



Research on the application of digital construction in dynamic compaction of the foundation

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Abstract: To overcome the shortcomings of traditional dynamic compaction construction methods, this paper uses geographic information technology, cloud computing, internet technology, and sensor technology to develop a digital construction management system for dynamic compaction. This paper elaborates on the design principles and implementation process of the system, including the collection, transmission, storage, and analysis of construction data. Verified by actual engineering projects, the system employs a construction status segmentation algorithm and spatial clustering analysis to address the dispersion of tamper pit location information and accurately extract the coordinates of the tamper pits. The results indicate that the system's implementation ensures precise, real-time monitoring of key dynamic compaction parameters, reduces the need for construction layout and supervision personnel, and increases construction efficiency by 20%. This significant enhancement in the quality and efficiency of foundation dynamic compaction provides scientific guidance and a basis for decision-making in construction practices.

Keywords: Digital Construction of Dynamic Compaction, Foundation Treatment, Cluster Analysis, Quality Control.

1 Introduction

Dynamic compaction[1] is an established ground improvement technique, distinguished by its cost-efficiency, effective reinforcement, and swift execution, widely applied in terrain infill, coastal reclamation, hillside backfill, and airport construction[2]–[5]. It operates by hoisting a tamper to significant heights and allowing it to drop freely, delivering substantial impact energy to strengthen the foundation, reduce settlement, and mitigate issues such as wet collapse, expansion, and susceptibility to liquefaction.

The dynamic compaction process is typically divided into two stages: point compaction and blanket compaction. Point compaction involves critical process parameters like hammer lifting height, tamping points, tamping times, and the average tamping settlement of the last two impacts. Real-time monitoring of these parameters is critical to reducing post-construction settlement and ensuring subgrade construction quality. The current practice relies heavily on operator experience with manual measurements and

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checks[6]–[7]. Traditional methods fall short in continuous monitoring, timely feedback, and immediate adjustment of these parameters, leading to insufficient process control and compromised project quality.

In recent years, with the advancement and application of digital technologies, digital construction has emerged as a research hotspot in the field of civil engineering. Scholars from home and abroad have conducted in-depth studies on the collection of key process parameters in dynamic compaction using emerging technologies such as sensor technology, Global Navigation Satellite System (GNSS), communication technology, and cloud computing. Yang Jianchong[8] used high-precision positioning antennas, wheel multi-axis encoders and other equipment to control parameters such as compaction point position and rammer height. Zhao Min[9] monitored the dynamic compaction process using settlement sensors and contact stress sensors, calculating the settlement by measuring cable travel, yet did not achieve real-time monitoring of all key construction parameters. Zhan Jinlin[10] proposed a GPS-based dynamic compaction construction information management system concept, utilizing GNSS to monitor the tamper's planar position and drop height in real time, but the corresponding digital technology has not yet been applied in projects. Li Zilong[11] implemented real-time monitoring of dynamic compaction quality using GNSS on the tamper hook, tension sensors on the cables, and automatic control technology. Gao Zhibin[12] employed steel rope travel and GNSS at the top of the boom, obtaining boom inclination to monitor tamping settlement and tamper positioning.

The research of the aforementioned scholars primarily focuses on the contact-based dynamic compaction digital monitoring system, with a lack of specific control analysis on vital parameters of dynamic compaction. Besides, some researchers have implemented non-contact intelligent detection using technologies such as artificial intelligence, machine vision, and close-up photography. Utilizing machine vision, position recognition, and photographic measurement methods, the analysis of the construction image sequence is conducted to detect the presence and location of tamping targets through image recognition and model training. The change in coordinates of the center point in the recognition area is used to determine the motion state of the tamp, realizing the monitoring of construction parameters such as the planar position of the tamper and compaction pit, tamping times, and tamping settlement[13]–[15]. Gao Qiaoyu[16] have proposed a single-eye vision measurement based posture estimation algorithm for compactors (P3P-RPE), applying it to the monitoring of compaction settlement. This method can acquire real-time compaction settlement data, avoiding construction interruptions caused by manual monitoring. The use of non-contact intelligent detection improves data collection accuracy and construction intelligence to a certain extent. However, its technical and cost inputs are high, and factors such as severe weather and complex terrain might influence the monitoring effect and data accuracy.

In summary, existing research has significantly propelled the rapid development of digital construction in dynamic compaction. However, current technology for digital construction in dynamic compaction within the country is still not mature, and most projects still employ traditional methods of construction. Influenced by factors like differing construction conditions, environmental complexity, and varying fortification results, universally applicable research results in this area still don't exist. To address the

deficiencies in traditional construction methods and current research, this study aims to achieve real-time monitoring of key dynamic compaction construction parameters using geographic information technology, cloud computing, internet technology, and sensor technology. Utilizing case study methodology from actual engineering projects, we plan to develop a comprehensive digital construction management system for dynamic compaction of foundations, covering data collection, integration, transmission, analysis, and storage.

2 Design of Digital Construction Management System for Dynamic Compaction

2.1 Overall Design and System Composition

According to the process and quality control requirements of dynamic compaction construction, the digital construction management system integrates geographic information technology, cloud computing, internet technology, and sensor technology to design the overall architecture of the digital construction management system as shown in Figure 1. It mainly includes data collection module, data transmission module, data analysis module, terminal display module, and construction management cloud platform.

The data acquisition module employs dual GNSS antennas for primary and auxiliary positioning to determine the compactor’s planar position, orientation, and ground elevation; the primary antenna, mounted at the top of the compactor’s boom, pinpoints the center position of the tamper, while the auxiliary antenna, located on the compactor’s rear mast, aids in determining the compactor’s bearing and direction. Tension sensors monitor the stress on the steel cables to infer the state of the hammer lifting and dropping, and encoders on the friction wheels measure the travel of the steel cables, thus monitoring the lifting height of the tamper and the tamping settlement. The gathered data is fused, integrated, and uploaded to the construction management cloud platform database via a wireless 4G network.

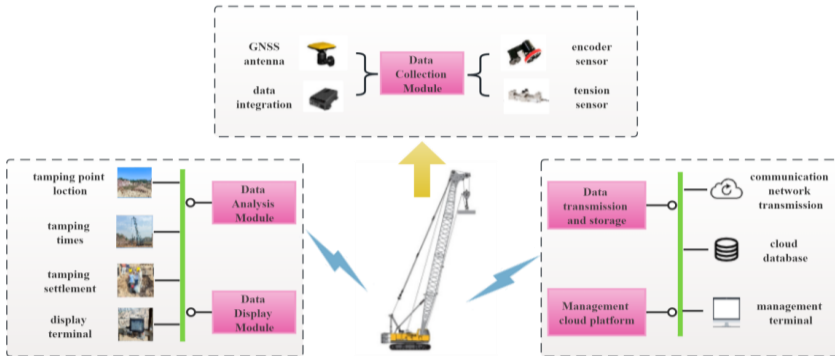


Fig. 1. Digital construction management system for dynamic compaction

The data analysis module processes the collected data to calculate key control parameters such as tamping point location, number of tamping strikes, hammer lifting height, and tamping settlement. These parameters are then displayed in real-time both on the terminal in the operator's cabin and on the construction management cloud platform. This real-time guidance for the compaction machine operators on-site also facilitates instant communication among all project stakeholders—including owners, supervisory bodies, and construction firms—enabling them to promptly access information on construction quality, project quantification, and progress. This system supports decision-making in construction management, quality tracing, and design optimization

2.2 Principles of Data Collection and Transmission

For quality control in digital construction, the most crucial information is the real-time position of the tamper strikes, the number of tamping times at each point, and the settlement of each tamping point. To collect the position of the tamper strikes in real time, this paper uses an integrated solution of GNSS positioning technology and sensor technology. Real-time dynamic positioning based on GNSS collects the position of the primary antenna, and the position of the tamper is then determined through the geometric relationship with the primary antenna. The encoder is installed on the winch behind the compactor's cabin, which drives the friction wheel to rotate. This rotation translates the distance pulled by the cable into the number of rotations of the friction wheel, thus determining the lifting height of the tamper. A tension sensor is clamped onto the last steel cable at the tail of the lifting arm, and the sensor screws are tightened. The stress on the compactor's steel cables is measured and analyzed in real-time using mechanical sensors to determine the number of tamping operations.

The position information collected by the satellite receiver, the cable travel data collected by the friction wheel sensor, and the cable stress information collected by the side pressure tension sensor are fused within an onboard integrated controller. This data is then sent to a cloud server via a wireless data transmission module for processing and analysis. The resulting data is displayed through the terminal display module and the construction quality management platform, allowing for real-time monitoring and control of the dynamic compaction process.

3 Principles of Data Analysis

The key control parameters for dynamic compaction construction include the distribution of tamping points, the number of tamping times, tamping energy, the designed lifting height of the tamper, and the amount of tamping settlement. In the construction process, the single tamping energy is controlled by the weight of the tamper and the designed lifting height of the tamper. The weight of the tamper is generally determined in advance and is not easily changed during the construction process. The designed lifting height of the tamper is usually achieved through the automatic unhooking system of the compactor and is also a fixed value during the construction process. Therefore,

the focus of the control parameter calculation is on the distribution of tamping points, the number of tamping times, and the amount of tamping settlement.

The GNSS positioning data of the dynamic compactor contains a lot of information about the state of the compactor itself, such as when the compactor is stationary, working, rotating, or moving. When the compactor is moving or rotating, there is no tamping pit, so this data must be excluded to avoid affecting the accuracy of tamping pit positioning. In order to extract the true data of the tamping pits from the GNSS data of the dynamic compactor, it is necessary to differentiate between the position data of the compactor when it is working and the position data of the compactor when it is moving or rotating.

3.1 Construction State Segmentation

The real-time collected positions of the tamper in space are a series of continuous coordinate points. In order to mine the true data of the tamping pits from these coordinates, it is necessary to segment the construction status of these points, dividing them into two states: compactor working and compactor transitioning.

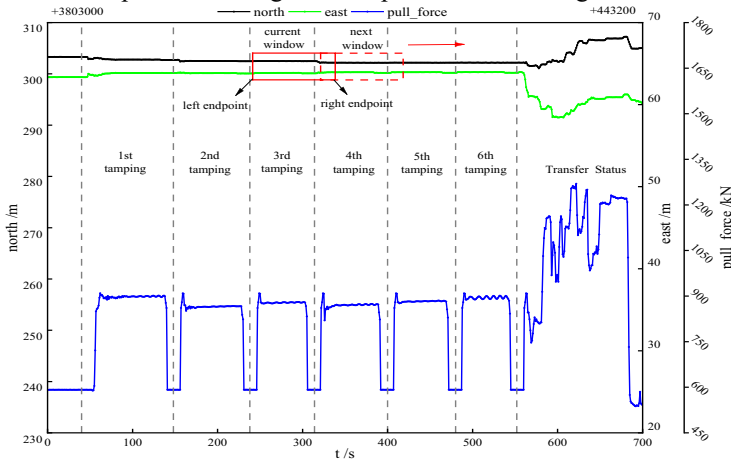


Fig. 2. Segmentation principle for status change of dynamic compactor

When the compactor is working at a tamping point, the position of the tamper generally does not change significantly, and the cable tension will show periodic changes. During transitioning, however, the position of the tamper will change significantly, and the cable tension will fluctuate as shown in figures 2. Based on these characteristics, this paper segments the construction status. By using a sliding window to sequentially calculate the difference in distance between the coordinate points at both ends of the window, if the distance difference within a certain window exceeds a certain threshold δ , it is determined that the compactor is beginning to transition. This continues until the distance difference calculated by a window is less than the threshold δ . This period is then divided into two states: compactor working and compactor transitioning.

3.2 Tamping pit position spatial clustering

Clustering analysis algorithms are a type of unsupervised learning algorithm that categorizes the data subjects according to certain criteria, aiming for high similarity within clusters and dissimilarity between different clusters. There are many existing clustering algorithms, among which the partitioning-based K-means algorithm is widely used across various fields due to its simplicity, intuitiveness, and ease of implementation.

The principle of the K-means algorithm is to divide the samples in the dataset into K clusters to maximize the similarity (usually measured by distance) within the clusters and minimize the similarity between different clusters. The specific steps are as follows:

a. The objective function of the K-means algorithm is to minimize the sum of the squared distances of all points to the centroid of their cluster, which is to minimize the objective function:

$$J = \sum_{i=1}^k \sum_{x \in s_i} \|x - \mu_i\|^2 \quad (1)$$

where μ_i is the centroid of cluster s_i , and x represents the sample points within cluster s_i .

b. The update of the cluster centroid: In each iteration, the centroid of each cluster is the average position of the points it contains, that is:

$$\mu_i = \frac{1}{|s_i|} \sum_{x \in s_i} x \quad (2)$$

c. The steps of updating cluster centroids and assigning sample points to clusters alternate, with each iteration either reducing or maintaining the value of the objective function J until the algorithm converges.

d. Clustering is complete, resulting in k clusters.

The k-means clustering algorithm generally requires pre-determination of the number of clusters, k , which is difficult to know in advance in many practical engineering scenarios. The iterative calculation for updating cluster centers, which relies solely on distance for classification, is significantly affected by outliers. In this study, by using a sliding window method to partition based on distance, the sample data during the tamping machine's transition phase is preemptively excluded. Moreover, by determining the number of clusters based on the number of tamping machine operating states that have been segmented, the accuracy and efficiency of the clustering analysis are greatly improved.

3.3 Obtaining the number of tamping times and tamping subsidence

Based on the data obtained from the lateral pressure tension sensor, the cable tension exhibits two different stable states: "lift \rightarrow release \rightarrow wait \rightarrow lift \rightarrow release", as shown in Figure 3. When the cable lifts the hammer, the tensile force output by the lateral

pressure tension sensor generally exceeds a certain threshold δ . Based on this characteristic, when the tensile force changes from exceeding the threshold to being less than the threshold, that is, the process of completing the "lift \rightarrow release" two stable states, it is considered that the number of tamping times increases by one. In this process, the maximum value of the friction wheel sensor is taken as the lifting height h_i of the rammer at that time, and the tamping subsidence Δ_i of each tamping is obtained through the difference with the previous lifting height h_{i-1} .

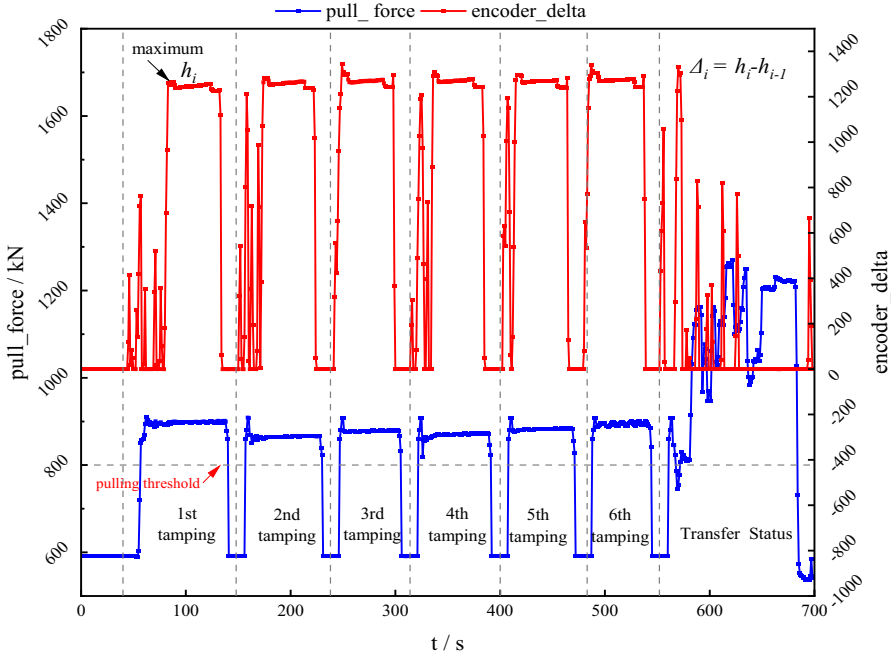


Fig. 3. Segmentation principle for tamping times and tamping settlement

4 Engineering Application

4.1 Project Overview

The digital dynamic compaction construction management system studied in this article was applied in the JPXX-1 section of the Jiaozuo to Pingdingshan expressway from Xinmi to Xiangcheng in Henan Province. The foundation soil is mainly mine backfill soil, consisting primarily of silty clay with mixed rock and gravel. The compaction area covers 5,411.0 m², and after compaction, soil is backfilled to the original surface level, with a fill volume of 12,186 m³.



Fig. 4. Location of dynamic compaction construction and layout of tamping point

The design for the ground improvement project using dynamic compaction in this engineering project adopts a two-time spot compaction followed by a one-time full compaction method. The single blow compaction energy for spot compaction is 4,000 kN/m, and for full compaction, it is 1,000 kN/m, with a hammer diameter of 2.52 m. The compaction points are arranged in a rectangular pattern with a spacing of 5.0 m. The second round of compaction points is located at the center of the rectangle formed by the first round of points, with the design number of blows per point compaction being 6 to 9. After two rounds of dynamic compaction, full compaction is carried out once, with a drop distance of twice the hammer diameter, ensuring that the hammer prints overlap by no less than a quarter of the hammer diameter, with generally no less than 5 to 7 blows per point. The location of the project and the arrangement of the compaction points are shown in Figure 4.

4.2 Digital construction process

The construction process of the digital dynamic compaction management system is shown in Figure 5. After preparing for construction and calibrating the sensors, a coordinate origin is set up on the construction site, and the coordinates of each compaction point from the design documents are calculated to form a file. This file is then imported into the onboard tablet computer in the driver's cab, which guides the dynamic compaction machine to automatically navigate to the designated position. The onsite display terminal can show construction information in real-time on the tablet in the driver's cab, including the compaction point number, current point east and north coordinates, navigation information, remaining number of blows for the current point, settlement amount from the previous blow, number of compaction passes, and hammer lifting height. The construction quality management cloud platform enables real-time monitoring and querying of construction information. This information includes the compaction point number, east and north coordinates, number of blows, total compaction energy, average hammer lifting height, total lifting height, total settlement, and average settlement of the last two blows. The digital dynamic compaction construction not only

guides the machine operators in real-time during onsite construction but also facilitates timely access for the project stakeholders such as owners, supervisory units, construction units, etc., to construction quality and progress information, providing decision support for construction management, quality tracing, and design optimization.

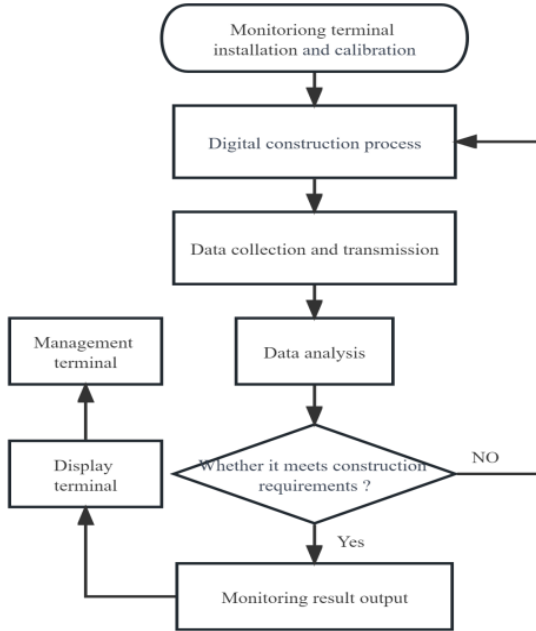


Fig. 5. Digital construction management system application process

4.3 Analysis of results

The construction data of this project were wirelessly transmitted through the 4G network from the onboard tablet in the compaction machine's cab to the cloud server database. Data such as the coordinates, lateral pressure tension sensors, and friction wheel sensors were filtered from the database for the morning of October 31, 2023. According to the construction state segmentation method introduced in Section 3, the data for this construction segment were divided into 13 compaction working states and 12 compaction machine transition states, within the time period from 9:03:56 to 11:21:59. The 13 segmented compaction working states were processed through the K-Means spatial clustering algorithm to determine the final positions of the compaction pits, as shown in Figure 6. By segmenting the dynamic compaction states and applying spatial clustering, many invalid values were eliminated, which significantly improved the precision and efficiency of the compaction pit location calculations.

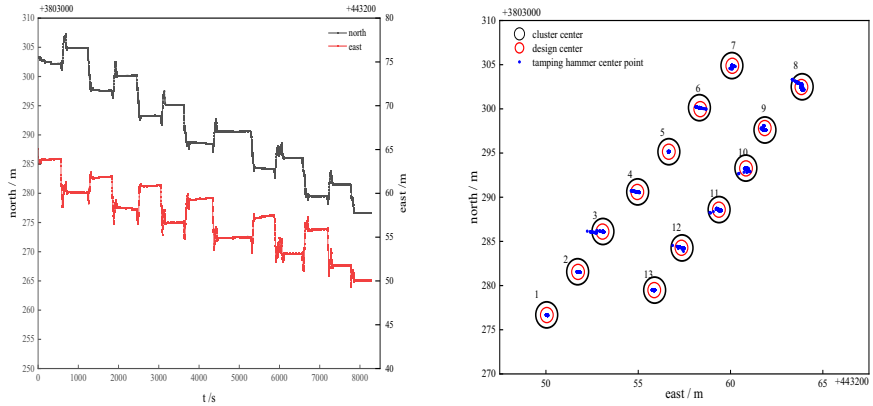


Fig. 6. Clustering results of tamping pit location

The analysis indicates that the primary sources of error in the compaction pit locations include the GNSS positioning system error, calculation error of the hammer position, and vibration error of the compaction machine. In practical engineering applications, the GNSS positioning system can currently achieve centimeter-level accuracy, and with the hammer positioned about 20cm from the main antenna, the error is relatively small. The main source of error comes from the vibrations of the compaction machine; during the moments of lifting and dropping the hammer, the machine shakes due to inertia, causing the coordinates received by the main antenna to deviate. Error calculations between the cluster center points and the actual measured center points on site indicate that, as shown in table 1, the maximum error was 21.6cm and the average error was 5.1cm, which meets the regulatory requirement of 0.1D, or 25cm.

Table 1. Comparison between calculated and measured results of tamping pit location

Id	calculated results		measured results		Δ/cm
	east / m	north / m	east / m	north / m	
1	443250.0534	3803276.665	443250.046	3803276.677	1.4
2	443251.7447	3803281.545	443251.721	3803281.557	2.6
3	443253.0688	3803286.105	443253.092	3803286.119	2.7
4	443254.9529	3803290.592	443254.973	3803290.595	2
5	443256.6616	3803295.142	443256.664	3803295.148	0.6
6	443258.3654	3803299.964	443258.318	3803300.129	17.1
7	443260.1011	3803304.874	443260.077	3803304.890	2.9
8	443263.8452	3803302.472	443263.885	3803302.492	4.5
9	443261.8564	3803297.823	443261.867	3803297.608	21.6
10	443260.8404	3803293.26	443260.835	3803293.298	3.8
11	443259.3729	3803288.583	443259.384	3803288.595	1.6
12	443257.3468	3803284.271	443257.377	3803284.257	3.3
13	443255.8712	3803279.484	443255.894	3803279.48	2.3
				average Δ	5.1

Compared to traditional dynamic compaction methods, the digital construction management system used in this study not only reduces the need for two staff members for pre-construction staking out and two more for supervision and record-keeping during construction, saving approximately 816,000 yuan in labor costs, it also increases construction efficiency by about 20%. Additionally, it enhances the precision of foundation dynamic compaction treatment, thereby providing a helpful guarantee for the quality of foundation treatment construction.

5 Conclusions

a This article aims to resolve the issues found in traditional dynamic compaction construction by utilizing geographic information technology, cloud computing, internet technology, and sensor technology to achieve real-time monitoring of key process parameters in dynamic compaction construction. Through the case analysis method of actual engineering projects, a comprehensive digital construction management system for dynamic compaction foundations has been developed, which includes data collection, integration, transmission, analysis, and storage, significantly advancing the rapid development of digital dynamic compaction construction.

b Based on the characteristics of dynamic compaction construction, the system delineates construction states using a sliding window approach on distances, and in conjunction with the K-Means spatial clustering algorithm, it calculates the locations of the compaction pits.

c By integrating equipment such as lateral pressure tension sensors and friction wheel sensors, and observing changes in cable tension to determine whether the hammer is being lifted, the system measures the displacement of the wire rope of the dynamic compaction machine, obtaining hammer height and compaction volume. This effectively prevents irregularities such as 'missing or false hammering' due to human subjectivity, ensuring construction quality.

d The application of digital construction techniques in dynamic compaction foundations signifies a shift for construction enterprises from traditional extensive management to a more refined, digitized, and intelligent management model. The current contact sensors are prone to significant noise interference and exhibit poor stability. Future enhancements can be achieved by improving data processing algorithms, reducing noise interference, and enhancing the precision and reliability of sensor data to improve the overall accuracy and stability of the system.

e The modern technical methods adopted in this study can also be extended to similar fields. For instance, in the areas of roadbed rolling and vibroflotation foundation treatment, these technologies can compensate for the deficiencies of traditional monitoring methods, achieving more effective operation monitoring and management.

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