to ensure optimal reinforcement outcomes. Deployed sensors at the site continuously monitor settlement, pore water pressure, and stress-strain changes, transmitting data to a central processing system. Through data analysis combined with predictive modeling, the system evaluates reinforcement effectiveness to guide construction decisions. Additionally, the smart monitoring system works seamlessly with construction equipment, achieving automated and intelligent operations throughout the process.

4.3 Practical application case analysis of intelligent reinforcement

Intelligent reinforcement technology has been widely implemented in practical engineering projects with remarkable results. For instance, a municipal road project in a certain city utilized smart dynamic compaction technology to reinforce soft soil foundations. By deploying sensors for real-time monitoring of foundation settlement and pore water pressure, the system continuously transmits data to its control module. This allows precise adjustment of compaction energy and frequency based on real-time feedback, ensuring the reinforcement achieves desired outcomes. Another project applied micro-pile reinforcement technology to address soft soil conditions. During construction, the intelligent monitoring system was integrated with micro-pile installation processes, enabling real-time tracking of pile parameters and ground response. Dynamic adjustments to construction plans were made to optimize reinforcement effectiveness throughout the project.

5. Countermeasures and prospects of intelligent reinforcement for settlement of soft soil foundation

5.1 The effect of intelligent reinforcement on settlement control

Intelligent reinforcement technology plays a vital role in controlling settlement of soft soil foundations. By implementing real-time monitoring of foundation settlement, pore water pressure, and soil stress, combined with big data analysis and AI algorithms, dynamic prediction and analysis of ground subsidence can be achieved, providing scientific basis for settlement control. During construction, this technology enables real-time adjustments to parameters and optimization of construction plans, enhancing efficiency and safety while keeping foundation settlement within safe limits. The automated and remote-controlled approach reduces manual intervention, further improving operational efficiency and safety. Through intelligent reinforcement technology, precise settlement control during engineering projects can be realized, ensuring stable and secure operation of construction facilities.

5.2 Future development trend of intelligent reinforcement technology

In the future, intelligent reinforcement technologies will see broader adoption and development in soft soil foundation engineering. Firstly, with advancements in artificial intelligence, big data, and IoT, these technologies will become increasingly intelligent and automated, enabling real-time monitoring, analysis, and intervention for ground settlement and related issues. Secondly, they will emphasize integration with construction processes, making operations smarter and more efficient while enhancing safety. Thirdly, these technologies will prioritize environmental compatibility to minimize ecological impact and promote green construction practices. Furthermore, smart management systems will be integrated throughout projects to improve quality and cost-effectiveness. As technology progresses, intelligent reinforcement methods will increasingly demonstrate their pivotal role in soft soil foundation engineering.

5.3 Prospects of intelligent reinforcement in geotechnical engineering

The promotion and application of intelligent reinforcement technology in geotechnical engineering show promising development prospects. With the accelerating urbanization process, issues related to soft soil foundations have become increasingly prominent, making conventional reinforcement methods inadequate for modern engineering needs. Intelligent reinforcement technology enables real-time monitoring, analysis, and intervention for ground settlement and similar conditions, thereby enhancing project safety and stability while reducing construction risks and costs. Consequently, this technology is expected to see widespread adoption in geotechnical engineering. To facilitate its application, efforts should focus on advancing technological research and innovation to improve maturity and adaptability. Simultaneously, relevant standards and specifications need refinement to ensure standardized implementation. Additionally, strengthening talent cultivation and technical training will help enhance professionals' technical proficiency and practical application capabilities.

6. Conclusions

Intelligent reinforcement technology provides an innovative solution for settlement control in soft soil foundations. Through real-time monitoring and data analysis, this technology enables precise prediction of ground subsidence and dynamic adjustment of construction plans, significantly enhancing the accuracy and efficiency of settlement management. Field applications demonstrate that intelligent reinforcement not only strengthens engineering safety but also optimizes construction processes while reducing both costs and risks. Looking ahead, with technological advancements, intelligent reinforcement will be widely adopted in soft soil foundation projects, driving geotechnical engineering toward more efficient, safer, and sustainable development.

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