Research, Development, and Application of Intelligent Subgrade Compaction Technology Postprint

Authors: Zang Jinhao, Li Jin, Zuo Shen

Date: 2025-07-17T00:00:00+00:00

Abstract

Against the backdrop of national new infrastructure initiatives and intelligent construction, the development of intelligent compaction technology for roadbeds is burgeoning; however, the low correlation and reliability of traditional compaction metrics hinder its promotion and application. To address this critical challenge, this study focuses on the dynamic response mechanisms and compaction characteristics of roadbeds, systematically investigating the dynamic behavior of roadbed fill materials, multi-scale structural evolution mechanisms, and intelligent control methodologies. First, dynamic triaxial tests are employed to investigate the macroscopic dynamic response characteristics of roadbed fill materials under various working conditions and stress paths, establishing a dynamic constitutive model applicable to intelligent compaction analysis. Second, discrete element simulation and CT three-dimensional reconstruction techniques are utilized to reveal microscopic compaction mechanisms including the evolution of inter-particle contact networks, particle rearrangement, pore closure, and changes in local stress transmission paths under vibratory loads, establishing a relationship between roller vibration acceleration characteristics and the dynamic modulus of roadbed materials, and proposing a dynamic modulus characterization model that infers compaction state from measured multi-dimensional acceleration signals. Subsequently, full-scale model tests are conducted to systematically investigate the dynamic modulus evolution of roadbed materials under varying compaction energy levels and porosity conditions, establishing a coupled mechanism model linking porosity, dynamic modulus, and vibration response, and proposing a novel compaction quality evaluation system based on dynamic parameters. Furthermore, an artificial neural network model is constructed based on deep learning algorithms, integrating construction rolling paths, vibration parameters, soil properties, and sensor signals to achieve high-precision compaction quality prediction and adaptive optimization of construction parameters, and developing an integrated intelligent compaction control system for roadbeds encompassing data acquisition, intelligent identification, and feedback control. The research outcomes will significantly enhance the scientific rigor, real-time capability, and intelligence level of roadbed compaction quality control, providing critical theoretical support and technical pathways for the deep integration of intelligent construction technology in transportation infrastructure engineering.

Full Text

Preamble

Research and Application of Intelligent Compaction Technology for Roadbeds

Jinhao Zang[1,2], Jin Li[1,2], Shen Zuo[1,2]

[1]Shandong Key Laboratory of Technologies and Systems for Intelligent Construction Equipment, Shandong Jiaotong University, Jinan, Shandong 250357, China
[2]School of Transportation and Civil Engineering, Shandong Jiaotong University, Jinan, Shandong 250357, China

Abstract

Against the backdrop of national new infrastructure development and intelligent construction, intelligent compaction technology for roadbeds is burgeoning. However, the low correlation and reliability of traditional compaction characterization indicators pose a significant obstacle to its widespread adoption and application. To address this core challenge, this research focuses on the dynamic response mechanisms and compaction characteristics of roadbeds, systematically investigating the dynamic behavior of roadbed fill materials, multi-scale structural evolution mechanisms, and intelligent control methods.

First, dynamic triaxial tests are employed to study the macroscopic dynamic response characteristics of roadbed fill materials under various working conditions and stress paths, establishing a dynamic constitutive model suitable for intelligent compaction analysis. Second, discrete element simulation and CT three-dimensional reconstruction technology are utilized to reveal microscopic compaction mechanisms, including the evolution of inter-particle contact networks, particle rearrangement, pore closure, and changes in local stress transmission paths under vibratory loading. The relationship between vibratory roller acceleration characteristics and the dynamic modulus of roadbed materials is established, and a dynamic modulus characterization model is proposed for inverse analysis of compaction state based on measured multi-dimensional acceleration signals. Subsequently, full-scale model tests are conducted to systematically investigate the variation characteristics of dynamic modulus under different compaction energy levels and porosity conditions, establishing a coupled mechanism model linking “porosity—dynamic modulus—vibration response” and proposing a novel compaction quality evaluation system based on dynamic parameters.

Furthermore, an artificial neural network model is constructed using deep learning algorithms, integrating construction rolling paths, vibration parameters, soil characteristics, and sensor signals to achieve high-precision prediction of compaction quality and adaptive optimization of construction parameters. This enables the development of an intelligent compaction control system for roadbeds that integrates data acquisition, intelligent identification, and feedback control. The research outcomes will significantly enhance the scientific rigor, real-time capability, and intelligent level of roadbed compaction quality control, providing key theoretical support and technical pathways for the deep integration of intelligent construction technologies in transportation civil engineering.

Keywords: roadbed; intelligent compaction; dynamic response; porosity; discrete element method; dynamic modulus