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Application and Numerical Simulation of a Portable Falling Weight Deflectometer for Compaction Quality Evaluation of Levee Embankment Filling Based on Abaqus

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Abstract: ***To achieve rapid, non-destructive, and quantitative evaluation of compaction quality in levee embankment construction, this study takes the Wenchao Flood Diversion River embankment project as a case study and integrates field testing using a portable falling weight deflectometer (PFWD) with finite element numerical simulation based on Abaqus. The mechanical response and compaction quality of embankment filling materials under different layer thicknesses were systematically investigated. Material parameters of the dam fill were obtained from PFWD field tests and converted into equivalent Young's modulus values. A finite element model was established in Abaqus to simulate the transient impact loading process, and the rationality of the modeling approach and parameter inversion method was verified through comparison between numerical results and field measurements. The results indicate that layer thickness has a significant influence on the elastic deformation and resilient modulus of the embankment body, with thinner layers being more favorable for improving the overall stiffness of the structure. The relative error between simulated and measured central deflection values was less than 5%, demonstrating good agreement. The proposed approach provides a reliable basis for compaction quality evaluation and optimization of construction parameters in levee embankment filling projects by combining non-destructive field testing with numerical simulation.***

Keywords: Portable falling weight deflectometer, Abaqus modeling, Deflection measurement, Levee embankment, Compaction quality.

1. Introduction

Levee embankments have been widely applied in water conservancy and flood control projects due to their advantages of convenient material sourcing, mature construction techniques, and strong adaptability to complex geological conditions. With the continuous expansion of project scale and increasing service life, engineering problems such as embankment deformation, seepage, and local instability have gradually become prominent. These issues are closely related to the compaction quality of embankment filling during the construction stage. Therefore, the accurate evaluation and effective control of filling quality are essential prerequisites for ensuring the long-term safety and stable operation of levee embankments. Traditional methods for evaluating compaction quality mainly include measurements of compaction degree, moisture content, and several in-situ tests, such as the sand replacement method and ring cutter method. Although these methods can provide relatively accurate results, they are often time-consuming, destructive, and limited in spatial representativeness, making them difficult to apply to rapid and continuous quality control in large-scale levee embankment projects. In recent years, non-destructive testing methods based on structural mechanical responses have attracted increasing attention as an effective alternative. The portable falling weight deflectometer (PFWD) applies a transient impact load to the ground surface and measures the resulting deflection response, enabling the back-calculation of mechanical parameters of the tested material. Owing to its advantages of non-destructive testing, high efficiency, and operational flexibility, PFWD has been gradually introduced into compaction quality evaluation of earth-rock embankment filling [1], providing a practical approach for rapid on-site assessment. However, the interpretation of PFWD test results is influenced by multiple factors, including material properties, layer thickness, boundary conditions, and loading characteristics. A clear understanding of the mechanical response mechanism under PFWD impact loading is therefore required to improve the reliability of test-based evaluations. With the development of numerical simulation techniques, finite element analysis has become an effective tool for investigating the mechanical behavior of geotechnical structures under dynamic loading [2]. Abaqus software exhibits significant advantages in dynamic response analysis and complex contact problem modeling. Considering that PFWD impact loading is characterized by short duration and relatively low strain levels, the filling material can be reasonably modeled using a linear elastic constitutive relationship under small-deformation assumptions. This provides a feasible framework for coupling PFWD field measurements with numerical simulations. In this study, the levee embankment of the Wenchao Flood Diversion River project is taken as the research background. PFWD field tests and Abaqus finite element simulations are combined to investigate the deflection response characteristics of embankment filling under different layer thicknesses. Field tests were conducted in three representative zones with layer thicknesses of 35 mm, 45 mm, and 50 mm, respectively, and a large number of deflection values, resilient modulus data, and converted compaction degrees were obtained. Based on these data, a finite element model consistent with field conditions was established, and the mechanical parameters of silty clay filling were determined through inverse analysis. By systematically analyzing the influence of layer thickness on the mechanical performance of earth-rock embankment filling and validating the numerical model against field measurements, this study proposes an integrated approach combining non-destructive testing and numerical simulation for compaction quality evaluation. The results provide valuable references for quality assessment and construction parameter optimization in levee embankment engineering, and offer practical significance for improving construction control and structural safety.

2. Field Testing and Data Analysis

2.1 Project Overview and Testing Scheme

The testing area of this study is located at the northern embankment section of the levee embankment in the Wenchao Flood Diversion River project. The embankment filling material mainly consists of silty clay. According to the construction layer thickness, the test area was divided into three representative zones for comparative analysis:

Zone I (layer thickness of 35 mm, chainage 0+850),
Zone II (layer thickness of 45 mm, chainage 0+900), and
Zone III (layer thickness of 50 mm, chainage 0+950).

Field tests were conducted using a GTJ-PFWD portable falling weight deflectometer. The device applies a transient impact load to the ground surface through a falling weight acting on a loading plate, and the resulting deflection response at the center and surrounding locations of the plate is measured using displacement sensors [3]. The diameter of the loading plate was 300 mm, and Poisson's ratio was taken as 0.32 during the testing process.

To ensure the stability and reliability of the test results, multiple repeated loadings were performed at each test point, and the average value was adopted as the final measurement. The testing procedure followed the basic principles of the *Standard for Soil Test Methods* (GB/T 50123–2019) [4], while taking into account the specific characteristics of hydraulic engineering projects to ensure data consistency and reliability.

2.2 Statistical Analysis of Test Results

The PFWD test data obtained from the three zones were organized and statistically analyzed. The main results, represented by average values, are summarized in **Table 1**.

Table 1: Summary of PFWD Test Results for Different Zones

Zone	Layer thickness (mm)	Average deflection (mm)	Average resilient modulus (MN/m²)	Average compaction degree (%)
Zone I	35	5.27	3.275	72.067
Zone II	45	5.34	3.133	72.054
Zone III	50	6.43	2.486	71.993

To facilitate comparison, the relationships between layer thickness and compaction degree, as well as between average deflection and resilient modulus, are illustrated in **Figure 1** and **Figure 2**, respectively.

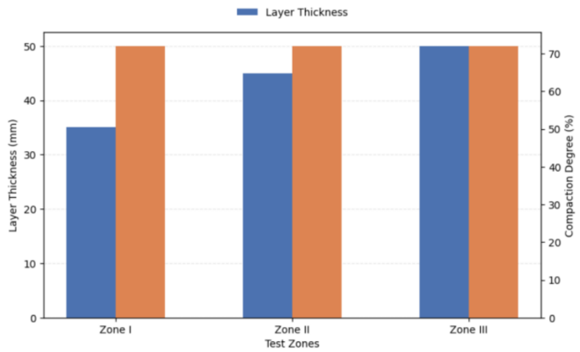

Figure 1: layer thickness and compaction degree

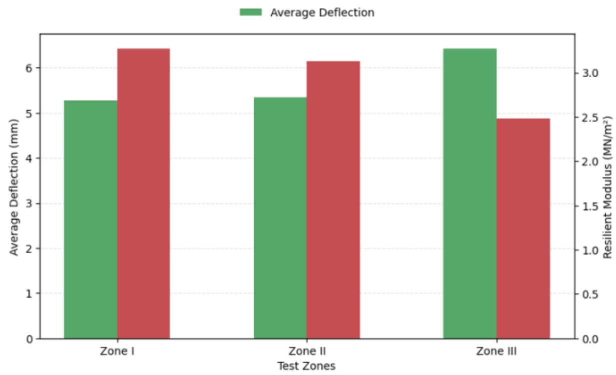

Figure 2: average deflection and resilient modulus

Based on the results presented in Table 1, the following observations can be made. Deflection analysis: Zone III (50 mm) exhibits the largest average deflection value (6.43 mm), whereas the deflection values of Zone I (35 mm) and Zone II (45 mm) are relatively close, at 5.27 mm and 5.34 mm, respectively. This indicates that, under the same filling material and initial compaction conditions, an increase in layer thickness leads to a greater instantaneous surface deformation under impact loading. This behavior can be attributed to the relatively lower initial density of thicker loose layers under self-weight and the larger volume of soil participating in deformation during dynamic loading. Resilient modulus analysis: The resilient modulus is a key parameter characterizing the resistance of embankment filling material to elastic deformation [5] and shows an inverse relationship with deflection. Zone I exhibits the highest average resilient modulus (3.275 MN/m²), followed by Zone II (3.133 MN/m²), while Zone III presents the lowest value (2.486 MN/m²). These results clearly indicate that, under the same construction process, thinner layers are more favorable for achieving higher stiffness and bearing capacity of the embankment body. Compaction degree analysis: The average converted compaction degrees of the three zones are very close, all around 72%, with fluctuations of less than 0.1%, indicating relatively uniform compaction control during field construction. However, compared with the commonly required compaction degree of no less than 93%–95% specified in levee embankment design standards, the compaction quality in all zones is significantly insufficient. This directly explains the generally low measured resilient modulus values and further highlights the necessity of strengthening compaction quality control as well as the importance of the present study [6].

3. Abaqus Finite Element Modeling

3.1 Geometry Model and Basic Assumptions

The finite element model established in Abaqus consists of two main parts: the upper filling layer and the underlying foundation soil. The thickness of the filling layer was set to 35 mm, 45 mm, and 50 mm to correspond to the three construction conditions investigated in the field tests, while the thickness of the foundation soil was taken as 1.5 m to minimize the influence of boundary effects on the calculated result [7]. In the model, the PFWD loading plate was simplified as a rigid circular plate in full contact with the embankment surface. Under the assumptions of small deformation and short-duration impact loading, the embankment filling material was treated as an isotropic linear elastic material [8]. The Young's modulus of the filling material was taken as the resilient modulus obtained from PFWD field measurements, and Poisson's ratio was uniformly set to 0.32. These assumptions are considered reasonable for simulating the PFWD testing process, as the impact duration is short and the induced strain level remains relatively low.

3.2 Mesh Generation and Element Types

The model was discretized using three-dimensional solid elements. Local mesh refinement was applied in the region directly beneath the loading plate to accurately capture stress concentration and displacement response, while a relatively coarser mesh was adopted in other regions to improve computational efficiency. A preliminary mesh sensitivity analysis was conducted to ensure that the selected mesh scheme satisfied accuracy requirements. Boundary conditions were defined such that vertical displacement at the bottom of the model was constrained, while radial displacement was restricted along the lateral boundaries. This configuration was intended to simulate semi-infinite foundation conditions and to reduce the influence of boundary constraints on deflection calculations.

3.3 Load Application Method

The PFWD impact load was applied in the form of an equivalent uniformly distributed pressure acting on the contact area of the loading plate. The magnitude of the pressure was determined based on the measured impact force obtained from field tests and the area of the loading plate. Through this equivalent loading approach, the transient impact effect of the PFWD can be reasonably reproduced in the finite element model, allowing for an effective simulation of the mechanical response of the embankment body under impact loading.

3.4 Material Parameters and Load Definition

For the foundation soil, the equivalent Young's modulus was assumed to be equal to the resilient modulus obtained from PFWD testing. Under the engineering assumptions adopted in this study, the levee embankment material was treated as a purely elastic material, without considering plastic deformation or cyclic degradation effects. Within the framework of small-deformation analysis, the resilient modulus can be reasonably regarded as equivalent to the elastic Young's modulus, i.e.,

$$1\, MN/m^2 = 1 Mpa$$

where E is the equivalent Young's modulus and M_r is the resilient modulus obtained from field measurements.

3.5 Model Validation

To verify the accuracy of the established finite element model, PFWD deflection measurements were conducted at a highway construction site, and the measured deflection values were compared with numerical simulation results. The comparison results are summarized in **Table 2**.

Table 2: Comparison between Measured and Simulated FWD Deflection Values

Layer thickness (mm)	Simulated deflection (mm)	Average measured deflection (mm)	Error (%)
35mm	5.19	5.27	1.5
45mm	5.38	5.34	0.8
50mm	6.41	6.43	0.3

As shown in Table 2, the relative errors between simulated and measured deflection values for all layer thicknesses are less than 5%. This demonstrates that the Abaqus finite element model can accurately reproduce the PFWD testing process and effectively simulate the deflection response of the embankment body under impact loading, indicating that the model has sufficient accuracy for engineering applications [9].

4. Simulation Results, Analysis and Model Validation

4.1 Deflection Basin Characteristics and Stress Distribution

The numerical simulations successfully reproduced a typical deflection basin characterized by a maximum value at the center of the loading plate and a gradual attenuation along the radial direction. By extracting the vertical displacement–time history of the central node beneath the loading plate, the peak value was identified as the simulated central deflection. The vertical displacement contours of the embankment surface under PFWD impact loading for different layer thicknesses are shown in **Figures 3–5**.

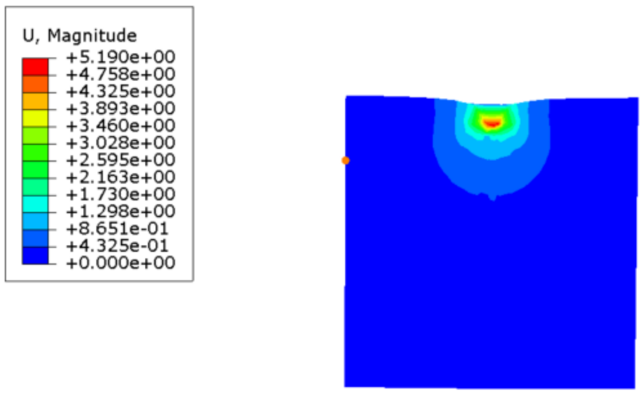

Figure 3: Vertical displacement contour of the embankment surface with a layer thickness of 35 mm under PFWD impact loading

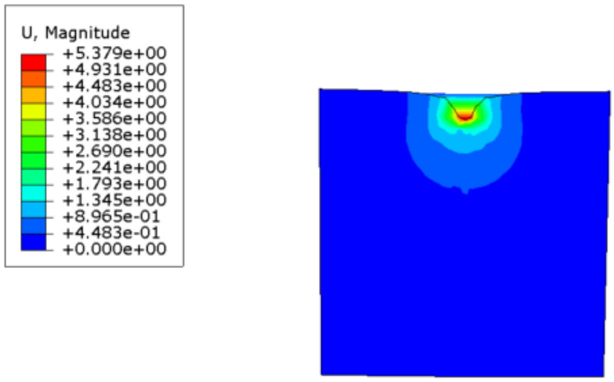

Figure 4: Vertical displacement contour of the embankment surface with a layer thickness of 45 mm under PFWD impact loading

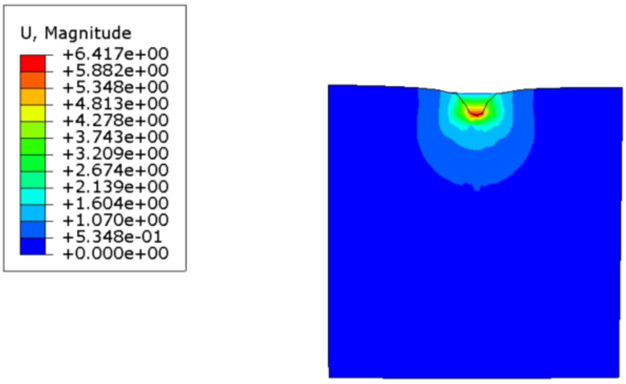

Figure 5: Vertical displacement contour of the embankment surface with a layer thickness of 50 mm under PFWD impact loading

The simulation results indicate that, under impact loading, the embankment surface exhibits a typical bowl-shaped deflection basin. The maximum deflection occurs directly beneath the center of the loading plate and decreases gradually with increasing radial distance. Although the overall deflection basin shape remains similar for different layer thicknesses, the magnitude of deflection shows significant difference. Specifically, with increasing layer thickness, the peak deflection value increases, indicating a reduction in the overall stiffness of the filling structure. This trend is consistent with the PFWD field test results and reflects the influence of construction layer thickness on the mechanical response of the embankment body [10].

4.2 Comparison between Numerical Simulation and Field Measurements

To further evaluate the reliability of the finite element model, the simulated central deflection values were compared with the average PFWD-measured values under corresponding layer thickness conditions. The comparison shows that the relative errors for all cases are controlled within 5%. The close agreement between numerical and experimental results demonstrates that the established Abaqus finite element model can effectively capture the mechanical response characteristics of earth-rock embankment filling under PFWD impact loading. This also confirms that, under small-deformation assumptions, adopting the resilient modulus obtained from PFWD testing as the equivalent Young's modulus is reasonable for linear elastic finite element analysis. Moreover, the consistency between simulated and measured deflection responses indicates that the modeling strategy, parameter selection, and boundary condition settings are appropriate. The proposed numerical approach therefore provides a reliable tool for interpreting PFWD test results and for analyzing the influence of construction parameters, such as layer thickness, on compaction quality.

5. Conclusions

Based on the PFWD field testing and Abaqus finite element simulations conducted in this study, the dynamic response characteristics of earth-rock embankment filling under different layer thickness conditions and their influence on compaction quality were systematically investigated. The following conclusions can be drawn:

1) An integrated numerical simulation model for PFWD-based compaction evaluation was established using Abaqus. The model is capable of effectively reproducing the load transfer mechanism and deflection response during PFWD testing. The relative errors between simulated and measured deflection values are less than 5%, indicating that the model accuracy satisfies engineering application requirements.

2) PFWD field test results demonstrate that construction layer thickness has a significant influence on the compaction quality of earth-rock embankment filling. Under the same construction process and material conditions, thinner layers are more conducive to achieving higher equivalent stiffness and smaller deflection responses.

3) Under reasonable engineering assumptions, it is feasible to adopt the resilient modulus obtained from PFWD testing as the equivalent Young's modulus of embankment filling material and to establish a linear elastic finite element model in Abaqus for simulating the PFWD testing process.

4) The good agreement between numerical simulation results and field measurements verifies the rationality of the modeling approach and parameter selection. The results indicate that the combination of PFWD non-destructive testing and finite element analysis provides an effective method for evaluating the compaction quality of earth-rock embankment filling.

5) The present study focuses on simulations under typical structural conditions. Future research may extend the proposed method to different pavement structures (e.g., cement concrete pavements) and more complex geological conditions (e.g., soft soil foundations). In addition, the integration of intelligent algorithms for optimizing compaction paths and PFWD testing parameters may further improve construction efficiency and evaluation accuracy.

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