

Method for Detecting Roadbed Compaction Degree Based on Machine Learning and Vibration Acceleration

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ABSTRACT

Roadbed construction occupies a core position in highway construction, but its quality is easily constrained by multiple factors such as changing environmental factors, the performance of construction equipment, and the professional abilities of construction personnel, leading to potential quality risks. Traditional quality inspection methods are mostly carried out after construction is completed, making it difficult to achieve continuous and real-time monitoring of roadbed compaction quality, which to some extent limits the real-time feedback and adjustment of construction quality. Vibration compaction technology has been widely used in the field of highway engineering due to its high efficiency and speed. The compaction degree is directly related to the durability and service life of the highway; therefore, accurate and efficient detection of compaction degree is crucial. This article proposes a method for detecting roadbed compaction degree by integrating machine learning (ML) and vibration acceleration signals. This method aims to achieve accurate evaluation of roadbed compaction by real-time monitoring and analysis of vibration acceleration data, combined with the powerful prediction and classification capabilities of ML algorithms. The experimental results show that this method not only improves the detection efficiency, but also significantly enhances the accuracy of compaction degree detection.

KEYWORDS

Machine Learning; Vibration Acceleration; Roadbed Compaction; Detection Methods.

1. INTRODUCTION

Highways, as an important component of modern transportation networks, have a direct impact on the construction quality and service performance of the national economy, as well as the convenience and safety of people's lives [1]. As a linear large-scale structure, highways are usually supported on semi-infinite foundations, bearing enormous loads from various vehicles [2]. When a car is speeding on a highway, the moment of contact between the wheels and the road surface not only transmits the vehicle's own weight, but also accompanies complex dynamic processes. These forces flow from top to bottom, passing through the surface layer and base layer, and ultimately acting on the roadbed, posing a severe challenge to the stability and durability of the roadbed [3]. As the cornerstone of highway structures, the construction quality of roadbeds directly affects the success or failure of the entire highway project. It not only needs to withstand vertical loads from the upper part, but also needs to cope with horizontal shear forces and bending moments, as well as long-term effects of natural environmental factors such as rainwater erosion and temperature changes [4]. Therefore, the importance of quality control in roadbed construction is self-evident. It is the key to ensuring the long-term service performance of highways, reducing maintenance costs, and extending service life.

Among the many factors that affect the service performance of roadbeds, compaction degree is a core indicator. Compaction degree refers to the ratio of the density of the compacted subgrade material to

its maximum possible density, and is an important parameter for measuring the compactness of the subgrade material [5]. Good compaction can not only significantly improve the bearing capacity of highway pavement, but also effectively resist water damage, reduce rutting formation, enhance pavement durability and service life [6]. On the contrary, insufficient compaction can lead to an increase in the void ratio between roadbed materials, making them susceptible to moisture infiltration and causing a series of diseases such as roadbed softening, uneven settlement, and permanent deformation, seriously affecting the safety and comfort of highways [7]. However, traditional methods for detecting roadbed compaction degree, such as sand filling method and nuclear density meter method, have limitations such as complex operation, time-consuming and laborious, and the detection results are greatly affected by human factors, which are difficult to meet the efficient and accurate quality control requirements of modern highway construction [8]. Therefore, it is particularly important to explore a more efficient and accurate technology for detecting the compaction degree of roadbeds.

In recent years, with the rapid development of sensor technology and the increasing maturity of ML theory, new ideas have been provided for real-time monitoring and accurate evaluation of roadbed compaction. Vibration compaction technology, as a commonly used method in modern roadbed construction, uses the high-frequency vibration energy generated by the vibratory roller to rearrange and tightly contact the roadbed material particles, thereby improving the compaction degree. During this process, the vibration acceleration signal serves as a direct source of information reflecting the compaction state and material properties, containing rich compaction quality information. Based on this understanding, this study proposes an innovative method for detecting roadbed compaction degree, which integrates ML algorithm and vibration acceleration signal analysis technology. Specifically, by installing high-precision acceleration sensors on the roller, real-time acceleration data is collected during the vibration compaction process, which includes the dynamic response characteristics of roadbed materials at different compaction stages. Subsequently, the collected acceleration signals were subjected to feature extraction, dimensionality reduction, and pattern recognition using ML algorithms, establishing a mapping relationship model between compaction degree and acceleration signal features.

2. APPLICATION OF ML AND VIBRATION ACCELERATION IN ROADBED COMPACTION DEGREE DETECTION

2.1. Application

In the field of roadbed engineering, the integration of ML and vibration acceleration technology has brought revolutionary progress to intelligent compaction technology [9]. This combination not only improves construction efficiency, but also ensures precise control of roadbed compaction, which is of great significance for ensuring road quality and extending service life [10]. By cleverly integrating vibration acceleration sensors on the road roller, the construction team can capture subtle vibration changes during the roller's operation in real time. These vibration acceleration data are like fingerprints of the roadbed state, faithfully recording the dynamic evolution of material properties during the compaction process. As the compaction degree gradually increases, the stiffness of the roadbed material also increases, which is reflected in the subtle adjustment of the response mode in the vibration acceleration data.

On this basis, a database containing a large amount of vibration acceleration data and corresponding compaction detection results was constructed, providing rich training resources for ML models. With the help of advanced algorithms, these complex mathematical models can deeply explore the inherent connections between data, learn and establish an accurate mapping model between vibration acceleration characteristics and roadbed compaction. Once the model is trained, its powerful predictive ability can be demonstrated in practical construction. By simply inputting newly collected

vibration acceleration data, the system can quickly and accurately evaluate the current compaction status of the roadbed, greatly simplifying the detection process, shortening the construction period, and improving the stability and consistency of compaction quality. In summary, the combination of ML and vibration acceleration technology not only promotes the intelligent upgrade of roadbed compaction detection technology, but also lays a solid foundation for the high-quality development of future road construction.

2.2. Algorithm Principle

Taking asphalt highways as an example, the compaction energy per unit volume E is a key indicator for measuring the compaction effect of a roller and the compressive response of asphalt mixtures. Its magnitude can directly reflect the degree of compaction of asphalt mixtures. However, due to the non-uniform distribution of asphalt mixture particles, even with the same compaction work, there may be significant differences in compaction effect. Therefore, combining the vibration acceleration frequency domain analysis indicators C_{V0} and E for real-time monitoring can not only reduce the evaluation error caused by C_{V0} anomalies, but also accurately reflect the compaction work done. Real time time-domain data is collected through the accelerometer on the vibrating wheel, and frequency-domain data is obtained through fast Fourier transform (FFT). Research shows that as the compaction degree increases, the acceleration distortion of the vibrating wheel intensifies, harmonic components increase, and the C_{V0} value increases accordingly; When the material is compacted to its limit, specific half harmonics will appear on the frequency domain graph. Therefore, C_{V0} can be defined as an important parameter for evaluating changes in compaction degree.

$$C_{V0} = \alpha \frac{A_4}{A_2} \quad (1)$$

In the formula, A_2, A_4 represents the amplitude of the first harmonic (fundamental frequency) and second harmonic in spectrum analysis; α is the coefficient, take 300.

There is a significant positive correlation between the amplitude of vibration acceleration and compaction degree during the compaction process. Based on this characteristic, using the amplitude of vibration acceleration as the evaluation model for compaction degree not only conforms to theoretical logic, but also effectively reflects the correlation between the two. This correlation can be mathematically expressed as follows:

$$y = kx + b \quad (2)$$

Among them, y is the compaction degree, x is the acceleration amplitude, and k, b is a constant.

In the field of ML, the PSO-BPNN-AdaBoost (PBA) model is widely used to predict the maximum dry density $\rho_{d\max}$ of materials. To quantify the uncertainty of predictions, we adopted a Bootstrap based approach. At a specific significance level α , we can construct a prediction interval PIS for $\rho_{d\max}$ using the following formula to effectively evaluate the uncertainty of the prediction results.

$$\hat{f}(x_n) - C_{confidence} \sqrt{\sigma_\rho^2(x_n)} \leq f(x_n) \leq \hat{f}(x_n) + C_{confidence} \sqrt{\sigma_\rho^2(x_n)} \quad (3)$$

$$C_{confidence} = -Z_{1-\alpha/2} = Z_{\alpha/2} \quad (4)$$

In the formula, $C_{confidence}$ represents the confidence level of the $\rho_{d_{max}}$ prediction interval, which is determined by the confidence level $(1-\alpha)*100\%$. Specifically, when the confidence levels are set at 90%, 95%, and 99%, the corresponding $C_{confidence}$ values are 1.65, 1.96, and 2.58, respectively.

3. EXPERIMENTS AND RESULTS

3.1. Comparison of Detection Efficiency

To verify the performance of our method, we will conduct comparative experiments with traditional sand filling method and nuclear density meter method. Figure 1 visually illustrates the comparison between the proposed method in this paper and the traditional sand filling method and nuclear density meter method in terms of the efficiency of roadbed compaction detection. From the figure, it can be clearly seen that the method proposed in this paper exhibits a significant time advantage when facing the same amount of tasks, that is, the time consumed to complete the detection task is the shortest. Specifically, this article cleverly combines the PBA model with vibration acceleration data. As an advanced ML algorithm, PBA model optimizes the initial weights and thresholds of BP neural network (BPNN) through particle swarm optimization (PSO) algorithm, and further improves the predictive performance of the model using AdaBoost algorithm. This combination enables the model to more accurately capture and analyze complex information during the compaction process of the roadbed, thereby improving detection accuracy.

Meanwhile, as an important physical quantity reflecting the compaction state of roadbed materials, the introduction of vibration acceleration data provides an additional source of information for the method proposed in this paper. By comprehensively analyzing the prediction results of the PBA model and vibration acceleration data, this method can more comprehensively evaluate the compaction situation of the roadbed, thereby achieving efficient and accurate detection. In summary, the comparison results in Figure 1 fully demonstrate the superiority of our method in detecting roadbed compaction efficiency. Compared with traditional methods, this method not only takes less time, but also achieves a dual improvement in detection accuracy and efficiency by combining the PBA model and vibration acceleration data, providing new ideas and solutions for rapid detection of roadbed compaction.

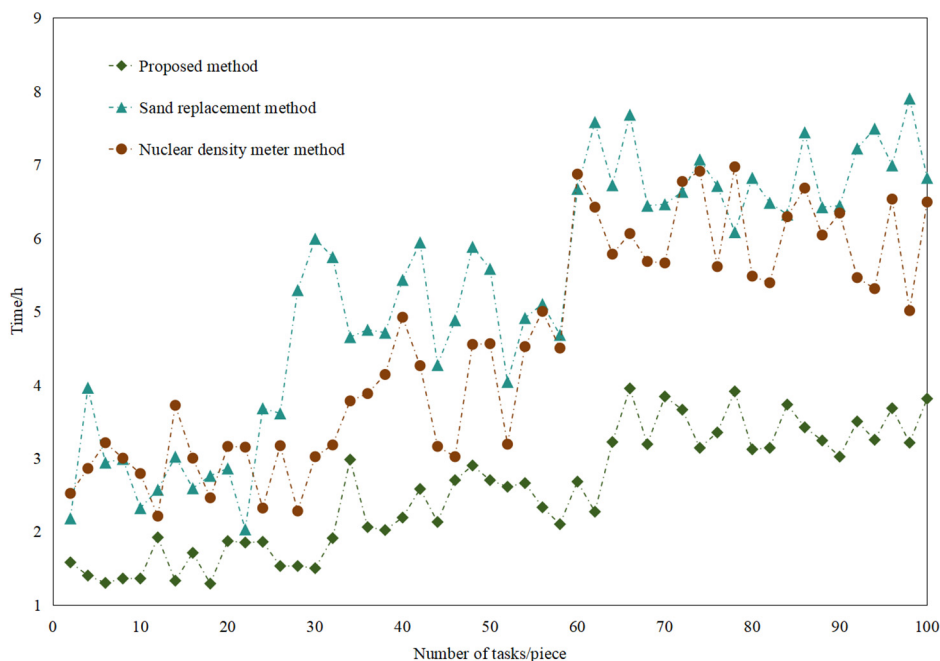


Figure 1. Comparison of detection efficiency

3.2. Comparison of Accuracy of Compaction Degree Detection

Figure 2 provides a detailed comparison of the performance of the method proposed in this paper with traditional sand filling method and nuclear density meter method in detecting the accuracy of roadbed compaction. From the figure, it can be intuitively seen that under the same workload conditions, the method proposed in this paper exhibits the highest detection accuracy. This outstanding performance is attributed to the unique combination strategy of the method proposed in this article, which combines the PBA model with vibration acceleration data. The PBA model, as an advanced machine learning algorithm, intelligently adjusts the parameters of BPNN through PSO, and integrates multiple weak classifiers using AdaBoost algorithm to form a strong classifier, significantly improving the predictive ability of the model. The vibration acceleration data serves as a key indicator reflecting the compaction status of roadbed materials, and its changes are closely related to the compaction degree.

By real-time monitoring and analysis of vibration acceleration data, this method can more accurately capture the dynamic changes during the compaction process of the roadbed, thereby achieving precise evaluation of compaction degree. Therefore, the method proposed in this paper, which combines the PBA model with vibration acceleration data, demonstrates higher accuracy in detecting roadbed compaction. This advantage not only helps to improve the control ability of construction quality, but also effectively reduces resource waste and safety hazards caused by detection errors. The comparison results in Figure 2 fully verify the progressiveness and practicability of this method in the field of subgrade compaction detection, and provide strong technical support for highway engineering construction.

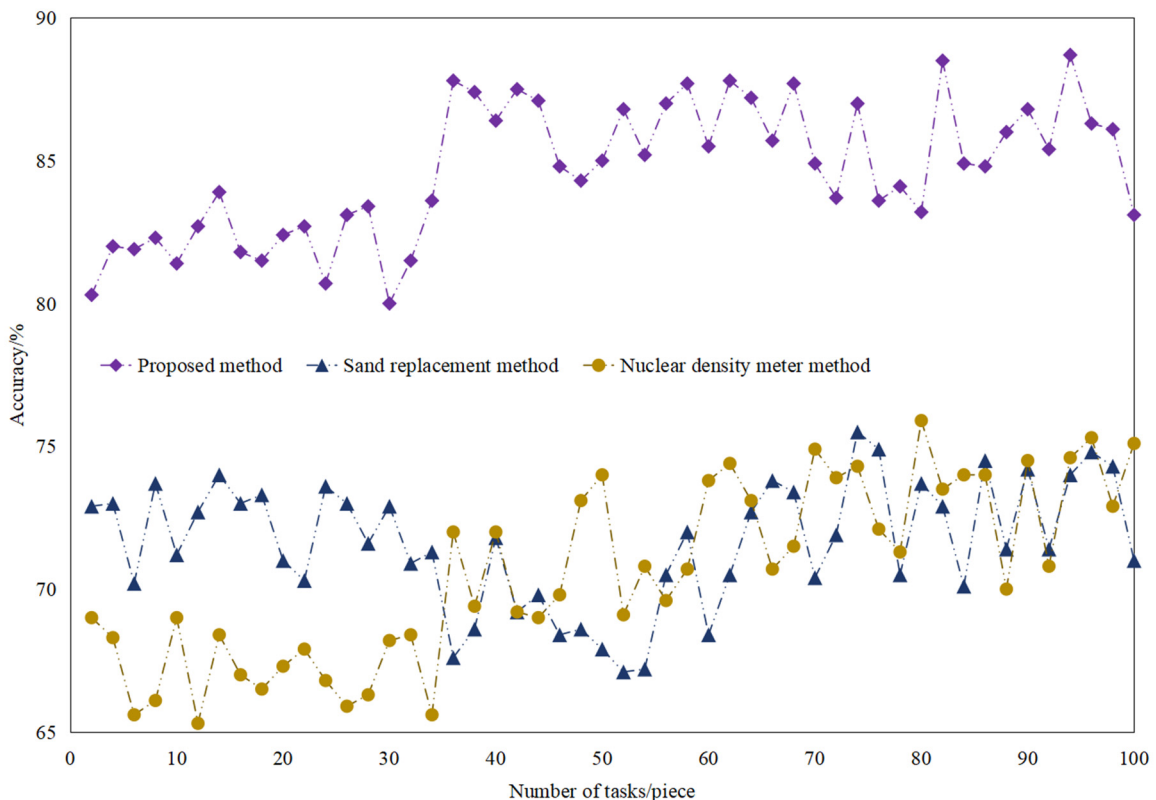


Figure 2. Comparison of detection accuracy

4. CONCLUSION

This article proposes an innovative method for detecting roadbed compaction degree, which integrates ML and vibration acceleration signals. The aim is to achieve accurate evaluation of roadbed

compaction degree through real-time monitoring and analysis of vibration acceleration data, combined with the powerful prediction and classification capabilities of ML algorithms. The experimental results show that compared to traditional methods, our method has demonstrated significant advantages in improving detection efficiency and accuracy. Specifically, this method achieves deep mining and efficient utilization of vibration acceleration data through the construction of a PBA model. The PBA model not only optimizes the parameter settings of BPNN, but also improves the predictive performance of the model through AdaBoost algorithm, ensuring the accuracy and reliability of the detection results. At the same time, real-time monitoring and analysis of vibration acceleration data also provide a richer source of information for the method proposed in this paper, further enhancing the accuracy of detection. However, the method proposed in this article also has certain limitations. For example, in practical applications, the collection and processing of vibration acceleration data may be affected by various factors such as environmental factors, equipment accuracy, etc., which may have a certain impact on the accuracy of the detection results. In addition, although the method proposed in this article has achieved good detection results under experimental conditions, further validation and optimization are still needed in practical engineering applications.

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REFERENCES

- [1] Li P, Dong Y. Characterization and impact analysis of freezing and expansion disease of roadbed in seasonal freezing zone: A case of heavy railroads[J]. *Geohazard Mechanics*, 2023, 1(3): 218-230.
- [2] Wu W, Wang G, Wang L, et al. Dynamic Response Analysis of Non-Uniform Unsaturated Soil Layer Roadbed under Uniform Moving Load[J]. *Mechanics of Solids*, 2024, 59(1): 280-296.
- [3] Wu K, Sun W, Liu S, et al. Discrete element modeling of vibration compaction effect of the vibratory roller in roundtrips on gravels[J]. *Journal of Testing and Evaluation*, 2021, 49(5): 3869-3884.
- [4] Beloborodov R, Gunning J, Pervukhina M, et al. Rock-physics machine learning toolkit for joint litho-fluid facies classification and compaction modeling[J]. *The Leading Edge*, 2021, 40(10): 742-750.
- [5] Wang Z Y, Ling X Z, Zhao Y Y, et al. Numerical simulation of vibrational response characteristics of railway subgrades with insulation boards[J]. *Sciences in Cold and Arid Regions*, 2022, 14(1): 23-31.
- [6] Ran Y, Bai W, Kong L, et al. Prediction of soil degree of compaction based on machine learning: a case study of two fine-grained soils[J]. *Engineering Computations*, 2024, 41(1): 46-67.
- [7] Yu S, Shen S. Compaction prediction for asphalt mixtures using wireless sensor and machine learning algorithms[J]. *IEEE Transactions on Intelligent Transportation Systems*, 2022, 24(1): 778-786.
- [8] Farshbaf Aghajani H, Karimi S, Hatefi Diznab M. An experimental and machine-learning investigation into compaction of the cemented sand-gravel mixtures and influencing factors[J]. *Transportation Infrastructure Geotechnology*, 2023, 10(5): 816-855.
- [9] Benbouras M A, Lefilef L. Progressive machine learning approaches for predicting the soil compaction parameters [J]. *Transportation Infrastructure Geotechnology*, 2023, 10(2): 211-238.
- [10] Xu Z, Khabbaz H, Fatahi B, et al. Real-time determination of sandy soil stiffness during vibratory compaction incorporating machine learning method for intelligent compaction[J]. *Journal of rock mechanics and geotechnical engineering*, 2022, 14(5): 1609-1625.