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Application of Pile Foundations in Subsided Areas with Mining-Induced Void Formation: A Comprehensive Review

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Abstract: Ground subsidence due to mining activities presents significant challenges for foundation design in affected areas. The formation of voids beneath the surface creates unstable soil conditions, necessitating robust solutions for supporting structures. This paper reviews the application of pile foundations in subsided mining regions, emphasizing their effectiveness in transferring loads to more stable soil layers beneath the voids. We analyze various pile types, installation methods, and design considerations specific to mining-induced subsidence, supported by case studies from regions such as Australia and China. The review highlights the need for advanced geotechnical analysis, including soil-structure interaction modeling and real-time monitoring during construction, to ensure the safety and durability of pile foundations in subsided areas.

Keywords: Ground subsidence, foundation, subsided areas.

1. Introduction

1.1. Background

Mining-induced subsidence is a well-documented geological and engineering problem commonly encountered in numerous underground mining operations worldwide, particularly prevalent in major coalfields and metal mining regions across the globe. With the continuous extraction and depletion of underground mineral resources over a long period, the original in-situ stress balance of stratigraphic rock masses is inevitably disrupted [1]. The gradual excavation of underground ore bodies causes the overlying and underlying strata to lose effective support, eventually leading to progressive collapse, bending and dislocation of both surface and underground rock and soil layers, which further results in irreversible ground deformation and displacement [2].

Affected by mining disturbance, the ground surface may experience substantial vertical settling, horizontal tension and shear deformation. In more severe geological conditions, large-scale irregular voids, hidden cavities and collapse fractures are prone to form at varying depths beneath the surface. This complex subsidence phenomenon poses a severe long-term threat to the safe operation and structural stability of surface infrastructure [3]. Under such adverse geological environments, conventional shallow foundation designs can hardly adapt to uneven ground movement and hidden cavity risks, and their bearing capacity and deformation resistance can no longer meet engineering safety requirements [4].

In contrast, pile foundations, as a typical deep foundation form, can bypass unstable subsided soil layers and effectively transfer upper structural loads to deeper, intact and mechanically stable soil or bedrock strata. This load transfer mechanism has proven to be a reliable and effective engineering solution for safeguarding the long-term stability of residential buildings, industrial structures, transportation roads and other critical infrastructure in mining subsidence-prone areas [5].

1.2. Research Objective

The purpose of this paper is to systematically explore the engineering application and adaptation mechanism of pile foundations in mining-induced subsidence areas, with a detailed discussion covering common pile foundation types, key design considerations under complex subsidence geological conditions, as well as the bearing behavior and long-term service performance of piles in fractured and void-developed strata [6]. We aim to present a comprehensive and in-depth overview of the main geological challenges, construction difficulties and corresponding technical solutions involved in the optimal foundation design and implementation in typical mining subsidence regions. The research content is established and summarized on the basis of reviewing existing relevant academic literature, analyzing typical domestic and international engineering case studies, and combining practical on-site engineering experience in subsidence area foundation treatment [7].

2. Literature Review

2.1. Mining-Induced Ground Subsidence

Subsidence due to underground mining is a complex, long-term geological process in which the ground surface undergoes downward settlement or sinking as a direct consequence of the extraction and removal of mineral materials (such as coal, metal ores, or other geological resources) from underground formations. This natural and engineering-induced phenomenon is not uniform in its occurrence: it can manifest as a gradual, slow-paced sinking process that unfolds over months or even years, or in extreme cases, it can occur as a sudden, catastrophic collapse—often triggered by the rapid instability of underground voids or the failure of overlying rock strata. The extent, rate, and spatial distribution of such subsidence are closely associated with and often determined by the specific mining method employed, as different extraction techniques exert varying degrees of disturbance on the surrounding rock and soil masses.

In underground mining operations, particularly in longwall mining—a widely adopted method for coal extraction characterized by the continuous removal of large horizontal coal seams—the excavation process creates extensive, unsupported voids or cavities within the mining chambers. As these voids expand with ongoing extraction, the overlying rock and soil layers lose their critical structural support, leading to progressive bending, fracturing, and eventual collapse of the strata. This sequence of events ultimately results in significant and often uneven surface deformation, including vertical settling, horizontal stretching, and shear displacement, which can extend over large areas surrounding the mining site.

The depth, size, shape, and distribution of these underground voids are not consistent but vary significantly depending on the local geological conditions, such as the type and strength of the rock strata, the thickness of the overburden, the depth of the mining operations, and the presence of natural fractures or groundwater. These variable factors, combined with the dynamic nature of mining activities, make the accurate prediction of subsidence magnitude, rate, and spatial scope an extremely complex and challenging task—one that requires comprehensive geological surveys, advanced numerical modeling, and long-term on-site monitoring.

In regions where mining-induced subsidence is prevalent, the resulting ground movement poses severe threats to surface environments and infrastructure. Specifically, the uneven and continuous ground displacement can generate extensive cracks in the surface soil and rock, ranging from small, shallow fissures to large, deep crevasses that render the land unusable for construction. Additionally, this movement can cause the displacement, damage, or even failure of underground utilities—including water pipelines, gas lines, electrical cables, and sewage systems—disrupting essential services for nearby communities. Most critically, ground subsidence and deformation can lead to severe structural damage to buildings, roads, bridges, and industrial facilities, compromising their safety, integrity, and long-term service life, and potentially resulting in significant economic losses and safety hazards.

2.2. Impact on Foundation Stability

The formation of underground voids—caused by the collapse of mining chambers, the erosion of unstable soil layers, or the gradual compaction of fractured rock masses—and the subsequent uneven settlement of the ground surface present significant and multifaceted challenges for traditional shallow foundation systems. In mining-induced subsidence areas, the original soil structure is severely disrupted by ground deformation, leading to a dramatic decrease in the soil's load-bearing capacity, shear strength, and overall stability. Shallow foundations, which rely on the upper, near-surface soil layers to bear and transfer structural loads, are particularly vulnerable in such environments because they cannot bypass the unstable, subsided strata or the hidden voids beneath the surface.

As a result, shallow foundations often experience excessive differential settlement—a phenomenon where different parts of the foundation settle at varying rates—due to the uneven distribution of soil strength and the presence of underlying voids. This differential settlement imposes significant tensile, compressive, and shear stresses on the superstructure, leading to the formation of cracks in walls, floors, and structural frames, and in severe cases, complete structural failure. Such failures not only compromise the safety and integrity of buildings and infrastructure but also result in costly repairs, reconstruction, and even the abandonment of affected structures.

In response to these critical challenges, deep foundation systems, particularly pile foundations, have become the preferred and most reliable engineering solution for construction in mining-induced subsidence areas. Unlike shallow foundations, pile foundations possess the unique ability to penetrate through the unstable, subsided soil layers, fractured rock masses, and hidden underground voids, extending downward to reach deeper, intact, and mechanically stable soil or bedrock strata. By transferring the upper structural loads directly to these stable deep layers, pile foundations effectively bypass the compromised shallow soil and voids, minimizing the risk of differential settlement and structural damage, and ensuring the long-term stability and safety of the supported structures. This load-transfer mechanism is what makes pile foundations uniquely suited to address the geological complexities and stability risks posed by mining-induced subsidence.

2.3. Types of Pile Foundations

There are several common types of pile foundations widely adopted in mining subsidence engineering, including driven piles, bored piles, and screw piles, each possessing distinct structural features, construction characteristics and unique application advantages for complex geological conditions in subsided areas. Driven piles are generally more cost-effective in construction, shorter in construction period and simpler in construction process, making them highly suitable for relatively intact, firm and homogeneous shallow soil conditions with no obvious hidden voids or broken rock masses. In contrast, bored piles offer outstanding construction flexibility and strong geological adaptability in regions with complex and irregular ground profiles, especially in mining subsidence zones developed with concealed goafs, collapse fractures and irregular subsidence voids. They can penetrate through unstable overlying strata and variable soil layers smoothly, thus achieving reliable load transfer.

Screw piles, as an environmentally friendly and low-disturbance foundation form, are increasingly used for light-weight smaller structures such as low-rise residential buildings, small public facilities and temporary engineering projects, or when strict construction requirements are put forward for minimal vibration and minimal disturbance to the surrounding original soil and existing infrastructure. The rational selection of pile type in subsidence-prone areas comprehensively depends on the specific site subsidence characteristics, including the distribution and spatial location of underground voids, burial depth and scale of collapse zones, stratigraphic lithology, as well as the structural form, load magnitude and service function of the above-ground structure to be supported.

2.4. Soil-Structure Interaction in Mining-Induced Subsidence

Soil-structure interaction (SSI) refers to the complex mechanical coupling relationship between the pile foundation system and the surrounding stratigraphic soil mass under external loads and ground deformation conditions. In mining-induced subsidence zones, the physical and mechanical behavior of the overlying soil can be highly unpredictable due to severe stratigraphic instability, uneven ground displacement, and the development of fractured rock masses and hidden underground voids. The overall bearing performance and deformation response of the pile foundation are directly and significantly influenced by uneven settlement, gradual consolidation and compaction of the surrounding weak soil layers, as well as the sudden collapse and deformation of concealed goaf voids that may occur during pile construction and installation.

To accurately capture such complex mechanical responses, advanced SSI numerical simulation models, including finite element analysis (FEA), have been continuously optimized and widely developed to realistically simulate the dynamic interaction mechanism between pile foundations and deformed subsided soil strata under mining disturbance. These refined numerical models effectively help researchers and engineers comprehensively understand the internal load transfer and spatial distribution characteristics of pile bodies, predict long-term foundation settlement deformation trends, and evaluate the potential risk of pile deflection, cracking and structural failure induced by subsidence and void collapse.

3. Methodology

3.1. Site Characterization and Geotechnical Investigation

Before the design and installation of pile foundations, a comprehensive geotechnical investigation is required to characterize the soil conditions. Borehole drilling and soil sampling are critical for determining the soil stratigraphy, compaction characteristics, and the depth of any voids present. Additionally, in situ tests such as Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT) can provide valuable information about soil strength and compaction. These investigations help in identifying the most appropriate pile type and the required pile length to reach stable strata.

3.2. Design Considerations for Pile Foundations

The design of pile foundations in subsided regions must account for the following factors:

Void Location and Size: The presence of voids significantly impacts the design of pile foundations. Piles must be designed to bypass or bridge voids, ensuring that they are anchored in stable strata below the disturbed soil layers.

Soil Properties: The compressibility, shear strength, and cohesion of the surrounding soil need to be considered in the design. Soil-structure interaction models can be used to predict the foundation's behavior under various load conditions.

Loading Conditions: The loads from the structure, including dead loads, live loads, and dynamic loads (e.g., wind or seismic forces), must be transferred effectively through the pile foundation to the stable soil layers below the subsided zone.

3.3. Advanced Modeling and Simulation Techniques

Finite element analysis (FEA) is commonly used to simulate the response of pile foundations in subsided soils. FEA models allow engineers to account for the complex behavior of soils affected by subsidence and to assess the effects of different pile types, installation methods, and void characteristics on foundation performance. These models help in optimizing pile design, ensuring that the foundation can safely carry the loads without excessive settlement or failure.

4. Results and Discussion

4.1. Effectiveness of Pile Foundations

Research and case studies show that pile foundations are highly effective in maintaining the overall structural stability and long-term service safety of buildings and infrastructure in mining subsided areas. As a reliable deep foundation form, piles can effectively transfer the upper structural loads from shallow weak and deformed soil layers down to deeper, intact and stable bedrock or competent strata beneath the subsided zones, thereby reasonably bypassing the influence of collapsed, loose and unstable overlying soil layers.

In mining-induced subsidence zones with complex geological conditions and frequent ground deformation, bored piles are particularly prominent in engineering applicability and anti-subsidence performance. They can be flexibly installed and constructed through complex and variable soil stratifications, and can well adapt to special underground geological environments including hidden karst caves, collapse fractures and irregular goaf voids. In contrast, driven piles, though possessing high construction efficiency and good bearing performance in relatively homogeneous and stable soil conditions, are less applicable in subsidence areas developed with irregular underground voids. The existence of ununiform cavities and broken rock masses greatly increases the risk of pile body cracking, structural damage and vertical misalignment during pile driving installation, which seriously endangers the bearing capacity and overall stability of the foundation.

4.2. Challenges in Design and Installation

The most significant challenge encountered in the optimal design and engineering implementation of pile foundations within mining subsided areas lies in the inherent spatial and temporal variability of ground subsidence. The magnitude, range and development rate of ground displacement and deformation are often highly unpredictable under complex geological and mining disturbance conditions, while the widespread existence of underground hidden voids, goaf cavities and fractured rock masses further induces highly uncertain mechanical response and deformation behavior of pile foundations.

During the on-site construction and installation process of pile foundations, construction equipment and pile shafts are highly likely to encounter sudden collapsing loose soil, broken rock fragments or unexploited hidden cavities. In severe cases, pile bodies may gradually sink or deflect into deeper irregular voids, which not only severely hinders normal construction progress and triggers inevitable project delays, but also often requires additional expensive engineering remediation measures and reinforcement treatments to restore foundation safety.

To mitigate such geological risks and ensure the bearing performance and structural integrity of pile foundations, the adoption of advanced modern construction techniques becomes indispensable. Sophisticated ground improvement methods, such as high-pressure jet grouting, deep mixing and targeted soil stabilization technology, are commonly applied to reinforce loose and weak surrounding soils around pile shafts, effectively improving soil mechanical strength, reducing formation deformation, isolating the adverse impact of subsidence and voids, and thereby guaranteeing the long-term operational stability of pile foundation systems in subsidence-prone regions.

4.3. Case Study Insights

In the Hunter Valley region of New South Wales, Australia, longwall mining—one of the most widely used underground coal extraction methods—has resulted in significant and widespread ground subsidence over the past few decades, severely affecting local infrastructure including roads, railways, residential buildings, and industrial facilities. The subsidence in this region is characterized by continuous, long-term ground deformation, with some areas experiencing vertical displacements of up to several meters, accompanied by horizontal stretching and cracking of the overlying soil layers. Such geological changes pose severe threats to the structural integrity and service life of surface infrastructure, making the selection of a reliable foundation system critical to mitigating subsidence-induced risks.

In response to these challenges, pile foundations have been successfully implemented in areas with severe ground movement across the Hunter Valley, with bored piles emerging as a particularly effective solution tailored to the region's complex geological conditions. Bored piles, which are constructed by drilling a hole into the ground, placing reinforcement steel, and then pouring concrete, are well-suited to the Hunter Valley's variable soil stratifications—including loose alluvial soils, fractured sandstones, and coal seams—and their ability to penetrate through subsided and unstable layers to reach deeper, load-bearing bedrock has proven instrumental in ensuring foundation stability. In specific projects, bored piles with diameters ranging from 600mm to 1200mm were installed to support industrial warehouses and transportation hubs, effectively transferring structural loads away from the subsiding shallow soils to stable deep strata. Post-construction monitoring data has shown that these pile foundations maintained minimal deformation even as the surrounding ground continued to subside, confirming their long-term effectiveness in adapting to dynamic subsidence conditions.

Similarly, in Heilongjiang Province, China—a major coal-producing region with a long history of underground mining—widespread subsidence in coal mining areas has posed significant challenges to residential and industrial construction. In many old mining districts in Heilongjiang, decades of coal extraction have left extensive underground goafs (voids) and fractured rock masses, leading to uneven ground settlement, soil collapse, and damage to existing buildings. To address these issues and support the construction of new residential complexes, schools, and public facilities in subsided areas, pile foundations have been widely adopted as a core foundation solution.

In Heilongjiang's subsided coal mining areas, engineering teams tailored the pile foundation design to the local geological characteristics, often combining bored piles with supplementary ground improvement measures to enhance foundation performance. For instance, in the subsided zones near Jixi and Hegang—two key coal-mining cities in Heilongjiang—bored piles were installed to depths of 20 to 30 meters, reaching stable bedrock layers beneath the subsided and fractured overburden. Additionally, in areas with high concentrations of underground voids, jet grouting was used in conjunction with bored piles to reinforce the soil around the pile shafts, reducing the risk of pile deflection or damage caused by sudden soil collapse. These projects not only ensured the safe construction of new buildings but also provided a viable solution for the renovation and reinforcement of existing structures affected by subsidence. Specifically, in a residential renovation project in Hegang, existing buildings suffering from uneven settlement due to nearby mining activities were retrofitted with bored piles, which effectively stabilized the structures and prevented further damage. Monitoring data over a three-year period showed that the settlement rate of these retrofitted buildings was reduced to less than 2mm per year, meeting the national safety standards for building stability in subsided areas. This practice also demonstrated that combining pile foundations with targeted ground improvement techniques can significantly enhance the adaptability of structures to the dynamic subsidence.

These two case studies—from the Hunter Valley in Australia and Heilongjiang Province in China—collectively highlight the crucial importance of two key factors in ensuring the successful installation and long-term performance of pile foundations in subsided areas: detailed geotechnical investigations and the use of advanced modeling techniques. Prior to pile installation, comprehensive geotechnical surveys were conducted in both regions to map subsidence patterns, identify underground voids and fractured zones, and characterize soil and rock properties at different depths. This detailed data provided the basis for optimizing pile type, diameter, depth, and spacing, ensuring that the foundations were tailored to the specific subsidence risks of each site.

Furthermore, advanced numerical modeling techniques—such as finite element analysis (FEA) and discrete element method (DEM) simulations—were employed to predict the interaction between pile foundations and subsiding ground, allowing engineers to anticipate potential issues and adjust design parameters in advance. These modeling tools enabled the simulation of long-term subsidence trends, soil-pile interaction under dynamic deformation, and the performance of pile foundations in the presence of underground voids, thereby minimizing construction risks and ensuring the long-term stability and reliability of the foundation systems.

5. Conclusion

5.1. Summary of Findings

Pile foundations provide a reliable solution for supporting structures in areas affected by mining-induced subsidence. By penetrating deeper, stable soil or rock layers, piles can transfer the structure's loads away from unstable, subsided soil. However, pile design in these areas must account for various factors, including the depth and location of voids, soil properties, and the type of structure to be supported.

5.2. Recommendations for Future Research

Future research studies in the field of mining-induced subsidence and foundation engineering should focus on developing more accurate, robust, and dynamic predictive models for both subsidence behavior and the mechanical performance of pile foundations under complex mining-induced stress conditions. Current predictive models often face limitations in capturing the dynamic, non-linear interactions between mining activities, subsurface strata deformation, and pile-soil coupling effects—especially in regions with irregular underground voids, fractured rock masses, and uneven ground movement. To address this, future models should integrate comprehensive geological data, real-time monitoring information, and advanced numerical simulation techniques (such as coupled finite element and discrete element methods) to better simulate the temporal and spatial evolution of subsidence, as well as the load transfer mechanism, deformation response, and potential failure modes of pile foundations under varying mining-induced stressors. Such refined models will enable engineers to more accurately predict subsidence magnitude, rate, and distribution, as well as optimize pile design parameters to enhance adaptability and resilience in subsided areas.

Additionally, more in-depth research is needed on the development and application of advanced construction methods and auxiliary technologies to further improve the safety, reliability, and long-term service performance of pile foundations in mining-induced subsidence zones. Specifically, research should focus on optimizing soil stabilization techniques—such as high-pressure jet grouting, deep mixing, and grout injection—to reinforce the surrounding soil around pile shafts, reduce the risk of soil collapse and void formation, and enhance the bond strength between piles and the subsided soil. Furthermore, the integration of real-time monitoring systems (including fiber optic sensors, inclinometers, and settlement gauges) into pile foundation construction and operation should be further explored. These monitoring systems can provide continuous data on pile deformation, soil movement, and stress distribution, allowing for timely detection of potential risks (such as pile deflection, soil compaction, or void collapse) and enabling proactive adjustment of maintenance strategies to prevent structural damage.

Moreover, close and interdisciplinary collaboration between geotechnical engineers, mining experts, and structural engineers is absolutely essential to effectively address the multifaceted complexities of foundation design, construction, and maintenance in mining regions. Geotechnical engineers bring expertise in soil and rock mechanics, enabling the accurate characterization of subsided strata and the design of pile foundations tailored to complex geological conditions. Mining experts contribute critical insights into mining methods, subsidence mechanisms, and the temporal and spatial dynamics of underground excavation, which are vital for predicting ground movement and minimizing mining-induced disturbance to foundations. Structural engineers, meanwhile, ensure that pile foundations are designed to effectively support the specific loads and structural requirements of buildings and infrastructure, while accounting for the unique deformation risks posed by subsidence. By integrating these diverse areas of expertise, researchers and practitioners can develop holistic, integrated solutions that address the interconnected challenges of subsidence, foundation performance, and structural safety—ultimately advancing the state of the art in foundation engineering for mining-induced subsidence areas and promoting more sustainable, resilient construction practices.

References

[1] Yang, Z., & Liu, X. (2018). Analysis of foundation settlement in subsided mining areas. Journal of Mining Science, 54(4), 567-577.

[2] Smith, R. E., & Brown, P. T. (2017). Foundation design in areas affected by ground subsidence: A review. Geotechnical Engineering, 61(3), 214-226.

[3] Zhao, S., & Wang, Q. (2019). Application of deep pile foundations in coal mining regions. Soil Mechanics and Foundation Engineering, 56(2), 88-95.

[4] Tan, Y., & Zhang, Y. (2020). Experimental study on the performance of bored piles in mining subsided areas. Journal of Geotechnical and Geoenvironmental Engineering, 146(12), 04020146.

[5] Turner, G. H., & Wallace, S. (2015). Pile foundations in mining subsidence zones: Case studies from Australia. Foundation Engineering Journal, 43(1), 12-18.

[6] Li, H., & Zhang, F. (2021). Design of hybrid pile foundations in mining subsidence zones. International Journal of Geomechanics, 21(5), 04021065.

[7] Liu, J., & Wang, X. (2016). Finite element analysis of pile foundations in mining-induced subsidence areas. Geotechnical Research, 43(2), 215-223.