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# Compaction Quality Standard of Earth-Rock Mixture Filler for Abutment Based on Dynamic Deformation Modulus

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ABSTRACT

This study investigates the control of compaction quality in earth-rock mixture fillers based on the dynamic deformation modulus (Evd). Discrete element simulations were employed to construct sub-grade models of earth-rock mixture fillers with varying rock contents. During the compaction process, Evd, settlement differences, porosity, and rolling passes were measured. Building on dual control indicators—porosity and settlement difference—a method for the rapid assessment of compaction quality in earth-rock mixture fillers based on Evd was proposed, accompanied by corresponding quality control standards. Field tests were conducted to validate the accuracy of these standards. The results show that, at a rock content of 70%, the settlement difference and porosity are minimized. After 8 rolling passes, the settlement differences for earth-rock mixture filler layers with 30%, 50%, and 70% rock contents are all less than 2 mm, with corresponding Evd values exceeding 55 MPa, 57 MPa, and 60 MPa, respectively, thus meeting the compaction quality requirements. The error between the field test results and simulation results is less than 5%. This study introduces an innovative approach to compaction quality control, offering a fast and accurate method for detecting roadbed compaction quality. It significantly enhances the precision of roadbed and filler compaction control, while optimizing quality management throughout the construction process. Additionally, it presents a novel technique for rapid compaction assessment of roadbeds across various soil types. This work provides valuable theoretical support for the standardization of related industries and contributes to the sustainable development of engineering construction.

***Keywords:*** Earth-rock mixture filler, Discrete element, Dynamic deformation modulus, Rolling passes, Porosity, Settlement difference.

## INTRODUCTION

### Background

In recent years, highway construction activities, such as cutting and tunnel excavation, have resulted in the production of numerous soil-rock mixtures. These materials are not only widely available and cost-effective, but also exhibit favorable engineering properties (Dong et al., 2024; Ling, 2021; Zhang et al., 2012; Zhang et al., 2023). Compared to fine-grained soils, these mixtures have a higher proportion of gravel, offering advantages, such as increased strength, enhanced erosion resistance, and reduced settlement deformation. Numerous geotechnical tests and engineering applications have demonstrated that these earth-rock mixtures are suitable materials for sub-grade filling (Wang et al., 2023; Ribeiro et al., 2011; Wang et al., 2022; Li et al., 2019; Babello et al., 2023).

The earth-rock mixture is inherently non-uniform, with variations in both the content and size of the stones, leading to differences in material gradation. These variations result in differing compaction qualities across the construction area. Currently, two primary indices are commonly used to assess compaction quality: settlement differences and the void ratio. However, measuring settlement differences requires significant labor, while determining the void ratio is time-consuming. Furthermore, the results obtained from these compaction tests may not provide a comprehensive evaluation of the overall compaction quality across the entire construction area, potentially overlooking regions with insufficient compaction (Chen et al., 2022; Zhong et al., 2018; H. Dolama et al., 2022).

## Literature Review

Building on traditional methods for assessing sub-grade compaction quality, several researchers have made significant advancements. Sun et al. (2011) employed the surface subsidence method to investigate the compaction standards for rock-filled sub-grades. Their findings indicated that for rock-filled sub-grades with thicknesses less than 40 cm, the settlement rate should be under 3%. For sub-grades with thicknesses between 40 cm and 60 cm, the settlement ratio ranged from 3% to 5%. Tan et al. (2010) examined the settlement, dry density, water content, and permeability coefficient of a backfill clay sub-grade before and after compaction. The results demonstrated that the sub-grade could achieve 100% compaction when subjected to 12 passes of an 18-ton vibratory impact roller. Zhang et al. (2017) applied the finite element method to derive the basic dynamic equation for roadbed compaction, establishing a physical model of the "vibratory roller-roadbed" system. This provided a theoretical foundation for discrete element modeling. More recently, Hu et al. (2024) developed a discrete element model for irregular rock and soil particles, simulating the vibration compaction of mixed soil-rock sub-grades using a vibratory roller. By coupling the sub-grade and roller models, they captured the roller's motion and determined the optimal vibration frequency for compaction. These studies contribute valuable insights into the compaction of earth-rock mixtures, enhancing roller efficiency and improving the overall compaction quality of earth-rock sub-grades.

However, most of the studies mentioned above relied on large-scale equipment to measure indicators, which makes it difficult to assess construction work in small areas or confined spaces, and the detection process is often complex. Furthermore, there is limited research on the dynamic compaction detection index for sub-grades behind abutments with earth–rock mixture fillers. Therefore, there is a need for a new, rapid sub-grade compaction detection method to address these shortcomings. The Light-Falling-Weight Deflectometer (LFWD) is well-suited for soils and earth–rock mixtures with a maximum particle size of less than 63 mm. Its detection index reflects the dynamic deformation modulus, Evd, which is an important indicator of ground stiffness (Kuttah, 2024; Ampadu, 2007; Kim et al., 2011). Yong et al. (2018) established a relationship between the Evd of loess, red sandstone, and red mudstone sub-grades and the degree of compaction (K). Their findings revealed a positive correlation between the two, with the degree of compaction measured using Evd aligning closely with that measured by the traditional sand replacement method. Zhang et al. (2012) conducted experiments on six representative fillers and studied the correlations between Evd, compaction degree, water content, and deflection. Based on the results, they proposed recommendations for using Evd to assess sub-grade compaction quality. The study found a strong correlation between the dynamic deformation modulus and deflection, indicating that Evd is a more convenient and efficient method for compaction detection.

Currently, there is limited research on Evd compaction detection of earth–rock mixture sub-grades, and previous studies have yet to establish quality control standards. Building on the aforementioned studies, this paper develops a sub-grade model for earth–rock mixture fillers using discrete element simulation software and conducts a simulation analysis for Evd detection. By considering two key control indicators—porosity and settlement difference, the relationships among parameters are analyzed, followed by a field test to verify the results. Based on this analysis, a control standard for rapidly evaluating the compaction quality of earth–rock mixture sub-grades, using the Evd value, is proposed.

The paper is composed of the following sections: Research Methods; Simulation Results and Discussion; Field Test Verification; and Conclusion.

## RESEARCH METHODS

The research methodology employed in this paper is illustrated in the flowchart illustrated in Figure (1), with each task completed according to the outlined steps.

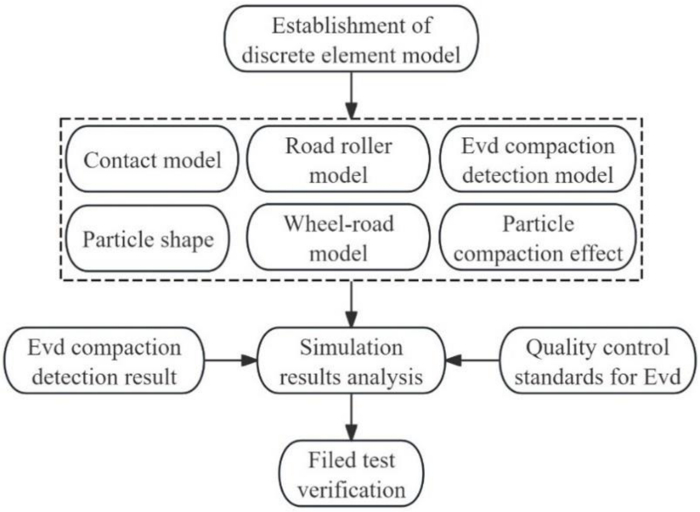


**Figure (1): Research flowchart**

### Particle Shape

The classification of soil and stone is based on particle size. In this study, particles larger than 5 mm are classified as stones, while particles smaller than 5 mm are considered soil particles (Medley, 1994; Lindquist et al., 1994; Wang et al., 2018; Wei et al., 2018). In the discrete element simulation model, spherical particles are typically used to represent material models. Accordingly, soil particles are modeled as single spheres with a particle size of 5 mm. However, single spherical particles are inadequate for simulating the interlocking and frictional behavior between stones. Previous discrete element simulation studies have demonstrated that the shape, particle size, and content of rock particles significantly influence the mechanical properties of earth–rock mixtures (Yao et al., 2022; Zhang et al., 2016; Barman et al., 2016; Wu et al., 2023). Therefore, multi-spherical particles are used to represent stone particles. To balance simulation efficiency and realism, rock particles are modeled as tetrahedral-shaped spherical particles with a particle size ranging from 10mm to 60 mm, as shown in Figure (2).

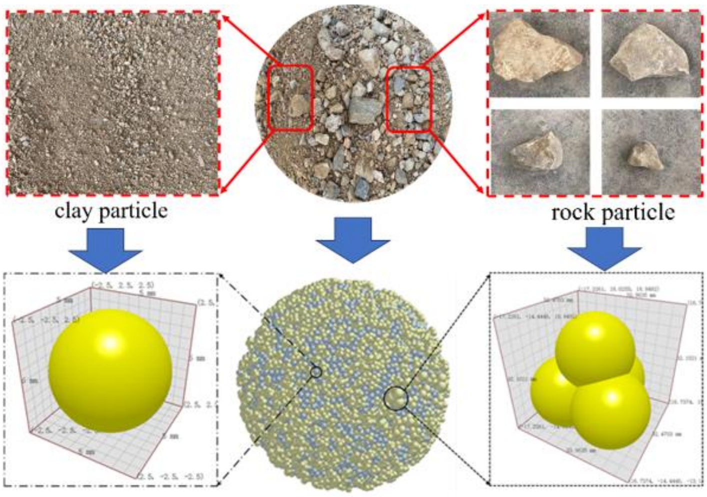


**Figure (2): Discrete element simulation of the particle shape**

**Particle Generation Mode**

In the PDEM (Particle Discrete Element Method) simulation software, particles can be generated either by number or by mass. In this study, discrete particles were generated by mass. To enhance computational efficiency and simplify the model, the average size of each sieve fraction was used as the size of the discrete element particles within that size range. The mass of each particle was determined based on the proportion of particles in that size range according to the actual gradation, as shown in Table 1.

**Table 1. Proportion of particle size content**

| Rock content (%) | Proportion of particles of each particle size (%) | | | | |
|---|---|---|---|---|---|
| | ≤5 mm | 5-10 mm | 10-20 mm | 20-40 mm | 40-60 mm |
| 30 | 70 | 5 | 7 | 10 | 8 |
| 50 | 50 | 8 | 12 | 17 | 13 |
| 70 | 30 | 11 | 17 | 24 | 18 |

**Establishment of the Sub-grade Model**

The physical parameters include density, Poisson's ratio, shear modulus, and Young's modulus. Since these parameters are intrinsic to the material properties, they remain relatively constant. The physical parameters of the earth-rock mixture filler were determined based on previous experiments and references (Ju et al., 2018; Ji et al., 2020; Ji et al., 2021; JTG/T 3610-2019; JTG 3450-2019), as summarized in Table 2.

**Table 2. Physical parameters of the materials**

| Material | Poisson's ratio$\upsilon$ | Density $\rho$/(kg/m$^3$) | Shear modulus G/Pa |
|---|---|---|---|
| Earth-rock mixture filler | 0.25 | 1800 | 2.5e+08 |
| Sand | 0.45 | 2500 | 2e+08 |
| Steel | 0.3 | 7800 | 7e+10 |

The contact parameters include the collision recovery coefficient, static friction coefficient and rolling friction coefficient. According to previous simulation tests (Ji et al.,2022; Ji et al., 2021), the contact parameters between materials were determined as shown in Table 3.

**Table 3. Material contact parameters**

| Material type | Collision coefficient of restitution | Coefficient of static friction | Coefficient of rolling friction |
|---|---|---|---|
| Sand–Sand | 0.4 | 0.2 | 0.1 |
| Sand–Steel | 0.5 | 0.6 | 0.07 |
| Earth rock–Earth rock | 0.2 | 0.8 | 0.1 |
| Earth rock–Steel | 0.56 | 0.5 | 0.07 |

Based on the parameters mentioned above, a sub-grade model was established to simulate the compaction process using a roller. To ensure that the simulation conditions accurately reflect field conditions, a large discrete element sub-grade model with dimensions of 5 m × 2.5 m × 0.6 m was created. The roller model was developed using the multi-body dynamics software RecurDyn. By integrating the discrete element model with the multi-body dynamics simulation, the roller’s operation—rolling back and forth across the sub-grade, as in the construction site—was accurately simulated, as shown in Figure (3). The compaction effect of different rolling passes on the sub-grade is illustrated in Figure (4).

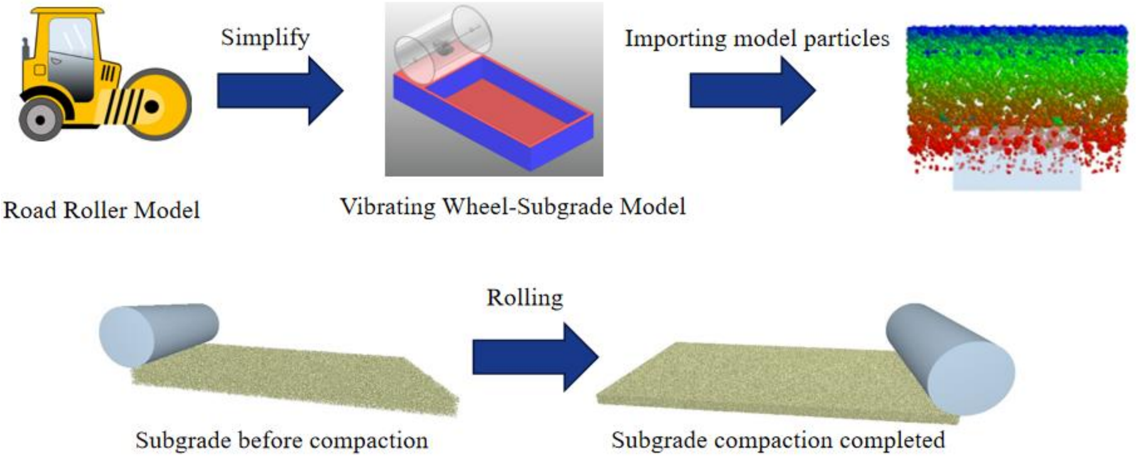
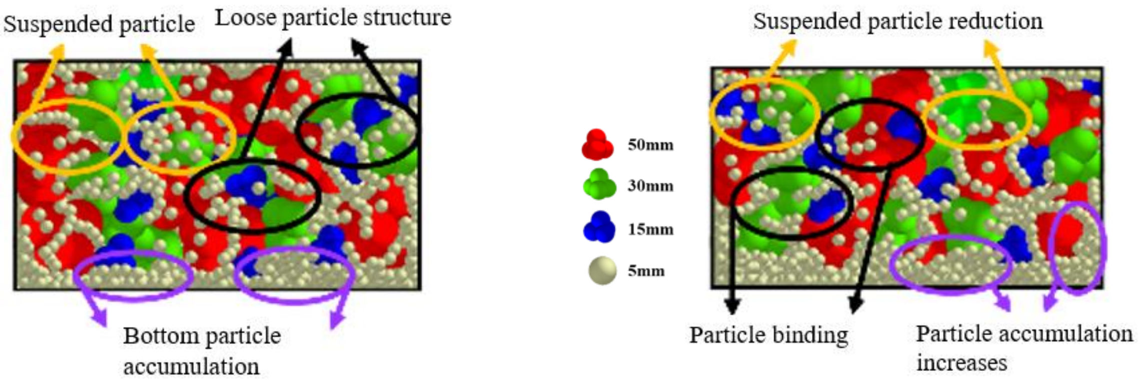
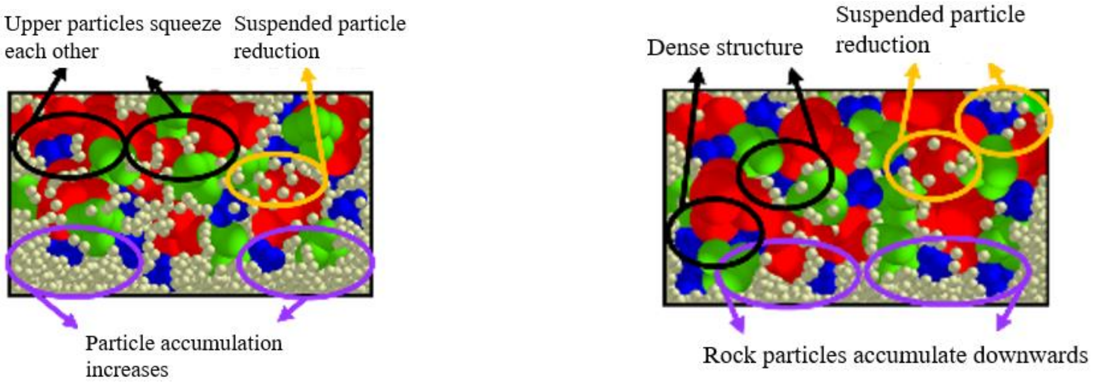


**Figure (3): Flowchart of model establishment**



(a) Rolling 2 passes

(b) Rolling 4 passes



(c) Rolling 6 passes

(d) Rolling 8 passes

**Figure (4): Compaction effects**

By the eighth pass, the mixture's density stabilizes, and the forces acting on the particles become more consistent, resulting in minimal particle movement and negligible increases in settlement. The recommended number of passes the roller is rolled is 8 passes.

## Establishing a Compaction Detection Model Based on Evd

The compaction of the earth–rock mixture filler for the abutment was tested using the Light-Falling-Weight Deflectometer (LFWD). Based on the mechanical parameters, a compaction detection machine model was established, and a compaction detection simulation was performed on the compacted earth–rock mixture subgrade using discrete element software. The machine parameters are presented in Table 4.

**Table 4. LFWD main technical parameters**

| Instrument structure name | | Instrument parameters |
|---|---|---|
| Drop weight loading device | Maximum impact load | 7.07kN |
| | Impact duration | 18.0±2ms |
| | Drop weight | 10.0kg |
| | Guide rod weight | 5.0kg |
| Loading plate | Weight | 15.0kg |
| | Diameter | 300.0mm |
| | Thickness | 20.0mm |
| Controller host | Evd value test range | <225MPa |
| | Applicable temperature range | 0~50℃ |
| Total weight | | 30.0kg |

## SIMULATION RESULTS AND DISCUSSION

The test results vary with different rock contents. Since the grading type is a crucial parameter influencing the compression and compaction of earth–rock mixture filler in later stages, this study uses rock content as a basis for classification. The rock content is roughly divided into three types: when the rock content is less than 30%, it forms a suspension-dense structure; when the rock content exceeds 70%, it forms a skeleton-void structure; and when the rock content falls between these values, it is designated as a skeleton-dense structure. Consequently, rock contents of 30%, 50%, and 70% were selected for representative analysis.

### Evd Compaction Detection Test with a 30% Rock Content

The simulation analyzed the relationships between the dynamic deformation modulus (Evd) and the number of rolling passes, settlement difference, and porosity at different rock contents, followed by correlation fitting. A compaction quality standard based on Evd was then established. The relationships among these four factors at a 30% rock content are presented in Figure (5).

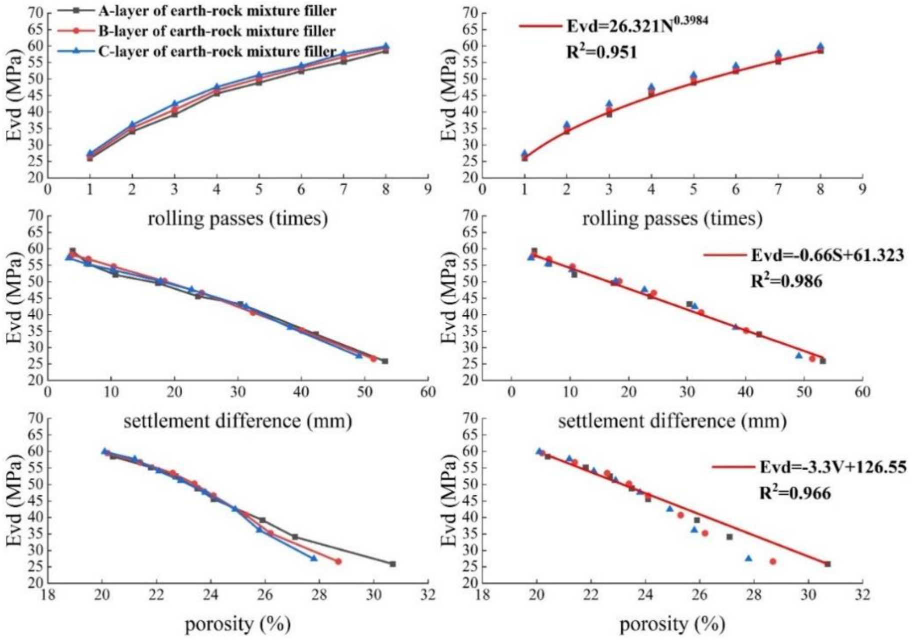


**Figure (5): 30% rock content test and fitting results**

As shown in Figure (5), at a rock content of 30%, Evd of the earth–rock mixture filler increases exponentially with the number of rolling passes, indicating that the sub-grade is gradually compacted. Eventually, Evd stabilizes as compaction reaches a certain level. The relationship between these variables is expressed in Eq. (1).

A negative linear correlation exists between the settlement difference of the earth–rock mixture filler layer and Evd, as shown in Eq. (2). As the number of rolling passes increases, the settlement difference of the sub-grade gradually decreases, indicating that the sub-grade is becoming more compacted. When the number of rolling passes reaches 8, Evd reaches its maximum value of 59.1 MPa, while the settlement difference is 3.3mm.

During the sub-grade compaction process, with an increasing number of rolling passes, the settlement difference gradually decreases. This leads to the interlocking of internal structures and particle contact, which in turn reduces the porosity. A strong linear relationship exists between porosity and Evd, as shown in Eq. (3).

## Evd Compaction Detection Test with a 50% Rock Content

Evd detection simulation was conducted with a 50% rock content. The relationships between Evd, rolling passes, settlement difference, and porosity, along with the corresponding fitting curves, are presented in Figure (6).

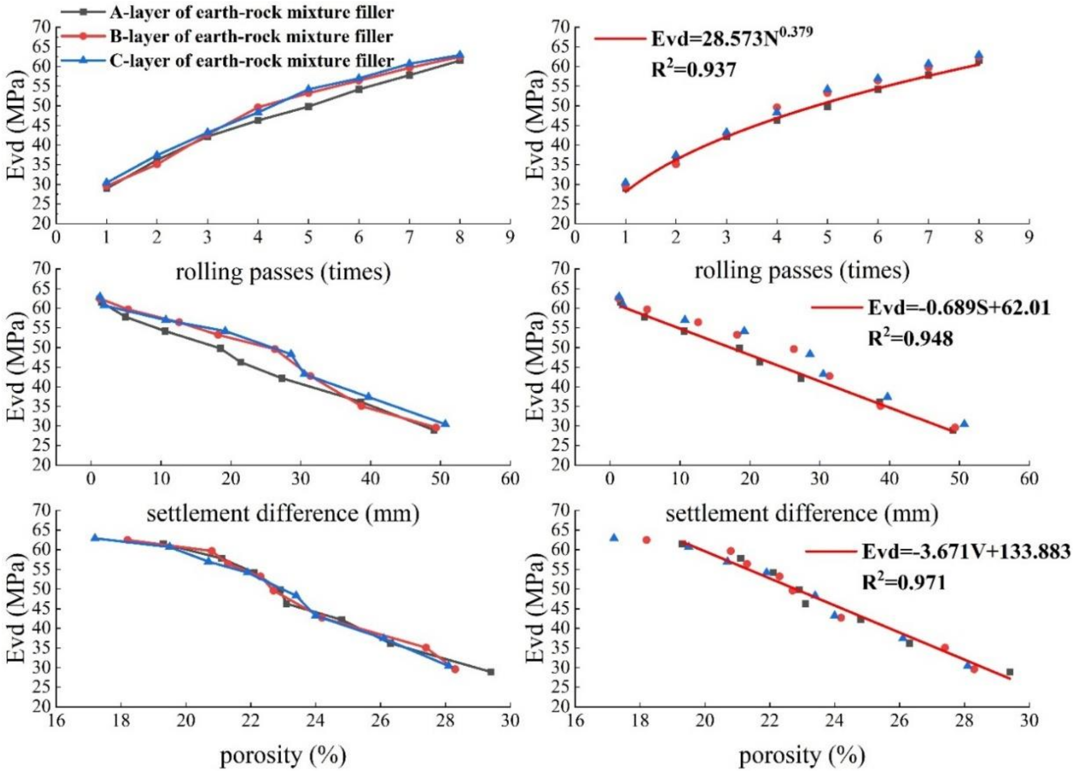


**Figure (6): 50% rock content test and fitting results**

Figure (6) demonstrate that Evd, for both 50% and 30% rock content, exhibits a similar trend with respect to the relationships between rolling passes, settlement difference, and porosity. However, the specific values of the four parameters differ due to the variation in rock content. At 50% rock content, the maximum Evd reaches 62.9 MPa. For the same number of rolling passes, the settlement difference is 2.1 mm, being smaller compared to its value at 30% rock content, and the porosity is reduced by 3%. When compared to the other samples, the compaction effect for the 50% rock content is more favorable.

Evd has the fitting relationship with the rolling passes, settlement difference and porosity, as shown in Eqs. (4)-(6).

### Evd Compaction Detection Test with 70% Rock Content

An Evd detection simulation was conducted with 70% rock content. The correlation between Evd, rolling passes, settlement difference, and porosity is shown in Figure (7).

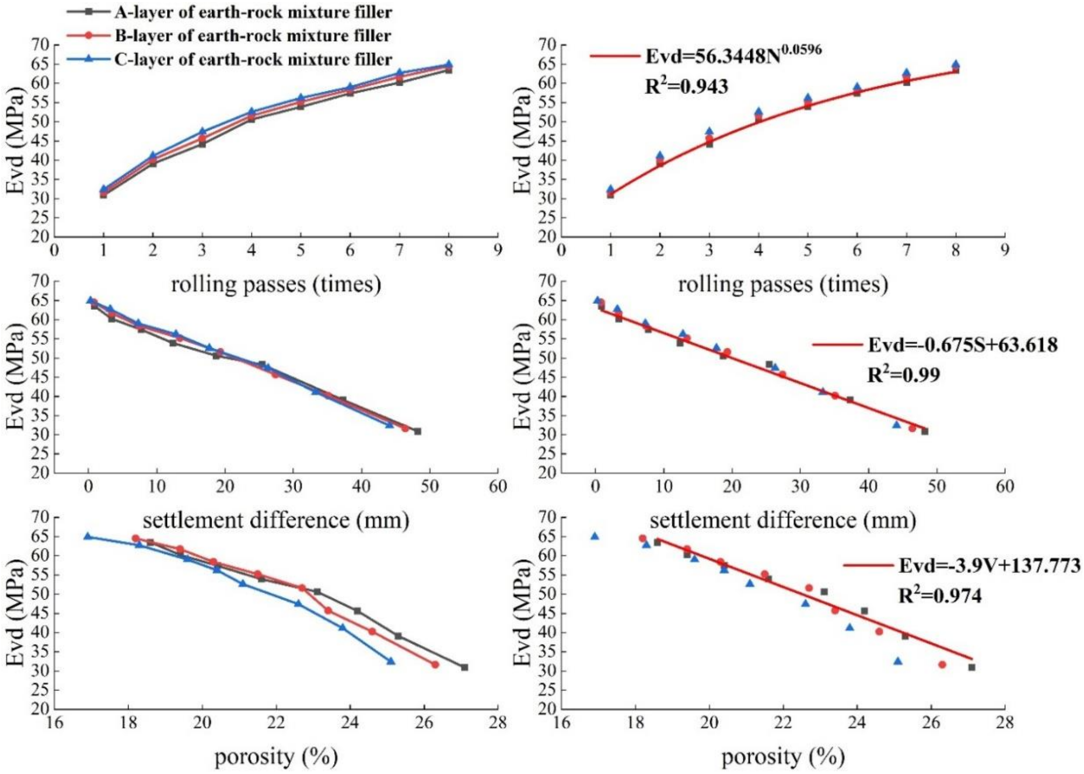


**Figure (7): 70% rock content test and fitting results**

As the number of rolling passes (N) increases, the earth-rock mixture becomes progressively compacted, thereby enhancing its resistance to external loading. A clear exponential relationship is observed between Evd and rolling passes, as expressed in Eq. (7).

As the rolling process progresses, the compactness of the earth-rock mixture filler continuously increases, while the settlement difference (S) gradually decreases. Concurrently, the resistance of the earth-rock mixture filling layer to external loads improves, as evidenced by the increase in Evd. An exponential relationship between the rolling settlement difference (S) and the corresponding Evd is observed, as described in Eq. (8).

A clear negative correlation exists between the porosity of the earth–rock mixture filler and Evd, with a strong linear relationship between the two, as shown in Eq. (9). As the porosity decreases, the earth–rock mixture sub-grade becomes more compacted, which is reflected by the increase in Evd.

Compared to the 30% and 50% rock content, the 70% rock content exhibits a strong correlation with rolling passes, settlement difference, and porosity. Under the same number of rolling passes, the settlement difference and porosity are the lowest, measuring 0.3 mm and 16.9%, respectively, while Evd reaches 64.9 MPa.

### Quality Control Standards for Evd

According to the specifications (JTG/T 3610-2019; JTG 3450-2019), a sub-grade is considered to have reached the desired compaction level when the differential settlement before and after two consecutive measurements is less than 2 mm. In order to assess the impact of rock content and rolling passes on the dynamic deformation modulus (Evd), the relationships among these factors were analyzed using regression, as shown in Figure (8). An estimation model for Evd under varying rock content levels and rolling passes is provided in Eq. (10).

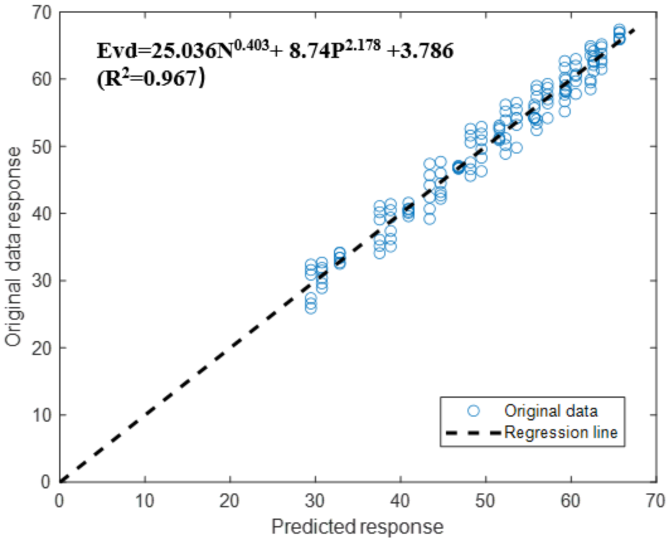


**Figure (8): Regression model results**

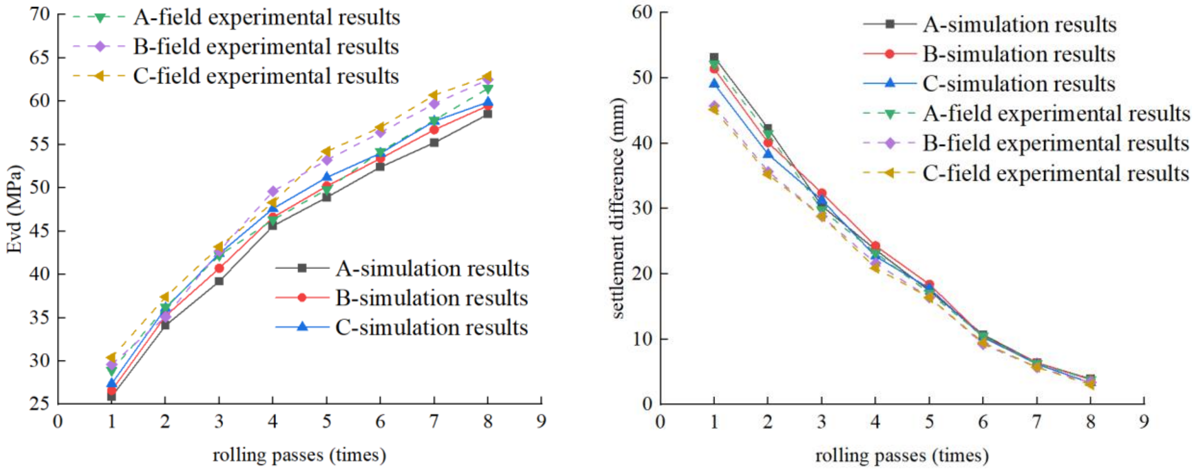
N is rolling passes; P is rock content. Considering the dual control indicators of settlement difference and porosity for earth–rock mixture embankment fill, an Evd control standard is proposed based on the simulation results from Evd testing. When the settlement difference is below the specified threshold of 2 mm, the following compaction requirements must be met: for an earth–rock mixture filler with 30% rock content, 8 rolling passes are required to achieve an Evd ≥ 55 MPa; for a rock content of 50%, 8 rolling passes are needed to achieve an Evd ≥ 57 MPa; and for 70% rock content, 7 rolling passes are required to achieve an Evd ≥ 60 MPa. The compaction quality requirements for the earth–rock mixture filler layer are satisfied.

**Table 5. Linear equations presenting the impact of the different parameters of the study**

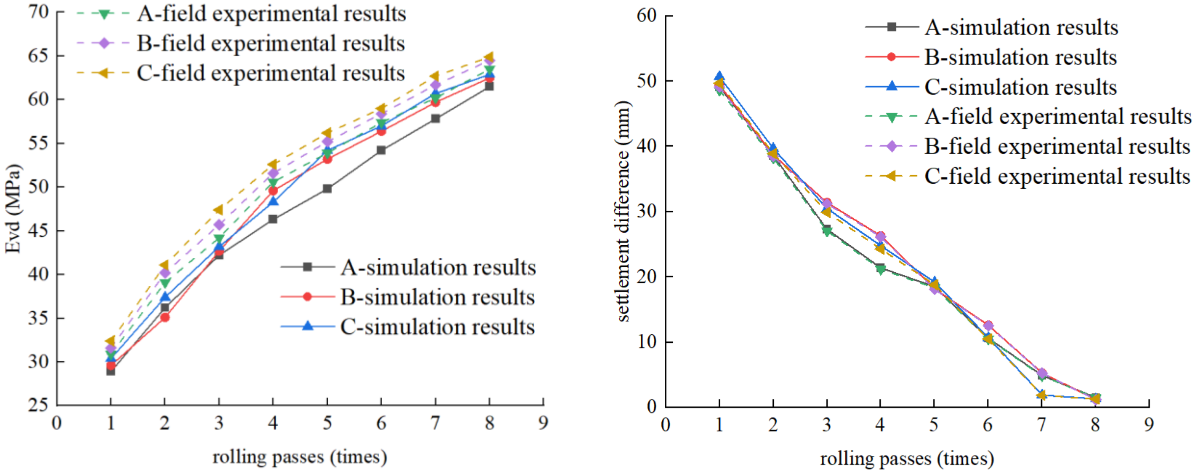
| Serial number | linear equations |
|---|---|
| (1) | $\mathrm{Evd} = 26.321\mathrm{N}^{0.3984}(\mathrm{R}^2 = 0.951)$ |
| (2) | $\mathrm{Evd} = -0.66\mathrm{S} + 61.323(\mathrm{R}^2 = 0.986)$ |
| (3) | $\mathrm{Evd} = -3.3\mathrm{V} + 126.55(\mathrm{R}^2 = 0.966)$ |
| (4) | $\mathrm{Evd} = 28.753\mathrm{N}^{0.379}(\mathrm{R}^2 = 0.937)$ |
| (5) | $\mathrm{Evd} = -0.689\mathrm{S} + 62.01(\mathrm{R}^2 = 0.948)$ |
| (6) | $\mathrm{Evd} = -3.67\mathrm{V} + 133.883(\mathrm{R}^2 = 0.971)$ |
| (7) | $\mathrm{Evd} = 56.3448\mathrm{N}^{0.0596}(\mathrm{R}^2 = 0.943)$ |
| (8) | $\mathrm{Evd} = -0.675\mathrm{S} + 63.618(\mathrm{R}^2 = 0.99)$ |
| (9) | $\mathrm{Evd} = -3.9\mathrm{V} + 137.773(\mathrm{R}^2 = 0.974)$ |
| (10) | $\mathrm{Evd} = 25.036\mathrm{N}^{0.403} + 8.74\mathrm{P}^{2.178} + 3.786(\mathrm{R}^2 = 0.967)$ |

## FIELD TEST VERIFICATION

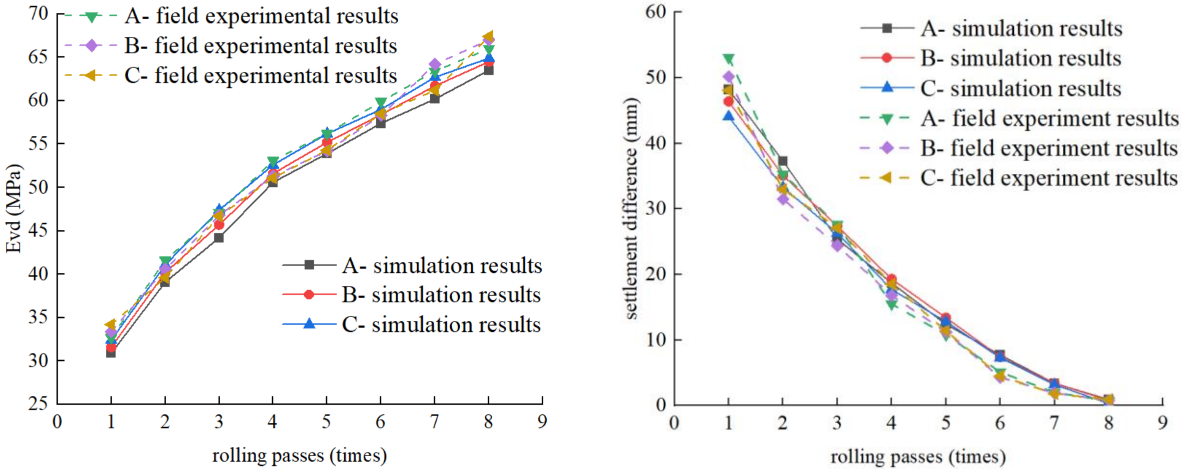
The simulation analysis indicated that the compaction effect is greatest when the rock content is 70%. Verification of the compaction testing quality was conducted for on-site earth-rock mixture filler layers with 30%, 50%, and 70% rock contents. Three consecutive layers of earth-rock mixture filler (from A to C) were selected, and rolling passes (N), settlement difference (S), and Evd were measured on-site for each layer. During the rolling process, the rolling speed should be controlled within 4 km/h, the overlapping width of the wheel tracks should be more than the 1/3th rolling wheel width, and rolling should be carried out from two sides to the middle. After the earth–rock mixture filler layer is rolled once, the top surface elevation and Evd were measured. The comparison between the field test results and the simulation results is shown in Figure (9).



**(a) 30% rock content**



**(a) 50% rock content**



**(c) 70% rock content**

**Figure (9): Comparison between field test results and simulation results**

Both the field test results and the simulation data show that Evd increases with the increase of rolling passes; the settlement difference gradually decreases and tends to be stable with the increase of rolling passes.Field tests revealed that, after 8 rolling passes for all three rock content levels, the requirement for the settlement difference before and after compaction to be less than 2 mm was satisfied, as specified. A comparison of the three rock contents showed that, at 70% rock content, the settlement difference was the smallest and

Evd was the highest, indicating that the compaction quality of the earth–rock mixture filler layer was superior to that of the layers with 50% and 30% rock contents.

A comparison between the field test results and the simulated data reveals that the error between the measured Evd and the simulated values for the three different rock contents is less than 5% (Liu et al., 2014; Yan et al., 2025; JTG F80/1-2017). These findings demonstrate that the established simulation model accurately predicts Evd, thereby validating the accuracy of the proposed standards and confirming the feasibility of using Evd to control the compaction quality of earth–rock mixture filler layers.

## CONCLUSIONS

In this study, discrete element software was used to develop a model of the earth–rock mixture filler sub-grade. During the compaction process, Evd compaction detection tests were conducted, and rolling passes, settlement difference, and porosity were measured. The relationships between these factors and Evd were established. A field test was subsequently performed to validate the findings from the simulation, leading to the following conclusions.

- A strong correlation exists between Evd and the rolling passes (N), settlement difference (S), and porosity (V). For different rock contents, the rolling passes exhibit a positive correlation with Evd, while both the settlement difference and porosity show a negative correlation with Evd.
- Considering the rock content and rolling passes of the sub-grade, a relationship has been established to quickly determine Evd. Based on different rock contents, a method and corresponding quality control standards for efficiently assessing the compaction quality of earth–rock mixture fillers using Evd are proposed: $Evd=25.036N^{0.403}+8.74P^{2.178}+3.786$. When the number of rolling passes for the earth–rock mixture filler reaches 8, the settlement differences across all three rock content layers are less than 2 mm. At 30% rock content, Evd is ≥ 55 MPa; at 50% rock content, Evd is ≥ 57 MPa; and at 70% rock content, Evd is ≥ 60 MPa.
- Through field testing, the error between the measured data and the simulation results is found to be less than 5%, thereby validating both the accuracy of the simulation model and the reliability of the proposed Evd standards for compaction quality control.
- This study primarily focuses on the compaction detection of earth-rock mixture filler for abutments, with the findings applicable to the analysis of various soil types. The simulation model involves certain simplifications for practical applications, and measurements may be influenced by factors, such as equipment accuracy and operational errors. These factors, particularly in different field conditions, may introduce some degree of uncertainty.
- The next step involves verifying and refining the control standards under various soil conditions, integrating them with other compaction quality indicators. By monitoring the trend of Evd changes throughout the long-term compaction process, Evd control standard can be further optimized through data analysis, thereby enhancing the reliability and adaptability of the standard.

### Conflict of Interests

The authors have no potential or actual conflict of interests to declare with respect to the research, authorship, and publication of this article.

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