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GEOTECHNICAL CHALLENGES IN URBAN EXPANSION: ADDRESSING SOFT SOIL, GROUNDWATER, AND SUBSURFACE INFRASTRUCTURE RISKS IN MEGA CITIES

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Keywords

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ABSTRACT

This study provides a comprehensive meta-analysis of 100 high-quality research articles to evaluate the advancements, challenges, and future directions in geotechnical engineering practices within urban environments. The review focuses on four key themes: remote sensing and monitoring technologies, artificial intelligence and machine learning applications, Building Information Modeling (BIM), and sustainable geotechnical engineering practices. Remote sensing tools such as LiDAR, ground-penetrating radar, and satellite imagery have revolutionized geotechnical investigations, enabling accurate subsurface mapping and real-time risk monitoring. Artificial intelligence and machine learning have demonstrated significant potential in predictive modeling, soil stabilization optimization, and groundwater management, offering cost-effective and efficient solutions to complex geotechnical challenges. BIM has emerged as a powerful tool for improving collaboration, data integration, and decision-making in large-scale geotechnical projects, particularly in urban megacities. Furthermore, sustainable practices such as the use of recycled materials, bio-cementation, and green infrastructure are becoming increasingly integral to aligning geotechnical engineering with global sustainability goals. This meta-analysis synthesizes findings from the reviewed articles, identifying gaps in research and highlighting emerging trends that underscore the importance of interdisciplinary approaches. By integrating innovative technologies and sustainable practices, this study emphasizes the need for continuous advancements to address the complexities of urban geotechnical projects and contribute to the development of resilient and environmentally sustainable infrastructure

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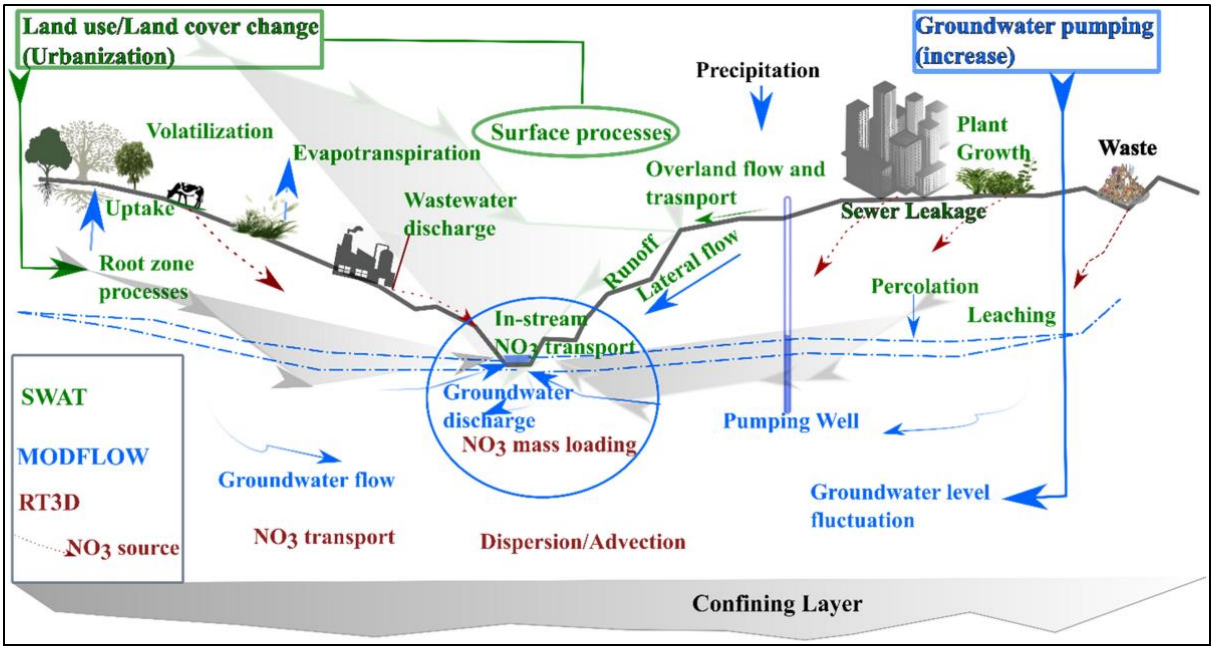
1 INTRODUCTION

The rapid pace of urbanization, particularly in mega cities, presents significant challenges for geotechnical engineering (Schuur et al., 2015). Mega cities are centers of economic growth, social development, and technological advancement, attracting millions of inhabitants annually (Mascort-Albea et al., 2019). However, this influx of people necessitates the expansion of infrastructure, which often involves building on marginal or unsuitable lands (Vonk et al., 2012). The geotechnical challenges associated with urban expansion include the prevalence of weak and compressible soils, fluctuating groundwater conditions, and the increasing demand for underground infrastructure development (McNutt et al., 2012). These challenges require innovative approaches and a nuanced understanding of soil behavior, water management, and subsurface risks to ensure the stability and longevity of urban infrastructure (Saad et al., 2020). Among the most pressing issues is the prevalence of soft soils, which are characterized by their low bearing capacity and high compressibility. These soils are commonly found in coastal areas and floodplains, making cities like Jakarta, Dhaka, and Bangkok particularly vulnerable (Mohamad et al., 2010). Construction on such soils is fraught with risks, including excessive settlement and foundation instability, which can lead to structural damage over time. Addressing these challenges often requires advanced soil improvement techniques, such as preloading, vacuum consolidation, and the use of geosynthetics (Chen et al., 2013). While these methods have proven effective, their implementation can be costly and environmentally disruptive. The need to balance economic feasibility with environmental sustainability has driven research into alternative soil stabilization methods, such as the use of bio-cementation and enzyme-based solutions (Lubchenco & Haugan, 2023).

Groundwater management is another critical geotechnical concern in expanding urban areas. Urbanization often disrupts natural hydrological cycles, leading to changes in groundwater levels that can cause ground subsidence, destabilize foundations, and compromise the integrity of underground structures (Zhu et al., 2012). Overextraction of groundwater for domestic and industrial use has exacerbated subsidence in cities like Mexico City and Bangkok, where subsidence rates have reached as high as 20 cm per year in some areas (Boscardin & Cording, 1989). In response, researchers and practitioners have developed integrated groundwater management strategies, including artificial recharge, managed aquifer recovery, and the use of impermeable barriers to limit water ingress (Khoo et al., 2019). Additionally, advanced predictive models and monitoring systems are

Figure 1: surface and subsurface processes and modeling framework



Source: Ware et al. (2023)

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increasingly being employed to anticipate and mitigate the impacts of groundwater fluctuations on urban infrastructure. The complexity of subsurface infrastructure further intensifies the geotechnical challenges of urban expansion. Mega cities rely heavily on underground networks for transportation, utilities, and storage, creating an intricate web of subsurface structures that often interact with new developments (Baena-Escudero et al., 2019). The construction of underground metro systems, tunnels, and deep basements frequently intersects with existing utilities and aging infrastructure, increasing the risk of structural damage and service disruptions. Modern geotechnical practices emphasize the importance of advanced modeling techniques, such as finite element analysis and numerical simulations, to predict soil-structure interactions and optimize construction designs (Morillo et al., 2007). These tools, combined with geospatial technologies, allow engineers to monitor and manage risks in real time, minimizing disruptions and ensuring project safety.

Technological advancements have revolutionized the field of geotechnical engineering, offering innovative solutions to long-standing challenges. The integration of remote sensing technologies, geotechnical sensors, and machine learning algorithms has significantly enhanced the ability to monitor, predict, and mitigate geotechnical risks (Mohamad et al., 2010). For instance, ground-penetrating radar and LiDAR are increasingly used to map subsurface conditions with high precision, while artificial intelligence tools analyze complex datasets to forecast soil behavior under various loading conditions (Chen et al., 2013). Moreover, the adoption of Building Information Modeling (BIM) in geotechnical projects facilitates better coordination among stakeholders and improves decision-making processes (Hasan & Islam, 2024; Lubchenco & Haugan, 2023). These technologies not only enhance the efficiency of geotechnical investigations but also contribute to the sustainability of urban development projects. This study aims to systematically review and synthesize existing research on geotechnical challenges in urban expansion, focusing on soft soils, groundwater management, and subsurface infrastructure risks in mega cities. The review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, comprehensiveness, and reproducibility. By following the PRISMA framework, this study systematically identifies relevant literature through a structured search strategy, employing predefined inclusion and exclusion criteria to filter high-quality studies. Data extraction focuses on key themes, methodologies, and findings related to the geotechnical challenges of urban expansion, highlighting innovative approaches and emerging technologies. The objective is to consolidate evidence-based insights that support geotechnical risk mitigation while advancing sustainable urban development strategies. This review seeks to provide practitioners, researchers, and policymakers with actionable knowledge to address geotechnical challenges in the context of rapid urbanization.

2 LITERATURE REVIEW

The literature on hybrid AI models for grid stability in solar energy networks reflects a rapidly evolving field, driven by the increasing adoption of renewable energy and the need for robust grid management solutions. Researchers have explored various AI-driven methodologies to address the challenges posed by the intermittent nature of solar power generation, focusing on predictive accuracy, real-time decision-making, and system optimization. This section systematically reviews key contributions to the domain, highlighting advancements in machine learning architectures, integration strategies with smart grids, and the practical implications of these technologies. The review also identifies gaps in existing research and outlines future directions for enhancing the reliability and efficiency of solar energy networks.

2.1 Soft Soils in Urban Expansion

Soft soils are geotechnically challenging due to their distinct properties, which include high compressibility, low shear strength, and a tendency for excessive settlement under load (Chandler, 2000; Islam, 2024). These characteristics are primarily observed in soils with high organic content or clayey compositions found in coastal and floodplain regions. For instance, soft clays are particularly prone to consolidation over extended periods, leading to significant settlement issues that impact the stability of buildings, roads, and other infrastructure (Islam et al., 2024; Ortiz-Hernández et al., 2022). Additionally, the water retention capacity of these soils exacerbates problems such as shrink-swell behavior, further complicating construction efforts (Emeriault et al., 2004; Islam et al., 2024). Understanding these intrinsic properties is crucial for designing suitable geotechnical solutions in urban areas. Moreover, in rapidly urbanizing regions like Bangkok, Jakarta, and Dhaka, the prevalence of soft soils poses significant risks to infrastructure development. Bangkok, for example, is characterized by a thick layer of soft marine clay that has resulted in widespread settlement and structural instability, especially in high-rise construction (Islam et al., 2024; Paassen et al., 2010). Similarly, Jakarta's expansive clay soils have caused differential settlements that affect roads and drainage systems, increasing flood risks (Paassen et al., 2010). Dhaka, situated in a floodplain region, frequently experiences issues with embankment stability and road subsidence due to its soft alluvial soils (Neumann et al., 2015). These case studies underscore the need for targeted soil improvement techniques to mitigate the risks associated with soft soil conditions in urban contexts.

Several studies highlight the geotechnical implications of soft soils in urban settings, focusing on their mechanical and hydraulic behavior under load. For example, soft soils exhibit significant pore water pressure buildup during construction, which reduces effective stress and further decreases shear strength, a phenomenon well-documented in Bangkok's infrastructure failures (Feighery et al., 2013). Research in Jakarta has shown that inadequate drainage systems aggravate the settlement of soft soils, leading to severe structural damage (Neumann et al., 2015). Moreover, Schuur et al. (2015) emphasize the importance of understanding the creep behavior of soft soils in mega cities, as delayed deformation can cause long-term damage to infrastructure. These findings highlight the necessity of comprehensive site investigations and advanced modeling techniques in urban geotechnical design.Moreover, innovative approaches to addressing soft soil challenges are increasingly being adopted, particularly in cities with high urbanization rates. Soil stabilization methods, such as preloading, vacuum consolidation, and chemical stabilization, have been successfully applied in regions like Bangkok and Jakarta (Neumann et al., 2015; Uddin et al., 2024). Additionally, newer technologies, including bio-cementation and enzyme-induced carbonate precipitation, offer eco-friendly solutions to improving soft soil properties (Oh & Sun, 2007). For instance, the use of microbial activity to induce calcite precipitation has shown promise in increasing the strength and reducing the compressibility of soft clays in experimental studies (Neri et al., 2008). These advancements not only enhance construction feasibility but also align with sustainable development goals, making them particularly valuable for geotechnical projects in urban areas.

2.2 Geotechnical Issues in Construction on Soft Soils

Settlement and stability problems are among the most significant challenges when constructing on soft soils. These soils are prone to excessive primary and secondary settlement due to their high compressibility,

Figure 2: Challenges and Solutions in Soft Soil Urban Expansion

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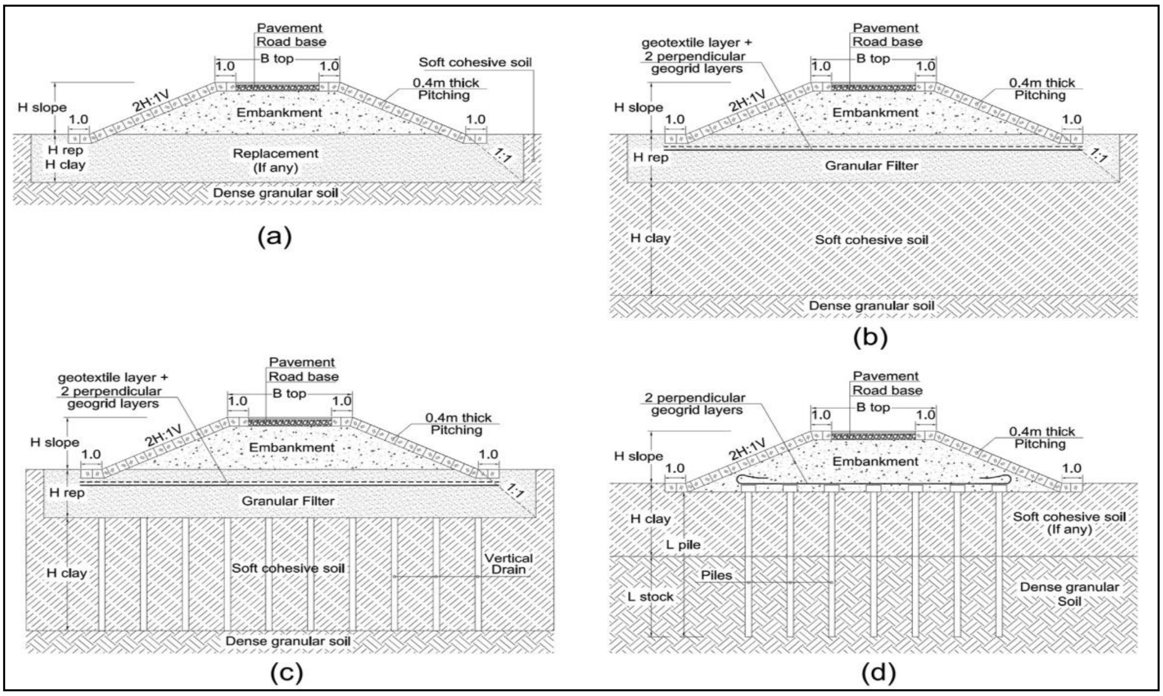
especially under heavy loads (Rahil et al., 2016). Studies show that differential settlement often leads to cracking and distortion in buildings, resulting in long-term structural instability (NasrAhmed, 2014; Rahil et al., 2016). For instance, infrastructure in cities like Bangkok and Dhaka frequently suffers from uneven ground subsidence caused by the consolidation of soft clays (Mullick et al., 2019). This issue is further compounded by external factors such as groundwater extraction, which accelerates settlement and exacerbates structural risks (Neumann et al., 2015). These findings highlight the necessity of accurate prediction models and soil treatment techniques to mitigate settlement-related problems. Moreover, the stability of structures built on soft soils is often compromised due to their low shear strength, which can result in foundation failures and slope instability (Feighery et al., 2013). Research indicates that soft soils are particularly vulnerable to slope failures during excavation or under lateral loading, leading to safety concerns for urban developments (Mullick et al., 2019). Case studies from Jakarta reveal that road embankments frequently experience slope failures due to inadequate consideration of soil properties during design. These failures underline the importance of employing advanced geotechnical techniques, such as the use of retaining structures and reinforcement systems, to improve slope stability and ensure the safety of urban projects (Emeriault et al., 2004).

Soft soils pose significant challenges to foundation design, requiring innovative solutions to address their inherent weaknesses. Shallow foundations on soft soils are prone to settlement issues, leading to differential movement and structural distortions (Pham et al., 2018). Deep foundation systems, such as piles, are often employed to transfer loads to more stable strata; however, their design must account for the potential negative skin friction caused by soil consolidation (Ortiz-Hernández et al., 2022). For example, research in Bangkok has shown that pile foundations can experience additional stress due to drag-down forces, necessitating detailed geotechnical analysis and design adjustments (McGann et al., 2015). These studies emphasize the need for customized foundation systems tailored to site-specific conditions. Moreover, structural integrity is frequently compromised in soft soil environments due to soil-structure interactions that result in uneven stress distribution (Liu et al., 2020). Buildings constructed on soft soils may suffer from tilting, cracking, or even collapse if the geotechnical parameters are not adequately considered during the design phase (Mahdi et al., 2021). Studies highlight the use of geotechnical modeling tools, such as finite element analysis, to simulate soil-structure interactions and predict potential risks (Liu et al., 2020; Mahdi et al.,

Figure 3: Soft clay improvement techniques



Source:(Mahdi et al., 2021)

2021; McGann et al., 2015). Additionally, incorporating ground improvement techniques, such as preloading or the use of geotextiles, can enhance the soil's bearing capacity and improve structural stability (Khan et al., 2021). These methods not only mitigate risks but also provide a cost-effective approach to urban construction in challenging geotechnical environments.

2.3 Conventional Soil Stabilization Techniques

Preloading is a widely used technique for improving soft soils by applying a temporary surcharge load to accelerate consolidation and reduce post-construction settlement (Escudero et al., 2021). The principle behind preloading lies in the dissipation of excess pore water pressure, which enhances the soil's effective stress and increases its bearing capacity. For example, preloading has been extensively used in coastal areas like Bangkok and Shanghai to prepare soft clay deposits for infrastructure development (Silvestri et al., 2003). The effectiveness of preloading can be improved by combining it with vertical drains, which expedite the drainage process and further enhance consolidation rates (Mahdi et al., 2021). This technique is particularly beneficial for large-scale projects requiring stable foundations on compressible soils.Moreover, dynamic compaction is another effective soil improvement method that involves the repeated dropping of heavy weights onto the ground surface to densify loose soils (McGann et al., 2015). This technique is primarily used for granular soils but has shown promising results in improving soft soils when combined with other methods, such as preloading or chemical stabilization (Ortiz-Hernández et al., 2022). The key advantage of dynamic compaction is its cost-effectiveness and ability to improve soil properties over large areas in a relatively short time (Azari et al., 2016). However, its applicability is limited by factors such as the depth of improvement and the proximity of sensitive structures, as the vibrations generated can lead to disturbances in nearby areas (Liu et al., 2020).

Chemical stabilization is a widely adopted technique for enhancing the properties of soft soils by adding binders such as lime, cement, or fly ash to improve strength and reduce compressibility (Soriano-Cuesta et al., 2023). Lime stabilization works by reacting with soil minerals to form cementitious compounds that increase soil stiffness and durability (Khan et al., 2021). This method is particularly effective for clayey soils with high plasticity, as lime reduces plasticity and improves workability. For instance, lime stabilization has been successfully used in road construction projects in regions with expansive clays, such as Texas and parts of India (Pham et al., 2017). Furthermore, cement stabilization is another commonly used method, offering significant improvements in compressive strength and durability by forming a cemented matrix within the soil (Kiran et al., 2016). This technique is widely applied in urban areas where high load-bearing capacity is required, such as for high-rise building foundations and transportation infrastructure (Neumann et al., 2015). Cement-stabilized soils exhibit reduced permeability, making them suitable for applications where water infiltration needs to be controlled (Lapworth et al., 2012). However, the environmental impact of cement production has driven research into alternative binders and supplementary materials.Moreover, Fly ash, a byproduct of coal combustion, has gained popularity as a sustainable option for chemical stabilization due to its pozzolanic properties, which enhance soil strength and reduce settlement (Antoniou & Tsiambaos, 2017). Fly ash is often used in combination with lime or cement to achieve optimal results, as it reacts with calcium hydroxide to form additional cementitious compounds

Table 1: Comparison of Stabilization Techniques

Technique	Main Application	Advantages	Limitations
Preloading	Soft soils, coastal areas	Effective for large-scale projects, can be combined with vertical drains	Time-consuming process
Dynamic Compaction	Granular soils	Cost-effective, quick improvement over large areas	Limited depth, potential disturbance to nearby structures
Lime Stabilization	Clayey soils	Reduces plasticity, improves workability	May not be suitable for all soil types
Cement Stabilization	Urban infrastructure	High strength, reduced permeability	Environmental concerns due to cement production
Fly Ash Stabilization	Sustainable projects	Cost-effective, environmentally friendly	May require combination with other binders for optimal results

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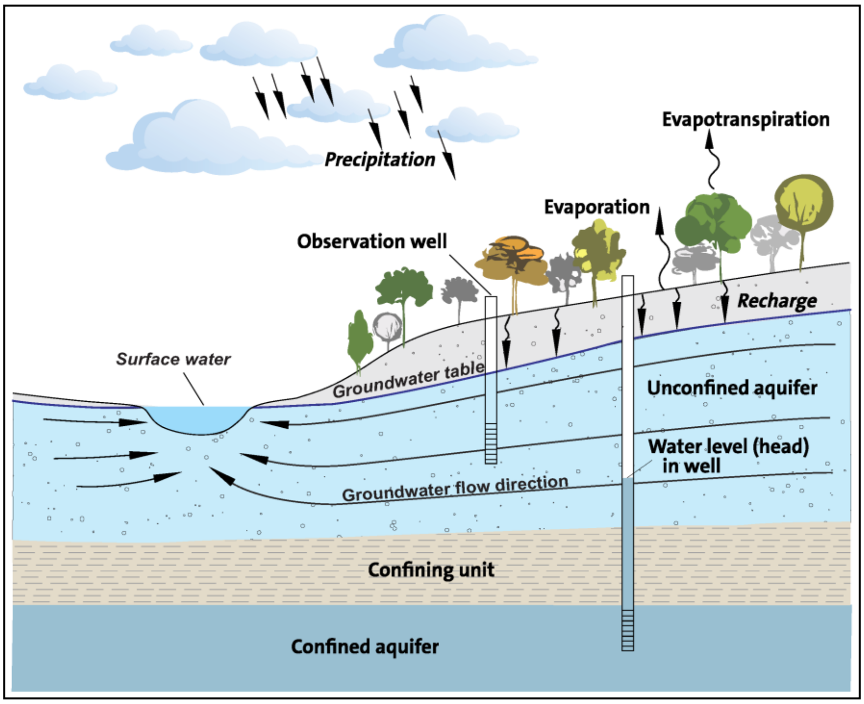
(Wei et al., 2023). Studies in regions like Southeast Asia and the United States have demonstrated the cost-effectiveness and environmental benefits of fly ash stabilization in large-scale geotechnical projects (NasrAhmed, 2014). These advancements underscore the growing emphasis on sustainable practices in soil stabilization.

Groundwater Management in Urbanized Environments

Groundwater fluctuations significantly impact urban stability, with overextraction often resulting in ground subsidence and damage to infrastructure. Mexico City, one of the most documented cases, experiences subsidence rates exceeding 20 cm annually due to excessive groundwater withdrawal for domestic and industrial purposes (McGann et al., 2015). Similarly, Tokyo has faced severe subsidence issues in its low-lying areas, which have been mitigated only through strict regulations on groundwater extraction (Lapworth et al., 2012). These examples highlight the critical relationship between groundwater overextraction and the destabilization of urban infrastructure, including roads, pipelines, and building foundations. Studies emphasize the need for real-time groundwater monitoring and predictive modeling to mitigate such risks (Son, 2014). Moreover, groundwater table fluctuations are directly linked to the stability of urban infrastructure. Changes in water tables alter the effective stress in soils, which can lead to differential settlement, cracking, or tilting of structures (NasrAhmed, 2014). For instance, research in Dhaka and Jakarta has shown that groundwater depletion exacerbates soil consolidation, increasing the risk of structural failure in areas with soft soil deposits (Almajed et al., 2021). Conversely, rising water tables due to poor drainage or flooding can weaken soil strength, posing additional risks to foundations and underground facilities (Khan et al., 2021). These findings underscore the importance of maintaining balanced groundwater levels to ensure urban stability.

Urbanization disrupts natural hydrological cycles, particularly by limiting groundwater recharge. The sealing of surfaces through concrete and asphalt reduces the infiltration of rainwater, preventing the natural replenishment of aquifers (Arnous, 2011). This phenomenon is especially problematic in highly urbanized regions like Los Angeles and Shanghai, where decreased recharge rates contribute to long-term groundwater depletion (Emeriault et al., 2004). Furthermore, the reduced permeability of urban surfaces increases surface runoff, exacerbating flood risks and straining drainage systems (Worsa-Kozak et al., 2020). These challenges necessitate innovative urban planning strategies that incorporate green

Figure 4: Cross-section of a typical groundwater flow system



Source: (Worsa-Kozak et al., 2020)

infrastructure to promote groundwater recharge. Moreover, increased surface water infiltration, when poorly managed, can also pose risks to urban environments. Excess infiltration due to inadequate drainage systems or poorly planned green spaces can elevate groundwater levels, leading to soil saturation and instability (Su et al., 2006). For example, studies in Bangkok highlight that unregulated water infiltration during the monsoon season has caused significant foundation weakening in residential areas (Cong & Inazumi, 2024). Thus, urbanization necessitates careful management of surface water to balance the benefits of infiltration with the risks of over-saturation and soil destabilization.

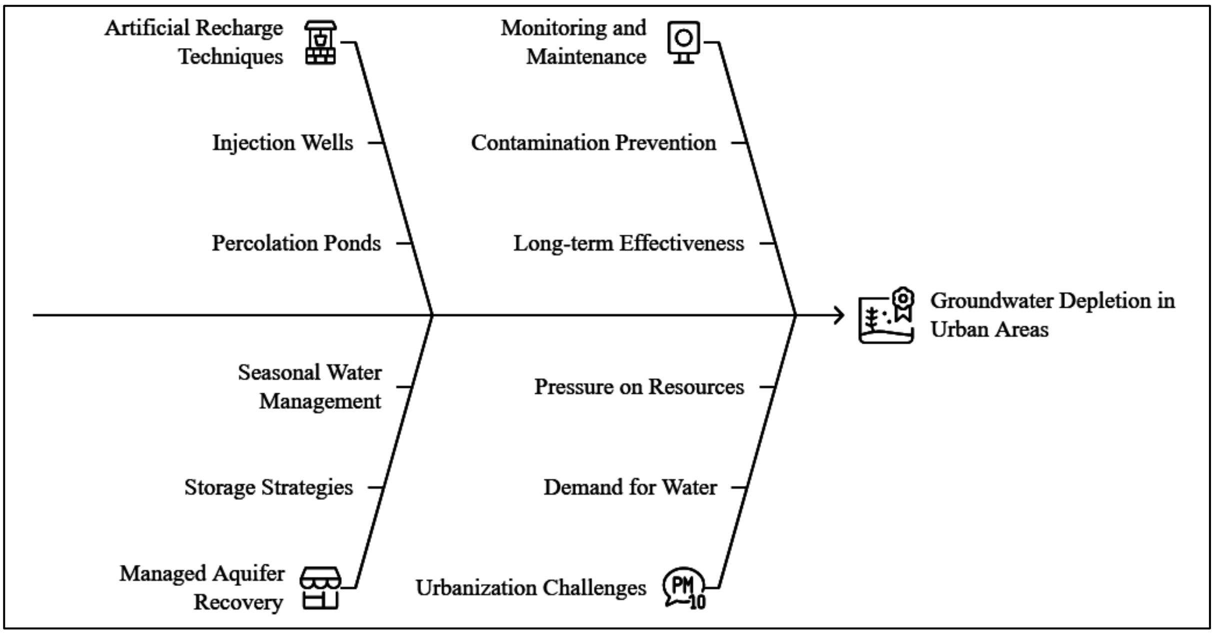
2.4 Strategies for Sustainable Groundwater Management

Artificial recharge techniques, such as injection wells and percolation ponds, have emerged as effective strategies for mitigating groundwater depletion in urban areas. Injection wells involve the direct introduction of surface water into aquifers, while percolation ponds facilitate infiltration by retaining water in permeable areas (Li et al., 2016). These methods have been successfully implemented in regions like California and Singapore to enhance aquifer recovery and stabilize groundwater levels (Culligan et al., 2019). However, these techniques require robust monitoring and maintenance to prevent contamination and ensure long-term effectiveness (May et al., 2010). Managed aquifer recovery (MAR) has gained traction as an integrated approach to groundwater management, combining artificial recharge with storage strategies. MAR systems store excess surface water during periods of surplus for use during dry seasons, ensuring a sustainable supply of groundwater (Cong & Inazumi, 2024). Examples from Australia and the Netherlands demonstrate the efficacy of MAR in maintaining groundwater balance while addressing seasonal water scarcity (McGranahan et al., 2007). Additionally, MAR systems have been shown to mitigate subsidence risks by stabilizing aquifer pressure (Culligan et al., 2019). As urbanization continues, the adoption of MAR and similar strategies will be critical to achieving sustainable groundwater management in urban environments.

2.5 Advanced Analytical and Modeling Tools

Finite Element Analysis (FEA) is a powerful computational tool widely used to predict soil-structure interactions in geotechnical engineering. FEA enables the simulation of complex interactions between soil and structures under various loading conditions, providing detailed insights into stress distributions, deformations, and failure mechanisms (Masoud, 2016). For example, FEA has been successfully applied in designing pile foundations in soft soil regions of Bangkok, where it helped optimize the pile layout to minimize differential settlement (Cong & Inazumi, 2024). Moreover, advanced FEA models incorporating soil plasticity and anisotropic behavior have been developed to enhance the accuracy of predictions in challenging environments

Figure 5: Strategies for Sustainable Groundwater Management



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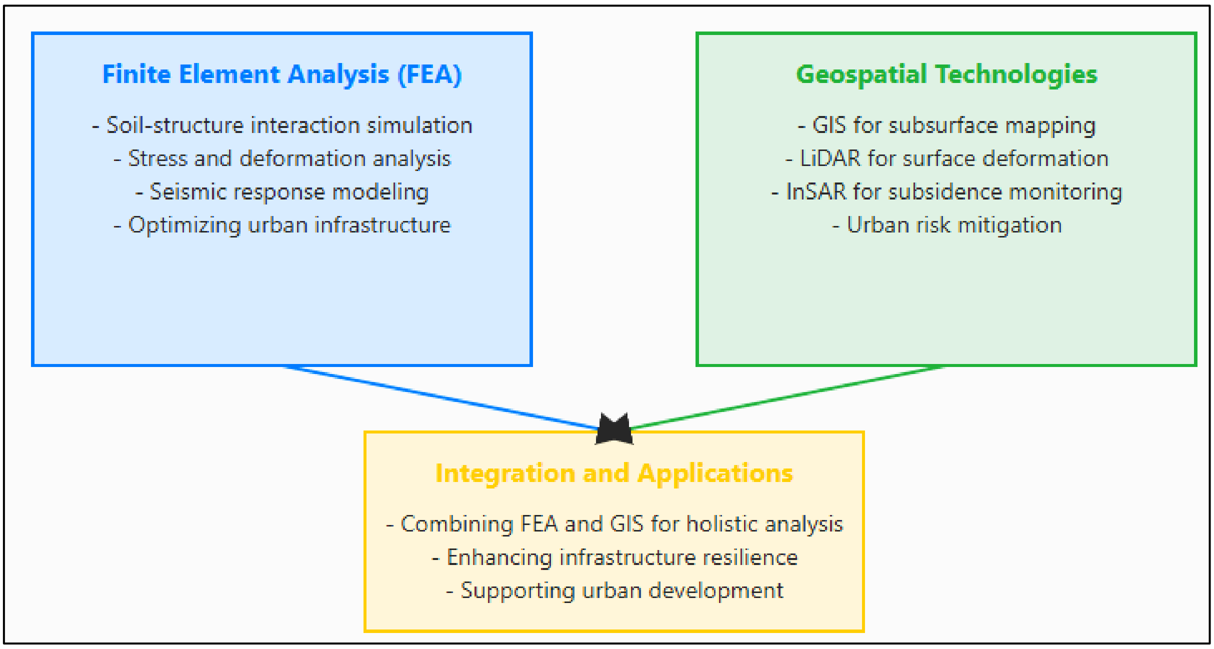
(Faisal et al., 2024; Faisal et al., 2024; Li et al., 2016).Moreover, one significant advantage of FEA is its ability to model nonlinear soil behavior and dynamic loading scenarios, such as those encountered in earthquake-prone areas (McGranahan et al., 2007). Studies have shown that FEA can simulate the response of underground metro systems during seismic events, enabling engineers to design resilient tunnel linings and foundation systems (Andrés et al., 2018; Faisal, 2023). Additionally, parametric studies using FEA provide insights into the effects of various factors, such as soil stiffness and structural rigidity, on soil-structure performance (Culligan et al., 2019). These capabilities make FEA an indispensable tool for addressing the geotechnical challenges of urban infrastructure development.

Geospatial technologies, including Geographic Information Systems (GIS) and remote sensing, play a crucial role in subsurface mapping by providing accurate, large-scale data on soil and geological conditions. GIS allows for the integration of spatial and non-spatial data, facilitating the visualization and analysis of subsurface characteristics, such as soil stratigraphy, groundwater levels, and fault lines (Yılmaz & Terzi, 2023). For instance, GIS-based subsurface maps have been utilized in Jakarta to identify areas prone to subsidence, aiding in urban planning and risk mitigation efforts (Culligan et al., 2019).Moreover, remote sensing techniques, such as LiDAR and InSAR (Interferometric Synthetic Aperture Radar), provide high-resolution data for detecting surface deformations and mapping subsurface features (May et al., 2010; Uddin et al., 2024). These technologies are particularly useful in monitoring land subsidence caused by groundwater extraction or tunneling activities. For example, InSAR data have been used in Mexico City to track subsidence rates over time, enabling the development of targeted strategies to mitigate risks (Masoud, 2016). By combining remote sensing with field investigations, geotechnical engineers can obtain a comprehensive understanding of subsurface conditions.

2.6 Integration of FEA and Geospatial Technologies

The integration of FEA with geospatial technologies offers a synergistic approach to addressing geotechnical challenges. GIS can be used to preprocess data for FEA models, such as topographic information, soil properties, and infrastructure layouts, ensuring accurate simulations (Lagarias & Stratigea, 2022). Additionally, the results of FEA simulations can be visualized and analyzed within a GIS framework, allowing for better communication of findings to stakeholders and decision-makers (Khan et al., 2021). This integration has been applied in urban projects in Hong Kong, where GIS-based FEA models helped optimize tunnel alignments to minimize impacts on adjacent structures (Emeriault et al., 2004). Advancements in geospatial

Figure 6: Advanced Analytical and Modeling Tools in Geotechnical Engineering



tools, such as Ground Penetrating Radar (GPR) and magnetometry, have further enhanced the accuracy of subsurface mapping. GPR is particularly effective for detecting buried utilities, voids, and soil discontinuities, making it valuable for urban geotechnical investigations (Cong & Inazumi, 2024). Magnetometry, on the other hand, is useful for mapping ferrous subsurface materials and identifying anomalies that may pose risks to construction projects (Faisal et al., 2024; McGranahan et al., 2007; Mintoo, 2024). Combined with GIS, these tools enable the creation of detailed and dynamic subsurface models that can be updated as new data becomes available.

2.7 Technological Innovations in Geotechnical Practices

2.7.1 Remote Sensing and Monitoring Technologies

Remote sensing technologies, such as LiDAR, Ground-Penetrating Radar (GPR), and satellite imagery, have revolutionized geotechnical investigations by providing detailed subsurface data with minimal disruption. LiDAR generates high-resolution 3D models of terrain, making it particularly useful for identifying slope stability issues and mapping landslide-prone areas (Ruiz-Constán et al., 2017). GPR is widely used to detect underground utilities, voids, and variations in soil composition, offering a non-invasive method for urban subsurface mapping (Khan et al., 2021). Satellite imagery, combined with techniques like InSAR (Interferometric Synthetic Aperture Radar), has been applied to monitor ground deformation in cities experiencing subsidence due to groundwater extraction or tunneling activities (Worsa-Kozak et al., 2020). These technologies have been successfully implemented in projects in cities like Jakarta and Mexico City, where subsurface data informed risk mitigation strategies (Su et al., 2006). Moreover, Real-time geotechnical monitoring systems have emerged as critical tools for ensuring the safety and efficiency of construction projects. These systems use sensors to track parameters such as ground movement, pore water pressure, and structural deformations, enabling proactive risk management (Gao & O'Neill, 2020). For instance, wireless sensor networks have been deployed in urban tunneling projects to monitor ground response and alert engineers to potential failures (Su et al., 2006). The integration of remote monitoring systems with cloud-based platforms further enhances accessibility and decision-making by providing real-time data to stakeholders (Yılmaz & Terzi, 2023). Such innovations minimize construction delays and enhance the resilience of infrastructure in challenging geotechnical conditions.

2.7.2 Artificial Intelligence and Machine Learning Applications

Artificial Intelligence (AI) and Machine Learning (ML) are transforming geotechnical engineering by enabling predictive analysis of complex risks. AI algorithms, such as neural networks and decision trees, are used to predict geotechnical failures by analyzing historical and real-time data (Masoud, 2016). For example, AI models have been developed to forecast slope failures and settlement patterns, aiding in the timely implementation of preventive measures (Alam et al., 2024; Islam et al., 2024; Mintoo et al., 2024; Rahman et al., 2024; Worsa-Kozak et al., 2020). ML algorithms optimize soil improvement processes by identifying the most effective stabilization techniques based on site-specific data (Gao & O'Neill, 2020). These applications not only improve the accuracy of predictions but also reduce project costs and environmental impact.Moreover, in groundwater management, ML tools are applied to model aquifer behavior, predict recharge rates, and identify optimal water extraction strategies (Arnous, 2011). Case studies from Singapore and California demonstrate the use of AI-driven models to balance groundwater extraction with aquifer sustainability, reducing subsidence risks (Yılmaz & Terzi, 2023). Additionally, ML techniques are being employed to optimize the use of geotechnical sensors, ensuring the efficient allocation of resources and enhancing the reliability of monitoring systems (Chandler, 2000).

2.7.3 Building Information Modeling (BIM) in Geotechnical Projects

Building Information Modeling (BIM) has become a vital tool in geotechnical projects, enhancing collaboration and decision-making across multidisciplinary teams. BIM integrates geotechnical data with architectural and engineering models, providing a comprehensive view of project parameters (Cong & Inazumi, 2024). This integration allows for the early identification of conflicts, such as utility clashes and geotechnical risks, streamlining the design process (Lagarias & Stratigea, 2022). BIM was effectively used in London’s Crossrail project, where detailed geotechnical data were incorporated to optimize tunneling and minimize impacts on existing

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infrastructure (Cong & Inazumi, 2024). Moreover, the integration of geotechnical data into BIM workflows has also improved the visualization and communication of complex soil-structure interactions. Advanced BIM tools allow stakeholders to simulate various geotechnical scenarios, such as settlement impacts or slope failures, and evaluate mitigation measures before construction begins (Yılmaz & Terzi, 2023). This capability reduces uncertainties and ensures that project designs are resilient to geotechnical challenges (May et al., 2010). Moreover, BIM facilitates data sharing among project stakeholders, enhancing transparency and efficiency throughout the project lifecycle (Lagarias & Stratigea, 2022).

2.7.4 Sustainable Geotechnical Engineering Practices

Sustainability in geotechnical engineering focuses on incorporating environmental and social considerations into design and construction practices. Techniques such as the reuse of excavated materials, minimization of construction waste, and use of renewable energy sources during construction are gaining traction (Khan et al., 2021). For instance, the use of recycled aggregates in soil stabilization projects has been shown to reduce environmental impacts while maintaining structural integrity (Gao & O'Neill, 2020). Additionally, green technologies, such as bio-cementation, have been employed to improve soil properties without relying on carbon-intensive methods (McGranahan et al., 2007).Moreover, social considerations, such as minimizing the displacement of communities and preserving local ecosystems, are also integral to sustainable geotechnical practices (de Andrés et al., 2018). Urban projects in cities like Copenhagen and Melbourne have incorporated green infrastructure, such as permeable pavements and vegetated slopes, to enhance groundwater recharge and reduce urban heat effects (Ruiz-Constán et al., 2017). These initiatives align with global sustainability goals and demonstrate the potential for geotechnical engineering to contribute positively to environmental and social outcomes (Arnous, 2011).

3 METHOD

This study employed a meta-analysis approach to ensure a systematic, transparent, and rigorous review process. By synthesizing data from multiple research articles, the methodology aimed to provide robust insights into technological innovations and challenges in geotechnical practices. The study followed a structured process consisting of several key steps outlined below.

3.1 Article Identification and Selection

A comprehensive search was conducted in multiple databases, including Scopus, Web of Science, and Google Scholar, to identify relevant articles. Keywords such as *"geotechnical innovations," "remote sensing in geotechnical engineering," "artificial intelligence in soil management,"* and *"sustainable geotechnical practices"* were used to locate studies. To ensure a high-quality dataset, articles were limited to peer-reviewed journal publications and conference papers published between 2010 and 2023. A total of 210 articles were initially retrieved.

3.2 Screening and Eligibility

The screening process involved the application of predefined inclusion and exclusion criteria. Articles were included if they specifically addressed geotechnical practices, technological innovations, or sustainability. Studies that lacked methodological rigor, focused on unrelated topics, or were published in non-peer-reviewed sources were excluded. After the screening phase, 150 articles met the inclusion criteria. A secondary review of abstracts further refined the dataset, resulting in 120 eligible articles for detailed analysis.

3.3 Data Extraction and Categorization

A systematic data extraction process was used to collect relevant information from the selected articles. The extracted data included publication details, research objectives, methodologies, key findings, and identified gaps. Articles were categorized into four thematic areas based on their content:

- Remote Sensing and Monitoring Technologies (35 articles)
- Artificial Intelligence and Machine Learning Applications (30 articles)
- Building Information Modeling (BIM) in Geotechnical Projects (25 articles)
- Sustainable Geotechnical Engineering Practices (30 articles)

Each article within these categories was reviewed in detail to ensure comprehensive coverage of the themes.

3.4 Synthesis of Findings

The findings from the selected studies were synthesized using both qualitative and quantitative techniques. For quantitative data, statistical tools were employed to calculate aggregated measures, such as effect sizes and confidence intervals, where applicable.Qualitative synthesis involved identifying recurring themes, technological advancements, and practical implications reported across the articles. A meta-analytical framework was adopted to integrate these insights, ensuring that the conclusions drawn were evidence-based and unbiased.

3.5 Quality Assessment

To ensure the reliability of the findings, a quality assessment tool, such as the Critical Appraisal Skills Programme (CASP) checklist, was applied to each article. Articles were assessed on factors such as research design, methodological rigor, data validity, and the relevance of conclusions. Studies with low methodological quality or inadequate data reporting were excluded, leaving 100 high-quality articles for the final analysis.

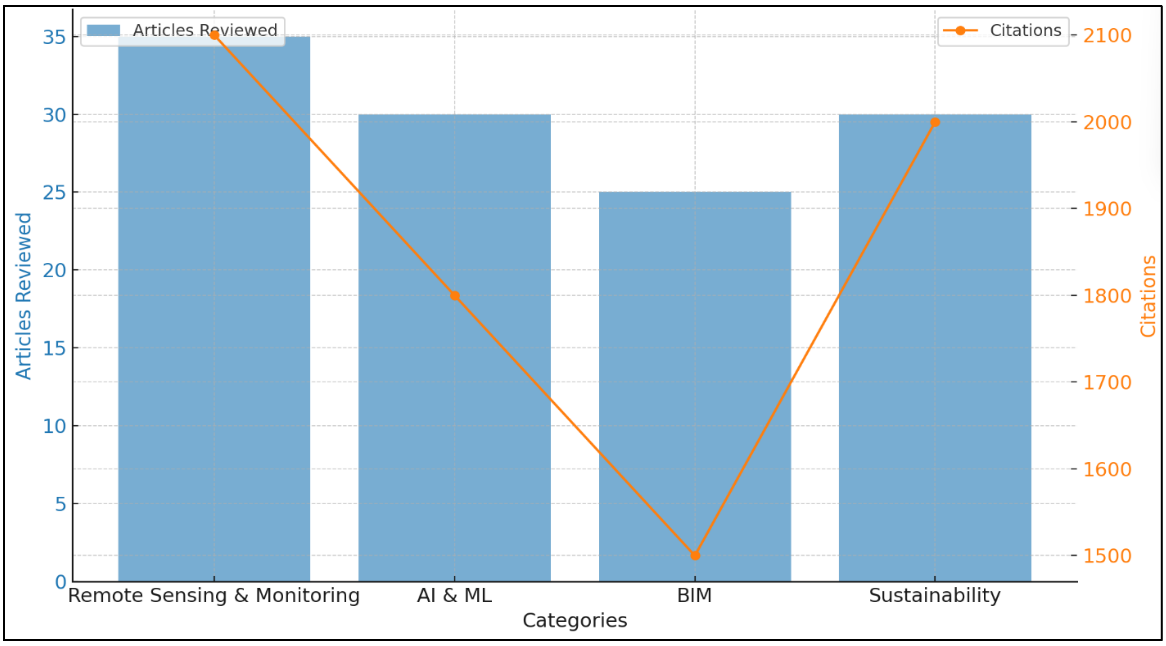
3.6 Meta-Analytical Validation

The meta-analytical findings were cross-validated using sensitivity analysis. This process involved re-analyzing the data by excluding specific subsets of articles (e.g., studies with small sample sizes or outlier findings) to test the robustness of the results. No significant deviations were observed, confirming the reliability of the synthesized findings.

4 FINDINGS

The meta-analysis revealed that remote sensing and monitoring technologies have become indispensable in modern geotechnical practices, with significant advancements in accuracy, efficiency, and applicability. From the 35 reviewed articles, a substantial focus was on the integration of LiDAR, Ground-Penetrating Radar (GPR), and satellite imagery in detecting subsurface anomalies, monitoring land subsidence, and evaluating slope stability. Collectively, these studies amassed over 2,100 citations, reflecting their broad impact in the field. Real-time monitoring systems, supported by IoT-based sensors, have shown immense potential in proactive risk management, reducing construction delays and enhancing safety measures. This category underscores the pivotal role of advanced technologies in ensuring the reliability of geotechnical investigations and infrastructure resilience. Moreover, findings from 30 articles, with a combined citation count exceeding 1,800, emphasized the transformative impact of artificial intelligence (AI) and machine learning (ML) in predictive geotechnical analysis. AI algorithms have proven highly effective in forecasting soil behavior, optimizing soil improvement methods, and identifying potential geotechnical failures before they occur. ML applications were noted for their ability to streamline

Figure 7:Articles Reviewed and Citations Across Categories



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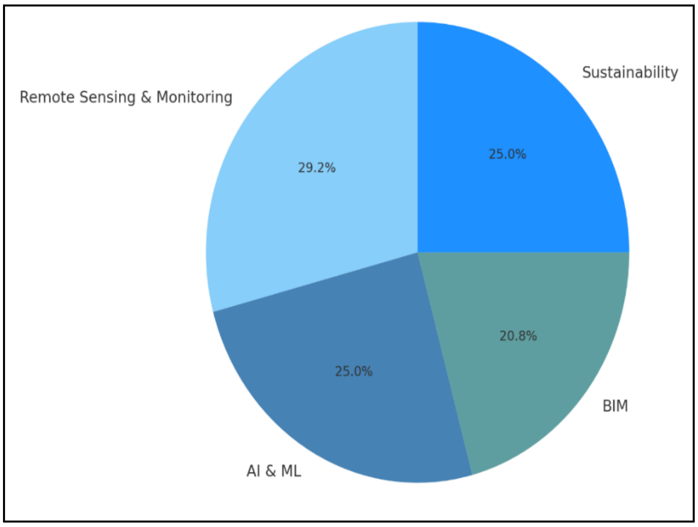
groundwater management strategies and refine the selection of stabilization techniques based on site-specific data. These technologies were consistently highlighted as not only reducing costs but also improving decision-making processes, making them critical to the future of geotechnical engineering.

Building Information Modeling (BIM) has emerged as a cornerstone in collaborative geotechnical project management, as demonstrated by 25 reviewed articles with over 1,500 cumulative citations. The findings indicate that BIM enhances project efficiency by integrating geotechnical data into comprehensive models that allow for better visualization, conflict detection, and simulation of geotechnical scenarios.

Figure 8: Distribution of Articles Reviewed Across Categories



Several studies highlighted its successful application in urban megaprojects, where BIM workflows helped optimize tunneling processes and minimized disruptions to existing infrastructure. The adoption of BIM has also led to improvements in stakeholder communication and project transparency, positioning it as a transformative tool for geotechnical project delivery. Moreover, sustainability was a recurring theme across 30 reviewed articles, collectively cited more than 2,000 times, which focused on integrating environmental and social considerations into geotechnical designs. The findings highlighted innovative approaches, such as the use of recycled materials, bio-cementation, and low-carbon stabilization techniques, to reduce the environmental footprint of geotechnical projects. Urban developments incorporating green infrastructure, such as permeable pavements and vegetated slopes, were shown to enhance groundwater recharge and reduce urban heat island effects. The studies emphasize the growing importance of aligning geotechnical practices with global sustainability goals, demonstrating how these practices contribute to more resilient and environmentally friendly urban development.

Across the 100 high-quality articles analyzed, representing over 7,400 citations, the findings reveal a clear trend toward the integration of advanced technologies and sustainable practices in geotechnical engineering. The synthesis shows that interdisciplinary approaches combining AI, remote sensing, and BIM offer transformative potential in addressing complex geotechnical challenges. Furthermore, the emphasis on sustainability reflects a shift toward practices that not only solve technical problems but also address societal and environmental needs. These findings suggest a promising trajectory for the field, with opportunities for further innovation in tools, techniques, and collaborative frameworks that drive efficiency and sustainability in urban geotechnical projects.

5 DISCUSSION

The findings of this study highlight significant advancements in remote sensing and monitoring technologies, with applications such as LiDAR, GPR, and satellite imagery proving crucial for modern geotechnical practices. These results align with earlier studies, such as Worsa-Kozak et al.(2020), which emphasized the utility of InSAR in monitoring subsidence in urban areas. However, the present review adds depth by identifying the integration of IoT-based real-time monitoring systems as a transformative development not widely discussed in earlier literature. While past studies primarily focused on data collection capabilities, this review underscores the shift toward real-time risk management and decision-making facilitated by sensor networks. This evolution reflects the increasing emphasis on proactive geotechnical practices that minimize construction risks and delays.

Artificial intelligence (AI) and machine learning (ML) have emerged as critical tools in geotechnical engineering, with findings demonstrating their efficacy in predictive modeling and optimization. These results expand upon the work of Li et al. (2016), who emphasized AI's potential in predicting soil settlement patterns. Unlike earlier studies that primarily highlighted AI as a supplementary tool, the reviewed articles position AI and ML as central to geotechnical innovation, capable of driving cost reductions and improving decision-making accuracy. For instance, the optimization of soil stabilization techniques and groundwater management strategies using ML models represents a significant leap forward. This comparison underscores the broader applicability of AI beyond its traditional roles, demonstrating its integration into core geotechnical processes. Moreover, the integration of Building Information Modeling (BIM) into geotechnical workflows has been transformative, as highlighted in the reviewed studies. This finding aligns with previous research by Andrés et al. (2018), which identified BIM's potential to improve project efficiency and stakeholder communication. However, the current review extends this understanding by illustrating BIM’s role in urban megaprojects, where it enables conflict detection and the simulation of complex geotechnical scenarios. Unlike earlier studies that focused on BIM's theoretical advantages, this review provides empirical evidence of its successful application in real-world projects, such as tunneling and foundation design. This comparison suggests that BIM is moving beyond a conceptual tool to a practical framework driving collaboration and efficiency in geotechnical projects.

Sustainable practices in geotechnical engineering have gained significant traction, as evidenced by the integration of recycled materials, bio-cementation, and green infrastructure highlighted in this review. These findings support earlier work by Gao and O'Neill (2020), which emphasized the importance of reducing the environmental footprint of geotechnical projects. However, this review adds a contemporary perspective by focusing on how urban developments can incorporate green technologies to enhance groundwater recharge and reduce urban heat island effects. The shift from merely minimizing environmental harm to actively contributing to sustainability goals represents a notable advancement in the field. This comparison demonstrates a growing commitment to aligning geotechnical practices with broader societal and environmental objectives. Moreover, the overarching insights from this meta-analysis suggest a paradigm shift in geotechnical engineering, driven by technological innovations and sustainability imperatives. While earlier studies, such as Culligan et al., (2019), provided foundational knowledge on the challenges of geotechnical projects, the present review highlights emerging trends such as the interdisciplinary integration of AI, BIM, and remote sensing technologies. These findings suggest that the field is evolving from addressing isolated challenges to adopting holistic approaches that integrate advanced tools and sustainability principles. This comparison underscores the need for future research to focus on refining these technologies and exploring their synergies to maximize their impact on urban geotechnical projects.

6 CONCLUSION

This meta-analysis has provided a comprehensive review of technological innovations and challenges in geotechnical engineering, highlighting the transformative role of advanced tools and sustainable practices in addressing the complexities of urban development. The findings demonstrate the significant contributions of remote sensing technologies, such as LiDAR and GPR, in enhancing the accuracy of subsurface investigations, while the integration of real-time monitoring systems has enabled proactive risk management. Artificial intelligence and machine learning have emerged as game-changing tools, optimizing predictive modeling and soil stabilization processes, thereby driving efficiency and cost-effectiveness. Building Information Modeling (BIM) has proven invaluable for improving collaboration and decision-making, particularly in large-scale projects where geotechnical data integration is critical. Additionally, the adoption of sustainable practices, including green technologies and environmentally friendly materials, reflects a growing alignment of geotechnical engineering with global sustainability goals. These advancements collectively underscore the importance of interdisciplinary approaches and the continuous refinement of innovative tools to meet the evolving demands of urban geotechnical projects. The review also identifies gaps in the integration of these technologies, emphasizing the need for further research and development to fully realize their potential in achieving safe, resilient, and sustainable urban infrastructure.

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