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Research Article

Research on Identification Model of Continuous Compaction Based on Energy Dissipation

Longliang Wu,[1,2,3] **Jun Teng**,[1] **Zhenyang Ren**,[2] **Huihuang Jiang**,[3] **and Mingxian Gao**[3]

[1]*School of Civil and Environmental Engineering, Harbin Institute of Technology (Shenzhen), Shenzhen, Guangdong 518055, China*
[2]*Bureau Public Works of Shenzhne Municipality, Shenzhen, Guangdong 518031, China*
[3]*China Academy of Railway Sciences-Research and Design Institute of Shenzhen, Shenzhen, Guangdong 518054, China*

Correspondence should be addressed to Huihuang Jiang; wuaq@hku-szh.org

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A continuous compaction control energy model suitable for contact decoupling between the vibrating wheel and the filling body surface is established through analyzing the energy state of the filling body in the compaction detection stage and calculating nonlinear vibration energy dissipation rate based on the basic principle of continuous compaction control technology and the principle of energy conservation. The significance of the parameters contained in the energy model is analyzed, and the energy index-dissipation measured value (DMV) for evaluating the continuous compaction quality is put forward in combination with engineering practice. The feasibility of DMV is verified, and the applicability of DMV is discussed according to the field test results. The results show that the variation range of the DMV index is about 1.66–2.73 times of the Evd index, the DMV has good repeatability and sensitivity for both coarse-grained and fine-grained filler, and it is less affected by the interference caused by the small fluctuation of mechanical parameters, and has good stability for the local unevenness of filler in horizontal direction. The engineering application shows that the correlation coefficient between energy index DMV and Evd index reach more than 0.87, there is a good correlation between DMV and the conventional quality inspection index Evd, indicating that the energy model is applicable.

1. Introduction

In recent years, a lot of engineering in hydropower and transportation fields are planned, are under construction, and have been built. A high-quality control was required in the filling projects in the engineering [1–5]. At present, the quality control of filling engineering mainly adopts the conventional quality sampling inspection method. However, there are some shortcomings in the conventional method. It is not reasonable to use limited sampling results to evaluate the compaction quality of the whole construction area [6, 7]. Moreover, it is difficult to get results quickly during sample inspection, which causes delays in the construction period. In addition, it belongs to post-event control, which is not conducive to the process management of the owner, supervision and construction contractor [8, 9]. Hence, the conventional method is difficult to meet the needs of the rapid development of filling engineering. Therefore, the continuous compaction control technology, which makes possible the continuity, comprehensiveness and real-time control of the compaction process, has gained more attention in China's filling projects. In this technology, the dynamic response signals of vibration wheels are collected, and the data are calculated and processed through the identification model to obtain the continuous measured value of monitoring indicators in real time, and evaluate the compaction degree of the filling body according to the measured value [10]. The essence of continuous compaction control technology is the issue of system identification, and a reliable identification model is important for the applicability of this technology [11–14].

The existing continuous compaction identification models mainly include harmonic ratio model and vibration mechanics model [12, 13]. Harmonic ratio model is an early empirical model of continuous compaction control technology, which indirectly estimates the compaction degree of filling body according to the frequency spectrum change of response signal. Vibration mechanics model is a mechanical model of roller vibrating and rolling filling body based on the classical mechanics principle. Through the vibration mechanics model, the force and displacement of particles in the vibration process can be solved, and then the physical and mechanical parameters of the filling body can be deduced. Although it has a good theoretical basis, the vibration mechanics model involves the value of a lag angle when solving the model, and it is difficult to determine the lag angle in real time in engineering practice. In addition, the existing identification models are not suitable for the work condition of contact decoupling between the vibrating wheel and the surface of the filling body [13, 14]. Most of the current technical regulations of continuous compaction control put forward the requirement ensuring that there is no vibratory roller "jumping vibration" in the continuous rolling test. In reality, with the compaction of the filling body gradually, the vibration jump phenomenon will occur during the rolling process (i.e., contact decoupling work condition), and the probability of this contact decoupling phenomenon occurring in daily construction exceeds 50% [11]. Van Susante [11] and Mooney [15] reported that contact decoupling was the main cause of nonlinear vibration and the key factor affecting the reliability of continuous compaction control technology. The shortcomings of the existing identification models limit the development and application of continuous compaction control technology to a great extent. Therefore, it has great theoretical and practical significance to explore a new recognition model and put forward control indexes suitable for different working conditions.

2. Basic Theory of Energy Model

Researches have shown that water content has a great influence on the mechanical properties of filler (especially for fine-grained filler), but little effect on energy absorption [16, 17]. At the same time, it is considered that the filling body and rolling machinery can not only establish the connection through the whole energy conservation, but also carry out independent energy calculation according to their respective vibration states, which makes it possible to solve the contact decoupling situation. Therefore, this paper establishes a continuous compaction control identification model suitable for contact decoupling from the energy point of view. In reality, it can be considered that the vibratory roller is a dynamic equilibrium process of energy distribution and dissipation. The energy generated by the internal combustion engine is absorbed and consumed by the dam of the filling body and the machinery itself, and the law of conservation of energy is observed. Under the condition that the total energy W_1 is known, the energy dissipated W_2 by the machinery is calculated by measuring the vibration signal in real time, and then the energy state W_3 of the filling body is indirectly determined according to the principle of energy conservation. Finally, the physical and mechanical parameters of the filling body are deduced from the energy state, thus realizing continuous vibration monitoring. The energy model is schematically shown in Figure 1.

2.1. Vibration Compaction Mechanism Based on Energy Principle. The process of vibratory compaction of filling body is a process of energy transfer and dynamic distribution. At the initial stage of rolling, the filler is relatively loose, and the filling body is allocated with more energy for plastic deformation, crushing particles (for coarse-grained filler) and friction loss. At this time, the elastic modulus of the filling body is relatively small, the damping of the filler is relatively large, and the energy of friction loss is relatively large. According to the theory of vibration mechanics, there is a positive correlation between the response acceleration and the intensity of mechanical energy dissipation [18]. Therefore, at the initial stage of rolling, the energy of the system is dissipated mainly by the filling body, and the vibration system distributes less energy to the machinery for dissipation, so the response acceleration of the vibration wheel is relatively small. With the increase of rolling times, the packing is gradually compacted. The amount of plastic deformation and particle crushing caused by vibration rolling will decrease and gradually approach to zero. At this time, the energy consumption of plastic deformation and particle crushing is very small, and the energy is lost mainly by particle friction. At the same time, the elastic modulus of the filling body gradually increases, and the damping gradually decreases, and the energy of friction loss also decreases. On the whole, the dissipated energy allocated to the filling body decreases, while the dissipated energy allocated to the machinery gradually increases, so the response acceleration of the vibrating wheel presents an increasing trend. When the filling body is compacted tightly, the elastic modulus of the filling body is further increased, the damping is further reduced, and the energy that can be lost by particle friction reaches the minimum value. At this time, the energy allocated to the filling body reaches the lowest value, while the energy allocated to the mechanical loss reaches the maximum value, and the response acceleration of the vibrating wheel further increases. When the maximum response acceleration that can be achieved when the vibrating wheel is in close contact with the filling body still does not meet the requirement of large mechanical energy loss, the vibrating wheel will produce decoupling contact with the filling body (that is, "jumping vibration" phenomenon). At this time, the mechanical vibration frequency will be greater than that of the filling body, that is, the ratio of viscous cycles between the machinery and the filling body will increase in unit time, and the machinery will produce more friction cycles and larger acceleration amplitude to consume more energy, thus making the energy distribution reach a new balance.

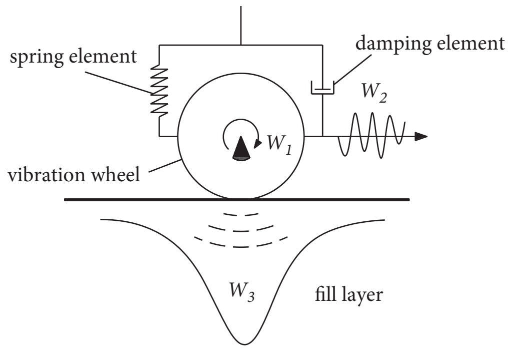

Figure 1: Schematic diagram of energy model of vibration system.

2.2. Energy State of System. To simplify the calculation and facilitate the application, the following assumptions are made:

(1) The filling body has only slight elastic deformation in the vibration monitoring stage, and the soil can be simulated by Kelvin model [10]. At this time, the energy consumption inside the filling body is mainly material friction energy consumption, and the energy consumption of particle crushing and plastic deformation of the filler is not considered.

(2) At the instant of vibration detection, the system is in a stable vibration state. That is to say, in a period of energy calculation, the distribution of energy field in the filling body is stable and satisfies Poisson equation.

(3) The packing is uniform and isotropic, and the rolling parameters remain relatively unchanged during continuous compaction monitoring.

2.2.1. Total Energy of Vibration System W_1. In the process of vibratory rolling, the vibratory roller and the filling body are regarded as an energy conservation system, and the total energy of the vibratory system is generated by the work done by the internal combustion engine. According to the theory of vibration mechanics, only the exciting force component have $\pi/2$ phase difference with the displacement can do work for the system. Therefore, the total work W_1 done by the internal combustion engine in unit time is [18].

$$W_1 = \frac{1}{2}\omega B P_0 \sin \varphi, \tag{1}$$

$$B = \frac{me}{M}\frac{\lambda^2}{\sqrt{\left(1-\lambda^2\right)^2 + (2\xi\lambda)^2}}, \tag{2}$$

$$\phi = tg^{-1}\frac{2\xi\lambda}{1-\lambda^2}, \tag{3}$$

$$P_0 = me\omega^2. \tag{4}$$

where P_0 is the amplitude of exciting force; B is the displacement amplitude; ω is the circular frequency; φ is the lag angle; M is the mass of the excitation system; m is the mass of eccentric block; e is the eccentric moment; ξ is the damping ratio of the excitation system; λ is the frequency ratio of the excitation system.

2.2.2. Energy Dissipated by Mechanical Nonlinear Vibration W_2. The energy dissipated by the machinery itself is equal to the sum of the frame damping and the energy dissipated by the damping block at the joint between the vibrating wheel and the frame. According to the research in references [11, 15], in the vibration compaction process, the vibration of the frame is approximately harmonic vibration, and the effective value of the frame vibration amplitude is about 1/20–1/10 of the vibration wheel. Therefore, it can be considered that the energy dissipated by the machinery itself is mainly consumed by the damping block. Due to the contact decoupling between the vibrating wheel and the filling body, the vibrating wheel usually vibrates nonlinearly. Therefore, this thesis presents an energy calculation formula for nonlinear vibration signals.

According to Parseval theorem [19], the energy (power) contained in a signal is always equal to the sum of the energy (power) of each component of the signal in the complete orthogonal function set. It shows that the total energy of signal in time domain is equal to the total energy of signal in frequency domain, that is, the total energy of signal remains unchanged after Fourier transform, which accords with the law of conservation of energy [19]. Therefore, the energy dissipated by nonlinear vibration per unit volume in unit time is equal to the sum of the energy dissipated by infinite simple harmonic vibrations in its frequency domain. According to the calculation formula of energy dissipation rate of simple harmonic vibration proposed in reference [18], the energy dissipation rate D of nonlinear vibration with acceleration as variable can be deduced, as shown in equation (5).

$$D = \pi c \int_0^{+\infty} \frac{A_{\overline{\omega}}^2}{\overline{\omega}^3}\,\mathrm{d}\overline{\omega}, \tag{5}$$

where D is the energy dissipation rate of nonlinear vibration signal; c is damping; $\overline{\omega}$ is the circular frequency; $A_{\overline{\omega}}$ is the acceleration amplitude corresponding to the circular frequency $\overline{\omega}$ in frequency domain.

Therefore, the energy dissipated by mechanical nonlinear vibration per unit time is

$$W_2 = V_0 c_0 \pi \int_0^{+\infty} \frac{A_{\omega}^2}{\overline{\omega}^3}\,\mathrm{d}\overline{\omega}, \tag{6}$$

where V_0 is the equivalent volume of machinery, which can be replaced by the volume of damping block; As the equivalent damping of machinery c_0, it can be replaced by damping block.

2.2.3. Energy Dissipated by Filling Body W_3. Under the condition of meeting the basic assumptions of the energy model, the energy consumption intensity inside the filling body can be simplified as the viscous energy consumption intensity of Kelvin model, as shown in equation (7) [20].

$$D_s = \frac{\sigma_s^2}{2} \cdot \frac{\eta {\omega_s}^2}{E^2 + \eta^2 {\omega_s}^2}, \tag{7}$$

where, σ_s is the stress amplitude; ω_0 is the vibration angular velocity of the filling body; E is the composite elastic modulus of the filling body; η is the composite viscosity coefficient of the filling body.

Therefore, the energy dissipated by the filling body in unit time is

$$W_3 = \frac{\sigma_s^2}{2} \cdot \frac{\eta {\omega_s}^2}{E^2 + \eta^2 {\omega_s}^2} \cdot V_s, \tag{8}$$

where V_s is the filling body volume participating in vibration.

2.3. Energy Model and Its Index. According to the law of conservation of energy,

$$W_1 = W_2 + W_3. \tag{9}$$

The energy model of continuous compaction control can be obtained from equations (1), (6), (8), and (9):

$$\pi \int_0^{+\infty} \frac{{A_{\overline{\omega}}}^2}{\overline{\omega}^3} \mathrm{d}\overline{\omega} = \frac{W_1}{V_0 c_0} - \frac{\eta V_s \sigma_s^2 {\omega_s}^2}{2 V_0 c_0 \left(E^2 + \eta^2 {\omega_s}^2\right)}. \tag{10}$$

Therefore, an index—Dissipation Measured Value (DMV) related to energy consumption of machinery can be defined, as shown in equation (11), and this index can be used as the energy index of continuous compaction control.

$$\mathrm{DMV} = \kappa^3 \pi \int_0^{+\infty} \frac{{A_{\overline{\omega}}}^2}{\overline{\omega}^3} \mathrm{d}\overline{\omega}. \tag{11}$$

In equation (11), κ represents the circular frequency of the fundamental frequency. The index DMV indicates the energy dissipated by unit volume and unit damping in unit time, which can represent the intensity of energy dissipated by vibratory roller itself. When DMV is larger, it indicates that the intensity of mechanical energy consumption is greater, otherwise, it indicates that the intensity of mechanical energy consumption is smaller.

According to the basic assumption of energy model, rolling parameters including mechanical parameters remain unchanged during vibration monitoring. At the same time, according to the existing research experience [21–24], the compaction degree and water content have little influence on soil viscosity coefficient but significant influence on the soil elastic modulus. Therefore, with the increase of rolling times, the elastic modulus E of the filling body will change to some extent, while other parameters remain relatively constant and can be approximated as constants. Therefore, a simplified form of the energy model can be obtained according to equation (12).

$$\mathrm{DMV} = a - \frac{b}{E^2 + c}, \tag{12}$$

where E is the composite elastic modulus of the filling body, and the dynamic deformation modulus E_{vd} is used to replace it in engineering application; a is defined as the total energy coefficient, which can be determined according to the ratio of the total energy of the vibration system to the damping and volume of the damping block, and represents the intensity of the total energy of the vibration system took damping block as the measurement standard; b is the energy consumption coefficient of filling body, which is directly proportional to the filling body volume participating in vibration, viscosity coefficient, square of exciting force and square of circular frequency of filling body, and inversely proportional to the damping and volume of damping block, representing the intensity of energy consumption of filling body with damping block as the measurement standard; The adjustment coefficient c is proportional to the square of the vibration circle frequency of the filling body and the square of the viscosity coefficient. The three coefficients a, b and c can be determined by fitting through field test.

In practical engineering, the plastic deformation caused by weak vibration rolling on the basis of strong vibration rolling is relatively small. Therefore, it is possible to carry out preliminary strong vibration rolling on the filling body, and then use the measured value of weak vibration rolling as the evaluation basis of continuous compaction monitoring, so as to approximately meet the requirements of hypothesis (1). In fact, the above measures are consistent with the rolling process of “first strong then weak”. The vibration frequency of vibratory roller is usually 10–30 Hz, and the working period of exciting force is very short, about 0.03–0.1 s. Therefore, the energy distribution of the vibration system can be regarded as stable when the exciting force works. At this time, the calculation period of the energy model adopts the working period of the exciting force, and the output result per unit time adopts the average value of each calculation period, thus better meeting the requirements of the hypothesis (2). Different types of filler with different water content and thickness and different types of rolling machines are divided into different continuous compaction control units, so as to ensure that the filler characteristic parameters and rolling parameters remain unchanged when the same continuous compaction evaluation standard is adopted, thus approaching the requirements of hypothesis (3). Through the above methods and measures, the practical application of energy model and its indexes can be promoted.

3. Test and Engineering Verification

Good repeatability, sensitivity and stability of vibration monitoring index are the basic conditions for introducing this index into engineering application. Whether there is a good correlation between vibration monitoring index and conventional index affects the applicability of this index. According to the current regulations of continuous compaction control technology [25–27], continuous compaction control technology can only be applied when the correlation coefficient between vibration monitoring index and conventional quality inspection index is no less than 0.7. Therefore, the correlation between vibration monitoring index and conventional quality inspection index affects the applicability of the index and its model. In order to study the applicability of the energy model and its indicators, different field rolling tests were carried out, and the repeatability and sensitivity of the indicators for coarse and fine filler and the stability under different rolling parameters and local uneven filler were studied. The correlation between the indicators DMV and conventional quality inspection indicators E_{vd} was analyzed through preliminary engineering application. In the field test and engineering application, the SRM type roller produced by Wanbang Heavy Industry Co., Ltd. is used, which has a working quality of 22 t, an exciting frequency of 30 Hz and an exciting force of 340/220 KN. On the vibratory roller, the DCA type compaction analyzer produced by Dynapac Company and the continuous compaction control equipment produced by Guangzhou HI TARGET are installed at the same time, which are used to collect Compacted Measured Value (CMV) and Vibration Compaction Value (VCV) index respectively. At the same time, INV9823 type vertical acceleration sensor is installed on the vibrating wheel, and INV3062C type acquisition instrument is used to collect the response acceleration data in real time. The fast Fourier transform is carried out on the collected acceleration data by the CCC V1.0 calculation and analysis program independently developed by the research group, and the indexes DMV are obtained in real time according to equation (11). The collected data of various indexes, such as measured value, vibration acceleration, frequency and position coordinates, are uploaded to the remote control platform through 4G networks for subsequent analysis. The coarse-grained and fine-grained fillers tested in the field are common breccia soil and granite residual soil in Shenzhen. Among them, the inhomogeneity coefficient, curvature coefficient and maximum dry density of coarse-grained filler obtained by geotechnical test are 6.4, 1.83 and 2.03, respectively. The fine content of the fine filler is 64.5%. The natural and optimum water contents is 29.8% and 12.5%, respectively. The plasticity index is 31.6. The maximum dry density is $1.94\,\mathrm{g/cm^3}$. During the test, the measured value CMV obtained by different computing systems are compared and checked, and the data with the deviation between the measured value not more than 10% is used for subsequent analysis. The test equipment and calculation program are shown in Figures 2 and 3.

3.1. Repeatability of DMV Indicators. Set a test strip with a length of 25 m and a width of 2 m in the rolling area of coarse and fine filler respectively. The virtual paving thickness of both coarse and fine-grained filler is 30 cm, the test driving speed is about 1.5 km/h, and the test adopts forward driving and weak vibration rolling. The repeatability test results are shown in Figures 4 and 5. In Figures 4 and 5, μ_{a-b} refers to the difference between the vibration measurement value of the a-th pass and b-th pass. In order to evaluate the fluctuation level between measured value conveniently, the difference coefficient δ shown in equation (13) is introduced to characterize the fluctuation degree of the difference between measured value relative to the overall level, and the larger the difference coefficient δ, the more significant the difference between the two values relative to the whole.

$$\delta = \frac{\sigma}{\mu}, \tag{13}$$

where, σ is the standard deviation of the difference between measured value; μ is the average of the overall measured value of the two.

It can be seen from Figures 4(a) and 5(a) that the measured curve moves up and tends to be stable gradually with the increase of rolling times. The measured value of the 7th and 8th passes of rolling fine filler are very close, and the measured value of the 5th and 6th passes of rolling coarse-grained filler are basically the same. Intuitively, it shows that under the condition of sufficient rolling, the index DMV has good repeatability for both coarse and fine filler. It can be seen from Figure 4(b) that the measured value of rolling fine filler in the third pass increase by about $110\,\mathrm{km^{-1}s^{-1}}$on average compared with that in the second pass, while that in the eighth pass only increase by $8\,\mathrm{km^{-1}s^{-1}}$on average compared with that in the seventh pass. It shows that the index DMV increases rapidly in the initial stage of insufficient rolling and slowly in the later stage of relatively sufficient rolling. According to the analysis, with the increase of rolling times, the filling body is gradually compacted tightly, and the energy required by the filling body gradually reduced and tends to be stable. According to the principle of total energy conservation, under the condition of constant rolling parameters, the index DMV that can characterize the mechanical energy consumption intensity will increase and gradually stabilize. The coefficient of difference between the 3rd and 2nd rolling passes is 0.254, and the coefficient of difference between the 8th and 7th rolling passes is 0.046, which indicates that when the rolling is more sufficient, the fluctuation level of the measured value is smaller and the repeatability of the DMV is better. A similar conclusion can be obtained by analyzing the results of Figure 5(b). The results in Figures 4 and 5 show that the index has good repeatability for both coarse and fine-grained fillers.

3.2. Sensitivity of DMV Indicators. In order to study the sensitivity of DMV indexes, the measured value and conventional quality inspection results of different types of road rollers are counted when rolling different types of filler. Among them, the 1#, 2# and 3# road rollers are SRM type road rollers produced by Wanbang Heavy Industry Co., Ltd., and the mechanical parameters of this type of road rollers are as mentioned above. 4# and 5# SSR type road rollers are produced by Sany Heavy Industry. KNF or the convenience of statistics, silt, silty clay and clay in newly added filler are grouped into fine-grained filler 1, 2 and 3 in turn, and coarse sand, crushed stone soil and crushed stone are grouped into coarse-grained filler 1, 2 and 3. The length of rolling sections used as statistical samples shall not be less than 50 m, and the rolling parameters of the same rolling section shall remain unchanged. More than 5 measuring points of every rolling pass shall be uniformly selected for E_{vd} detection. With the DMV average value and E_{vd} average value of each rolling pass as statistical data, the normalized DMV and E_{vd} is analyzed by linear fitting, and the results are shown in Figure 6.

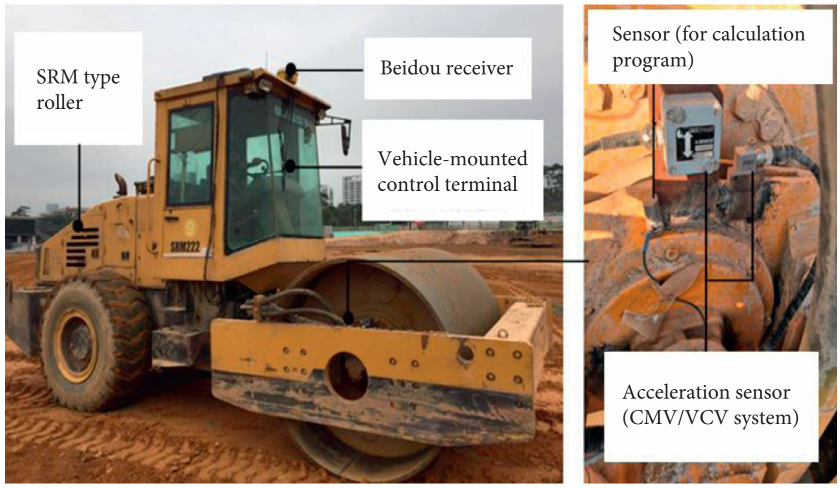

FIGURE 2: Field test equipment.

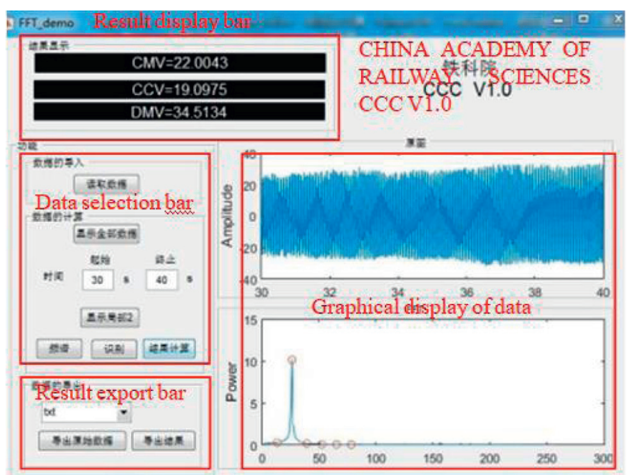

FIGURE 3: Interface of calculation program.

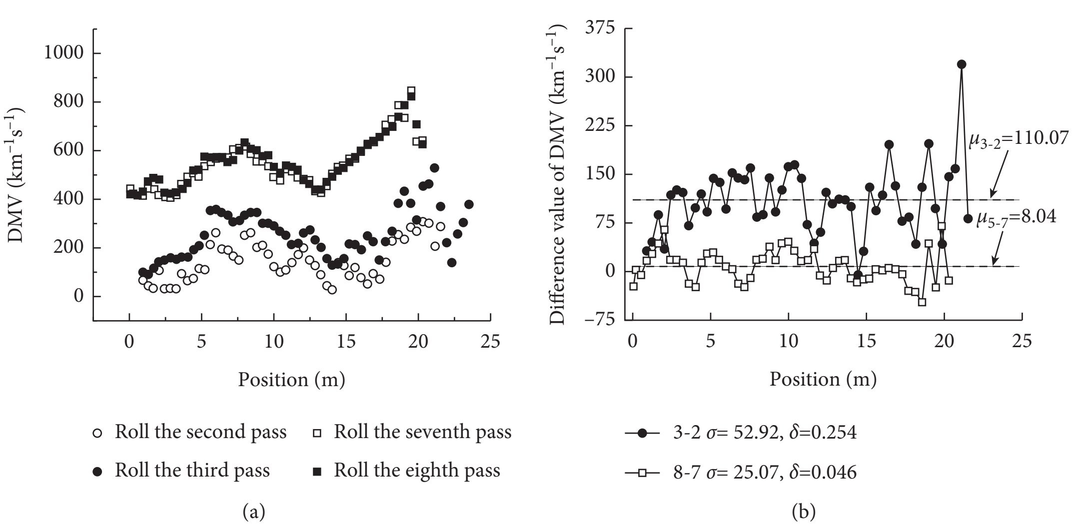

FIGURE 4: DMV of fine-grained filler. (a) Measured value of different times (b) Difference of measured value.

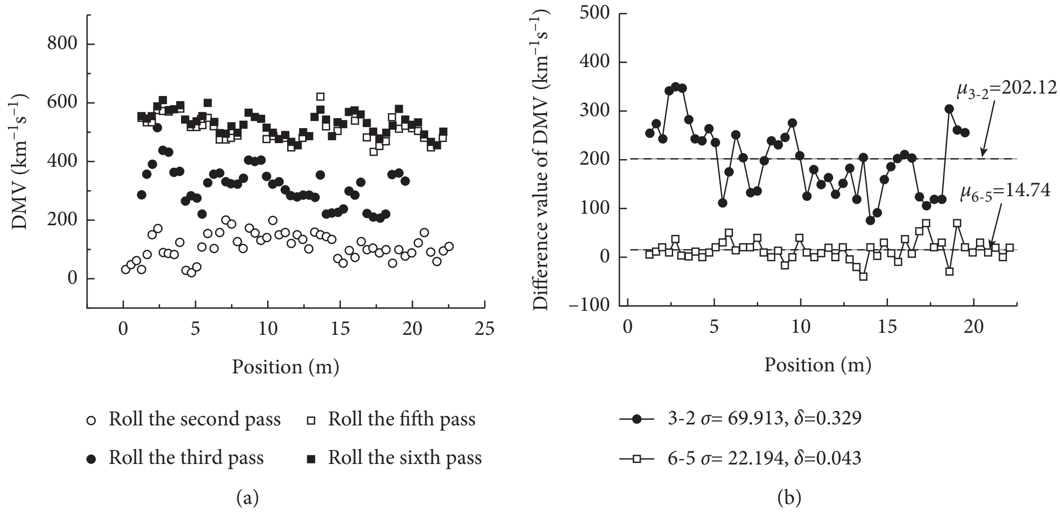

FIGURE 5: DMV of coarse-grained filler. (a) Measured value of different times (b) Difference of measured value.

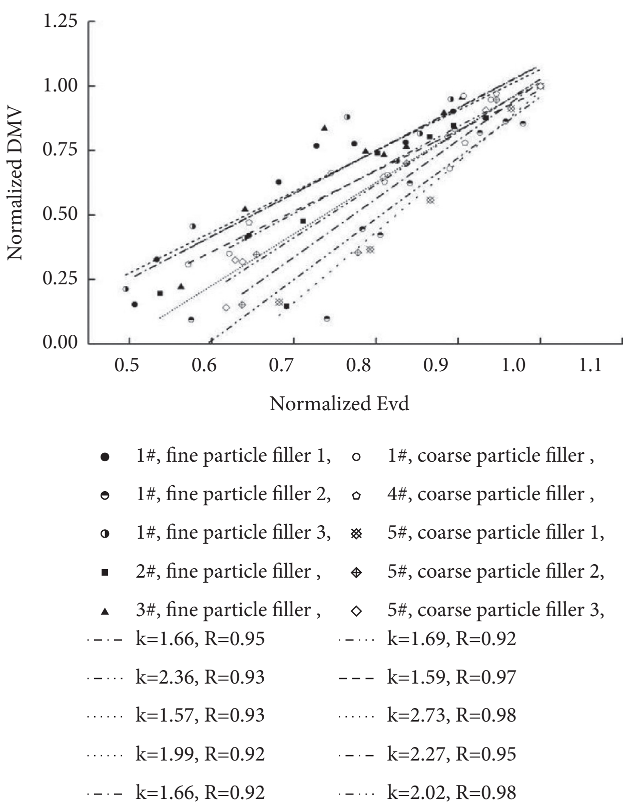

FIGURE 6: Sensitivity analysis results of normalized DMV and E_{vd}.

It can be seen from Figure 6 that the correlation coefficients between the normalized average DMV and the normalized average E_{vd} are both greater than 0.9, indicating that they have strong correlation. As a whole, the DMV index increases with the increase of the E_{vd} index. Moreover, the slope range of the fitted straight line is 1.66–2.73, that is, when the E_{vd} index changes by 1%, it will cause the DMV index to change by 1.66%–2.73% (>1%), which indicates that the DMV index is sensitive to the E_{vd} index.

3.3. Stability of DMV Indicators

3.3.1. Influence of Rolling Parameters on Stability of DMV Indicators. Engineering experience shows that, rolling parameters have a significant impact on continuous compaction monitoring indicators [10, 28–30]. Because the driving speed in reality is greatly influenced by human factors, there is a certain fluctuation in the vibration frequency and exciting force affected by the machinery self-performance and actual use conditions. Therefore, this thesis focuses on the stability of DMV indexes under different driving speeds and exciting forces. The length of the test section is 25 m, and the filler is fine-grained filler. Before the start of the test, the filler has been fully rolled, and the combined rolling process of strong/weak vibration and fast/slow speed is adopted for the test. Rolling parameter combinations are shown in Table 1, and test results under different rolling parameter combinations are shown in Figure 7. Considering that the uploading frequency of measured DMV value is once/second, the effective distance of monitoring will vary with different driving speeds. In order to compare the changes of measured value at different driving speeds, every 1 m in the wheel width range is divided into a monitoring unit, and the average measured value in the monitoring unit are taken as the analysis data in Figure 7(b).

It can be seen from Figure 7(a) that the measured DMV value is smaller when rolling with weak vibration and larger when rolling with strong vibration. It can be seen from Figure 7(b) that the average value of the difference between working conditions 1 and 3 and the difference between working conditions 2 and 4 is relatively small, indicating that different driving speeds have less influence on the measured value when the excitation force is the same. The average value of the difference between working conditions 2 and 1 and the difference between working conditions 4 and 3 is relatively large, which indicates that different exciting forces have great influence on the measured value at the same driving speed. The average value of the

Table 1: Rolling process parameters.

Work condition	Design rolling process		Measured rolling parameter range	
	Exciting force	Speed (km/h)	Acceleration (g)	Speed (km/h)
1	Weak vibration	1.5 (slow)	1.4–2.0	1.52–1.82
2	Strong vibration	1.5 (slow)	2.3–2.9	1.42–1.79
3	Weak vibration	3.0 (fast)	1.5–1.9	2.67–2.91
4	Strong vibration	3.0 (fast)	2.4–2.9	2.52–2.83

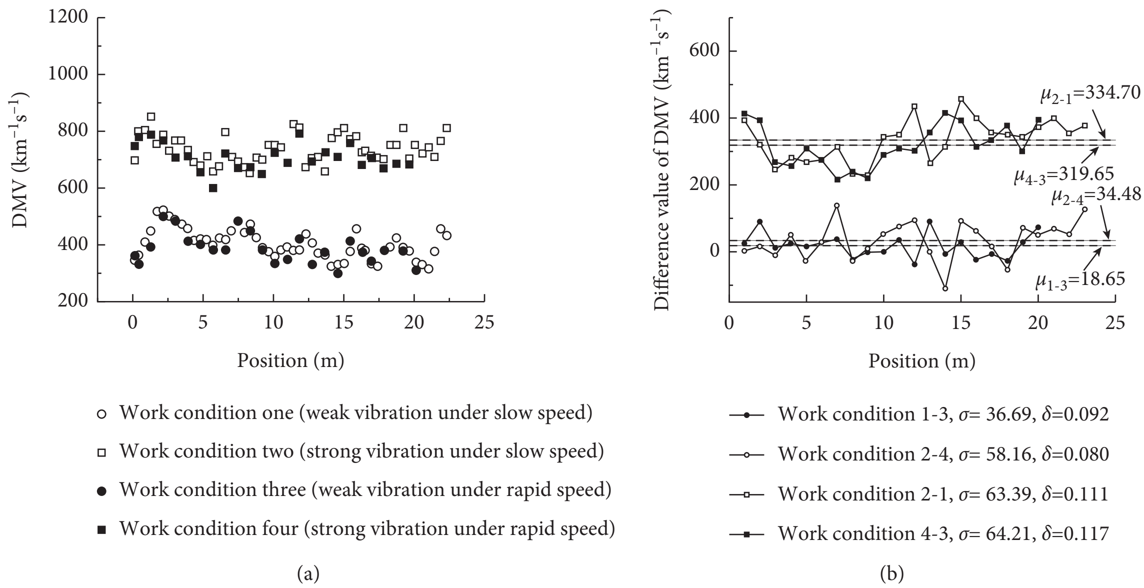

Figure 7: Influence of rolling parameters on stability of DMV indicators. (a) Measured value of different rolling processes. (b) Measured value difference.

differences between working conditions 1 and 3 and working conditions 2 and 4 are greater than zero, which indicates that the slower the driving speed is when the excitation force is constant, the larger the overall measured DMV value is. The average value of the differences between working conditions 2 and 1 and working conditions 4 and 3 are greater than zero, which indicates that the larger the excitation force is at a certain driving speed, the larger the measured DMV value is. By analyzing the difference coefficients, it can be seen that the difference coefficients of different exciting forces are larger than those of different speeds, which indicates that the exciting forces have a greater influence on stability, while the driving speed has a smaller influence on stability. On the whole, the difference coefficient between different working condition combinations is less than 0.12, which indicates that the DMV index has good stability to different driving speeds and exciting forces.

3.3.2. Influence of Local Unevenness of Filler on Stability of DMV Indicators. In reality, the filler often has local nonuniformity, for example, a small amount of crushed stones and pebbles are unevenly mixed in the fine-grained filler. If the continuous compaction monitoring index is too sensitive to the local unevenness of filler, it will be easily interfered by local factors and the whole real compaction degree cannot be accurately identified, which will easily lead to wrong evaluation of the quality of filling body. Therefore, it is necessary to test the stability of continuous monitoring index to local nonuniformity of filler. In this thesis, a test section with a length of 70 m is randomly set in the fully rolled coarse-grained and fine-grained filler rolling areas, and acceleration sensors are installed on both sides of the vibratory wheel of the road roller, and the measured value on the left and right sides of the vibratory wheel are compared to evaluate its stability. Weak vibration rolling is adopted in the test, and the driving speed is about 2 km/s. The test results are shown in Figure 8.

It can be seen from Figure 8 that the measured DMV value on the left and right sides of the vibrating wheel are in good agreement, and there are some deviations in the measured CMV value at local positions. When rolling coarse-grained and fine-grained filler, the difference coefficients of measured DMV value are 0.053 and 0.057, respectively, and the difference coefficients of measured CMV value are 0.364 and 0.344, respectively. The difference coefficients of the measured DMV value are all less than that of CMV, which indicates that the fluctuation of the measured DMV value on the left and right sides of the vibrating wheel is relatively smaller than those of CMV, and the measured DMV value have better stability to the local unevenness of

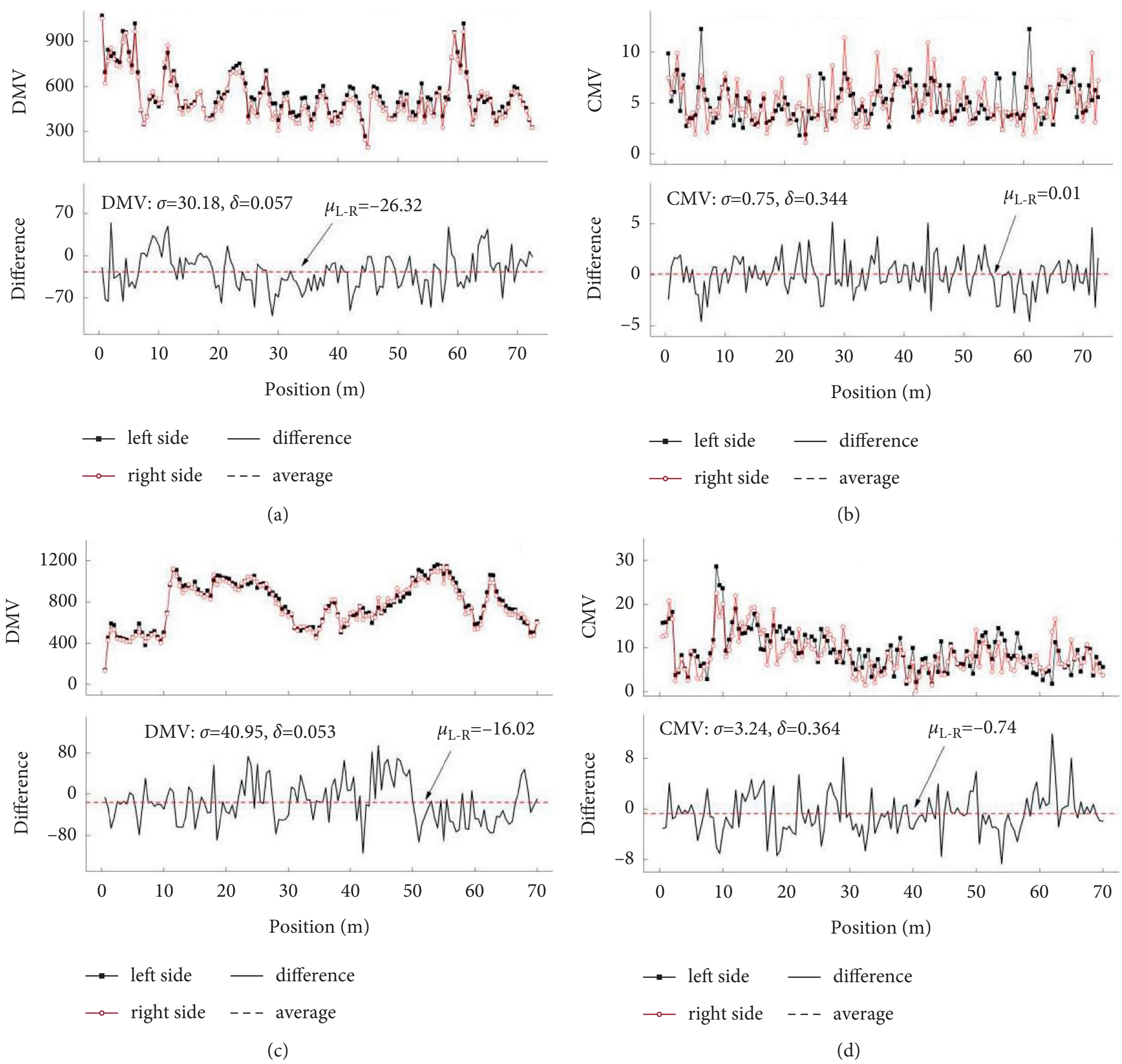

Figure 8: Influence of local unevenness of filler on stability of indicators (corresponding difference between left and right sides). (a) Fine-grained filler (DMV). (b) Fine-grained filler (CMV). (c) Coarse-grained filler (DMV). (d) Coarse-grained filler (CMV).

the filler. In reality, the local nonuniformity of filler has a great influence on the waveform change of the response signal, but has a relatively limited influence on the energy absorption of the filling body. According to the basic principle of each index, CMV characterizes the distortion degree of vibration signal, DMV can indirectly reflect the energy state of the filling body. Therefore, the local unevenness of filler has less influence on the DMV index, and the DMV index has better stability than the CMV index. According to references [10, 21], the CMV indexes are sensitive to the characteristics of local filler. Inconsistent measured CMV value on both sides of the vibrating wheel can indicate that the filler in the wheel width range is uneven at this position. It can be inferred that the measured value of the DMV indicators on the left and right sides of the local uneven area of the filler did not fluctuate greatly, showing good stability.

3.4. Engineering Application Verification of Energy Model. In order to test the applicability of the energy model, the field calibration test was carried out according to the Chinese continuous compaction control code [26, 27], and the preliminary engineering application of the energy model and DMV indicators was verified. Four test sections with a length of 100 m and a width of 2 m are respectively set in the rolling area of coarse-grained and fine-grained filler, and each test section is tested according to the principle of mild, moderate and severe rolling. Static rolling one time before the test, then rolling with strong vibration for n times, and finally rolling with weak vibration for one time. The measured value of weak vibration rolling is taken as the analysis data of continuous compaction control. During the field test, light and heavy dynamic penetration tests were carried out for coarse-grained and fine-grained filler, and the dynamic penetration test index (DPI) as shown in Figure 9 was

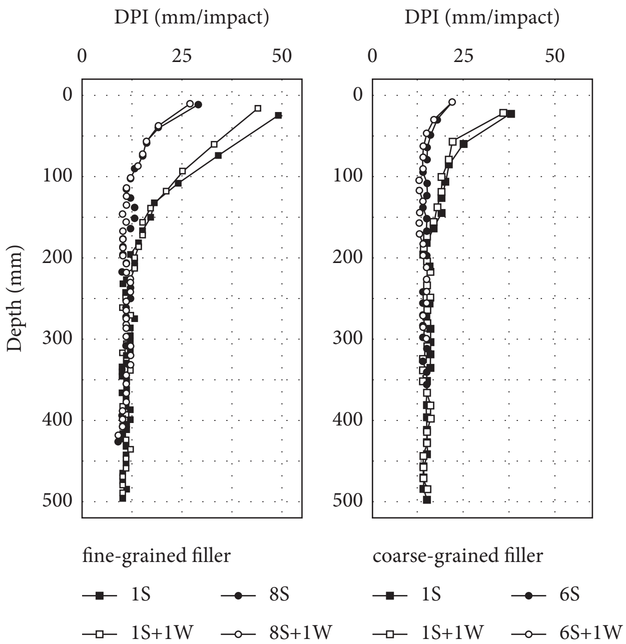

Figure 9: Dynamic sounding results.

obtained. According to the results of dynamic sounding test, the elastic-plastic deformation of the filling body is judged, so as to ensure that the application conditions of the energy model are met. After the rolling measurement is collected, the E_{vd} indicators are randomly sampled on each test strip by using a light weight drop meter, and the sampling quantity meets the requirements of the specification of not less than 18 sampling points. According to the test results, the correlation analysis of vibration monitoring indicators and E_{vd} indicators is carried out, and the results are shown in Figure 10.

It can be seen from Figure 9 that the DPI reduction of fine-grained filler after rolling for 8 times is obvious compared with that after rolling for 1 time. According to the analysis, with the increase of rolling times, the filler particles rearrange and thus produce certain plastic deformation, and the filling body becomes more and more dense, so the penetration sounding rod becomes more and more difficult to drill and DPI will decrease accordingly. Similar conclusions can be obtained by analyzing the test results of coarse-grained filler. Rolling with weak vibration is carried out on the basis of rolling with strong vibration one time. DPI slightly reduced, which indicates that only a small amount of plastic deformation is produced by weak vibration rolling. The DPI change of fine-grained filler near the rolling surface is relatively obvious. It is preliminarily judged that the surface of fine filler is loose due to severe vibration caused by strong vibration rolling, and the subsequent weak vibration rolling has a good compaction and tightening effect on the rolling surface. Rolling with weak vibration on the basis of strong vibration rolling for 6 times and 8 times for coarse-grained and fine-grained filler respectively, DPI basically did not change, which shows that the plastic deformation is hardly produced by weak vibration rolling at this time. Generally speaking, the assumption of elastic deformation of energy model can be basically satisfied by carrying out weak vibration rolling on the basis of strong vibration rolling and using the measured value of weak vibration rolling as analysis data. It can be seen from Figure 10 that the correlation coefficients obtained from correlation analysis of coarse-grained and fine-grained filler by using the energy model in this paper are 0.87 and 0.88, respectively, which meet the application standard that the correlation coefficient is no less than 0.7 stipulated by the current regulations in China. It shows that there is a good correspondence between the indexes DMV and E_{vd}, the accuracy of the energy model meets the requirements of engineering application, and the energy model has good applicability for both coarse-grained and fine-grained filler.

According to the field calibration test, the control value of energy index DMV can be determined: for fine-grained filler, $\mathrm{DMV} = 681.9\,\mathrm{km}^{-1}\mathrm{s}^{-1}$; For coarse-grained filler, $\mathrm{DMV} = 1045.5\,\mathrm{km}^{-1}\mathrm{s}^{-1}$. When the measured value is less than the control value, it indicates that the rolling quality is unqualified. When the measured value is greater than the control value, it indicates that the rolling quality is qualified. With reference to code requirements and application experience, when continuous compaction control is carried out by using energy model, the acceptance standard is that the pass rate of the whole rolled surface is no less than 95%, and the compaction uniformity and stability are evaluated according to the current code. At present, the accumulated rolling area of continuous compaction control in zone 2–1 of Section 2 of T4 Terminal Area Extension Project of Shenzhen Airport by using the energy model in this thesis is about 600,000 m^2. The qualified areas evaluated based on the energy model meet the acceptance requirements through routine inspection and recheck, and good engineering application results have been achieved by using the energy model.

4. Discussion

The energy model can calculate the vibration system, the frame damping and the filling body separately to obtain their respective energy state levels, and then establish the relationship among the three energy states according to the principle of energy conservation, thus theoretically solving the problem of contact decoupling between the vibrating wheel and the filling body. At the same time, the energy model does not need to determine the absolute value of the lag angle, which is more applicable than the mechanical model. The field test shows that the DMV index based on energy principle has good repeatability, sensitivity and stability, and it is feasible to use the DMV index as the continuous compaction control index. Correlation analysis based on energy model shows that there is a strong correlation between the energy indexes DMV and E_{vd} indexes of coarse and fine filler, which meets the application requirements of current codes. To sum up, the energy model and its indicators have been preliminarily verified to have good applicability. However, whether the energy model can be successfully applied and popularized in engineering still needs further in-depth study and discussion. The next research work of energy model is mainly as follows:

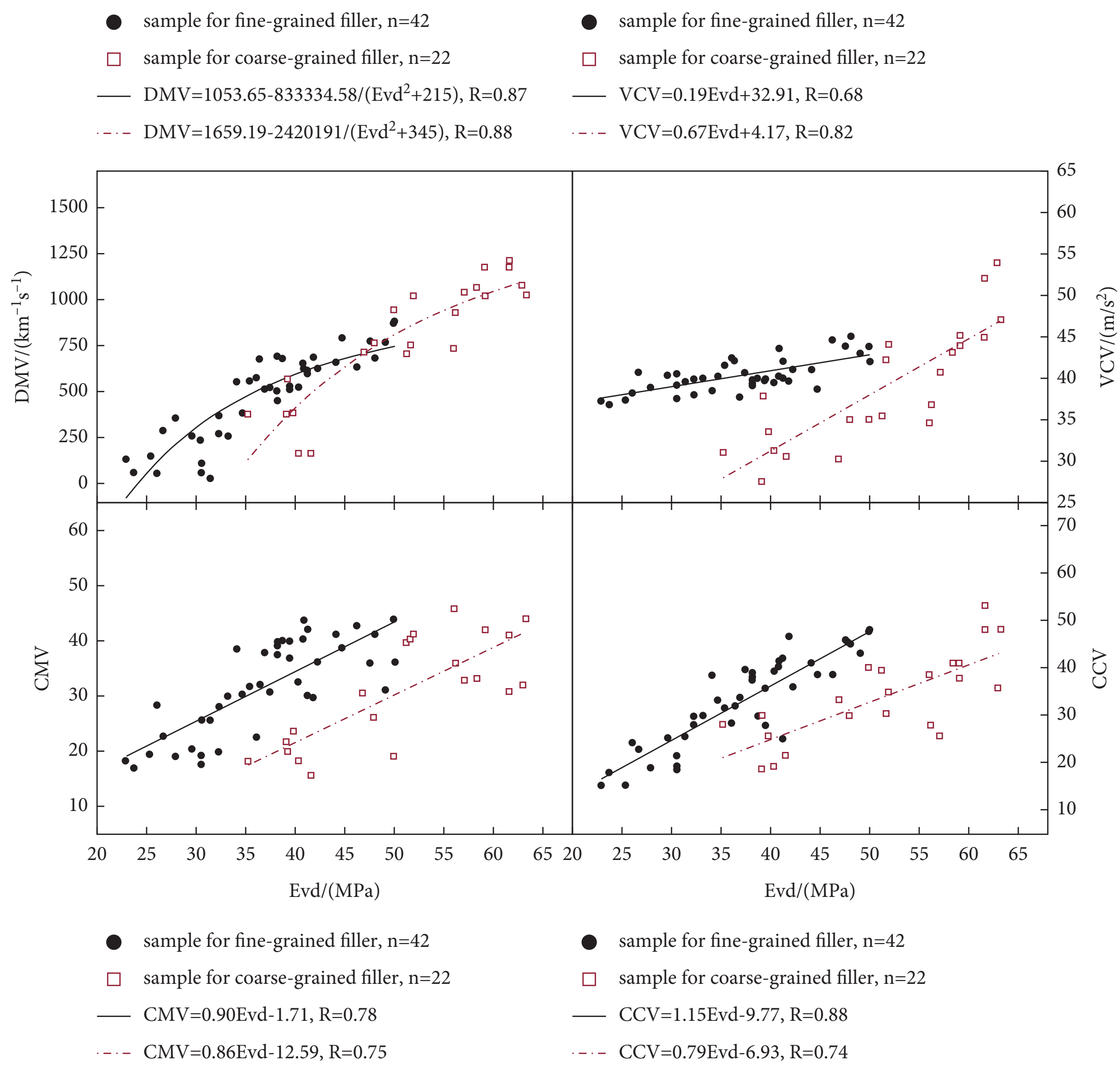

Figure 10: Correlation analysis results.

For the convenience of application, the energy model simplifies the filling body into Kelvin body, that is, it assumes only slight elastic deformation of the filling body and does not consider the influence of plastic deformation. However, in the process of vibration rolling, the filler particles are irreversibly displaced and gradually arranged closely, and the deformation of the filling body is elastic-plastic deformation. Although adopting weak vibration rolling on the basis of preliminary rolling, and using the measured value of weak vibration rolling as evaluation data, the application measures can basically meet the requirements of elastic deformation. However, it is difficult to quantify and unify the criteria for elastic deformation of various filler, and the field operation still depends on experience. Therefore, it is necessary to improve and perfect the energy model combined with the constitutive model of soil in order to improve the applicability of the energy model to elastic-plastic deformation.

The DMV index value is greatly influenced by the exciting force, so it is required to use the measured value under the same exciting force as the basis for quality discrimination. However, in practical engineering, it is usually necessary to reasonably adjust the rolling process including exciting force according to the specific rolling conditions to improve the rolling efficiency. At the same time, the requirement of constant exciting force in continuous compaction control is difficult to meet the development demand of automatic "amplitude modulation and frequency modulation" in smart compaction control. How to modify the indexes under different exciting forces for uniform application is the key point to achieve the development from continuous compaction control based on energy principle to smart compaction control.

In reality, the vibration frequencies of different types of road rollers are not the same. At the same time, the vibration frequencies are affected by mechanical properties, which often produce random fluctuations. In addition, the water content of the filler will also have great dynamic changes under the influence of groundwater and weather. Although the applicability of the energy model is preliminarily tested by field tests, the influence of vibration frequency and filler water content on the DMV index is not clear.

This paper only analyzes and verifies the feasibility of the representative granite residual soil and breccia soil filler in Shenzhen. The applicability of the energy model to other filler needs further discussion.

5. Conclusion

(1) The continuous compaction model based on energy dissipation can satisfactorily solve the vibration problem, and the model can be applied to both coarse-grained and fine-grained fillers, which can promote the wide application of continuous compaction control technology.

(2) With the increase of rolling times, the plastic deformation is smaller, and the repeatability and stability of DMV indexes are better. The variation range of the DMV index is about 1.66–2.73 times of the E_{vd} index, and the DMV index has good sensitivity. Compared with the driving speed, the exciting force has a great influence on the measured value and stability, so it is necessary to pay attention to the control of the exciting force during continuous compaction monitoring. In view of the local uneven distribution of filler, the DMV index has better stability than the CMV index.

(3) In order to approach the elastic deformation assumption of the energy model, the filling body should be preliminarily rolled in advance in practical engineering application, and the measured value of weak vibration rolling should be taken as the basis for continuous compaction evaluation, so as to obtain satisfactory application results.

(4) The engineering application shows that the correlation coefficient between energy index DMV and E_{vd} index reach more than 0.87, which meets the application requirement that the correlation coefficient is no less than 0.7 in the current code in China. The energy model has good applicability for both coarse and fine-grained filler.

Symbols

W_1: Total energy of the vibrating system
W_2: Energy dissipated by the machinery
W_3: Energy state of the filling body
P_0: Amplitude of exciting force
B: Displacement amplitude
ω: Circular frequency
φ: Lag angle
M: Mass of the excitation system
m: Mass of eccentric block
e: Eccentric moment
ξ: Damping ratio of the excitation system
λ: Frequency ratio of the excitation system
D: Energy dissipation rate of nonlinear vibration signal
c: Damping
σ_s: Stress amplitude
ω_0: Vibration angular velocity of the filling body
E: Composite elastic modulus of the filling body
η: Composite viscosity coefficient of the filling body
V_0: Equivalent volume of machinery
V_s: Filling body volume participating in vibration.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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