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APPLIED RESEARCH

Research on Digital Monitoring Technology for Airport High-Pressure Rotary Jet Piles

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ABSTRACT The high-pressure rotary jet pile construction method has been widely used in airport projects, particularly in regions with soft soil foundations, such as coastal areas. The method's primary aim is to establish a sound foundation bearing capacity. However, the conventional machinery used in constructing high-pressure rotary jet piles lacks automation. Therefore, it is necessary to find a method to achieve automatic monitoring of the construction quality of high-pressure rotary jet pile. To achieve real-time quality control in high-pressure rotary jet pile construction, the development of high-pressure rotary jet pile construction data acquisition and monitoring equipment is made possible by integrating key technologies such as the global navigation satellite system (GNSS), the Internet of Things and massive data processing. The acquisition and storage of crucial construction parameters, such as the drilling position, drill rod verticality, drilled hole depth, grouting pressure, grouting lifting speed and grouting volume for high-pressure rotary jet piles is successfully implemented in this paper. A large amount of actual construction data is collected through an on-site application, and the construction quality of the high-pressure rotary jet pile machine is monitored and analyzed using geographic information system (GIS) technology. Actual applications demonstrate that the proposed digital monitoring model and method for rotary jet pile construction quality control is viable, improves the on-site management level and efficiency and has significant future value.

INDEX TERMS High-pressure rotary jet pile, digital monitoring, the Internet of Things, global navigation satellite systems (GNSSs), geographic information systems (GISs).

I. INTRODUCTION

The high-pressure rotary jet pile method [1], [2] involves the use of a high-pressure rotating nozzle to distribute cement slurry into the soil, creating a continuous and overlapping cement reinforced structure. Various spraying modes, such as single-tube, double-tube and triple-tube spraying, have been developed for traditional high-pressure rotary spray piles [3], [4]. To implement this method, a drilling machine is used to insert the grouting pipe, fitted with a nozzle, into a predetermined location within the soil. High-pressure equipment is then employed to create a 20-40 MPa high-pressure jet of slurry or water (air) from the nozzle, which cuts, disturbs and destroys the soil. Simultaneously, the drilling rod is gradually lifted at a specific speed, forcing the slurry to mix with the soil particles. After solidification, a cylindrical consolidation structure (i.e., rotary spray pile) is formed, achieving the objective of reinforcing the foundation or preventing water seepage. This method is applicable for a variety of soils, including mud, silty soil, clay, loess and sand [5]. Rotary spray pile projects are classified as a hidden engineering type of foundation treatment [6], [7], [8] and are widely utilized in soft soil areas, particularly in the coastal regions in China. The construction quality is directly affected by the

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pressure of each pile sprayed, the total amount of cement injected and the amount of cement injected in each section, which must meet the design and construction requirements. The injection of the slurry volume depends on factors such as the flow rate of the slurry, and the speed of the drilling head's movement. The operation is challenging and primarily relies on the experience of construction personnel, leading to uneven pile quality.

Ground treatment is a fundamental aspect of airport construction, as it directly impacts the overall quality of the construction. Among the various methods of ground treatment, jet grouting stands out as an effective construction technique. However, due to the inherent complexity of jet grouting, its construction control presents a significant engineering challenge, and the quality of the construction is heavily dependent on the effectiveness of the construction control measures. The traditional construction machinery used for high-pressure jet grouting presents bottlenecks in construction supervision and project quality management, as the construction parameter settings are typically limited to theoretical analysis, making it difficult to ensure 24-hour on-site monitoring by experts. Moreover, traditional control measures are often inadequate, leading to a wide range of problems, such as the construction personnel lacking a strong sense of responsibility and employing effective supervision, intentional cutting of corners, subjective judgments, or inadequate management supervision. Consequently, the construction quality is often difficult to guarantee. After a construction is completed, the construction quality inspections mainly consist of spot checks, making it challenging to maintain process quality. Artificial factors have a significant impact, and the authenticity, timeliness and traceability of the data are not high. As a result, the pile quality is often difficult to guarantee, which poses construction safety hazards. To address these challenges, it is imperative to implement process control measures that enable the proactive prevention of systemic nonconformity factors. This involves monitoring the production process, promptly identifying signs of nonconformity, taking appropriate measures to eliminate their impact and maintaining the process in a controlled state. By doing so, passive post-result testing can be transformed into effective process control, reducing waste, improving engineering quality and efficiency. In terms of quality management control, the construction records and testing reports of pile foundations are typically used to assess the quality of the construction process. The construction records serve as first-hand original data reflecting the quality of the pile foundation construction process. On-site construction personnel play a crucial role in this regard, as they must monitor the continuously changing slurry pressure, mud flow rate, drill pipe lifting speed and drill pipe downward speed in real time during the construction process. However, the high-pressure jet grouting construction automation degree is generally low. Therefore, it is essential to implement effective process control measures to ensure the quality and safety of a construction.

In light of the imperatives of guaranteeing construction quality and enhancing management proficiency, there is a pressing need for technological innovations to address the challenge of monitoring the quality of traditional high-pressure rotary spraying pile construction. To this end, it is imperative to achieve real-time, dynamic and nondestructive measurements of the construction parameters [9]. With the advent of positioning technology, the Internet of Things, sensors and other advanced technologies [10], it is imperative to develop a digital monitoring system for high-pressure rotary jet pile construction. This system should be able to monitor the construction quality of high-pressure rotary jet piles and automatically collect, store and analyze the key indicators and parameters of the construction process. This enables managers to access the dynamic information on high-pressure rotary jet pile construction for an airport construction in a timely, comprehensive, accurate and intuitive manner, and control the construction quality and progress. This paper addresses the monitoring issues that arise in the construction control process of high-pressure rotary jet piles in airport construction. We first analyze the construction parameters of high-pressure rotary jet piles, integrate the relevant sensor modules based on the Internet of Things and design and develop a rotary jet pile construction parameter acquisition terminal and software platform. This platform helps to scientifically manage the construction data of high-pressure rotary jet piles throughout their lifecycle, and provides strong technical support for comprehensive quality supervision and design scheme disposals. The development of an automated data acquisition apparatus for high-pressure rotary jet piles is proposed. To ensure efficient construction, it is essential to capture and calculate real-time parameters such as position, grout volume, grouting pressure, depth and drilling speed variation. Additionally, data storage, analysis and uploading must be conducted in a timely and systematic manner. This proposal aims to enhance the overall quality and productivity of the construction activities. Furthermore, a cutting-edge GIS-based software system for monitoring and visualizing high voltage rotary spray pile construction is developed. This advanced system delivers an intuitive, visually engaging and real-time display of the data generated throughout the construction process, enabling prompt and effective quality control.

The salient contribution of this research paper resides in the real-time acquisition, retention and provision of feedback guidance pertaining to the key parameters associated with conventional high-pressure rotary jet pile production, with the aim of ameliorating construction quality issues. Specifically, data in regard to the construction parameters are obtained in real time through the installation of collection sensors at the corresponding positions on the high-pressure rotary jet pile. All data gathered from the sensors related to the construction parameters are collated through a wired connection to the principal unit situated next to the operating platform of the rotary jet machine for facile viewing of the operational data on a terminal tablet by the operators. By providing feedback on the collected parameters to the operator, adjustments are made expediently based on any incongruent data. Meanwhile, the 4G module incorporated within the central unit is capable of transmitting the construction data obtained from the sensors to a remote server in compliance with interface protocols, thereby facilitating data visualization and analysis through the visualization system. The collection of construction parameter data, in particular, entails using GNSS positioning antennas to capture the drill-hole locations and calculate the drill-hole depths. Inclination sensors are employed to gauge drill-rod verticality; pressure sensors are utilized to acquire jet grouting pump pressure, and flow sensors are utilized to measure the grout lifting speed and injection volume of the jet grouting pump.

At present, partially monitored parameters exist for the digitized monitoring of various foundation treatment techniques, including dynamic compaction, gravel piles and CFG piles. However, the complete digitization of rotary jet pile construction monitoring is noticeably scarce. Consequently, the research content proffered in this paper is an innovative and commendable undertaking. In the future, the digitized monitoring solution utilized in rotary jet pile construction can be fruitfully employed to control the quality of the foundation treatments for silt, silty soil, cohesive soil, sand, artificial fill and heavily weathered rocks, and can also positively impact the coastal airport engineering foundation treatments discussed in this study. The monitoring mechanism presented has multifold applications in diverse fields, such as the reinforcement engineering domain, which uses rotary jet piles in subway construction, the airport engineering foundation treatment sector and also in the realm of urban infrastructure development, and includes several other foundation treatment processes.

Hence, enabling all project participants to access the monitoring platform and promptly monitor the construction quality is immensely significant in ensuring the quality of the high-pressure jet grouting piles and elevating the level of engineering construction management.

II. ANALYSIS OF ROTARY JET PILE AND KEY SENSOR TECHNOLOGY

The rotational jet grouting method, commonly referred to as the jet grouting method, was initially developed in the 1970s from the high-pressure jet grouting method. It has since been extensively utilized in China during the 1980s and 1990s. The construction process comprises two primary stages, drilling before spraying, followed by spraying after lowering the drill, and then lifting and stirring to ensure the consistent quality and proper ratio of the slurry soil for each meter pile. In current geotechnical construction practices, digital monitoring research applications are mainly utilized during dynamic compaction, vibratory stone column construction and other similar processes [11], [12]. However, there is a paucity of research on the digital and intelligent construction of high-pressure rotary jet piles, with most studies limited to installing single sensors for detecting construction parameters and controlling construction quality.

The main objective of implementing digitized monitoring in high-pressure rotary jet pile construction is to automatically gather and dynamically record and analyze the operational actions and feedback data of the mechanical equipment during the construction process. This is done to monitor the level of compliance of the construction status with the design and construction expectations. The automated monitoring system facilitates the implementation of measures for managing engineering quality, progress and safety. Based on the unique characteristics of high-pressure rotary jet pile construction and construction engineering experience, the primary parameters for controlling the quality of the construction process are identified. At key processes and important stages, digital collection equipment is installed at the terminal of the construction tools, and the collected information is transmitted in real time to the server for analysis and processing. This provides fundamental data for quality and measurement control for high-pressure rotary jet pile construction.

Given the voluminous amount of construction data originating from various sources, and the specialized needs of the airport industry, the digital monitoring of airport high-pressure jet grouting piles is a concomitant and requisite phenomenon of our times. The fundamental essence of digital technology lies in its capacity to holistically resolve the multifarious challenges encountered in engineering through digitalization and to optimize the utilization of information resources to enhance engineering quality and efficiency. Through a unified platform system, decision-makers at all echelons can effortlessly access diverse critical information and analytical findings, thus facilitating the decision-making process. By streamlining the engineering construction management system, the concept of 'post-control' can be transformed into a paradigm of 'process control' and 'real-time warning', thereby enhancing the quality of airport engineering construction and its level of management.

Regarding the construction characteristics of the high-pressure rotary jetting pile method, and drawing on construction project experience, this study identifies key parameters for controlling the quality of the construction process. These control parameters include the borehole position, drill rod verticality, borehole depth, grouting pressure, grouting hoisting speed, grouting volume per meter and total grouting volume. While these measurement parameters are independent, they are closely interrelated. This research focuses on the application of digital monitoring technology for high-pressure rotary jetting piles in airports, utilizing technologies such as IoT, cloud computing, satellite positioning, and various sensors and mechanical controls, including GNSS positioning technology, tilt sensors, pressure sensors, current transformers and flow sensors. Through the integration of real-time data from the high-pressure rotary jetting pile mechanical construction process, a data chain and resource sharing platform based on transparent and quick-response data is established, forming a digital monitoring system for high-pressure rotary jetting piles in airports. This system is reliant on IoT and related sensor technologies.

The Internet of Things (IoT) is a phenomenon that involves the real-time accumulation of data from any object or process that necessitates monitoring, connection and interactions via diverse devices and technologies, such as information sensors, radio frequency identification technology and global positioning systems. This gathering of various types of critical information, including sound, light, heat, electricity and location, facilitates ubiquitous connectivity between things and between things and humans through a plethora of possible network connections, thereby establishing intelligent perception, recognition and management of goods and processes. IoT, the "Internet of everything," enables interconnections and intercommunications between people, machines, and objects at any time and any place. With the advancement of IoT and sensor technology, an increasing number of IoT sensor platforms are being implemented [13].

The global navigation satellite system (GNSS) is a satellite-based navigation system [14], [15] that offers users all-weather, high-dynamic and high-precision navigation and timing services. The system encompasses the United States' GPS, Russia's GLONASS, the Galileo system of the European Union and China's BeiDou [16]. While each system provides autonomous navigation services, users can leverage the resources of multiple systems to achieve superior or comparable services to those of the individual systems. Achieving high-precision GPS measurements necessitates the use of carrier phase observations. Real-time kinematic (RTK) [17], [18] positioning technology relies on real-time kinematic positioning technology and carrier phase observations, which furnish real-time three-dimensional positioning results in a specified coordinate system with an accuracy of up to the centimeter level [19]. This report implements RTK carrier phase real-time differential technology to provide centimeter-level positioning for the digital monitoring of rotary pile construction.

A geographic information system (GIS) is a specialized and crucial spatial data system, also known as a 'geospatial information system'. It is a technological framework that acquires, stores, organizes, processes, analyzes, visualizes and characterizes geographical data across the complete or partial surface of the Earth (including the atmosphere) with the assistance of computer software and hardware systems. In recent times, GIS technology has rapidly advanced and has been extensively employed in various business sectors, such as smart cities and natural disaster prediction [20]. In the digital monitoring and management of engineering construction, GIS possesses advantages in complete digitization, visualization and intuitive representation based on geographic coordinates [21].

The inclination sensor, commonly referred to as an inclinometer, tilt sensor, level gauge, or tilt meter, is extensively utilized for gauging variations in horizontal angles within a given system [22], [23]. The progression of automation and electronic measurement technology has led to the emergence of electronic level gauges, which have superseded the rudimentary bubble level gauges of yesteryear. Inclination sensors find application in diverse settings that necessitate angle measurement, including the leveling of engineering machinery, the measurement of pitch angle for directional satellite communication antennas, the determination of ship navigation attitudes, the detection of dams and the monitoring of tilt for geological equipment.

A pressure sensor is an apparatus that has the capability to sense pressure signals and convert them into electrical signals that can be utilized following certain rules. Pressure sensors are commonly composed of pressure-sensitive elements and signal processing units, and are extensively employed [24], [25], [26]. Based on the type of pressure being tested, pressure sensors can be categorized into gauge pressure sensors, differential pressure sensors and absolute pressure sensors. Traditional pressure sensors predominantly feature mechanical structures and employ the deformation of elastic elements to indicate pressure; however, this kind of structure is bulky and heavy, and is unable to provide electrical output. With the advancement of semiconductor technology, semiconductor pressure sensors have also emerged, characterized by their small size, light weight and high accuracy, among other advantages.

The current transformer is defined as an apparatus that transforms a primary current into a secondary current that is proportionate to it. Electronic transformers of current possess traits such as being lightweight, compact, easily digitized and appropriately isolated [27], [28]. A current transformer is an instrument that gauges a substantial primary current on the primary side and alters it into a minor secondary current on the secondary side using the electromagnetic induction principle. The current transformer is made up of a closed iron core and a winding. Its primary winding is constituted by a limited number of turns and is connected in a series with the current to be measured.

III. ARCHITECTURE DESIGN OF THE DIGITAL MONITORING SYSTEM

The construction of airports is a complex process that involves multiple parties, and it is imperative to ensure project quality and construction progress. Digital technology, which is distinct from traditional manual recording, presents a novel construction application that can meet the needs of airport construction and satisfy the requirements of various stakeholders. The process of digital monitoring involves digitization, networking, intelligence and visualization of the construction process. The central concept of digital monitoring is to address engineering construction challenges comprehensively by means of digitization and the optimal utilization of information resources. By allowing all participating parties to visually, and in real-time, control the construction progress and quality management of major airport projects, digital monitoring can detect potential construction risks, enable timely decisions, enhance work efficiency and management

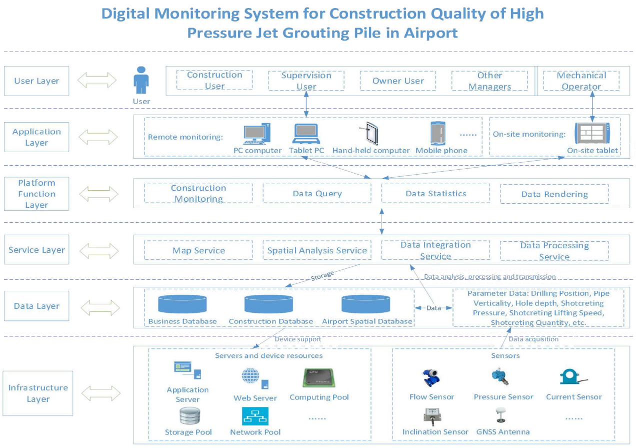


FIGURE 1. **Overall architecture diagram of the system.**

levels. By organizing, conducting statistical analyses, and integrating communication technology with on-site information resources for construction machinery, digital monitoring can manage and accurately control original construction data in real time. Digital monitoring technology encompasses the Internet of Things (IOT), Geographic Information System (GIS), Remote Sensing Technology (RS), Global Navigation Satellite System (GNSS) measurement technology, the internet (WEB), Virtual Reality (VR), etc.

By examining the construction control requirements of high-pressure rotary jet piles at airports, the primary construction parameters that require focus during the construction process include the drilling locations of the high-pressure rotary jet piles, the verticality of the drill bit, the depth of the hole, the grouting pressure, the grout lifting speed and the grout volume. This paper employs an academic approach to conduct research, design and develop both the hardware and software for the acquisition, transmission, storage and presentation of the construction parameters of rotary jet piles, utilizing Internet of Things technology. The construction machinery and grouting equipment for high-pressure rotary jet piles are fitted with the corresponding data acquisition sensors and control terminals. Guidance functions are also provided to operators to allow for real-time problem discovery and construction status adjustments. Data are transmitted to the backend server through the internet, where they are analyzed and processed, providing clients with real-time visualization of the rotary jet pile construction information. This system architecture design requires the installation of corresponding acquisition sensors on the construction machinery and the development of digital monitoring software on the backend. Fig. 1 displays the overall system architecture.

Specifically, a range of monitoring sensors are installed on the rotary jet pile to capture construction parameters such as the drilling position, drilling rod alignment, drilling depth, grouting pressure, grouting lifting speed, grouting volume per meter and total grouting volume. These parameters are processed, analyzed and integrated into the corresponding data modules of the monitoring software, including construction monitoring, data query, data analysis and data visualization rendering. The operators of the rotary jet pile can view the real-time data results on the software interface of the on-site monitoring host tablet and make necessary adjustments in case of abnormalities. Furthermore, the processed and analyzed data are stored in the database of the remote server through an interface protocol. The data processing results are presented in the form of a BS website on the remote monitoring end, which can be accessed by the relevant management personnel through a variety of devices such as desktop computers, laptops, handheld tablets and mobile phones. Users can also query and perform statistical analyses on the monitoring data through these devices to obtain construction quality data and to keep track of the progress of rotary jet pile construction.

The digital monitoring system for the construction quality of high-pressure jet grouting piles at airports has undergone optimization and standardization across six distinct levels. These levels are infrastructure, data, service, platform function, application and user. At the infrastructure layer, web servers, application servers, monitoring sensors and various equipment, such as calculation pools, storage pools, network pools and GPS resource pools, are employed to support the hardware environment necessary for the operation of the monitoring system. The data layer employs database storage software for both the permanent and cached storage of the construction process data, ensuring both data preservation and fast data access [29]. The service layer includes map services, spatial analysis services, data integration services and data processing services. The platform function serves as the foundation of the application layer and is responsible for implementing construction monitoring and system business functions such as data rendering, data querying, data statistics and construction analysis. The application layer encompasses both front-end construction data collection systems and back-end visualization digital monitoring platform software. Lastly, the user layer comprises the users of the monitoring platform, including personnel from project implementation-related construction, supervision and the owner units, who use different functions according to their role-based permissions.

The Internet of Things (IoT) technology system can be divided into four layers: the perception layer, the network layer, the platform layer, and the application layer. Each layer has different responsibilities, and this kind of division of labor, similar to a dedicated personnel system, can improve work quality and efficiency. Based on the overall architecture of the system, a digital construction IoT architecture for high-pressure rotary jet piles is proposed in Fig. 2.

The main function of the perception layer is to collect data from the physical world, making it a crucial bridge for communication between the human world and the physical world. The high-pressure jet grouting digital monitoring system collects relevant construction data in real time through

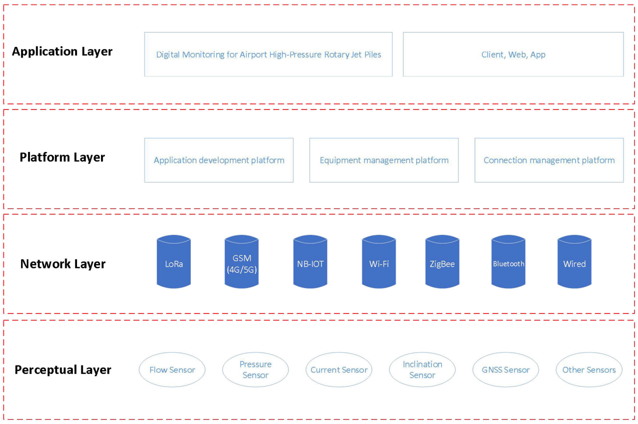


FIGURE 2. **Architecture diagram of the internet of things.**

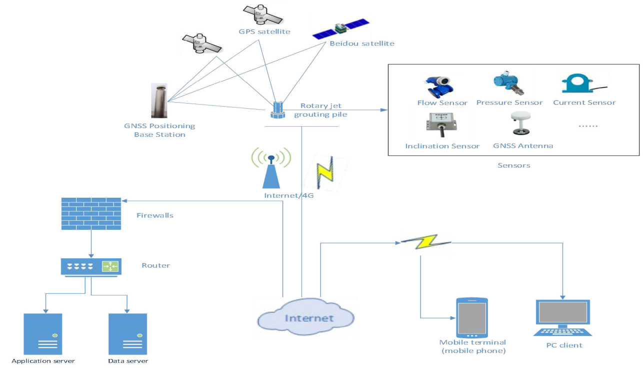


FIGURE 3. **Topology of digital monitoring and network transmission.**

sensors such as flow sensors, pressure sensors, current sensors, inclination sensors, and GNSS positioning sensors.

The main function of the network layer is to transmit information and send the data obtained from the perception layer. Specifically, the relevant collection sensors are connected to the main control box through wired methods such as serial communication (RS-232 and RS485) and wireless methods such as Bluetooth and ZigBee. The main control box uses wireless methods such as GSM (4G/5G) and TCP/HTTP transmission protocol to transmit the sensor data to the monitoring platform.

The platform layer mainly includes the device access platform, device management platform, application development platform, etc. Device access is primarily accomplished through transmission protocols for various sensors to connect and communicate with the IoT platform. Device management mainly involves device creation, maintenance, data conversion, data synchronization, and device distribution. Application development mainly implements the storage, analysis, and application of data, including data visualization display.

The application layer is the ultimate goal of the Internet of Things, primarily in processing the data collected by the sensors at the device end, thus providing intelligent services for high-pressure rotary jet pile construction quality monitoring. This includes business processing, data storage, and client applications. The client applications include PC clients, Web network clients, App handheld terminals, and on-site tablet systems.

In accordance with the functional module requirements of the digital monitoring platform, specific technological methodologies have been implemented, including the storage of spatial and attribute data. For permanent data storage, SQL server database software with a stable performance and large capacity has been utilized, while Redis (Remote Dictionary Server), a key-value storage system, is employed for cache data storage. In addition, GIS technology is utilized for spatiotemporal data processing and display. To acquire construction parameters for the high-pressure rotary jet pile, sensors must be installed at the front end. A positioning base station system is essential to enhance positioning accuracy, and a GNSS reference station system has been constructed to offer high-precision centimeter-level differential positioning services for the on-site positioning devices. During the construction process, the GNSS antenna installed on the high-pressure rotary jet pile receives GPS/Beidou satellite positioning signals and differential correction numbers sent by the GNSS positioning base station, which enables centimeter-level positioning accuracy. Moreover, the current sensors, flow sensors, pressure sensors and tilt sensors installed on the high-pressure rotary jet pile are utilized collectively to obtain critical parameters such as the drilling position, drilling rod verticality, drilling hole depth, grouting pressure, grouting lifting speed and grouting volume during construction. The collected construction parameters are then transmitted to the remote server through the network. Following receipt, the server resolves, processes and distributes the data, and the client can visualize the on-site construction parameters in real time through the network, which facilitates quality control. The digital monitoring network transmission topology diagram of the high-pressure rotary jet pile is illustrated in Fig. 3.

IV. DESIGN AND DEVELOPMENT OF THE DIGITAL SURVEILLANCE HARDWARE EQUIPMENT

Through an analysis of the control indicators and data acquisition devices employed in the construction process of high-pressure rotary jet piles, relevant data can be collected, stored, processed, analyzed and transmitted. The high-pressure rotary jet pile monitoring system primarily comprises a positioning module, inclination sensor, current sensor, pressure sensor, slurry volume sensor, data transmission system, outdoor terminal integrated machine and power supply to facilitate the real-time recording of the entire construction process of the rotary jet pile through collaborative cooperation. Automation is utilized to synchronously monitor crucial construction parameters such as the pile length, pile position, pile body verticality, lifting and drilling speed, pressure, and slurry volume, thereby enabling every stage of

TABLE 1. Communication data format for rotary jet grouting pile construction.

Field Name	Data Types	Attribute Name
code	Varchar(50)	Device number (terminal SN number)
pileCode	Varchar(50)	Station number
drillingDepth	Number(5,4)	Drilling depth
verticality	Number(5,4)	Verticality
dltaX	Number(5,4)	Northward offset
dltaY	Number(5,4)	Eastward offset
drillingSpeed	Number(5,2)	Drilling speed
electric	Number(5,2)	End hole current value
FillingVolume	Number(5,2)	Spray quantity
Pressure	Number(5,2)	Shotcrete pressure
startTime	decimal(13, 0)	Start time
endTime	decimal(13, 0)	End time
totalTime	int	Total time
seqid	varchar(50)	Time stamp
lon	Number(5,15)	Longitude
lat	Number(5,15)	Latitude
gf	varchar(50)	Construction method code
jetliftspeed	varchar(50)	Shotcrete lifting speed
spraypermeter	varchar(500)	Spraying quantity per meter of extension
remark	Varchar(20)	Remarks
fillingVolumeMinute	Number(5,2)	Amount of spray per minute

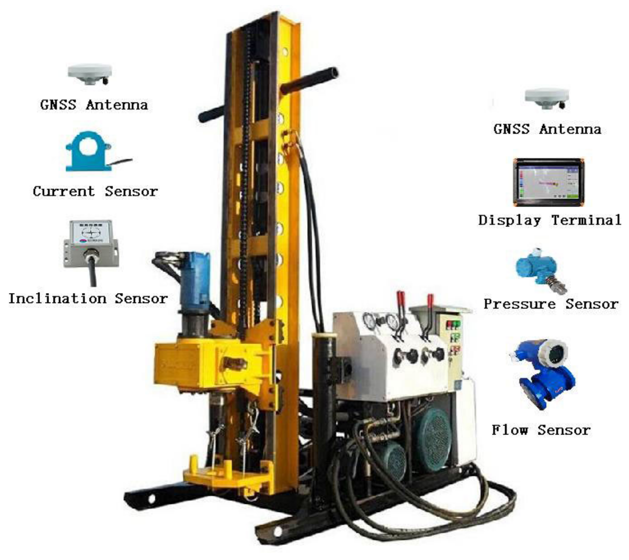


FIGURE 4. Schematic diagram of digital monitoring hardware sensors.

rotary jet pile construction to be traced and ensuring that the hole quality conforms to the design requirements.

In accordance with the stipulated process control parameters for high-pressure rotary jet piles, and taking into account the specific airport engineering circumstances, sensors that are in compliance with the monitoring requirements are carefully chosen. During the selection and development of the front-end hardware equipment for the digital construction monitoring system, an array of extreme environmental conditions and unforeseen scenarios that may arise on the construction site are duly considered. Multiple pressure tests of varying magnitudes are conducted, resulting in the equipment demonstrating remarkable stability. The transmission of construction parameter data, which has been acquired by the front-end sensor, must be sent to the server in a sequential manner, following the HTTP protocol for parsing. The data format utilized for communication during the rotary spray pile construction process can be found in Table 1.

To ensure the security of data transmission during data collection, the acquisition sensors installed on the front-end rotary drilling and grouting equipment employ encryption protocols to safeguard the construction data collected during the rotary drilling process. These encrypted data will then be transmitted via the Hyper Text Transfer Protocol (HTTP) to a remote server. Upon receiving the encrypted data, the server will perform the necessary decryption and data processing operations. The processing of data for rotary drilling is based on a spatial database that stores vectorized data on the location of each pile point, which is utilized for construction monitoring and GIS visualization. The front-end global navigation satellite system (GNSS) positioning antenna acquires World Geodetic System 1984 (WGS84) coordinates [30], which must be converted to the airport's independent plane coordinates. To accomplish this, a data processing class has been designed to provide the main monitoring data processing flow method. As the server-side data reception program receives all the construction data without filtering, a data classification service has been designed to sort and store the rotary drilling construction data. This allows for subsequent data processing programs to process data more efficiently, thereby increasing the overall system efficiency.

To ensure an optimal construction performance, it is imperative to closely monitor the critical indicators related to the construction parameters, including but not limited to the drill rod verticality, borehole depth, grouting pressure, grout lifting speed and grout volume. To achieve this, high-pressure rotary jet pile sensors are carefully selected based on their hardware characteristics, and the corresponding sensing equipment is appropriately installed on both the rotary jet pile and grouting equipment, as depicted in Fig. 4, according to the predesigned specifications.

The principal chassis is positioned in close proximity to the hand console of the pile machine, thereby providing convenient access to real-time operation data for the operators. All sensor data are collected via 4G and line connections and are transmitted to the main chassis for terminal display and remote server data uploading. The positioning module is installed at the rear of the rotary jet pile machine and utilizes an inertial navigation algorithm to guide the vehicle's pile point, thereby replacing the traditional manual placement methods. An inclination sensor is also installed to monitor the verticality of the pile, while a current sensor is situated within the control box of the pile machine's main cabinet, with the ring of the current transformer positioned on the hydraulic cylinder wire. In addition, a pressure sensor is installed for real-time monitoring of the grouting pressure from the background grouting pump, and a flow sensor is in place to monitor the flow value of the pump. Each sensor can communicate with the data processing module through cable or wireless connections, which may include 4G, Bluetooth and ZIGBEE protocols. The main control box computer is equipped with a 4G phone card and can transmit data to the monitoring platform using a wireless network.

V. DESIGN AND DEVELOPMENT OF DIGITAL MONITORING SOFTWARE

This article addresses the rotary jet drilling methodology and the necessity of incorporating multiple sensors and data sources, such as those for communication and positioning, into a monitoring platform for comprehensive visualization, analysis and more. The digital construction monitoring platform is a meticulous endeavor that requires a thorough consideration of the characteristics and requirements of all the stakeholders involved in the project, including the owners, designers, supervisors, contractors and inspectors, during the preliminary phase. This includes their respective business situation, management features, work objectives and other relevant factors. It is imperative to establish effective methods for information transmission and storage, efficient workflow procedures and to develop various report formats that are tailored to the specific work habits and needs to ensure optimal utilization of the system platform following delivery.

The digital surveillance software system for airport jet grouting piles employs contemporary information technologies, including the Internet of Things (IoT) and Geographic Information Systems (GIS), to construct a web-based platform for monitoring the quality of the construction processes. This platform is built on the spatial location foundation and visualizes and analyzes the construction data collected by various sensors on the front-end jet grouting pile. This provides a more convenient approach to managing the construction quality, progress and the problem analysis of the airport jet grouting piles. This paper proposes a method for massive data processing and display based on GIS technology, commencing with the monitoring parameters of the high-pressure jet grouting piles. By analyzing the key technologies involved in the digital monitoring platform for high-pressure jet grouting piles, the analysis and design of the monitoring system's composition and functional requirements are accomplished. In accordance with software engineering principles, a general architecture for the digital monitoring platform is established, and the monitoring software is developed.

Based on the data processing and presentation procedure, the high-pressure rotary spraying pile's terminal monitoring equipment transmits construction data to the server. Upon receipt of the data, the server dissects, allocates and archives it in the Redis database. The allocated data are then managed, archived in the attribute and spatial databases and ultimately exhibited in GIS on the monitoring platform. The comprehensive data processing and presentation process of the monitoring platform is depicted in Fig. 5.

Upon receipt of monitoring data pertaining to high-pressure rotary jet pile construction, the server proceeds to

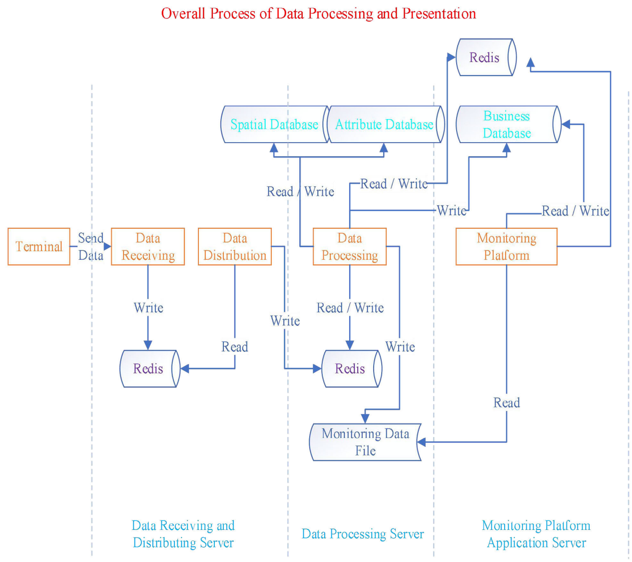


FIGURE 5. Overall process diagram for data processing and display.

decrypt the encrypted construction data to obtain the unique code of the terminal as well as the GPS coordinates of the monitoring sensors for inclination and pressure, among other information. Using the terminal's unique code, the server retrieves the vehicle's unique number. The relevant information for the construction data's corresponding area is determined and set based on the GPS coordinates. The parsed attribute data obtained through coordinate transformation are then stored in the database. The parsed construction data are subsequently processed through the utilization of data processing programs.

The digital monitoring software platform, designed for high-pressure rotary spray piles, functions as a display mechanism for the extensive backend database. Its primary objective is to consolidate and scrutinize the construction process data obtained by the front-end control equipment, subsequently presenting it in a graphical and tabular format to facilitate informed decision-making. By employing a standardized and comprehensive GIS platform, a multilayered architecture is structured that is compatible with major database systems. Additionally, a hybrid development structure of B/S + C/S is employed to achieve unified management and entry of the rotary spray pile control functions. The fundamental functions of the platform encompass visualization rendering, query analysis, and other control parameters, including the drill hole position, drill rod verticality, drill hole depth, grouting pressure, grouting lifting speed and grouting volume.

Concretely, the digital monitoring platform has the capacity to visually represent and discern diverse outcomes in construction quality, predicated on criteria such as verticality, grouting volume, grouting pressure and lifting speed, via the use of color-coded graphics. Furthermore, it facilitates various query and summarization functions, encompassing the provision of pile construction data through point-based, rectangular-based and condition-based query methods, as well as through statistical analysis. Consequently, the operational capabilities of this design platform are predicted.

Construction Monitoring: Select relevant indicators such as perpendicularity, injection volume, grouting pressure and lifting speed for the information to be displayed. Upon confirmation of monitoring, the drilling information corresponding to the construction site is presented on the map, proportionate to the preset pipe diameter. Diverse construction index data is exhibited in varying hues on the map, with the legend serving as a tool for comparative analysis.

Point Query: To initiate the query state, opt for the point query function. Subsequently, click on the monitoring data display point situated on the map to retrieve comprehensive information pertaining to the process data of the construction pile point located at the aforementioned point of the click.

Rectangle Query: The rectangle query function is used to activate the selection query status and delineate the search range box on the exhibited position of the scrutinized data on the map. All the data result information confined within the perimeter of the traced search box is procured.

Conditional Query: The retrieval of construction data is facilitated through conditional queries, which affords the user the ability to select data sources, including section, vehicle code and construction time range. The resultant data are presented in accordance with the specified query conditions and may be visually represented using statistical charts. This approach is consistent with academic conventions in scholarly discourses.

Construction Summary: The construction synopsis report facilitates the option to designate the commencement and cessation times of the construction process. Once finalized, the designated construction data during the specified timeframe are extracted. The summary encompasses statistical data on the initiation and cessation times of each vehicle, the quantity of the piles erected, the overall depth, the mean length of each pile, the mean duration of pile driving, the average speed of grouting lifting, the average grouting pressure, the mean verticality and equipment identification particulars.

Simultaneously, with regard to the design of the interface, to ensure lucid visualization of the data, it is feasible to superimpose the range image of the construction and the design map onto the GIS base map. Another option would be to fashion a distinct base map for presentation purposes. The design of the interface is illustrated in Fig. 6.

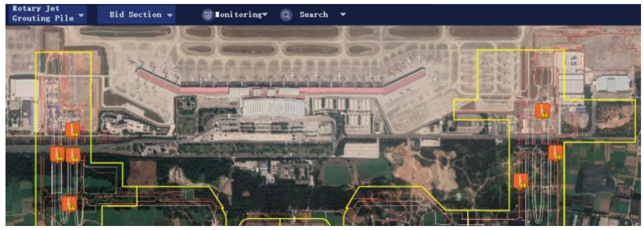


FIGURE 6. **Design diagram of the digital monitoring interface.**

VI. ENGINEERING APPLICATION AND RESULTS ANALYSIS

A. OVERVIEW OF PRACTICAL APPLICATIONS

The findings of this study have been implemented in the flight area project of the Phase II expansion project of Fuzhou Changle International Airport, specifically in the transitional treatment area of the rotary jet grouting piles on both sides of the project. The Phase II project of Fuzhou Changle International Airport encompasses a coastal low hill-plain landform, flanked by the sea to the east and south, while a series of north-eastern remnants of hills have developed along the East China Sea coast. The terrain is characterized by a flat plain, interspersed with sand dunes and sand ridges. Within the construction boundaries, a number of ditches and ponds are scattered, with some wells present sporadically. Notably, some of the aforementioned ditches and ponds are rather expansive, featuring variable thickness of silt accumulation at the bottom. In light of the deep and thick soft soil characteristics observed on site, rotary jet piles are to be employed for transitional treatment on both sides of the underpass project. These rotary jet piles are designed to address the silty clay and powdery clay in the impact zone of the underpass project, controlling foundation settlement unevenness by regulating the length change of the rotary jet piles. Given these conditions, diligent monitoring of construction machinery position, perpendicularity, pile depth, lifting speed, rotation speed, injection pressure, and slurry consumption, among other key indicators, are crucial for ensuring optimal outcomes. To facilitate efficient data acquisition and processing, a front-end sensor has been installed on the rotary jet grouting pile and grouting equipment, while data receiving and processing programs have been arranged on a remote server, with a distributed application service that enables easy access and visualization of construction data by clients. Through the digital management and control platform, all participating units can monitor the construction process of the rotary jet grouting pile and identify issues in a timely manner.

In the case of transition sections demanding high differential settlement postconstruction, it is recommended that the high-pressure rotary jet pile composite foundation method be utilized. The construction of high-pressure rotary jet pile foundations can vary based on the geological conditions of the region in question; hence, it is essential to perform a designated range of trial section construction and parameter detection before formal construction of the project can commence, to determine the specific index parameters within the construction project's scope. This approach allows for the assessment of the construction outcomes of the trial section while referencing geological survey data to establish the necessary design or construction standard requirements. Before the formal construction of the project area, a one-month trial section construction and relevant data detection are conducted. For key indicators, the requisite parameter or

TABLE 2. Monitoring standards for rotary jet piles.

Index	Monitoring Project	Monitoring Standard
1	Pile Verticality	No more than ±1%
2	Hole Depth	5 cm accuracy
3	Plane position	5 cm accuracy
4	Shotcrete Pressure	No less than 25MPa
5	Shotcrete Quantity	Design value 5%
6	Lifting Speed	No more than 0.15 m/min
7	Specific gravity	1.50

(a)

(b)

FIGURE 7. Random sampling of cement slurry density: (a) Actual operation; (b) Detected value.

quality requirements are defined, creating the foundation for the construction standards throughout the construction area. After the trial section construction, the rotary jet pile construction for this project should meet the following standards. The pile verticality should not exceed 1; the measurement accuracy of the plane position and hole depth should be within 5 cm; the shotcrete pressure should not be less than 25 MPa; the error of the shotcrete quantity should be within 5% of the design value; the lifting speed should not exceed 0.15 m/min, and the specific gravity should be 1.5. Proper monitoring of rotary jet pile construction is necessary for judging whether the construction meets the standards, as specified in Table 2.

Prior to executing the jet grouting pile, it is crucial to evaluate the density of the slurry. As illustrated in Fig. 7, the density of the slurry was measured to be 1.52, meeting the predetermined monitoring standards.

B. ON-SITE HARDWARE INSTALLATION

During the course of airport construction, a GNSS positioning base station was erected on site to more precisely collect the construction machinery coordinates, ensure construction quality and establish an engineering coordinate reference framework. This station serves as a positioning reference for collecting coordinate data during high-pressure rotary sprayed pile construction. With the installation of GNSS positioning antennas on the rotary sprayed pile construction equipment, satellite signals were received, and correction data transmitted by the base station were utilized to achieve centimeter-level, precise positioning results. The on-site installation of the GNSS positioning base station

FIGURE 8. Installation diagram of GNSS positioning base station.

was designed to cover the entire construction area, taking into account crucial factors such as power supply, network, security and convenience. This base station was also able to facilitate the conversion between the GNSS coordinate system and the construction coordinate system, as well as coordinate verification. The positioning base station erected on site is clearly depicted in Fig. 8.

To procure data pertaining to the key construction parameters, including but not limited to the position of the high-pressure rotary jet pile drilling, the verticality of the drilling rod, the depth of the hole, the grouting pressure, the grouting lifting speed and the amount of grouting, it is imperative to install corresponding sensors. To monitor the drilling position, depth, lifting speed, etc., two positioning antennas are employed, while tilt sensors are utilized to monitor the verticality of the drilling rod. Pressure sensors and current sensors are deployed to monitor the grouting pressure, and flow sensors are employed to monitor the amount of grouting. A tablet computer serves as the display terminal, providing a real-time display of the data collected on site, including pressure, verticality and slurry volume, as well as offering guidance functions for the pile points. Following compilation, encryption, processing and conversion of construction data, transmission to a remote server is carried out through a wireless network. The installation effect of on-site sensors for high-pressure rotary jet piles is illustrated in Fig. 9.

To increase the capability of the site operator to monitor the construction progress, a tablet terminal display is implemented on the site, as depicted in Fig. 10, to showcase the display effect.

C. DIGITAL PLATFORM FUNCTIONALITY AND EFFECTIVENESS

In accordance with the monitoring requirements for high-pressure jet grouting pile construction, a digital monitoring software platform is designed and developed for practical application. The platform incorporates real-time monitoring of various parameters, including verticality, injection volume,

FIGURE 9. On-site installation of high pressure rotary spraying pile sensors.

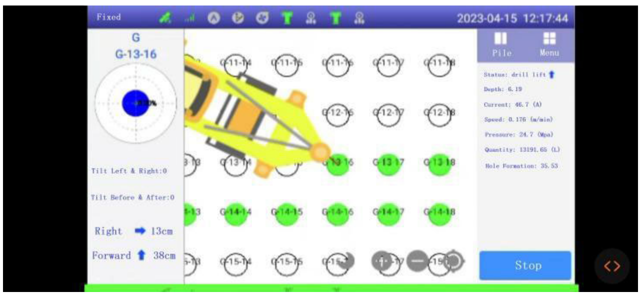
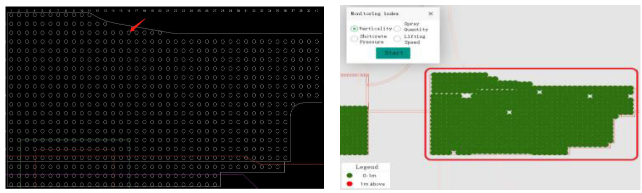


FIGURE 10. The on-site display of the flat panel monitoring effect.

FIGURE 11. Digitally monitored position diagram of the rotary spray pile.



(a) (b)

FIGURE 12. Design and implementation of rotary jet pile: (a) Design plan for the location of rotary jet pile; (b) Implementation illustration of the rotary jet pile at a actual construction site.

grouting pressure, lifting speed and other indicators. Additionally, the platform offers a range of querying functions, including point querying, rectangular querying, conditional querying and a construction summary. The monitoring platform is designed to simultaneously monitor the construction data of two targets, namely, target one and target four. The functional effect diagram presented below illustrates an example of target one data. The digital monitoring software was developed using GIS technology, with the main interface capable of superimposing images and design vector data. The icons located at different positions on the map display varying numbers of jet grouting machine equipment. By clicking on an icon, users can view information such as the corresponding jet grouting pile number, the last record's pile point position and the construction time. This information is presented in Fig. 11.

During the implementation of foundation treatment for airport engineering on-site, the prescribed design documents will be adhered to. In relation to the specific construction of rotary jet piles at Fuzhou Airport, drilling activities are carried out on-site in accordance with the coordinate arrangement specified in the design documents. By employing the digital monitoring system of rotary jet piles, the real-time construction data is transmitted through the network to a central server, allowing for the visualization of monitoring results on a digital monitoring software platform. Fig. 12 illustrates the design arrangement of a particular construction area for the rotary jet piles, depicted as Fig. 12a, whereas Fig. 12b showcases the visual representation of the actual data collected through the digital monitoring system of rotary jet iles.

D. MONITORING OF A SINGLE PILE CONSTRUCTION PROCESS

A digital construction monitoring system can monitor the working process of a spiral jet grouting pile in real time, ensuring that the construction data meet the design requirements. The workflow of the digital construction system for monitoring individual piles is shown in Fig. 13.

In digital construction system monitoring, the indicators are derived from design documents. That is, the design unit requires the construction unit to choose the indicators during the process. The digital system will strictly monitor the construction process in real time in accordance with the design requirements. The indicators that need to be monitored for this project include verticality, injection amount, grouting pressure and lifting speed. We have already introduced the sensors we have chosen for monitoring in the previous section, and the following section mainly introduces the data recording and analysis of the monitoring platform.

The selection of different indicators leads to a display of the corresponding data on the monitoring map, and a legend is designed based on the specific parameter requirements of the project. For instance, if the chosen indicator necessitates a verticality of no more than 1%, injection pressure of

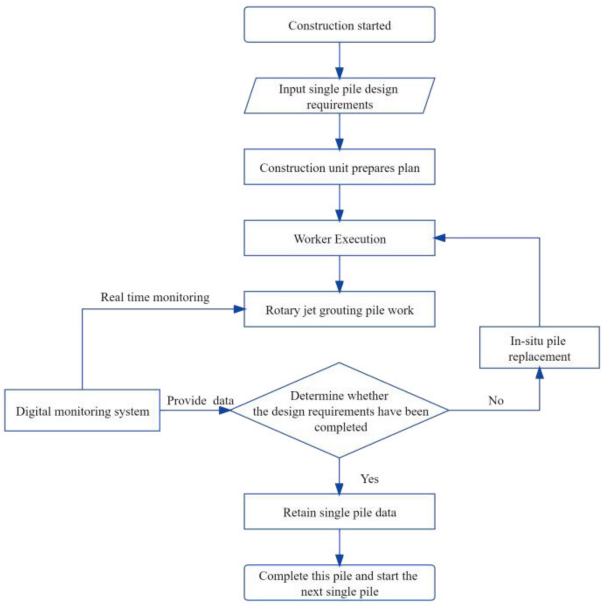
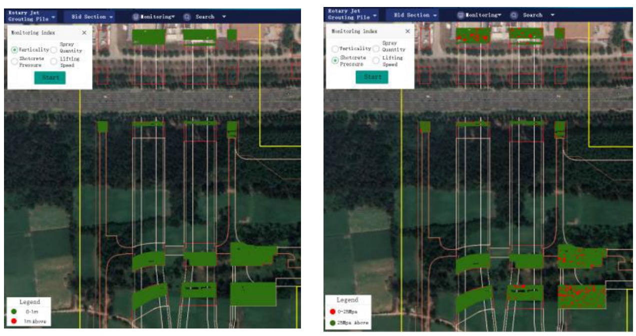


FIGURE 13. Digital Construction System Monitoring Single Pile Workflow Diagram.



(a) (b)

FIGURE 14. Real-time monitoring of the verticality and shotcrete pressure of spiral jet piles: (a) Real-time monitoring of verticality; (b) Real-time monitoring of shotcrete pressure.

not less than 25 MPa, and a lifting speed of no more than 0.15 m/min, the legend is created accordingly. By comparing the differences in the legend and the colors rendered on the map, it possible to understand any of the data deviations from the requirements. The real-time monitoring of construction verticality and injection pressure is visually displayed via a monitoring interface, as illustrated in Fig. 14.

Utilizing the a green hue to denote data that satisfy the construction criteria, and employing the color red to signify anomalous data, the observations from Fig. 14 reveal that the verticality criterion has been met, albeit with a few red indicators for spray pressure exhibiting values below 25 mega pascals. Such visualization aids in the identification of the causes for unmet criteria and facilitates improvement efforts. Comparable monitoring protocols are applied to other performance metrics. The inquiry function encompasses point inquiry, box selection inquiry, conditional inquiry and a construction summary, as presented in Fig. 15.

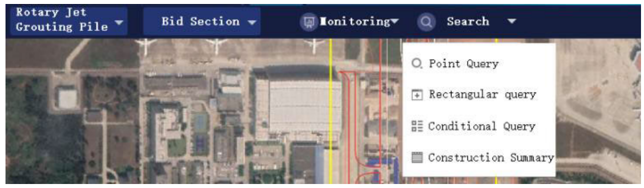


FIGURE 15. Digital monitoring and a query menu for rotary jetting piles.

(a) (b)

FIGURE 16. Query of digital monitoring points for rotary spraying piles: (a) Point query rendering selection; (b) Point query property sheet.

The point query functionality facilitates the examination of comprehensive construction process information pertaining to the targeted pile points, encompassing the attribute data and a statistical data analysis. Notably, as illustrated in Fig. 16, upon selecting the point query menu button and clicking on a specific pile point on the map (displayed as a crimson dot on the lower left-hand corner of the figure), the monitoring data of the rotary jet pile located at that designated point are promptly retrieved.

The presentation of information through statistical graphics is also made possible by activating the point query feature. Upon selecting the statistical button, a line graph will be exhibited, as depicted in Fig. 17.

The point query facilitates the display of comprehensive data pertaining to each individual pile, encompassing the entirety of the pile driving process, drilling progress, attainment of design depth and the complete extraction process of the pile, beginning from the ground. In terms of construction quality, particular attention is directed toward the post-design depth pile extraction process. This scrutiny includes a real-time measurement of pile depth, spray quantity, shotcrete pressure and shotcrete lifting speed, among other parameters, to discern their variations and maintain stability. The statistical analysis depicted in Fig. 17 offers a visual depiction of the complete data pertaining to the pile driving process for the selected pile point. The line graph illustrated therein situates the selected pile point numbers along the horizontal axis, capturing the chronological span from the commencement of pile driving to the termination, while the vertical axis represents the specific construction parameters that have been collected. The topmost line graph, which depicts the pile depth, exhibits a consistent increment in depth from the initiation of pile driving until the

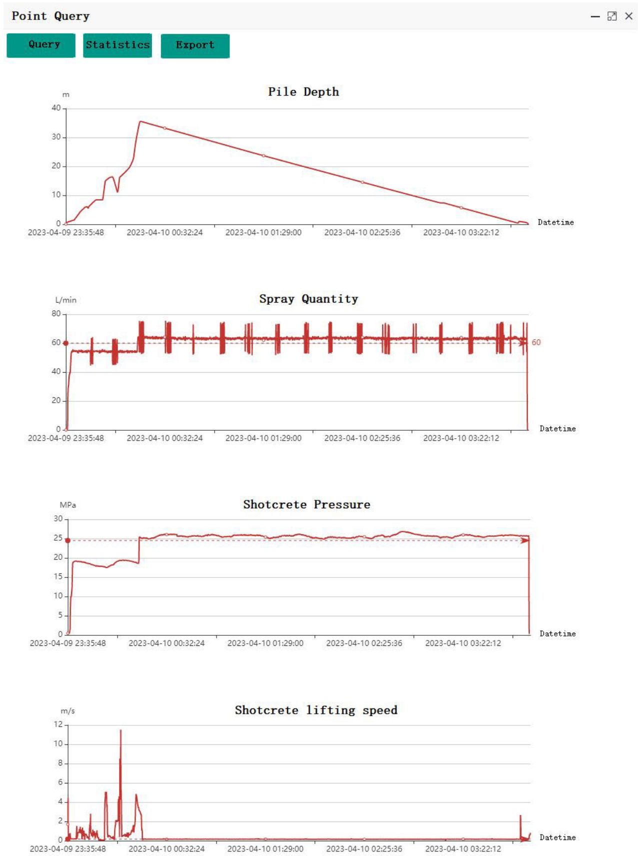


FIGURE 17. **Point query line statistics.**

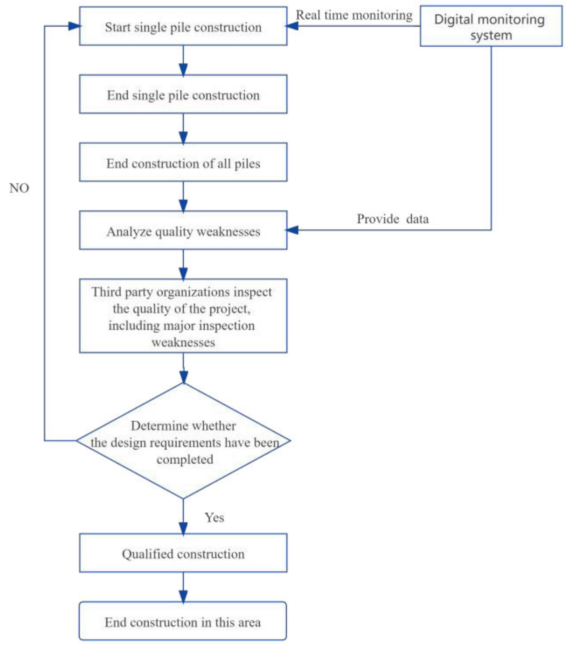


FIGURE 18. **Analysis workflow of weak points in construction quality for spiral jetting pile area.**

(a) (b)

FIGURE 19. **Digital monitoring rectangular query of rotary jet pile: (a) Rectangular query rendering the selection; (b) Rectangular query property sheet.**

attainment of the design depth. This is followed by a gradual decrease during the pile extraction process. The line graph effectively indicates the critical point and the corresponding time at which the pile extraction occurs. The second graph encompasses the average spray speed (L/min) over time, enabling a comprehensive evaluation of the stability of the grouting process. The third graph portrays the average grouting pressure over time, facilitating the monitoring of potential abnormal fluctuations in pressure. Finally, the bottommost line graph captures the shotcrete lifting speed, with a particular emphasis on stability post-pile extraction, and serves as a mechanism for detecting instances in which the speed surpasses 0.15 m/s. Such occurrences can then be further examined to elucidate the underlying causes. Point queries afford an all-encompassing analysis of the complete construction process pertaining to the chosen pile point.

Furthermore, the attributes and icon data that have been requested can be exported to Microsoft Excel.

E. ANALYSIS OF WEAK POINTS IN THE CONSTRUCTION QUALITY

Traditional third-party inspection units randomly select points for quality inspection based on project types. After the implementation of digital construction monitoring systems, the system collects and records the construction process data and result data for all the single piles in the area. Through a big data analysis of the massive construction data, weak points in the construction quality within the area can be identified, providing suggestions for the selection of inspection points for the third-party inspection units. The workflow for analyzing weak points in construction quality in the rotary spray pile area is shown in Fig. 18.

Analysis of weak points in regional construction quality requires knowledge of all the rotary jet piles in the area. If it is necessary to obtain real-time construction data for all the rotary jet piles in the construction area, the platform's rectangular query function can be used to view the detailed construction data, including the attribute data and data statistics for all the rotary jet piles in the selected area. As shown in Fig. 19, by selecting a rectangular area, the corresponding construction result information can be viewed for the selected pile points.

Furthermore, it is possible to export the attributes and icon data that were queried to Microsoft Excel. In addition, the

FIGURE 20. Rectangular query line statistics.

data gathered from the rectangular queries can be visually represented through statistical graphs. By clicking on the statistical button, users can view a line graph or export the data to Excel. The statistical line graph can be seen in Fig. 20.

According to the data presented in Fig. 20, a comprehensive overview of the selected pile points can be obtained. The graph exhibits the number of selected pile points on the horizontal axis, while specific construction parameters are displayed on the vertical axis. The topmost line chart delineates the depth distribution of each pile point. The middle line chart, which demonstrates the average spray speed (L/min) for each pile point, aims to provide insight into the overall grouting volume. The final line chart details the distribution of the average grouting pressure at each pile point. Upon examination, it becomes apparent that a minority of pile points exhibit an average pressure below 25 MPa. Therefore, it is recommended that a detailed analysis of these data points be conducted to determine the root cause, and to subsequently optimize the construction process as a whole.

A conditional query is used to limit the corresponding data of the query based on specific conditions, such as querying specific sections, specific construction equipment and data on spun pile construction during a certain time period, as shown in Fig. 21.

Moreover, the attributes and icon data that have been queried have the capability to be exported into Microsoft Excel. Additionally, the data that were obtained through conditional queries can be visually represented with statistical graphs. By selecting the statistical button, the data can be showcased as either a bar chart or transferred into an Excel file. For the statistical bar chart, please refer to Fig. 22.

According to the data presented in Fig. 22, the examined pile point situation can be readily observed. The histogram

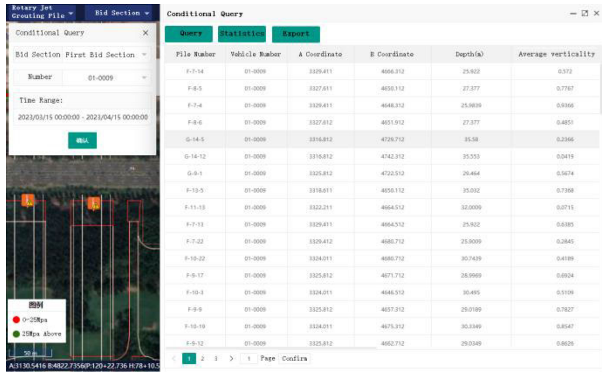


FIGURE 21. Digital monitoring condition query.

FIGURE 22. Digital monitoring condition query column statistical chart.

depicts the selected pile point numbers on the x-axis and the corresponding construction parameter data on the y-axis. The graph at the top illustrates the depth distribution of each pile point, which varies as a result of the heterogeneous geological formations. The middle graph displays the grouting volume of each pile point per minute, as measured by the average spray speed (L/min) for the purpose of evaluation. Finally, the lowermost graph illustrates the distribution of the average grouting pressure at each pile point. Notably, a few of the pile points exhibit an average shotcrete pressure below 25 MPa, which merits further consideration of the specific process data to discern the underlying causes of this outcome. Potential contributing factors might include machinery or equipment malfunctions, improper personnel operation, or other reasons. By studying these data in greater depth, it may be possible to improve the quality of construction monitoring.

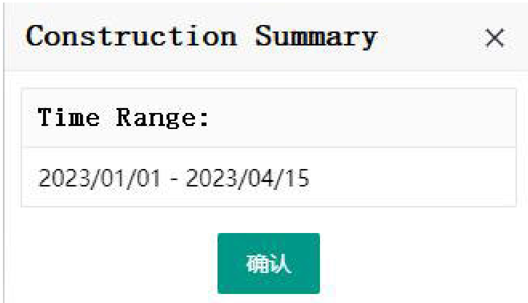


FIGURE 23. Summary interface for digital monitoring construction.

Moreover, the attributes and icon data that were requested can be exported to an Excel format. The construction summary, which is based on the statistical analysis of high-pressure rotary jet pile construction within a specific timeframe, is presented in Fig. 23. Specifically, the construction summary pertains to the period between January 1, 2023 and April 15, 2023.

Furthermore, it is possible to export the requested attributes and icon data to Microsoft Excel. It is recommended to export the summary table for rotary jet pile digital monitoring construction, as exemplified in Table 3.

There are four rotary jet piles, numbered 01-0010, 01-0011, 01-0009 and 01-0007. It is necessary to list the four rotary jet piles belonging to each bidding section, as well as the start and end times for each rotary jet pile machine. There are parameters such as pile numbers, total depth, average pile length, average pile time, average shotcreting speed, average shotcrete pressure and verticality. Specifically, as shown in Table 3, take the rotary jet pile machine with the number 01-0011 as an example. The rotary jet pile machine of 01-0011 belongs to the first bidding section, and a total of 99 piles were constructed. The first pile began on December 31, 2022, 12:49:52, and the last pile was completed on March 4, 2023, 13:36:35. The total depth of these 99 piles was 3,558 meters, so the average length of each pile was 35.9 meters. The average pile time for each pile was 25,992 seconds, and the average shotcreting speed was 0.129797 m/min. The average shotcrete pressure was 25.964848 MPa, and the verticality was 0.529754. Thus, the overall situation can be calculated.

By importing the data of 957 rotary jet grouting piles collected from the digital construction monitoring system into MATLAB for data analysis, a distribution map of the pile depths in the construction area can be formed. The X and Y axes represent the pile location (Using the AB coordinate system of airport engineering), and the Z-axis represents the depth of the rotary jet grouting pile. Comprehensive analysis of the data shows the following:

(1) Rotary jet grouting piles are concealed by engineering with a wide construction area. Traditional construction of rotary jet grouting piles relied solely on the manual judgment of the pile location by workers, but with the application of a digital construction monitoring system, the system's onboard

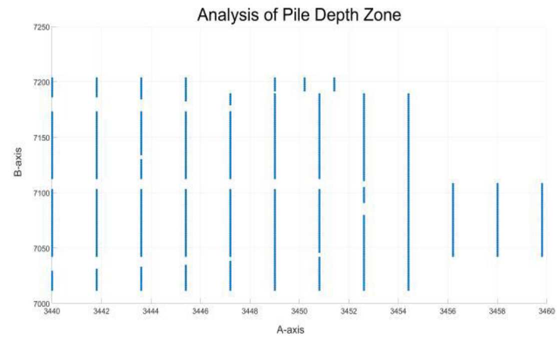


FIGURE 24. Plan Distribution Diagram of Pile Positions.

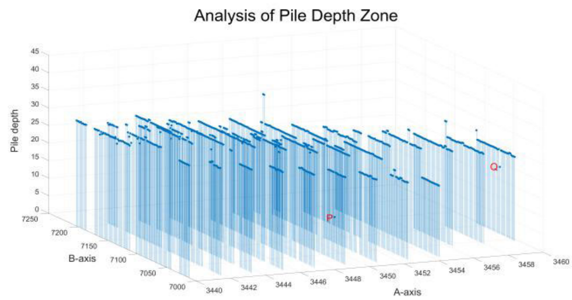


FIGURE 25. Three-dimensional analysis chart of pile depth.

tablet guides workers to perform pile driving operations at the coordinates specified in the design, thus ensuring an accurate pile location, and better guaranteeing the requirements of the pile body bearing capacity on the foundation. The pile distribution is shown in Fig. 24.

(2) The depth of a pile formation in screw pile construction affects its bearing capacity and stability to a certain degree, and is an important indicator that affects the quality of screw pile construction. This article conducts a three-dimensional analysis of the screw pile depth in the construction area, as shown in Fig. 25, providing an intuitive understanding of the change in pile formation depth. For piles with sudden changes in depth, the weak point analysis in the area, as shown in Fig. 26, can preliminarily determine the weak points in the construction quality in that area, namely, points P and Q. It is recommended that third-party testing units, in addition to randomly inspecting check points according to the normal quality inspection process, also test the quality of the weak points.

F. COMPARISON STUDY

(1)Conventional methods

The intricate construction process, stringent technical prerequisites, and quality control challenges attributed to high-pressure rotary jet piles render them a clandestine form of construction. Variations in geological conditions mandate judicious parameter selection and the operators are required to hold rigorous qualifications. Conventionally, scrutiny of operator performance during the construction phase,

TABLE 3. Summary table of digital monitoring construction.

Bid Section	Start Time	End Time	Vehicle Number	Pile Numbers	Total Depth(m)	Average Pile Length(m)	Average Pile Time(s)	Average Shotcreting Speed(m/min)	Average Shotcrete Pressure(MPa)	Verticality
First Bid Section	2023/1/1 6:53:02	2023/3/4 16:03:07	01-0010	75	2697.7043	35.969390	89047	0.134666	26.604533	0.529754
First Bid Section	2022/12/31 12:49:52	2023/3/4 13:36:35	01-0011	99	3558.3332	35.942759	25992	0.129797	25.964848	0.517816
First Bid Section	2022/12/3 16:16:17	2023/4/14 23:33:14	01-0009	483	13024.0383	26.964882	55755	0.138074	25.520165	0.510113
First Bid Section	2022/7/27 0:35:15	2023/2/27 8:15:52	01-0007	46	1950.4317	42.400689	65035	0.116304	24.331521	0.461465

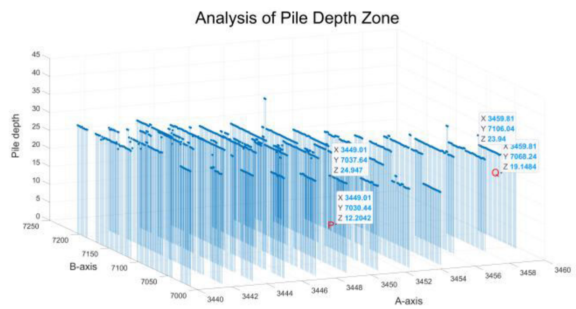


FIGURE 26. Analysis map of weak points in the region.

FIGURE 27. A core drilling and coring diagram of a rotary jet grouting pile: (a) Example of drilling coring; (b) Drill hole coring number.

complemented by subsequent sampling and coring inspections, constitute the primary quality control measures for rotary jet piles.

Throughout the duration of the construction process, the deficient mechanization of the drilling rig utilized for the creation of high-pressure rotary jet piles necessitates a reliance on manual operation for key procedures. Since high-pressure rotary jet piles serve as covert subterranean projects, the manual operation required for construction relies heavily on on-site control and prior experience. This becomes problematic as it leads to inaccuracies and imprecision, ultimately hindering the assurance of pile quality. To monitor and record the various construction process indicators, operators collect the data on-site, as shown in Table 4.

Indeed, on account of the fact that the fabrication of high-pressure rotary jet piles pertains to subterranean covert engineering, the manufacture of a solitary pile necessitates an extensive duration. Conventional manufacturing techniques commonly hinge on the know-how and accountability of operators, resulting in predicaments such as intentional shortcuts, erroneous subjective judgments, and inadequate traceability of procedural record data.

The conventional evaluation of the quality of high-pressure rotary jet pile construction principally encompasses post-construction quality surveillance through the procurement of cores by sampling drilling. This procedure falls within the ambit of postconstruction quality inspection. The traditional core drilling technique is depicted in Fig. 27. After the regional construction has been accomplished, the implementation of the sampling inspection method is undertaken to validate the construction quality of high-pressure rotary jet piles. This procedure involves the random selection of multiple piles for sampling, followed by the evaluation of their pile quality.

(2)Digital monitoring methods

During the construction process, the assurance of quality primarily rests on the experience and responsibility of the construction personnel and the monitoring and supervision of the process by on-site inspectors. However, this approach is not always discerning or precise. Consequently, this study presents a digitally monitored jet-grouting pile system that collects construction data and visualizes construction outcomes, resulting in a convenient and reliable method for quality control, as well as identifying the weak points in the construction and determining whether reconstruction is necessary. Specific construction anomalies can be identified to facilitate improvements while determining whether the abnormal situations require reconstruction. For instance, the jet grouting pressure monitoring, as depicted in Fig. 28, highlights a pile point with insufficient pressure, represented by the red circle. Moreover, the pile point at the lower right corner depicts an average pressure of 24.39 MPa, which is indeed below the required standard.

Fig. 29 presents a comprehensive and meticulous analysis of the process data situation at the aforementioned site, providing further insights into the underlying dynamics of the system.

Observations from Fig. 29 reveal that the rotary jetting pile casing began to elevate at a depth of 35.5866 meters from the ground. The casing abruptly reaches the ground when it was lifted to a distance of approximately 10.71 meters at approximately 02:05, as indicated by the data provided in the yellow

TABLE 4. Construction record of rotary jet grouting piles.

Index	Pile Number	Hole-forming Date	Depth (m)	Pile top elevation(m)		Effective length (m)	Verticality deviation(%)	Rotary spray time(h:min)		Speed (mm/min)	rotation speed (r/min)	Pressure (MPa)
				Design	Actual			Start	End			
	H-10-1	5.16	29.2		4	24.5	0.1	3:22	6:41	150	15	25
	H-10-2	5.16	29.2		4	24.5	0.1	3:22	6:41	150	15	25
	H-10-3	5.16	29.2		4	24.5	0.1	7:03	10:17	150	15	25
	H-10-4	5.16	29.2		4	24.5	0.1	7:03	10:17	150	15	25
	H-10-5	5.16	29.2		4	24.5	0.1	12:47	20:10	150	15	25
	H-10-6	5.16	29.2		4	24.5	0.1	12:47	20:10	150	15	25

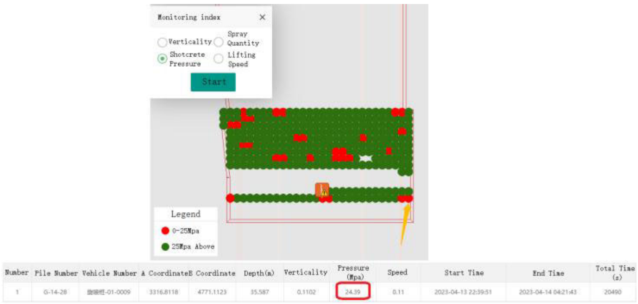


FIGURE 28. Selection of abnormal points in digital monitoring.

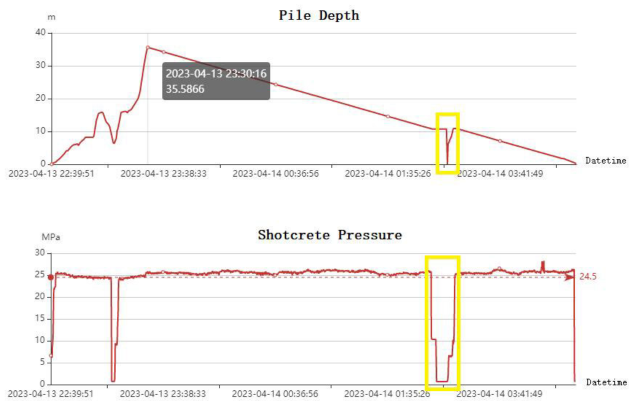


FIGURE 29. Analysis of abnormal points in digital monitoring.

box. Subsequently, the data resumed at approximately 03:14, and the casing sank to a depth of approximately 10.7 meters before elevating to reach the ground once again.

Analysis of the pressure graph indicates a linear pressure drop from approximately 25.7 at 01:58 until it reaches 0 at 02:05. The absence of pressure data from 02:05 to 03:14 suggests a halt in construction during this period. However, the resumption of normal data indicates proper functioning of the monitoring and collection equipment. This infers a mechanical malfunction during the halted construction period. Upon verification with the construction site, it was confirmed that the rotary jetting pile machine had malfunctioned and undergone repairs during this time. The pressure abruptly dropped to approximately 0 for 5-6 minutes before the equipment malfunctioned and stopped working, resulting in a lower average pressure. Using a pile point constructed on a certain day as an example, Table 5 presents an analysis of the abnormal data by comparing it with the design values.

It was deduced that the R-17-4 and R-17-5 piles exhibited atypical lifting speeds owing to the rapid collation speed during the lifting process. The O-10-17 pile registered a slightly suboptimal average pressure due to the pressure oscillating at approximately 25 MPa during the lifting process. The O-8-38 pile manifested an abnormal infusion quantity due to an inadvertent act of a laborer who unplugged the internal sensing module. Finally, the pressure of the O-8-37 pile experienced a decline to 2 MPa for a period of 50 minutes due to the untimely suspension of equipment maintenance, leading to anomalous pressure.

(3)Summary

The conventional method for constructing high-pressure rotary jet piles largely hinges on the expertise and conscientiousness of construction personnel for quality control. However, manual operations are prone to mistakes and exhibit suboptimal precision. On the other hand, digital monitoring systems leverage appropriate sensors to capture pertinent indicators, thereby facilitating instantaneous tracking of the construction progress of individual piles and enhancing operators' comprehension of the construction procedures. This technology ensured improved pile precision, mitigated uncertainty in manual operations,reduced labor costs, and elevated construction quality. Additionally, through auxiliary monitoring during the construction process, weak points of the pile, which indicate areas with fewer indicators during construction, could be identified. It has the potential to address random sampling issues and enhance sample representativeness during result testing. The use of digital systems improves construction accuracy and facilitates easy identification of weak points in the pile. The deployment of digital construction techniques can facilitating continuous 24-hour monitoring of the construction process, thus enabling regulatory personnel to manage and address issues with great accuracy. The equipment utilized is highly reliable and durable, thereby enhancing the overall construction quality level of the project. Furthermore, the analytical and guidance capabilities integrated into the system can save labor costs, ensure engineering quality, prevent rework, and provide a cost-effective solution that offers numerous benefits.

TABLE 5. Statistics of digital construction.

Regional	Number of Piles	Vehicle Number	Pile Number	Design Depth (m)	Depth (m)	Design Pressure (MPa)	Pressure (MPa)	Design Speed (m/min)	Speed (m/min)	Design Verticality	Verticality	Spray Speed (L/min)	Spray Amount (L)
R Region	5 Piles	01-0006	R-17-4	23.10	24.80	>25	25.07	≤0.15	0.18	<1	0.37	65.68	9034.22
			R-17-5	23.10	25.01	>25	25.39	≤0.15	0.17	<1	0.09	68.27	9883.77
			R-17-6	23.10	24.63	>25	25.45	≤0.15	0.15	<1	0.44	70.01	11136.89
			R-17-8	23.10	25.05	>25	25.61	≤0.15	0.15	<1	0.15	61.48	9861.14
	4 Piles	01-0007	R-8-4	36.60	37.53	>25	25.48	≤0.15	0.15	<1	0.93	64.36	15621.64
			R-8-3	36.60	37.30	>25	25.62	≤0.15	0.15	<1	0.92	72.91	17632.23
			R-8-2	36.60	37.30	>25	25.05	≤0.15	0.15	<1	0.41	69.46	17163.63
			R-7-2	38.10	39.05	>25	26.86	≤0.15	0.14	<1	0.06	56.26	14659.69
O Region	9 Piles	01-0008	O-10-18	31.80	32.82	>25	25.20	≤0.15	0.09	<1	0.28	68.30	23949.76
			O-10-17	31.80	32.82	>25	24.15	≤0.15	0.09	<1	0.22	69.21	24213.65
			O-10-15	31.80	32.06	>25	26.38	≤0.15	0.15	<1	0.97	72.08	14776.88
			O-10-14	31.80	32.04	>25	25.92	≤0.15	0.15	<1	0.34	66.08	13379.67
			O-10-13	31.80	32.04	>25	26.58	≤0.15	0.15	<1	0.12	73.09	14798.97
			O-10-12	31.80	32.04	>25	25.79	≤0.15	0.15	<1	0.28	69.70	14219.38
			O-10-11	31.80	32.04	>25	25.89	≤0.15	0.15	<1	0.20	77.96	15911.00
			O-10-10	31.80	32.28	>25	26.82	≤0.15	0.15	<1	0.82	67.73	13682.01
			O-10-9	31.80	32.28	>25	26.47	≤0.15	0.15	<1	0.74	76.67	15480.39
	6 Piles	01-0009	O-7-40	27.30	27.55	>25	26.21	≤0.15	0.14	<1	0.74	63.77	11732.42
			O-7-39	27.30	27.55	>25	26.36	≤0.15	0.14	<1	0.29	72.56	13334.52
			O-8-40	28.80	29.10	>25	27.61	≤0.15	0.14	<1	0.58	53.89	10530.04
			O-8-39	28.80	29.10	>25	27.18	≤0.15	0.14	<1	0.06	63.99	12483.67
			O-8-38	28.80	29.09	>25	25.39	≤0.15	0.05	<1	0.65	13.82	6887.95
			O-8-37	28.80	29.09	>25	23.50	≤0.15	0.05	<1	0.87	32.76	16331.78

In fact, the period from March 2022 to the present has seen the full implementation of the digital construction monitoring system for rotary jet grouting piles in the second phase expansion runway project of Changle International Airport in Fuzhou. The system has undergone continuous optimization and improvement, effectively monitoring thousands of piles. The system is capable of accurately monitoring various indicators, including the pressure, lifting speed, infusion amount, length and verticality, and can promptly identify problems and provide feedback to the owner and supervisor. This guidance aids in ensuring the construction quality of the vertical slip and underpass areas, and any exceptions to this are typically related to faults, maintenance of the slurry pump during construction, nozzle blockages, sudden changes in pressure due to geological factors, circuit failures or operator unfamiliarity, and failures to pause construction in a timely manner without short-term repairs. Overall, the digital monitoring system for the rotary jet grouting pile is an effective tool for collecting real-time construction data and assisting with process quality control.

VII. CONCLUSION

Presently, the use of high-pressure rotary jet pile construction has become increasingly prevalent in the construction of airports, particularly in areas with soft soil foundations and in coastal regions. However, the quality inspection of its construction is predominantly conducted through traditional methods, such as post-sampling excavations to obtain cores. These methods do not sufficiently reflect the overall construction quality of the site and do not allow for process monitoring. In addition, the traditional high-pressure rotary jet pile foundation treatment method has low automation levels for the construction machinery and exceedingly long construction times, with a single pile taking four hours or more to construct. Consequently, it is imperative to implement real-time and automatic acquisition of construction parameter data to effectively control the construction quality of the entire site. Thus, research on digital monitoring technology for the construction quality of high-pressure rotary jet piles in airports is of significant importance.

This paper comprehensively investigates digital monitoring technology for the construction of high-pressure rotary jetting piles at airports. The study begins by analyzing the characteristics of such pile constructions and then examines the key parameter indicators that are essential to manage and control this technology. The variability patterns of the construction quality and efficiency are also investigated. On this foundation, a critical combination of technologies, including global navigation satellite system (GNSS) measurement technology, the Internet of Things, and massive data processing, is applied. Selection of the current sensors, flow sensors, pressure sensors and tilt sensors is employed to develop corresponding hardware devices for construction parameter data collection. Automatic data collection and storage are implemented, providing a data basis for high-pressure rotary jetting pile construction quality. To present the process data collected in real time to the relevant management personnel in a timely and highly visual manner, and to facilitate control of the construction quality, the requirements for digital monitoring software are analyzed based on the control parameters for rotary jetting piles. GIS technology is used to design the overall architecture, network architecture and the transmission protocol of the monitoring software. The marine data process flow is established, i.e., the front-end collected data are transmitted to a remote server through an appropriate transmission protocol, and the server parses, classifies, distributes and processes the construction data. The use of digital technology confers a significant benefit by enabling a rapid and intuitive visual representation of the quality of the construction of the rotary-spray piles. Following secondary development on the GIS platform, pile points were plotted on the map and arranged in a circular pattern in accordance with the received coordinate data and pile diameter. Key control indicators were then categorized according to construction standards and assigned diverse hues as prescribed by the legend. Subsequently, on the GIS map, the circles signifying pile points were colored as per the corresponding legend ranges, thereby offering an easily comprehensible overview of the general construction situation. In the event of detection of substandard construction at any given pile point, the data were scrutinized comprehensively to ascertain the need for reinforcement, which might necessitate the raising of an additional pile. Finally, the development of digital monitoring platform software for high-pressure rotary jetting piles is completed, starting with the key algorithms for visualized monitoring. The use of the monitoring platform software can provide intuitive and visualized construction data, shows construction weak areas or abnormal construction points, and produces a corresponding statistical analysis for monitoring indicators throughout the process. It can achieve real-time online monitoring of each pile, observe the construction process at all times, improve the accuracy of the pile work and enhance the construction quality.

This paper reports on the development and comprehensive testing of a digital monitoring system for high-pressure rotary jet piles, which was subsequently applied in the rotary jet pile project of the flight area of the Phase II expansion project of Fuzhou Changle International Airport. Our findings demonstrate that the digital acquisition device exhibits strong hardware performance, high accuracy, good data acquisition integrity, real-time performance and high reliability. This technology is capable of fully reflecting the construction process of high-pressure rotary jet pile machines, operates 24/7 in foundation treatment and is not affected by weather conditions, thereby revolutionizing the traditional manual recording of data for high-pressure rotary jet pile construction. The successful application of this technology validates the feasibility of our research results for practical engineering. Drawing on our actual application experience, this article details the installation and debugging of the GNSS positioning base stations, the installation of digital acquisition devices for integrated relevant sensors for rotary jet piles and the functional effects of the digital monitoring platforms. By continuously improving and monitoring numerous pile points, this system enhances on-site management efficiencies and levels, and encourages wide-range application and future usage.

The research results of this paper have been applied in actual practice in the coastal soft soil foundation area, with significant effects. However, the effectiveness of digital monitoring of rotary jet pile construction in other geological conditions requires further verification. At the same time, as sensor accuracy improves, higher precision devices can be gradually replaced to improve measurement accuracy and efficiency. In future research projects, we hope to promote the application of this system to more practical engineering scenarios and continuously improve its efficacy. Digital monitoring platforms could incorporate advanced technologies such as 3D visualization, VR/AR and others to provide an enhanced user experience. Additionally, the data collection hardware terminal could be integrated with AI and other technologies to facilitate the automation of data collection, as being used with unmanned or minimally manned construction processes.

APPENDIX A

Part of the algorithm source code is attached:

```
/**
  * Initialize the antenna
  */
public void initEncoderServer(){
  try{
    DeviceTransEnum trans =
ConfigUtil.getInstancegetEncoderTrans();
    DeviceConnection connection =
ConfigUtil.getInstancegetEncoderSerial();
    String key =
Generator.encodeAddress(connection.getDevice(),
connection.getBaudrate());
    ConnectionParam encoderConnection = new
ConnectionParam(key);
    DeviceActiveEnum active =
ConfigUtil.getInstancegetEncoderActive();
    encoderConnection.setActive(active ==
DeviceActiveEnum. ACTIVE);
    encoderConnection.setSentinel(true);
    encoderConnection.setSentinelTime(10 * 1000);
    encoderConnection.setRecord(false);
    encoderConnection.setHex(false);

    if(trans == DeviceTransEnum. CLOSE) {
      unRegister(ComponentType. SSM_ENCODER);
    } else{
      int type = ConfigUtil.getInstance () getEncoder-
Type
      ();
      int address =
ConfigUtil.getInstance()getEncoderAddress();
      EncoderServer encoderServer = new
EncoderServer(ComponentType. SSM_ENCODER,
encoderConnection, trans, type, address);
```

```
        register(encoderServer);
      }
    } catch(Exception ex) {
      System. out.println("initElectricServer:"+
ex.getMessage());
    }
}

/**
* Draw a dynamic diagram
*/
public final voidRenderMapV(Bitmap bmp) {
    try{
      showPiles.clear();
      Canvas g = newCanvas(bmp);
      g.drawColor(backgroundColor);
      if(dataSource== null) {
        return;
      }
      Point2D tmpLeftTop = leftTop;
      PointF car = Transform.WorldtoMap(
        curPoint, this);
      List<RegonData> list =
dataSource.getWorkPilingZone();
      if(list == null|| list.size() == 0){
        return;
      }
      Point2D point2D = newPoint2D();
      for(RegonData regonData: list){
       List<PilePointModel> modes = regonData. lregon;
       if(modes == null){
         continue;
       }
       for(int i = 0; i < modes.size(); i++) {
         PilePointModel pile = regonData. lregon.get(i);
         point2D.setX(pile.getDesignY());
         point2D.setY(pile.getDesignX());
         if(!envelope.Contains(point2D)) {
           continue;
         }
         PointF pointF =
Transform.WorldtoMap(pile.getDesignY(),
pile.getDesignX(), this);
         if(pile.getIsFinish() ==
PileFinishStateEnum. FINISH.getMode()) {
           curPaint.setStyle(Paint.Style. FILL);
           curPaint.setColor(finishColor);
         } else{
           curPaint.setStyle(Paint.Style. STROKE);
           if(pile.getIsFirst() ==
PileOpenStateEnum. ISFIRST.getMode()) {
             curPaint.setColor(tipColor);
         } else if(pile.getIsFirst() ==
PileOpenStateEnum. UNFIRST.getMode()) {
           curPaint.setStyle(Paint.Style. FILL);
           curPaint.setColor(finishColor);
```

```
         } else{
           curPaint.setColor(Color. BLUE);
         }
       }
       curPaint.setStrokeWidth(2);
       radius= pile.getPileDiameter() / 2000.0f;
       if(radius== 0) {
         radius= 0.5f;
       }
       if(pointF. x>=1 && pointF. y>= 0) {
         if(pixelSize<= radius) {
          g.drawCircle(pointF. x, pointF. y, radius/ pixelSize,
           curPaint);
         } else{
          g.drawPoint(pointF. x, pointF. y, curPaint);
         }
         if(pixelSize< 0.02){
          int sp = ScreenConvertUtils.px2sp(radius/
         pixelSize);
          textPaint.setTextSize(sp);
          textPaint.setColor(tipColor);
          g.drawText(pile.getPileName(), pointF. x, pointF. y,
         textPaint);
         }
         showPiles.add(pile);
       }
      }
    }
    if(car. x> 0 && car. x< bmp.getWidth() && car. y> 0
&& car. y< bmp.getHeight()) {
      mMachineCar.drawRollingCar(g, curPoint.getX() -
tmpLeftTop.getX(),
      tmpLeftTop.getY() - curPoint.getY(), mDegress,
      pixelSize);
    }
    if(mSelectedPile!= null) {
      PointF start =
Transform.WorldtoMap(curPoint.getX(), curPoint.
getY(), this);
      PointF stop =
Transform.WorldtoMap(mSelectedPile.getDesignY(),
mSelectedPile.getDesignX(), this);
      guidePaint.setColor(unFinishColor);
      g.drawLine(start. x, start. y, stop. x, stop. y,
      guidePaint);
    }else{
      if(callBack!= null) {
        callBack.selected(null, null);
      }
    }
  }
catch(Exception e){
      LogToFile.e(TAG, "RenderMapV:"+e.
      getMessage());
  }
}
```

REFERENCES

[1] C. Guan and Y. Yang, "Field study on the waterstop of the rodin jet pile method in a water-rich sandy gravel stratum," *Appl. Sci.*, vol. 9, no. 8, p. 1709, Apr. 2019, doi: 10.3390/app9081709.

[2] Z. Li, J. Zhao, K. Hu, Y. Li, and L. Liu, "Adaptability evaluation of rotary jet grouting pile composite foundation for shallow buried collapsible loess tunnel," *Appl. Sci.*, vol. 13, no. 3, p. 1570, Jan. 2023, doi: 10.3390/app13031570.

[3] S. L. Shen, Z. F. Wang, and W. C. Cheng, "Estimation of lateral displacement induced by jet grouting in clayey soils," *Géotechnique*, vol. 67, no. 7, pp. 621–630, Jul. 2017, doi: 10.1680/jgeot.16.P.159.

[4] Z.-F. Wang, S.-L. Shen, C.-E. Ho, and Y.-S. Xu, "Jet grouting for mitigation of installation disturbance," *Proc. Inst. Civil Eng., Geotech. Eng.*, vol. 167, no. 6, pp. 526–536, Dec. 2014, doi: 10.1680/geng.13.00103.

[5] A. Flora, G. Modoni, S. Lirer, and P. Croce, "The diameter of single, double and triple fluid jet grouting columns: Prediction method and field trial results," *Géotechnique*, vol. 63, no. 11, pp. 934–945, Sep. 2013, doi: 10.1680/geot.12.P.062.

[6] G. Long, L. Li, W. Li, K. Ma, W. Dong, C. Bai, and J. L. Zhou, "Enhanced mechanical properties and durability of coal gangue reinforced cement-soil mixture for foundation treatments," *J. Cleaner Prod.*, vol. 231, pp. 468–482, Sep. 2019, doi: 10.1016/j.jclepro.2019.05.210.

[7] Y. Mei, C. M. Hu, and X. Y. Wang, "Experimental research on deep collapsible loess foundation treatment by dynamic compaction under super high fill," *Appl. Mech. Mater.*, vols. 256–259, pp. 129–138, Dec. 2012, doi: 10.4028/www.scientific.net/AMM.256-259.129.

[8] F. Liu, Y. Zhang, and J. Zhang, "Foundation treatment in urban underground engineering using big data analysis for smart city applications," *Comput. Model. Eng. Sci.*, vol. 132, no. 1, pp. 153–172, 2022, doi: 10.32604/cmes.2022.017967.

[9] J. Ranz, S. Aparicio, H. Romero, M. Casati, M. Molero, and M. González, "Monitoring of freeze-thaw cycles in concrete using embedded sensors and ultrasonic imaging," *Sensors*, vol. 14, no. 2, pp. 2280–2304, Jan. 2014, doi: 10.3390/s140202280.

[10] Y. Huang, L. Wang, Y. Hou, W. Zhang, and Y. Zhang, "A prototype IoT based wireless sensor network for traffic information monitoring," *Int. J. Pavement Res. Technol.*, vol. 11, no. 2, pp. 146–152, Mar. 2018, doi: 10.1016/j.ijprt.2017.07.005.

[11] K. Tang, H. Yuan, J. Lv, and F. Chen, "Developing an intelligent monitoring technology for airport stone column machines," *Sensors*, vol. 20, no. 11, p. 3050, May 2020, doi: 10.3390/s20113050.

[12] F. Chen, H. Jiao, L. Han, L. Shen, W. Du, Q. Ye, and G. Yu, "Real-time monitoring of construction quality for gravel piles based on Internet of Things," *Autom. Construction*, vol. 116, Aug. 2020, Art. no. 103228, doi: 10.1016/j.autcon.2020.103228.

[13] X. Fafoutis, A. Elsts, R. Piechocki, and I. Craddock, "Experiences and lessons learned from making IoT sensing platforms for large-scale deployments," *IEEE Access*, vol. 6, pp. 3140–3148, 2018, doi: 10.1109/ACCESS.2017.2787418.

[14] G. Katsigianni, S. Loyer, and F. Perosanz, "PPP and PPP-AR kinematic post-processed performance of GPS-only, Galileo-only and multi-GNSS," *Remote Sens.*, vol. 11, no. 21, p. 2477, Oct. 2019, doi: 10.3390/rs11212477.

[15] S. Ivanovic, A.-M. Olteanu-Raimond, S. Mustière, and T. Devogele, "A filtering-based approach for improving crowdsourced GNSS traces in a data update context," *ISPRS Int. J. Geo-Inf.*, vol. 8, no. 9, p. 380, Aug. 2019, doi: 10.3390/ijgi8090380.

[16] Q. He, L. Chen, L. Liu, D. Zhao, X. Gong, Y. Lou, and Q. Guan, "Long-term performance evaluation of BeiDou PPP-B2b products and its application in time service," *Remote Sens.*, vol. 15, no. 5, p. 1358, Feb. 2023, doi: 10.3390/rs15051358.

[17] Y. Tian, L. Sui, G. Xiao, D. Zhao, and Y. Tian, "Analysis of Galileo/BDS/GPS signals and RTK performance," *GPS Solutions*, vol. 23, no. 2, p. 37, Feb. 2019, doi: 10.1007/s10291-019-0831-5.

[18] P. J. G. Teunissen, R. Odolinski, and D. Odijk, "Instantaneous BeiDou+GPS RTK positioning with high cut-off elevation angles," *J. Geodesy*, vol. 88, no. 4, pp. 335–350, Apr. 2014, doi: 10.1007/s00190-013-0686-4.

[19] M. Sahmoudi and R. Landry, "A nonlinear filtering approach for robust multi-GNSS RTK positioning in presence of multipath and ionospheric delays," *IEEE J. Sel. Topics Signal Process.*, vol. 3, no. 5, pp. 764–776, Oct. 2009, doi: 10.1109/JSTSP.2009.2033158.

[20] A. Comber, C. Brunsdon, and E. Green, "Using a GIS-based network analysis to determine urban greenspace accessibility for different ethnic and religious groups," *Landscape Urban Planning*, vol. 86, no. 1, pp. 103–114, May 2008, doi: 10.1016/j.landurbplan.2008.01.002.

[21] X. Su, A. R. Andoh, H. Cai, J. Pan, A. Kandil, and H. M. Said, "GIS-based dynamic construction site material layout evaluation for building renovation projects," *Autom. Construct.*, vol. 27, pp. 40–49, Nov. 2012, doi: 10.1016/j.autcon.2012.04.007.

[22] H. Zhang and J. Han, "Design of photoelectric inclination sensor and its application in target tracking," *J. Nanoelectron. Optoelectron.*, vol. 16, no. 10, pp. 1675–1683, Oct. 2021, doi: 10.1166/jno.2021.3123.

[23] H. Xu, F. Li, W. Zhao, S. Wang, Y. Du, and C. Bian, "A high precision fiber Bragg grating inclination sensor for slope monitoring," *J. Sensors*, vol. 2019, pp. 1–7, Jun. 2019, doi: 10.1155/2019/1354029.

[24] S. Peng, J. Cheng, X. Wu, X. Fang, and Q. Wu, "Pressure sensor placement in water supply network based on graph neural network clustering method," *Water*, vol. 14, no. 2, p. 150, Jan. 2022, doi: 10.3390/w14020150.

[25] Q. Tan, C. Li, J. Xiong, P. Jia, W. Zhang, J. Liu, C. Xue, Y. Hong, Z. Ren, and T. Luo, "A high temperature capacitive pressure sensor based on alumina ceramic for in situ measurement at 600 °C," *Sensors*, vol. 14, no. 2, pp. 2417–2430, Jan. 2014, doi: 10.3390/s140202417.

[26] Z. Ren, W. Fu, and J. Yan, "Gust perturbation alleviation control of small unmanned aerial vehicle based on pressure sensor," *Int. J. Aerospace. Eng.*, vol. 2018, pp. 7259363.1–7259363.7, Jul. 2018, doi: 10.1155/2018/7259363.

[27] M. Kaczmarek, A. Szczęsny, and E. Stano, "Operation of the electronic current transformer for transformation of distorted current higher harmonics," *Energies*, vol. 15, no. 12, p. 4368, Jun. 2022, doi: 10.3390/en15124368.

[28] Y. Zhuang, C. Xu, C. Song, A. Chen, W. Lee, Y. Huang, and J. Zhou, "Improving current transformer-based energy extraction from AC power lines by manipulating magnetic field," *IEEE Trans. Ind. Electron.*, vol. 67, no. 11, pp. 9471–9479, Nov. 2020, doi: 10.1109/TIE.2019.2952795.

[29] D. Roehm, R. S. Pavel, K. Barros, B. Rouet-Leduc, A. L. McPherson, T. C. Germann, and C. Junghans, "Distributed database Kriging for adaptive sampling (D2KAS)," *Comput. Phys. Commun.*, vol. 192, pp. 138–147, Jul. 2015, doi: 10.1016/j.cpc.2015.03.006.

[30] Y. A. Felus and R. C. Burtch, "On symmetrical three-dimensional datum conversion," *GPS Solutions*, vol. 13, no. 1, pp. 65–74, Jan. 2009, doi: 10.1007/s10291-008-0100-5.

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