Compaction Quality Inspection Method of Soil-Rock Filled Embankment Based on Continuous Compaction Control Technology

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Affected by the site construction conditions, the measurement passes of the Taihang Expressway K8 + 105 ~ K8 + 341 (K8 worksite) in the Taihang Expressway did not meet the requirements of data analysis, and the quantity of the control points was insufficient so that the linear correlation between the dynamic deformation modulus \( E_{vd} \) and the vibratory compaction value (VCV) was not strong. Therefore, the target value of VCV cannot be used to diagnose the \( E_{vd} \) compaction quality of soil-rock filler. This paper analyzes the roller measurement VCV value and in situ measurements \( E_{vd} \) value separately. Results reveal the difference between the VCV mean measured in the last two passes and the standard deviation of the measured VCV mean in the last pass are used as the main basis for the actual compaction quality. In addition, the \( E_{vd} \) mean in the last rolling can be used as an auxiliary judgment basis for the quality control of the compaction.

1. Introduction

Compaction quality is vital in water conservancy and hydroelectric power engineering and highway engineering. Whether it reaches the index is a vital factor to ensure compaction quality control. Based on the relationship between wave propagation and electrical resistivity characteristics of filler and compaction status, such as dry density, the water content, and electrical resistivity, the compaction quality can be analyzed by a wave seismic refraction survey [1, 2]. But these methods are not able to use for controlling the compaction quality quantitatively.

Many highway pavements deploy field inspectors to conduct in situ measurements of embankment properties, such as portable falling weight deflectometer (PFWD) and light weight deflectometer (LWD) [3–9]. The traditional quality inspection method relies primarily on testing randomly sampled spots in site, which may cause unreliable representation of the compaction quality of the entire work and lead to delays not only in performing construction work but also in identifying and rectifying quality issues [10]. Following several years of use of intelligent compaction (IC) technology in Europe [11, 12], the United States started using it in highway engineering. White et al. [13] credited the TH-64 construction project in Minnesota as the first earthwork project to require IC technology. More states in the US have been involved in researches exploring IC for compaction quality control [14–18]. Through the research of the relationship between sedimentation quantity and compaction quality, Mei et al. [19] settled the problems of construction technology and quality control of embankment. But the sedimentation difference method also has a shortage, and it does not directly demonstrate the technique index such as density and water content, only indirectly indicates the compaction quality of the compaction layer. In recent years, continuous compaction control technology has appeared in the compaction quality inspection of highway and railway subgrades in China. In well-graded coarse-grained soil or fine-grained soil near the optimal moisture content, there is a good linear correlation between roller
measurement values and in situ measurements, and the compaction quality can be detected and controlled by target values, such as compaction meter value, compaction control value, machine drive power, acceleration amplitude, sound compaction value, and compaction value [20–26]. Therefore, IC can quickly monitor the compaction quality by the measurements of the roller vibration in contact with the ground.

However, in fillers with large differences in the filler particle size, it is difficult to establish the linear correlation between roller measurement values and in situ measurements due to the large discreteness [27]. It is not convenient to diagnose the compaction quality by the target value. Based on the field compaction test at the Taihang K8 + 105 to K8 + 341 (K8 work point), an in situ inspection evaluation method and evaluation standard for the compaction quality of soil-rock filled embankment are proposed based on continuous compaction control technology.

2. Materials and Methods

The source of the Taihang Expressway K8 + 105 to K8 + 341 (K8 work point) site filled material is the excavated soil-rock excavation of adjacent roads. There are mainly two types of fillers with different weathering degrees, the strongly weathered to fully weathered granite gneiss soil-rock mixed filler, type A filler, and the medium-weathered to strongly weathered granite gneiss soil-rock mixed filler, type B filler (Figure 1).

2.1. Test Bed Construction and Testing. The Liugong CLG6126 vibratory roller was used in the field test. The specific model data are shown in Table 1. To guarantee the compaction quality, each test strip was checked by the settlement difference method. Before the vibration rolling, the test strip was precompacted to obtain a flat surface. The length of the wheel track selected at the site was basically 20 m, and then, the PFWD test point was set at a spacing of 2 m or 3 m. The VCV test was carried out with the roller compaction first, and then, the PFWD test was carried.

2.2. In Situ Point Tests. Xu [24] described an index, vibratory compaction value (VCV), which is based on the embankment compaction status established by vertical vibration response signal of the vibration wheel in rolling. The VCV can reflect the change of the embankment resistance and the compaction status, and there is a good relation between embankment resistance and its increment

\[ VCV = P \sin \omega t + Mg - \eta M f (\ddot{u}, \omega), \]

(1)

where \( f (\ddot{u}, \omega) \) represents function of vibration wheel acceleration, vibratory frequency, and the function needs monitoring data to define; \( \eta \) is comprehensive correction function, and it is a dynamic quantity.

Using the PFWD for testing on the subgrade and the ground, the dynamic deformation modulus (\( E_{vd} \)) can be acquired. The equipment has several advantages such as higher efficiency, less operators, nondestructive, and longer service life as well as the FWD, and it also has the advantages as follows: lightweight, objective tested data, high precision, easy operation, and less costing [28].

The loading equipment used a vibratory roller with a dead weight of not less than 16 t, and the fluctuation range of the vibration frequency did not exceed \( \pm 0.5 \) Hz of the specified value. Detection equipment was composed of vibration sensor, signal conditioning (amplification and filtering), data acquisition and analysis processing, data recording, display device, and system control software. The vibration sensor adopted an acceleration sensor, the sensitivity was not less than 10 mV/(m s\(^{-2}\)), and the range was not less than 10 g, and it was installed vertically, as shown in Figure 2.

3. Results and Discussion

3.1. Data Processing. From the 16 sets of field test data, 8 comparatively complete and representative working conditions (WCs) were selected for analysis, as shown in Table 2. The quantity of the test passes for each group of the selected WCs was more than 3, and the number of points controlled by \( E_{vd} \) was more than 10. The selected data are shown in Figures 3 and 4.

3.2. Correlations between Roller Measurement Values and Point Measurements. According to the in situ test, the linear correlation analysis is performed on the data obtained in each working condition, and the linear correlation coefficient and regression equation corresponding to the VCV and the \( E_{vd} \) in each working condition are calculated. In this paper, when the linear correlation coefficient \( R > 0.7 \), it is considered that there is a strong linear correlation between the two indicators [10], and a linear regression equation is given. Otherwise, the linear correlation between the two indicators is considered weak, and no regression equation is given.

This paper considers the linear correlation between the \( E_{vd} \) and the VCV among all the measurement points, the different compaction degrees, and their mean.

Figure 5 illustrates the linear correlation coefficient between the \( E_{vd} \) value and the VCV value in all working conditions. During the rolling process, the change trend of the \( E_{vd} \) value and the VCV value is not completely consistent, and the \( E_{vd} \) value has a large dispersion, and the correlation is poor.

Three compaction conditions, mild, moderate, and severe, are considered in this paper, and selection of data is shown in Table 3. Figure 6 shows the linear correlation results of the \( E_{vd} \) value and the VCV value. The correlation considering different compaction degrees in the K8 work point is poor, unless the WC 7.

Using the \( E_{vd} \) mean and the VCV mean for analysis, the relationship between the VCV mean and the \( E_{vd} \) mean measured during a certain rolling can be partly reflected to avoid large errors caused by the large dispersion of \( E_{vd} \) values. As shown in Figure 7 and Table 4, the result reveals
Table 2: K8 test condition table.

| Working condition | Thickness (cm) | Machinery (t) | Roller strips | Wheel track number | Measuring points number | Filler |
|-------------------|----------------|---------------|---------------|--------------------|------------------------|--------|
| 1                 | 60             | 26            | 4             | 1                  | 11                     | $A:B = 2:5$ |
| 2                 | 70             | 26            | 6             | 1                  | 10                     | $A:B = 2:5$ |
| 3                 | 70             | 26            | 4             | 1                  | 16                     | $A:B = 2:4$ |
| 4                 | 60             | 26            | 5             | 1                  | 11                     | $A:B = 2:4$ |
| 5                 | 70             | 26            | 4             | 1                  | 11                     | $B$     |
| 6                 | 60             | 26            | 6             | 1                  | 11                     | $B$     |
| 7                 | 60             | 26            | 6             | 1                  | 11                     | $A$     |
| 8                 | 70             | 26            | 5             | 1                  | 11                     | $A$     |

Figure 1: Type A filler and type B filler. The left is type A filler, and the right is type B filler.

Table 1: Liugong CLG6126 roller parameters.

| Parameter                          | Value          |
|------------------------------------|----------------|
| Total static mass (kg)             | 26000          |
| Eccentric force (kN)               | 300/400        |
| Excitation frequency (Hz)          | 28/33          |
| Excitation amplitude (mm)          | 1.95/0.90      |
| Total sizes (length × width × height) (mm) | 6640 × 2360 × 3050 |
Figure 3: Continued.
Figure 3: $E_{nt}$ test results. (a) WC 1; (b) WC 2; (c) WC3; (d) WC 4; (e) WC 5; (f) WC 6; (g) WC 7; (h) WC 8.

Figure 4: Continued.
that the linear correlation between the $E_{vd}$ mean and the VCV mean is poor, when the lift thickness is 70 cm, but the linear correlation coefficient between the $E_{vd}$ mean and the VCV mean is strong when the lift thickness is 60 cm.

3.3. Compaction Quality Inspection Method of Soil-Rock Filled Embankment. Due to various factors such as filler properties, rolling machinery, and technology, the linear correlation between the VCV and the $E_{vd}$ for soil-rock mixed fillers is not generally strong. However, the measured data are insufficient, and its reliability needs further verification. Therefore, the method of using the VCV target value has limitations for the compaction quality detection of the soil-rock filled embankment.

According to the analysis of the continuous compaction test results of the field compaction test, it is found that, overall, the VCV value increases with the increase of the vibration time and finally stabilizes. Therefore, this paper considers the difference between the mean value of VCV from the last two times of rolling and the standard deviation of the VCV value of each measurement point from the last time of rolling to determine whether the compaction quality of the soil-rock filled embankment meets the requirements.

It is shown in Table 5 that the difference between the VCV mean values obtained from the last two roller passes under each working condition does not exceed 5 kN/m; in other words, the relative difference between the VCV mean values obtained from the last two roller passes is less than 1%. And the maximum of the VCV standard deviation from
Figure 5: $E_{vd}$ values and their corresponding VCV values all the measurement points. (a) WC 1; (b) WC 2; (c) WC 3; (d) WC 4; (e) WC 5; (f) WC 6; (g) WC 7; (h) WC 8.
Table 3: Selection of rolling passes among the different compaction degrees.

| Working condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-------------------|---|---|---|---|---|---|---|---|
| Selection of passes | 1/2/4 | 1/3/5 | 1/2/4 | 1/3/4 | 1/2/4 | 1/3/5 | 1/3/5 | 1/3/5 |

Figure 6: Continued.
Figure 6: $E_{vd}$ values and their corresponding VCV values among different compaction degrees. (a) WC 1; (b) WC 2; (c) WC 3; (d) WC 4; (e) WC 5; (f) WC 6; (g) WC 7; (h) WC 8.

Figure 7: Continued.
the last rolling is 3.59 kN/m, which does not exceed 1% of the average VCV, indicating that the rolling uniformity is also good. Therefore, this method can be used to quickly determine whether the compaction quality meets the requirements for the soil-rock mixed filler at the K8 working point.

Since the VCV value measured by continuous compaction does not correlate with the in situ measurement used in the test of the compaction quality of the subgrade, the above-mentioned determination method merely reflects the compaction degree of the subgrade indirectly. From the perspective of ensuring that the detection method is more reliable, the test results of \( E_{pd} \) can be considered to further judge the embankment compaction quality. The \( E_{pd} \) test results of each working condition at the K8 station are analyzed. The analysis results are shown in Table 6.

Generally, in the soil-rock mixed filler, when the number of rolling passes is enough, the hard rock block content is higher, the lift thickness is thinner, and the \( E_{pd} \) value is higher. The maximum standard deviation of the \( E_{pd} \) value of each measurement point after the last rolling is 2.44 MPa, which also indicates that the \( E_{pd} \) value is relatively discrete. Most \( E_{pd} \) are larger than 20 MPa except WC 8, and the range is 20.70 to 27 MPa, which indicates that whether \( E_{pd} \) mean of the last rolling is more than 20 MPa can be the auxiliary evaluation standard.

| Working condition | Linear correlation coefficient | Linear regression equation |
|-------------------|-------------------------------|----------------------------|
| 1                 | 0.733                         | VCV = 5.581 \( E_{pd} + 413.637 \) |
| 2                 | 0.320                         | —                          |
| 3                 | 0.554                         | —                          |
| 4                 | 0.816                         | VCV = 2.151 \( E_{pd} + 478.194 \) |
| 5                 | 0.478                         | —                          |
| 6                 | 0.968                         | VCV = 3.064 \( E_{pd} + 458.956 \) |
| 7                 | 0.816                         | VCV = 2.379 \( E_{pd} + 489.890 \) |
| 8                 | 0.256                         | —                          |

**Figure 7:** \( E_{pd} \) mean and their corresponding VCV mean. (a) WC 1; (b) WC 2; (c) WC 3; (d) WC 4; (e) WC 5; (f) WC 6; (g) WC 7; (h) WC 8.
4. Conclusion

When it is difficult to establish a linear correlation between roller measurement values and in situ measurements due to discrete data, roller measurement values and in situ measurements can be separately analyzed to detect the compaction quality of soil-rock filled embankment. Based on the field compaction test and test of Taihang Expressway K8, this paper proposes a rapid diagnostic method for compaction quality of soil-rock filled embankment based on continuous compaction control technology as follows:

(1) The difference between the average value of VCV measured during the last two passes (\(\Delta \text{VCV} \leq 5 \text{kN/m}\)) and the standard deviation of the value of VCV measured during the last two passes (\(\sigma \text{VCV} \leq 5 \text{kN/m}\)) are used as the main basis of soil-rock filled embankment compaction quality.

(2) Whether the average \(E_{\text{vd}}\) of the last rolling is greater than or equal to 20 MPa is used as the auxiliary evaluation standard for the quality control of the embankment compaction in this site.

**Data Availability**

The test data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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### References

[1] A. O. Ilori, E. E. Okwueze, and V. I. Obianwu, "Evaluating compaction quality using elastic seismic P wave," Journal of Materials in Civil Engineering, vol. 25, no. 6, pp. 693–700, 2013.

[2] K. Wang, M.-j. Zhao, and X. Sun, "Wave-electric field coupling imaging diagnostic method for filled subgrade," Journal of Mountain Science, vol. 14, no. 2, pp. 382–389, 2017.

[3] J.-L. Briaud, Y. Li, and K. Rhee, "BCD: a soil modulus device for compaction control," Journal of Geotechnical and Geoenvironmental Engineering, vol. 132, no. 1, pp. 108–115, 2006.

[4] F. M. Wang, J. W. Wang, Y. S. Wang, and J. Li, "A Study on Controlling the Quality of Filled Soil-Stone Compaction," in Proceedings of the Fifth International Conference on Natural Computation, pp. 400–403, Tianjin, China, August 2009.

[5] J. S. Qian, H. L. Wang, and P. Wang, "Test and control methods for on-site compaction of fine sand subgrade on coastal regions," Springer Geology, pp. 75–78, 2013.

[6] L. Xing, "Technology Research on Detecting the Compaction Quality of Embankment Slope in High-Speed Railway," Railway construction technology, vol. 1, 2016, in Chinese.

[7] J. J. Wang, D. H. Zhong, H. Adeli, D. Wang, and M. H. Liu, Smart Bacteria-Foraging Algorithm-Based Customized Kernel Support Vector Regression and Enhanced Probabilistic Neural Network
Network for Compaction Quality Assessment and Control of Soil-Rock Dam, John Wiley & Sons, Hoboken, NY, USA, 2018.

[8] H. Chennarapu, U. Balunaini, and K. G. Thejesh, “Light weight deflectometer for compaction quality control,” geotechnical characterisation and geoenvironmental engineering,” Lecture Notes in Civil Engineering, vol. 16, pp. 35–47, 2019.

[9] D. Liu, Z. Li, and Z. Lian, “Compaction quality assessment of earth-rock dam materials using roller-integrated compaction monitoring technology,” Automation in Construction, vol. 44, pp. 234–246, 2014.

[10] D. White, M. Thompson, P. Vennapusa, and J. Siekmeyer, “Implementing intelligent compaction specification on Minnesota TH-64: synopsis of measurement values, data management, and geostatistical analysis,” Transport Research Record, vol. 2045, pp. 1–9, 2008.

[11] P. Castaldo, F. Jalayer, and B. Palazzo, “Probabilistic assessment of groundwater leakage in diaphragm wall joints for deep excavations,” Tunnelling and Underground Space Technology, vol. 71, pp. 531–543, 2018.

[12] P. Castaldo and M. De Iuliis, “Effects of deep excavation on seismic vulnerability of existing reinforced concrete framed structures,” Soil Dynamics and Earthquake Engineering, vol. 64, pp. 102–112, 2014.

[13] M. A. Mooney, R. V. Rinehart, N. W. Facas et al., “Intelligent Soil Compaction Systems,” NCHRP Rep. 676, Transportation Research Board of the National Academies, Washington, DC, 2010.

[14] G. Chang, Q. Xu, J. Rutledge et al., “Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials,” FHWA-IF-12-002, Federal Highway Administration, Washington, DC, 2011.

[15] D. J. White, P. K. R. Vennapusa, and H. H. Gieselman, “Field assessment and specification review for roller-integrated compaction monitoring technologies,” Advances in Civil Engineering, vol. 2011, pp. 1–15, 2011.

[16] D. V. Cacciola, C. L. Meehan, and M. Khosravi, An Evaluation of Specification Methodologies for Use with Continuous Compaction Control Equipment, pp. 413–416, GeoCongress ASCE, Reston, VA, 2013.

[17] R. D. Bland, L. B Harden, and M. Z. Lai, “Rapid infusion of sodium bicarbonate and albumin into high-risk premature infants soon after birth: a controlled, prospective trial,” American Journal of Obstetrics and Gynecology, vol. 124, no. 3, pp. 263–267, 1976.

[18] M. Lifang, F. Ying, and L. Minzhi, “Construction Technology and Quality Control Research for Rock Embankment,” in Proceedings of the International Conference on Transportation Engineering, Chengdu, China, July 2007.

[19] J. M. Ling, S. Lin, J. S. Qian et al., “Continuous compaction control technology for granite residual subgrade compaction,” Journal of Materials in Civil Engineering, vol. 30, no. 12, pp. 1–9, Article ID 04018316, 2018.

[20] D. Liu, J. Sun, D. Zhong, and L. Song, “Compaction quality control of earth-rock dam construction using real-time field operation data,” Journal of Construction Engineering and Management, vol. 138, no. 9, pp. 1085–1094, 2012.

[21] G. H. Xu, Dynamic Principle and Engineering Application of Subgrade Continuous Compaction Control, Science Press, Beijing, China, 2016, in Chinese.

[22] Q. Zhang, T. Liu, Z. Zhang, Z. Huangfu, Q. Li, and Z. An, “Compaction quality assessment of rockfill materials using roller-integrated acoustic wave detection technique,” Automation in Construction, vol. 97, pp. 110–121, 2019.

[23] G. H. Xu and K. C. George, “Continuous compaction control—mathematical models and parameter identification”, Information Technology in Geo-engineering, Proceedings of the 3rd International Conference (ICITG), Guimarães, Portugal, pp. 563–584, 2019.

[24] Y. M. Xie and H. Zhang, “Experimental study on intelligent compaction field of soil-rock filled subgrade,” Transportation Science & Technology, vol. 15–182019, in Chinese.

[25] F. Aria, T. Cesar, M. Mehran, R. Sergio, and N. Soheil, “Correlating continuous compaction control measurements to in situ modulus-based testing for quality”, Information Technology in Geo-Engineering, Proceedings of the 3rd International Conference (ICITG), Guimarães, Portugal, pp. 585–595, 2019.

[26] W. Duan, G. Cai, S. Liu, J. Yuan, and A. J. Puppala, “Assessment of ground improvement by vibro-compaction method for liquefiable deposits from in-situ testing data,” International Journal of Civil Engineering, vol. 17, no. 6, pp. 723–735, 2019.

[27] Z. He, J. Zhang, and T. Sun, “Influence of maximum particle diameter on the mechanical behavior of soil-rock mixtures,” Advances in Civil Engineering, vol. 2020, Article ID 8850221, 9 pages, 2021.

[28] M. Livneh, N. Livneh, and E. Elhadad, “Determining a pavement modulus from portable FWD testing,” Geotechnical Testing Journal, vol. 20, no. 4, pp. 373–382, 1997.