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Digitalization of underground infrastructure for effective asset management: Technological Approaches, Opportunities and Challenges

Abstract

As urbanization accelerates, underground infrastructures, including utility networks, have become vital components of cities, providing essential services to urban life. These infrastructures are crucial assets requiring efficient planning, construction, and maintenance. Integrating technologies like Building Information Modeling (BIM), machine learning, and computer vision into underground construction and maintenance enhances visibility and reliability. However, applying these technologies presents unique challenges and opportunities distinct from above-ground contexts. This study therefore adopts a systematic review of 26 articles to discuss the technological approaches, opportunities and challenges in digitalizing underground infrastructure. Key opportunities include integrating GPS, GIS, AR, and computer vision to improve locating accuracy and efficiency. 3D models and advanced visualization systems can prevent excavation damages, while BIM improves construction management and coordination. Accurate defect characterization and infrastructure condition diagnosis through information modeling are also highlighted. Challenges include the limited capabilities of traditional image processing, a shortage of accurate as-built and as-is information, and difficulties in reconstructing buried infrastructure models. Data collection for deep learning is labor-intensive, and automated data interpretation faces uncertainties. Additionally, existing robotic systems are not fully automated, and reliance on historical data affects prediction models. Addressing these challenges is essential for the effective digitalization of underground infrastructure.

Keywords

Digitalization, Underground, Infrastructure, Asset Management, Approaches, Challenges, Requirements

1. Introduction

Urban underground infrastructures are essential assets that require efficient planning, construction, and maintenance. Implementing tools such as BIM, machine learning, and computer vision in underground construction offers enhanced visibility and reliability into its processes and subsystems. However, the application of these technologies in underground construction presents distinct opportunities and challenges compared to their use in above-ground construction. The increasing development and maintenance of urban infrastructure significantly affects underground resources. Having an accurate understanding of infrastructure performance is crucial for preventing potentially serious accidents during construction processes. Ultradeep and continuous underground structures with large cross-sectional areas are being constructed. In numerous metropolitan areas, underground spaces have developed into extensive networks (Foria et al., 2023). Unfortunately, new underground structures can negatively impact the environment, causing soil disturbances around complex underground conditions like metro tunnels beneath existing pipes or subway stations. Accurately understanding infrastructure performance during building construction is a more effective approach. Advances in digital technologies provide a wider array of methods for assessing structural conditions and monitoring their health (Batkov et al., 2016)(Ma et al., 2021). The need to understand the approaches, challenges, and opportunities offered by digitalizing underground infrastructure is essential for improving awareness and adoption of these technologies. This paper presents the state-of-the-art development of digitalisation of underground infrastructure by examining the approaches adopted, current requirements and challenges. Section 1 presents the introduction to the study, Section 2 introduces the research method, Section 3 reviews the approaches, challenges and opportunities. Section 4 concludes the study.

2. Research Methods

We utilized a rigorous six-step review methodology to scrutinize advancements in underground infrastructure within the construction industry, drawing insights from studies such as (Jiang et al., 2021). This research aimed to explore the approaches, opportunities, and challenges associated with underground infrastructure. Initially, we defined the review's scope to enable a thorough examination of underground infrastructure. Our objective was to provide a comprehensive overview of the latest developments, barriers, applications, and future research directions in this field, building on methodologies from previous studies like (Onososen and Musonda, 2022) and (Starzyńska-Grześ et al., 2023).

The second phase involved systematically identifying relevant literature and documents through predefined search strategies using various data sources and keywords (Tjebane et al., 2022). We gathered academic materials from databases such as Google Scholar and Scopus, including journal articles, conference papers, and book chapters. Keywords such as "Digitalisation," “Underground” "Challenges," "Approaches," and "Infrastructure" guided our data collection process. Following this, we conducted data collection and quality assessment to ensure the inclusion of credible and pertinent resources. A detailed text analysis, aligned with the study's objectives, facilitated the interpretation of results within the broader research context, as outlined by Tjebane et al. (2023). This comprehensive methodology ensured a robust and insightful review of Underground Infrastructure current landscape and future potential. This process is further illustrated in Figure 1 below.

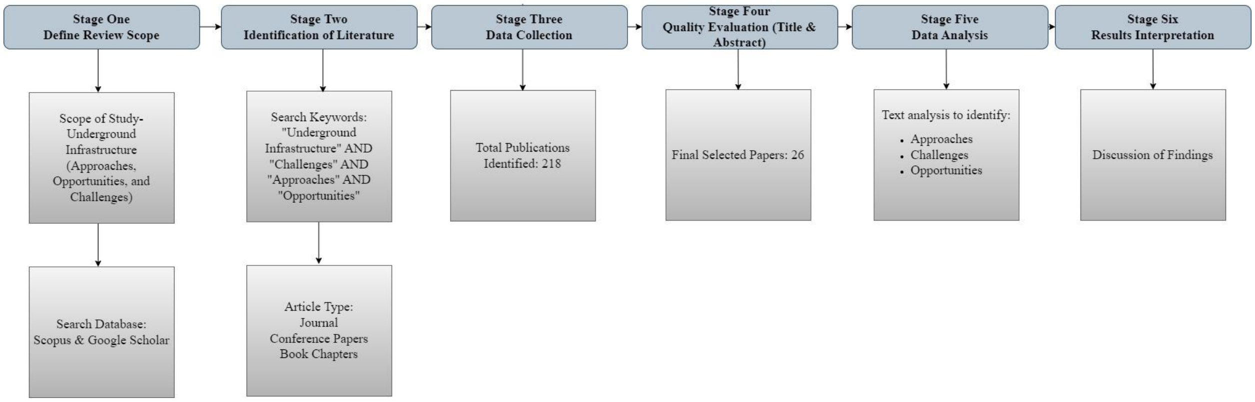

Fig. 1. Research Method

3. Results and Discussion

3. 1 Approaches

The lack of a management platform supporting visualization and real-time updates on the locations and statuses of existing underground projects significantly increases the maintenance burden. Accidental strikes on underground pipes and cables can incur costs of up to £1.2 billion per year (Huang et al., 2021). In response to this issue and to mitigate the risk to workers, the UK government's Geospatial Commission developed the Underground Asset Register (Huang et al., 2021). This register aims to provide a digital map of underground pipes and cables, enabling more efficient access, utilization, and sharing of data regarding underground assets (Huang et al., 2021). Similarly, the Singapore-ETH Centre, in collaboration with the Singapore Land Authority, is creating a digital twin of Singapore's underground using 3D technology. This initiative aligns with Singapore's national plan, which prioritizes the effective utilization of underground space as a core strategy. These efforts underscore the need for adopting digital information technologies to reinforce efficient and effective planning, development, and management of underground construction. The growing interest in the architecture, engineering, and construction (AEC) industry in utilizing BIM reflects a multifaceted transition in aspects of facility design, construction management, and stakeholder collaboration. As indicated by (Wang and Yin, 2022), BIM and geographical information systems (GIS) have garnered attention for modeling underground infrastructure information, offering improved visualization and enabling simulations at various levels. However, their applications are still in the early stages of development. To enhance locating accuracy, new technologies like RFID and global positioning systems (GPS) are being used to complement traditional methods such as ground-penetrating radar (GPR) (Yu et al., 2021). Locating underground assets stands as a pivotal task across various activities in underground infrastructure projects, encompassing the design and construction of new infrastructure, as well as the inspection and maintenance of existing ones. Accurate locating aids in understanding the distribution and precise positioning of underground assets within the target area, thus minimizing risks and enhancing efficiency in subsequent operations. Several technologies have been explored to aid in this endeavor (Mazak-Huemer et al., 2020).

Traditionally, ground-penetrating radar (GPR) has been the primary technique for detecting, locating, and characterizing buried assets by scanning the designated area and analyzing the resulting imagery (Dong et al., 2016). However, the manual interpretation of GPR scans poses challenges in terms of difficulty and inefficiency. Consequently, various data processing techniques have been investigated to streamline the interpretation process, including signal processing methods such as Translation Invariant Wavelet Packet Detection (TIWPD), discrete wavelet transform (DWT), and fractional Fourier transform (FRFT), as well as image processing techniques coupled with classifiers (Lieberman et al., 2017).

To enhance localization capabilities, additional devices or methods have been developed for integration with GPR. For instance, a sensing suite comprising a camera and GPR has been devised for both surface and subsurface infrastructure inspection, with innovative approaches developed for GPR-camera calibration and sensor data fusion (Zhu et al., 2016). This system has proven effective in reducing errors in infrastructure inspection and facilitating 3D reconstruction of structures. Moreover, a geospatial system has been created for mapping and uncertainty-aware visualization of underground utilities through the integration of GPR, GPS, and GIS (DeWardt et al., 2013). Additionally, a hybrid approach has been proposed to simultaneously estimate the radius and depth of underground utilities by collecting GPS data alongside GPR scanning. Furthermore, certain studies have begun exploring augmented reality (AR) applications for the underground domain. Overall, research efforts are transitioning from the use of standalone devices (such as GPR) to the integration of multiple sensing technologies (including GPS, GIS, AR, etc.) to enhance the accuracy of locating underground infrastructure (Chapman et al., 2020). Data processing methods, such as image and signal processing, are being developed to facilitate the interpretation of acquired data. However, new technologies encounter technical challenges when applied to underground infrastructures, such as the registration accuracy of AR devices. Moreover, approaches need to be devised to efficiently process and integrate data from multiple devices.

Ma et al., (2021) proposed innovative solutions for evaluating conditions and monitoring the structural health of underground infrastructure using state-of-the-art sensing technologies. To further reduce strikes on underground infrastructure during excavation, augmented reality (AR) technologies are being explored to enhance visualization of the underground environment alongside the physical surroundings, providing valuable information. Additionally, to improve efficiency in inspection and assessment, digital non-destructive technologies such as visual devices and sensors, as well as automatic interpretation of inspection data, are increasingly being investigated for the operation and maintenance of underground infrastructure (Shahrour et al., 2021). Depending on the specific needs of underground construction, fiber optics, photogrammetry, and other advanced sensing technologies are employed. These techniques, now commercially available, cater to the construction characteristics and monitoring goals of urban underground engineering with high precision, automation, high-frequency, and high-resolution capabilities. Chen et al. (2024) developed a framework that offers a digitalization-based guideline for conducting embodied carbon assessments specifically for TBM tunneling projects.

Emerging advanced sensing technologies for underground construction include fiber optic sensing in the field of structural health monitoring (AlJaber et al., 2023). Although the high cost and complexity of implementing fiber optic sensing have limited its widespread use, especially in the complex processes of underground engineering, it offers benefits such as automation, accuracy, and spatial resolution. The use of fiber optic sensing for monitoring urban underground engineering projects with high accuracy requirements is anticipated to increase over the long term (Shahrour et al., 2021).

Recent advancements in sensor technologies have led to the development of MEMS and sensors with high precision, low energy consumption, and wireless transmission capabilities. These features meet the demands of underground construction and align with emerging industry trends (Zaneldin et al., 2020). While deep learning excels in certain domains like object detection and recognition, traditional computer vision techniques still demonstrate superiority in areas such as panoramic vision and 3D reconstruction (Luo et al., 2021a). Computer vision algorithms find extensive applications, with examples including stereo matching, person tracking, and face detection. These computer vision-based sensing systems are crucial for capturing and documenting the continuously evolving state of infrastructure, thereby supporting decision-making processes when integrated with BIM. A significant difference between surface and underground excavation lies in the complexity of the geological environment. A comprehensive understanding of geological, geotechnical, and geohydrological conditions is imperative for planning underground infrastructure and, consequently, for the adoption of BIM in underground construction (Foria et al., 2023). Geological models, derived from project-specific ground investigations or existing geological knowledge, form the foundation for tunnel and underground construction design. These models enhance design quality and enable early identification of critical geological issues by characterizing the spatial distribution, stratigraphic settings, and structural relationships of geological features (Pereira et al., 2019).

The digital management of both historical and newly acquired data through computer-based systems like GIS is gaining acceptance. GIS, as the predominant tool for handling geo-referenced data, has evolved over the last century. It not only provides spatial context for ground conditions but also aids in localizing physical constraints and emergency situations. GIS services are increasingly utilized in earlier lifecycle stages of underground infrastructure projects (Petschen et al., 2023). Furthermore, GIS-based monitoring extends to various applications such as tunnel deformation, underground mine subsidence, mining-induced surface deformation, underground pipeline surveying, and underground utilities mapping, often integrating augmented reality for enhanced visualization and analysis. Before commencing additional excavation, identifying existing underground infrastructure and utility networks is essential for efficient planning and management of underground space. Previous studies have proposed InversionNet, a data-driven model that maps seismic waves to subsurface velocity models. Seismic-wave-based methods are commonly used for detecting geological discontinuities such as faults and dykes, particularly in drilling-and-blasting operations (Huang et al., 2022). Another example is PhaseNet, which uses three-component waveforms to predict the probability distributions of P-waves, S-waves, and noise (Huang et al., 2021).

Countries with limited national terrestrial areas, like Singapore and the UK, have initiated programs to digitalize underground spaces by mapping and assessing built infrastructure, such as utilities, to create shareable 3D models. A back-end database containing data acquired onsite using ground-penetrating radar (GPR) and seismic methods supports expert interpretation, providing geological insights and imagery evidence. With the establishment of such databases, deep neural networks can be applied to extract features and learn patterns (Huang et al., 2021). Terrestrial laser scanning (TLS) and mobile laser scanning (MLS) are increasingly used in underground geotechnical applications, including tunnel deformation measurements, water leakage detection, and identifying structural discontinuities (Fekete et al., 2010). These technologies can achieve a comprehensive point cloud dataset of the surveyed area through automatic rotation up to 360 degrees (Huang et al., 2021).

3.2 Challenges

While offering numerous opportunities, the digital transformation in urban underground development encounters distinct challenges arising from the inherent complexity associated with spatial opacity, geological uncertainties, high-risk working environments, and interactions between ground and structures (Huang et al., 2021). Excavation conducted without a thorough understanding of ground features can be particularly problematic. Underground infrastructure is in need of improved ways of locating technologies to avoid damage as is current practice (Federico Foria et al., 2023). AR visualization techniques, inspection and assessment methods, deterioration modeling, and predictive condition forecasting, as well as factors affecting sewer pipe conditions and automated vision-based assessment methods, are all existing initiatives. However, they still face challenges in accurately mapping and locating existing facilities (Wang and Yin, 2022).

It is crucial to establish a project-scale geological understanding incorporating GIS databases, geological observation, and geophysical investigation to mitigate uncertainties inherent in the ground (Huang et al., 2021). Therefore, modeling with close reference to geographical and geological information emerges as a crucial strategy for BIM in underground construction (Yu et al., 2021). The accuracy of the federated BIM model should be continuously improved by integrating domain-specific knowledge with as-built and as-damaged information (Huang et al., 2021). Previously, manual surveying using levels or total stations was crucial for monitoring structural deformation. Today, global positioning system (GPS) devices are used in civil engineering to monitor deformation due to their automation and ease of use. However, GPS devices often lack accuracy (millimeter level) and suffer from poor signal reception, especially in underground environments. A common issue with these methods is that they all require direct contact with the monitored targets, meaning they are not suitable for remote sensing (Ma et al., 2021). The study also noted that laser measurement is prohibitively expensive and unsuitable for dynamic monitoring because laser scanning is time-consuming (Yu et al., 2021). In contrast, photogrammetry is precise, automated, and cost-effective. In civil engineering, two types of photogrammetry are used: aerial and close-range image capturing.

However, aerial photogrammetry is rarely used in underground engineering due to the confined spaces and complex construction environments (Chen et al., 2024). Two key factors that enhance measurement in underground construction are advanced algorithms and communication. Advanced algorithms, such as support vector machines and long short-term memory networks, are important for predicting deformation and managing data, yet they are currently underutilized in construction measurement (Wang and Yin, 2022). These algorithms can be written into modules and embedded in sensors to enable a single sensor to perform a range of intelligent activities. Additionally, mature communication techniques facilitate automatic and wireless transmission, which are especially crucial for underground construction sites (Yin and Wang, 2022). A difficulty arises in modeling condition (defect) data due to its potential unavailability or inaccuracy, and there is a need to explore the integration of this data with the infrastructure component model. One potential solution involves acquiring current condition data from IoT devices (if accessible) and inspection outcomes. Regarding the modeling of defect data, existing data standards like IFC and CityGML can be expanded, or new data models can be devised to depict defects, their attributes, and their associations with infrastructure components (Luo et al., 2021b)

3.3 Opportunities

As urbanization rapidly progresses, underground infrastructures, including utility networks and tunnels, have become crucial components of cities, providing essential services to urban life. Like other infrastructure projects, the lifecycle of underground infrastructure involves various stages, such as planning, design, construction, and operation and maintenance. Due to their subterranean nature, activities at each stage are often highly complex and challenging. Accurately locating underground infrastructure is essential for many activities. This accuracy helps optimize the routing of new infrastructure, prevents collisions with existing structures, and provides references for inspection and maintenance. However, achieving precise location is challenging due to the complex distribution and vast number of buried assets, as well as environmental influences such as soil and groundwater (Wang and Yin, 2022;Yin and Wang, 2022). Technologies employed in the delivery and maintenance of underground infrastructure include BIM, computer vision, and related technologies. These are enhanced by integrating GIS and 3D geological modeling into the as-designed BIM workflow and using construction simulation and machine sensing techniques to model dynamic ground-machine-structure interactions. Computer vision-based infrastructure sensing and analysis are essential for ensuring the accuracy and reliability of the as-built BIM model. Additionally, the capabilities of robotics and automation, in collaboration with machine learning and computer vision techniques, play a crucial role in improving efficiency and precision in underground construction and maintenance (Yu et al., 2021). These advanced technologies collectively contribute to a more accurate, reliable, and efficient approach to managing underground infrastructure projects (Huang et al., 2022) Another emerging approach involves training and evaluating deep neural networks using plentiful samples to identify and map underground infrastructure. This method leverages the power of machine learning to automatically detect and categorize underground elements such as pipes, cables, and tunnels from various data sources, including ground-penetrating radar, LiDAR, and satellite imagery. By analyzing vast datasets, deep neural networks can learn complex patterns and features, enabling accurate and efficient mapping of underground assets (Lee et al., 2023). Additionally, ongoing advancements in artificial intelligence and deep learning techniques continue to enhance the performance and reliability of these models, making them valuable tools for urban underground development projects. These technologies holds immense opportunities for improving how we deliver and manage underground infrastructure, for instance, information about underground infrastructure is still shared and managed through paper-based documents or 2D CAD drawings (Esekhaigbe et al., 2020). This approach makes it difficult to visualize and comprehend the situation of buried assets due to their complex and dense distribution. Furthermore, accidentally striking existing underground infrastructure during excavation is a major concern, potentially leading to severe consequences such as water pipe bursts, explosions, and fires (Ofluoglu et al., 2019). This problem largely arises from the lack of accurate as-built and current information, as well as inadequate methods for visualizing underground structures. Due to their subterranean placement, underground assets are prone to being struck during excavation activities. Current shortcomings in damage prevention efforts during excavation have been identified, including inadequate excavation practices, locating procedures, and notification errors (Koseoglu et al., 2019). To mitigate excavation-related issues, a visual system has been proposed to prevent collisions between excavators and utilities. This system involves creating 3D models of underground utilities using geospatial data and overlaying them onto the excavator's workspace using augmented reality (AR) technology with real-time Kinematic GPS. By providing visual information on the location and type of existing utilities, this system aims to facilitate the excavation process and reduce damage to buried assets. Additionally, an analytical approach has been suggested to enhance site photos with computer-generated 3D graphics (Yin and Wang, 2022).

Furthermore, a 4D Building Information Modeling (BIM) system has been developed in conjunction with Geographic Information Systems (GIS) for utility relocation management. This system enables visualization of existing buried assets, clash detection, and 4D simulation to enhance project scheduling and coordination. Overall, previous research has primarily focused on minimizing damage to buried assets during construction and improving stakeholder coordination through the use of 3D modeling, advanced positioning, and visualization techniques (He et al., 2010). However, the lack of accurate as-built and as-is information for underground infrastructure poses challenges in locating and detecting existing buried assets. Future research is expected to explore methods for obtaining and maintaining updated as-built and as-is data for underground infrastructure.

Research on the operation and maintenance of underground infrastructure has centered on automated inspection data interpretation, automated condition assessment and prediction, robotic systems for inspection and assessment, intelligent inspection and maintenance planning, and information modeling for maintenance management. Recently, there has been growing interest in utilizing deep learning-based approaches to automate the data interpretation process, leveraging their ability to learn features and produce desired results automatically without manual intervention (Ortega et al., 2019). A primary method for predicting future conditions involves deterioration modeling of infrastructure. Various statistical methods, including the cohort survival model, Markov-chain based models, the semi-Markov model, logistic regression model, and multiple discriminant analysis, have been explored for structural deterioration modeling of urban drainage pipes.

The process of 3D modeling for infrastructure differs from that of buildings, as building information modeling (BIM) is relatively advanced with established practices and standards. Additionally, obtaining accurate and up-to-date data (e.g., location, condition) for underground infrastructure is more challenging compared to buildings or above-ground infrastructure (Mazzanti et al., 2020). A potential area for future research is the development of digital twins for underground infrastructure. This involves collecting various data types from multiple sensors and integrating the data to reconstruct a 3D model of the infrastructure.

4. Conclusions

The architecture, engineering, and construction (AEC) industry is undergoing a technological revolution fueled by rapid digitization and automation. Advances in information technology and computer science, including building information modeling (BIM), machine learning, and computer vision, have significant potential to improve the construction, maintenance, and operation of underground infrastructure. As digital transformation extends into the underground domain, we explored the latest applications, limitations, and future opportunities of BIM, machine learning, and computer vision-based techniques. These technologies are believed to have significant potential in underground construction. The study concludes that the major opportunities for the digitalization of underground infrastructure include integrating new technologies such as cameras, GPS, GIS, AR, computer vision, and machine learning into locating technologies, which can significantly enhance accuracy and efficiency. Additionally, using 3D models and advanced visualization systems can help prevent excavation-related damages. Information models like CAD and BIM can improve construction management and stakeholder coordination. Extracting characteristics such as width, length, and area of defects is crucial for accurate defect characterization. Diagnosing infrastructure conditions through information modeling and the semantic web, investigating factors that influence the condition of underground infrastructure, and using demand forecasting and deterioration modeling to predict future conditions are also key opportunities.

However, the study also identifies several challenges. Traditional image processing techniques have limited capabilities, and there is a shortage of as-built and as-is information for underground infrastructure. Reconstructing accurate models of buried infrastructure is difficult, and the process of collecting and preparing data for deep learning methods is time-consuming and labor-intensive. Automated data interpretation is subject to uncertainties, and as-is condition data, such as defect information, are not well-modeled or integrated with 3D models. Existing robotic systems are not fully automated, and there is a heavy reliance on historical data. Additionally, the quality and uncertainties of existing condition rating data can impact the assessment of other infrastructure and the development of prediction models

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