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Development of a Continuous Testing Device for Pavement Structure Bearing Capacity

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Abstract: Pavement structure bearing capacity is an important evaluation parameter in pavement design, construction, maintenance management, and reconstruction, and is generally expressed by the pavement deflection value. Some of the current road bearing capacity detection equipment have high detection accuracy, but the detection speed is slow, they cannot achieve real-time continuous detection; and some detection speeds are fast, but the measurement accuracy is easily affected by the pavement roughness and vehicle vibration. Moreover, the detection result is the pavement displacement, which cannot directly reflect the comprehensive modulus of the pavement structure. In this paper, firstly, a two-stage jump mechanical model of "machine-pavement" system is established in order to develop a device that can simulate the real driving load and continuously test the bearing capacity of pavement structure, and the main factors affecting the acceleration response of vibrating drums were determined through analysis. Then, a finite element model of the "machine-pavement" system was established to overcome the difficulty in obtaining the parameters such as vibrating weight, equivalent stiffness, and equivalent damping of pavement structure in numerical solution of dynamic model. Next, the mean value A of the maximum acceleration signal of the vibrating drum and the coefficient of variation a_{cv} of the maximum acceleration signal were selected as evaluation indicators to analyze the change trend of the maximum acceleration of the vibrating drum with the excitation frequency and excitation force under different composite modulus of pavement structures. Finally, the relationship between the composite modulus E of the pavement structure and the maximum acceleration A of the vibrating drum was obtained by simulating the pavement structure with the composite modulus ranging from 100 MPa to 2900 MPa, and the accuracy of this relationship was verified by field tests. The research showed that the acceleration signal of the vibrating drum had a good fitting relationship with the bearing capacity of the pavement structure when the testing device with the vibrating drum mass of 100 kg, the exciting frequency of 60 Hz, and the exciting force of 650 N jumped on the pavement structure, and the error was about 20% after comparing with the results of Benkelman beam testing, which basically met the engineering requirements. Therefore, the device can be used to continuously detect the bearing capacity of pavement structures.

Keywords: jumping; acceleration signal; composite modulus of pavement structure; excitation frequency; excitation force; finite element model

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1. Introduction

The pavement structure bearing capacity, as an important parameter in pavement design, construction, maintenance, and reconstruction, reflects the ability of pavement structure to bear and distribute vehicle loads, and can predict the number of axle loads or service life that pavement structure can continue to bear. Hence, the detection of pavement structure bearing capacity has always been an important research topic for many scholars [1].

In the current subgrade and pavement testing standards in China, pavement deflection value is used to evaluate the bearing capacity of pavement structure. According to Reference [2], Benkelman beam deflectometer, Lacroix automatic deflectometer, laser automatic deflectometer, falling weight deflectometer, and traffic speed deflectometer can be used to detect the deflection value of the pavement. The characteristics of various detection methods are shown in Table 1.

Table 1. Comparison of common pavement bearing capacity testing methods.

Detecting Equipment	The Invention Time	Loading Type	Sampling Mode	Whether Calibration Is Required	Detection Speed	Limitations in the Application Process
Benkelman beam deflectometer	1950s	100 KN Static load	Single point detection	No	Slow	The test speed is slow, and cannot test continuously, the human error of the measurement result is large.
Lacroix automatic deflectometer and laser automatic deflectometer	1960s	100 KN Quasi-Static load	Continuous detection	Yes	≤3.5 km/h	The test speed is slow, and the measurement results are greatly affected by the measurement speed. The difference of pavement structure and subgrade condition will affect the calibration result.
Falling weight deflectometer	1970s	50 KN Dynamic pulse load	Single point detection	Yes	Slow	The test speed is slow, and cannot test continuously, the measurement process affects vehicle traffic. The details of the pavement structure thickness, material and so on are needed when back-calculating the modulus of the pavement, otherwise the result of the back-calculation will have a large error.
Traffic speed deflectometer	2000s	100 KN Dynamic traffic load	Continuous detection	Yes	30–90 km/h	The pavement structure type and design thickness are needed when testing and back-calculating the modulus of the pavement. When the road roughness is poor and there is vehicle vibration, the measurement error is large.

At present, a large number of scholars have studied the pavement structure layer modulus back-calculation based on FWD deflection basin information and temperature correction [3–5]. Many scholars have also studied the traffic speed deflectometer and compared its detection results with those of FWD [6–8]. However, there are few studies on the detection method of pavement structural bearing capacity which can simulate the actual traffic load better and realize real-time continuous detection, and the detection accuracy is not easily affected by external factors.

The vibration wheel in jumping condition can provide continuous impact load to the pavement, which can simulate the traffic load borne by the pavement structure well [9]. Therefore, a method to continuously apply impact load to pavement structure and test its bearing capacity can be explored on this basis.

As for the dynamic model of the "machine-pavement" system under jumping vibration condition, it mainly adopts the three-phase dynamic model including contact, jump, and impact, considering the viscoelasticity of the pavement structure and applying different directions of excitation force to solve, and studies the chaos phenomenon in the jumping vibration process [10,11]. Cao Zhipo et al. [12] studied the two degree freedom of jump vibration condition of the "machine-pavement" system dynamics model, and studied the relationship between the acceleration feedback signal of vibrating drums of the vibrating roller and the bearing capacity of pavement structure, but found that the impact force of vibrating roller used in the process of jumping was too large, which would cause damage to pavement structure, so it cannot be directly used to test the bearing capacity of pavement structure.

In order to develop a real-time continuous testing system for pavement bearing capacity, which can apply continuous impact load to pavement structure without damaging the pavement structure, a "machine-pavement" system was proposed by taking the mean value of the maximum acceleration signal of the vibrating drum and the coefficient of variation of the maximum acceleration signal as statistical indicators, optimizing the excitation force and excitation frequency of the vibrating device to get a stable feedback signal within the range of the composite modulus of common pavement structures, and further obtaining the relationship between the mean value of the maximum acceleration signal of the vibrating drum and the composite modulus of the pavement structures, thus developing a detection system which can continuously detect the bearing capacity of the pavement structures. Compared with the test results of the commonly used pavement bearing capacity testing equipment, the test results of the equipment can meet the engineering requirements.

2. Methods and Materials

2.1. Determining the Method of Detecting the Factors Affecting the Acceleration of Steel Wheel

The dynamic model of "machine-pavement" system was established based on the following assumptions: (1) The pavement structure is equivalent to an elastic half-space; (2) the impact process of the "machine-pavement" system is simplified as conforming to the coincidence movement stage and the jumping movement stage, and each movement stage conforms to the law of conservation of momentum; (3) the contact between the vibrating drum and the pavement structure conforms to the Hertz contact theory; (4) the static balance position of the vibrating drum is set as the origin, and the direction upward is the positive direction; (5) the rubber pad is equivalent to a combination of spring and damper. The dynamic model of "machine-pavement" system is established as shown in Figure 1.

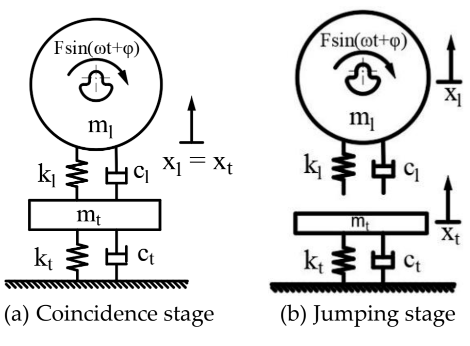


Figure 1. Dynamic model of "machine-pavement" system jumping condition.

At the initial stage of movement, the "machine-pavement" system was in the stage of coincidence movement when the vibrating drum m_l did not jump and moved together with the vibrating weight m_t of the pavement structure, ignoring the influence of gravity. When the speed and displacement of the vibrating drum were all less than 0, the vibrating drum was considered to enter the jumping movement stage. At this stage, the vibrating drum was separated from the vibrating weight, there was no contact between the pavement structure and the vibrating device, and the effect of gravity could not be ignored. The dynamic equations of the system were established as expressed below:

At coincidence stage

$$\begin{cases} m_l\ddot{x}_l + c_l\dot{x}_l + k_lx_l - k_lx_t - c_l\dot{x}_t = F\sin(\omega t + \varphi) \\ m_t\ddot{x}_t + c_l(\dot{x}_t - \dot{x}_l) + k_l(x_t - x_l) + k_tx_t + c_t\dot{x}_t = 0 \end{cases} \tag{1}$$

At jumping stage

$$\begin{cases} m_l\ddot{x}_l = Mg + F\sin(\omega t + \varphi) \\ m_t\ddot{x}_t + kx_t + c\dot{x}_t = 0 \end{cases} \tag{2}$$

where,

m_l = the mass of steel wheel, kg;
m_t = the vibrating weight of pavement structure, kg;
k_l = the equivalent stiffness of rubber pad, N/m;
k_t = the equivalent stiffness of pavement structure, N/m;
c_l = the equivalent damping of rubber pad, N·s/m;
c_t = the equivalent damping of pavement structure, N·s/m;
x_l = the displacement of steel wheel, mm;
x_t = the displacement of pavement structure, mm;
F = the amplitude of excitation force, N;
ω = the rotational angular velocity of the exciter, rad/s;
and φ = the initial phase angle of this stage, rad.

Solving Equation (1) leads to:

$$\ddot{x}_l = -\omega^2 F\sqrt{\frac{q^2 + r^2}{j^2 + p^2}}\sin(\omega t + \varphi) \tag{3}$$

where,

$$\begin{aligned} &j = (k_l - m_l\omega^2)(k_l + k_t - m_t\omega^2) - \omega^2 c_l(c_l + c_t) \\ &-{k_l}^2 + \omega^2{c_l}^2 \\ &p = (k_l - M\omega^2)(c_l + c_t)\omega + (k_l + k_t - m_t\omega^2)\omega c_l \\ &-2k_lc_l\omega \\ &q = k_l + k_t - m_t\omega^2 \\ &r = (c_l + c_t)\omega \end{aligned}$$

Equation (2) can be solved as follows:

$$\ddot{x}_l = \frac{F\sin(\omega t + \varphi)}{m_l} + g \tag{4}$$

Equations (3) and (4) show that the acceleration of the steel wheel was mainly affected by factors such as the mass of the steel wheel and its vibrating weight, the equivalent stiffness and damping of the rubber pad and pavement structure, and the amplitude and frequency of the excitation force in the process of jumping.

The parameters of steel wheel mass, rubber pad stiffness, and damping in the dynamic equation can be easily obtained by measuring when solving the relationship between the acceleration of steel wheel and the bearing capacity of pavement structure by numerical method. However, it is difficult to obtain the parameters of the pavement structure, such as vibration mass, equivalent stiffness, equivalent damping, and so on [13]. Therefore, the finite element method was adopted to simulate the "machine-pavement" system, because by establishing the simulation model of the system in the finite element simulation software ABAQUS, the material properties can be directly input, thus overcoming the difficulty in obtaining parameters such as vibrating weight, equivalent stiffness, and equivalent damping of pavement structure by the numerical method.

2.2. Finite Element Model and Materials of "Machine-Pavement" System

According to the reference [14], the impact load of 100 kg steel wheel applied to the pavement structure can be close to 50 kN, which meets the requirements of dynamic load applied to the pavement structure during FWD detection, so the mass of steel wheel was set at 100 kg in the simulation model. A finite element model of the test equipment and the pavement structure was established with symmetric constraints as shown in Figure 2.

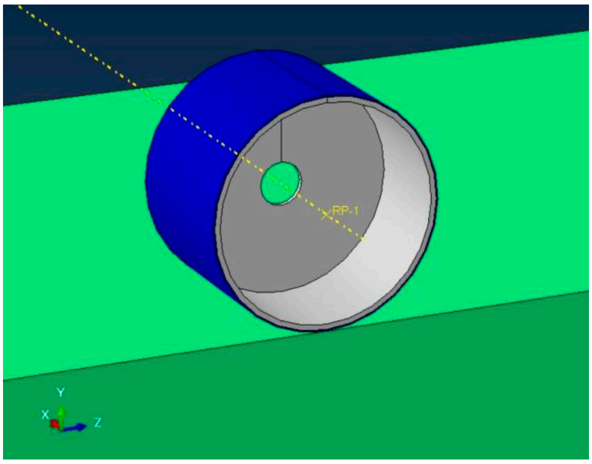


Figure 2. Finite element model of "machine-pavement" system.

In the model, the steel wheel had a width of 600 mm, a diameter of 425 mm, and a steel plate thickness of 10 mm made of ISO standard steel number C45E4. The steel wheel was coated with a 30 mm-thick nitrile rubber pad that was made of super-elastic material and adopted MR configuration. The rubber material characteristics and parameter settings are shown in Table 2.

Table 2. Rubber material characteristics and parameter settings.

Rubber Material Test Results		M-R Model Parameters	
Tensile strength (MPa)	13.0	C10	0.193
Elongation at break (%)	574	C01	0.139
Shore hardness (Shore A)	62	D1	0.00139

Because the rigidity of steel wheel was very different from that of rubber material, the steel wheel was set as a rigid body with a density of 7.8 $\times$ 10^{-6} kg/mm^3. According to reference [15], the density of elastic half-space was set to 2.4 $\times$ 10^{-6} kg/mm^3, Poisson's ratio was 0.25, and the composite modulus of pavement structure was the independent variable E. The elastic half-space was set as a cuboid with a size of 6000 mm $\times$ 3000 mm $\times$ 3000 mm, the symmetry plane was constrained symmetrically, and the bottom surface and the periphery were constrained fixedly. According to reference [14], both the vibrating drum and the pavement structure adopted C3D8R mesh, and the size of the pavement structure mesh was set to be 60 mm. The system parameters were set to E = 1300 MPa, F = 650 N, f = 60 Hz, with A defined by Equation (5) and a_{cv} defined by Equation (6) as evaluation indicators, and the sensitivity analysis was performed on the mesh size of vibrating drum and rubber pad. The results are shown in Figure 3.

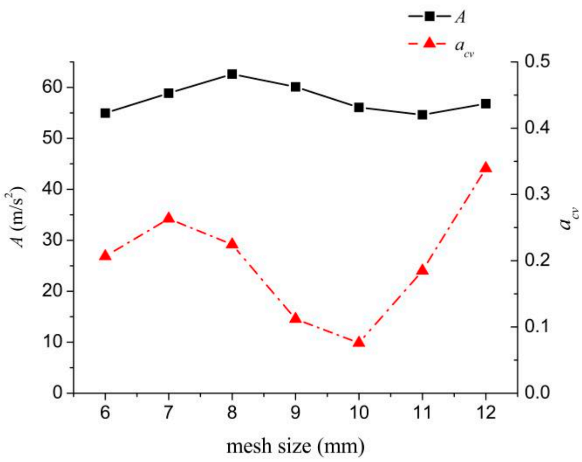


Figure 3. Sensitivity analysis of mesh size.

As shown in Figure 3, the mean value A of the maximum acceleration signal of the vibrating drum is basically not affected by the changes in the mesh size, but the coefficient of variation a_{cv} of the maximum acceleration signal is greatly affected by the changes in the grid. Moreover, the value of a_{cv} is the smallest when the mesh size is 10 mm, which indicates that the maximum acceleration signal of the vibrating drum is the most stable at this time, and good results can be obtained when the system is simulated.

To verify the correctness of the model, the system simulation parameters were set to E = 1300 MPa, F = 650 N, and f = 60 Hz for simulation, and the stress nephogram was obtained as shown in Figure 4 that the contact force of the vibrating drum impacting the road surface was almost uniformly distributed along the contact element line, and the contact stress was almost elliptically distributed within the contact width, which was in accordance with the Hertz contact theory.

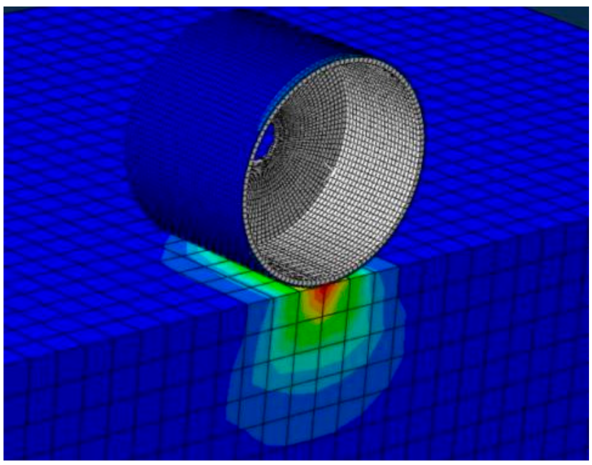


Figure 4. Stress nephogram of finite element simulation of "machine-pavement" system during jumping.

2.3. Methods for Determining Statistical Indicators

To select appropriate indicators to evaluate the stability of the vibratory system and the steel wheel acceleration signal, the system simulation parameters were set as E = 1300 MPa, f = 60 Hz, and F = 650 N. The simulation results are shown in Figure 5. In order to obtain a more stable signal, the excitation force was zero within 0.06 s at the beginning of the simulation, so that the system entered a stable static equilibrium state. As shown in Figure 5, when the excitation force was applied from 0.06 s, the acceleration signal entered a relatively stable state after the transition of 0.1 s.

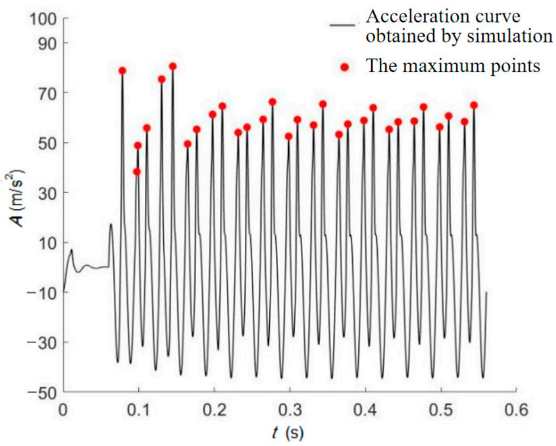


Figure 5. Schematic diagram of maximum point of simulation results.

As shown in Figure 5, when the vibrating drum impacts the road surface, a peak will appear in its acceleration value, which is called the acceleration maximum of the vibrating drum as shown by the red dot in Figure 5, where the first maximum is recorded as a_1, the second maximum as a_2, . . . , and the i-th maximum as a_i. The acceleration maxima of steel wheels are different every time they hit the pavement in the process of jumping, so they cannot be directly used to evaluate the composite modulus of pavement structure. Thus, it is necessary to select appropriate evaluation indicators to study the relationship between the acceleration maxima of vibrating drums and the composite modulus of pavement structure in the process of jumping.

The mean value of the sample is a commonly used indicator in statistics to reflect the central position where the samples are relatively concentrated. The coefficient of variation is an important indicator to measure the dispersion of samples. Therefore, the mean value of the maximum acceleration signal of the vibrating drum (expressed as A) and the coefficient of variation of the maximum acceleration signal within a certain time (expressed as a_{cv}) were taken as evaluation indicators to better reflect the distribution and dispersion degree of the maximum acceleration of the steel wheel. The mean value of the maximum acceleration signal of the vibrating drum (expressed as A) and the coefficient of variation of the maximum acceleration signal (expressed as a_{cv}) were calculated by Equations (5) and (6).

Mean value of maximum acceleration signal of vibrating drum:

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i \tag{5}$$

Coefficient of variation of the maximum acceleration signal of vibrating drum:

$$a_{cv} = \frac{1}{a_{mean}}\sqrt{\frac{\sum_{i=1}^{n}(a_i - a_{mean})^2}{n}} \tag{6}$$

The vibration systems with the pavement structure composite modulus E of 500 MPa, 1300 MPa, 2100 MPa, 2900 MPa, excitation frequency f of 55 Hz, 60 Hz, 65 Hz, and excitation force F of 500 N and 600 N, respectively, were simulated, and the mean value of the maximum acceleration signal of the vibrating drum (expressed as A) and the coefficient of variation of the maximum acceleration signal within a certain time (expressed as a_{cv}) within the time length of 0.1 to 0.5 s were counted, respectively, to obtain the curves of A and a_{cv} changing with the statistical time length, as shown in Figure 6.

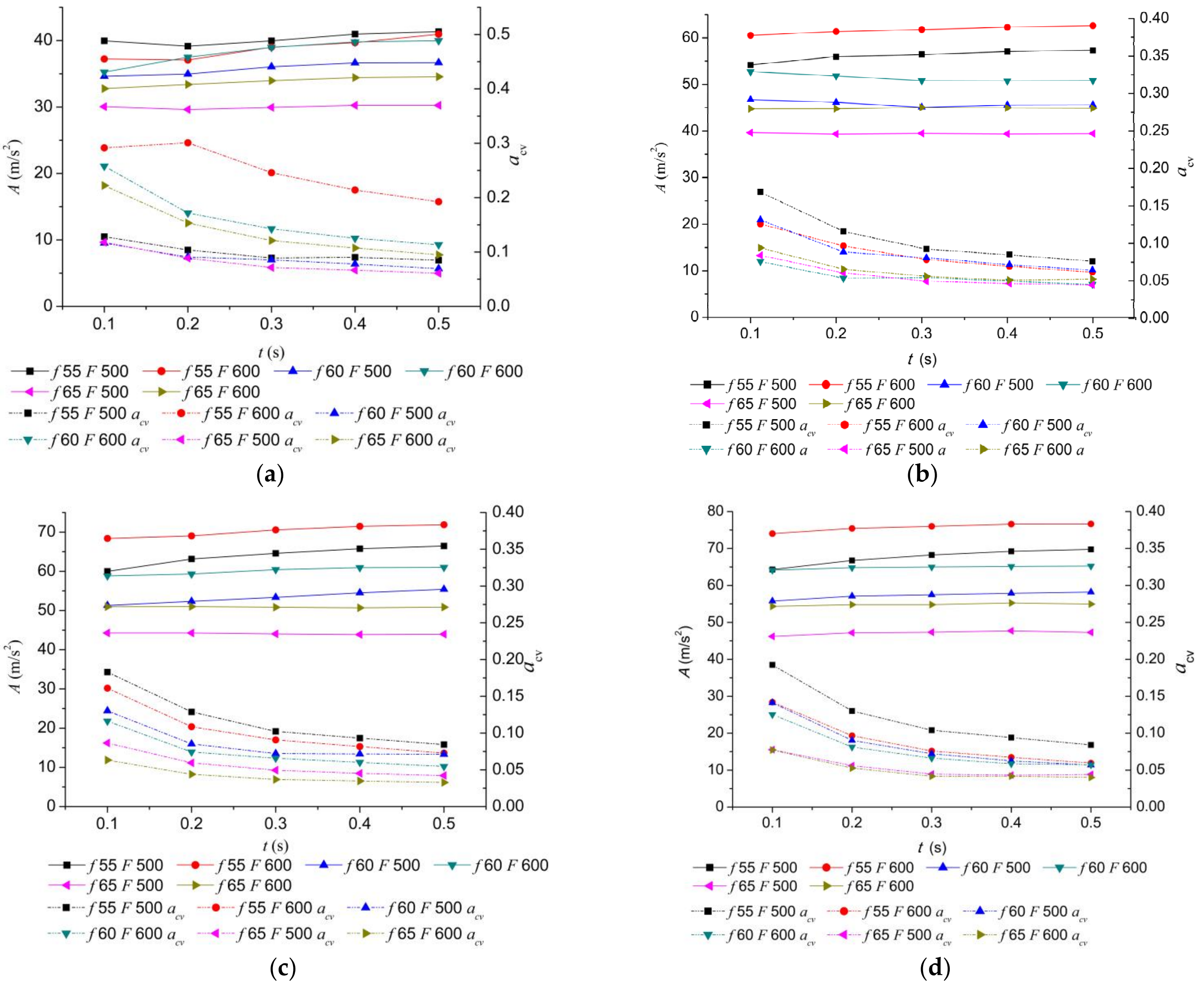


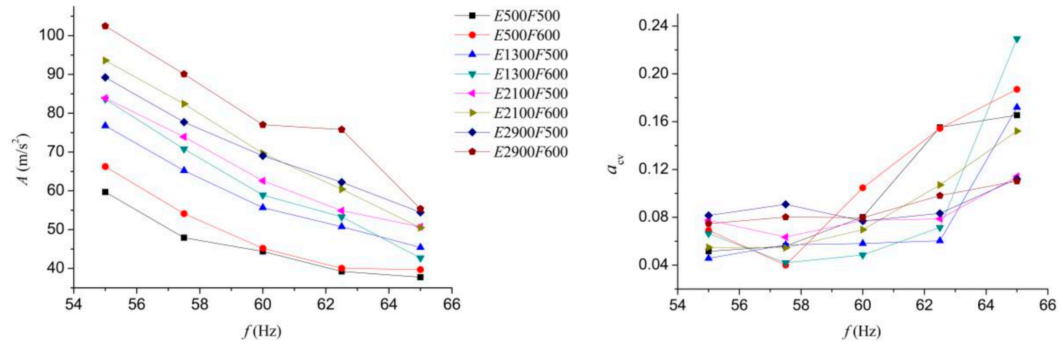
Figure 6. Curves of A and a_{cv} changing with the statistical time length. (**a**) E = 500, (**b**) E = 1300, (**c**) E = 2100, (**d**) E = 2900.

As shown in Figure 6, when the composite modulus, excitation force, and frequency are changed, the value of A basically does not change with the increase of statistical time length, while the value of a_{cv} decreases with the increase of statistical time length. When the statistical time length is greater than 0.4 s, the value of a_{cv} basically does not change. Therefore, the mean value A of the maximum acceleration signal of vibrating drum and the coefficient of variation a_{cv} of the maximum acceleration signal were selected as statistical indicators to determine the appropriate excitation frequency and excitation force of the "machine-pavement" system to study the relationship between the maximum acceleration of vibrating drum and the composite modulus of pavement structure under the impact load.

3. Analysis of Simulation Results

3.1. Influence of Excitation Frequency Variation on Acceleration Signal of Vibrating Drum

In order to study the influence of excitation frequency change of "machine-pavement" system on vibrating drum acceleration signal, the vibratory system with pavement structure composite modulus E of 500 MPa, 1300 MPa, 2100 MPa, 2900 MPa and excitation force F of 500 N and 600 N was simulated to obtain the relationship curves of A and a_{cv} with vibration frequency f under different excitation force and pavement structure composite modulus, as shown in Figure 7.



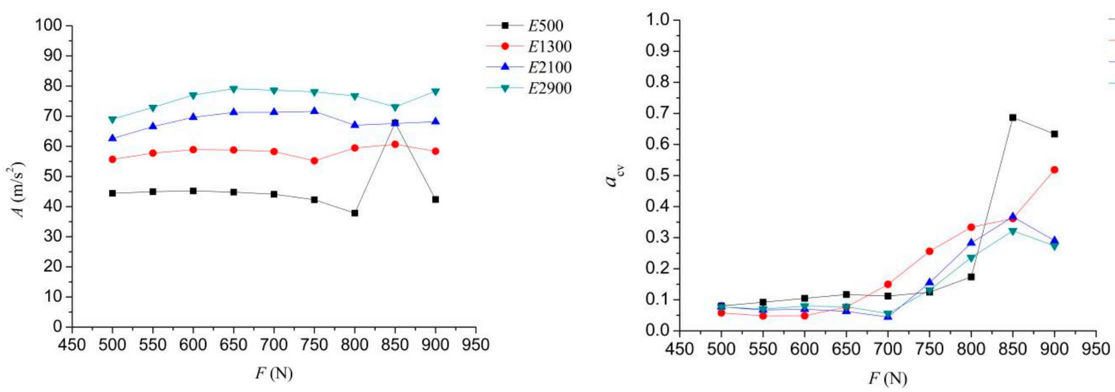
(**a**) (**b**)

Figure 7. The curves of A and a_{cv} changing with excitation frequency. (**a**) The curve of A changing with excitation frequency. (**b**) The curve of a_{cv} changing with excitation frequency.

As shown in Figure 7a, under the same composite modulus and excitation force, A decreases with the increase of excitation frequency; under the same composite modulus and excitation frequency, A increases with the increase of the exciting force; under the same excitation frequency and excitation force, A increases with the increase of the composite modulus. As shown in Figure 7b, under the same composite modulus and excitation force, when the excitation frequency is less than 60 Hz, a_{cv} basically does not change with the excitation frequency and is less than 0.1; when the excitation frequency is greater than 60 Hz, a_{cv} increases rapidly with the increase of the excitation frequency. Thus, it is appropriate to choose the excitation frequency f of "machine-pavement" system as 60 Hz.

3.2. Influence of Excitation Force Variation on Acceleration Signal of Vibrating Drum

In order to study the influence of excitation force change of "machine-pavement" system on vibrating drum acceleration signal, the "machine-pavement" system with pavement structure composite modulus E of 500 MPa, 1300 Mpa, 2100 Mpa, 2900 Mpa and excitation frequency f of 60 Hz, and excitation force F ranging from 500 N to 900 N was simulated to obtain the relationship curves of A and a_{cv} changing with vibration force under different pavement structure composite modulus, as shown in Figure 8.



(**a**) (**b**)

Figure 8. The curves of A and a_{cv} changing with excitation force F. (**a**) The curve of A changing with excitation force F. (**b**) The curve of a_{cv} changing with excitation force F.

As shown in Figure 8a, when the exciting force F is less than 650 N, A increases with the increase of the excitation force, and when the excitation force F is greater than 650 N, A decreases with the increase of the excitation force. As shown in Figure 8b, when the excitation force F is less than 650 N, a_{cv} basically does not change with the variation of the excitation force. When the excitation force F is greater than 650 N, a_{cv} increases rapidly with the increase of the excitation force, indicating that the system enters an unstable state.

Therefore, the excitation force F of "machine-pavement" system was determined to be 650 N.

3.3. Relationship between Acceleration Feedback Signal of Steel Wheel and Bearing Capacity of Pavement Structure

According to reference [15], the asphalt pavement structure is a multi-layer structure made from four layers of different materials according to a certain thickness, as shown in Figure 9. In order to determine the composite modulus range of the pavement structure used in the simulation, according to the asphalt pavement structure scheme recommended in Reference [15], the materials and thicknesses of each layer corresponding to the pavement structures with the strongest and weakest composite modulus were taken as shown in Table 3, respectively.

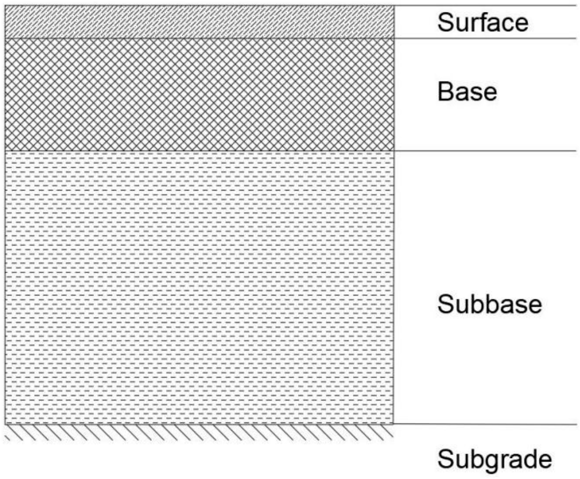


Figure 9. Schematic diagram of asphalt pavement structure layers.

Table 3. Recommended scheme of pavement structure and converted composite modulus.

Pavement Structure	Strongest Pavement Structure				Converted Modulus (MPa)	Weakest Pavement Structure				Converted Modulus (MPa)
	Materials	Modulus (MPa)	Thickness (m)	Poisson's Ratio		Materials	Modulus (MPa)	Thickness (m)	Poisson's Ratio	
Surface layer	Asphalt mixture	13,500	0.25	0.25	2623.3	Asphalt mixture	7000	0.1	0.4	227.1
Substratum	Inorganic binding material	28,000	0.5	0.25		Aggregates	250	0.25	0.35	
Subbase layer	Inorganic binding material	28,000	0.2	0.25		Aggregates	130	0.15	0.35	
Soil matrix	——	70	——	0.4		——	40	——	0.4	

According to theory of multilayer elastic half-space, the elastic modulus of the multilayer structure can be converted into the composite modulus, in which the composite moduli E of the strongest and the weakest pavement structure were 2623.3 MPa and 227.1 MPa, respectively. Therefore, in order to appropriately expand the scope of application of the simulation results, the composite modulus of the pavement structure was taken ranging from 100 MPa to 2900 MPa, and a sampling point was taken every 200 MPa to simulate the "machine-pavement" system with the excitation frequency f of 60 Hz and the excitation force F of 650 N. The quadratic polynomial method was used to fit the relationship between A and composite modulus E to get the fitting curve as shown in Figure 10, thus the relationship between the mean value of the maximum acceleration of vibrating drum and the composite modulus of pavement structure was obtained, as shown in Figure 7.

$$E = 0.61057A^2 - 4.5478A - 650.338, R^2 = 0.99048 \tag{7}$$

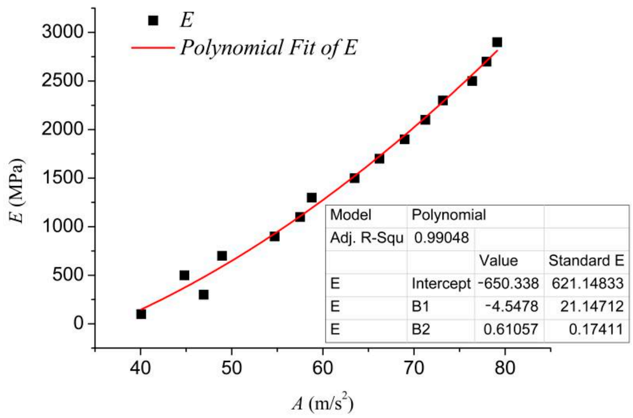


Figure 10. Fitting curve of the relationship between A and composite modulus.

4. Experimental Verification

4.1. Experimental Verification on the Correctness of the Simulation Model

A test prototype of the continuous testing device for pavement structure bearing capacity was made in order to verify the correctness of the simulation model, as shown in Figure 11. The parameters of the vibrating drum of the test prototype were consistent with those of the finite element model. The eccentric shaft was driven by a motor with a belt drive, and the motor speed ranged from 0 to 5000 r/min. The data acquisition systems used in the test were a DH5902 dynamic data acquisition instrument and an ICP piezoelectric acceleration sensor, with the sampling frequency of 1000 Hz and sensitivity of 10.13 mV/(m·s^{-2}). The installation position of the acceleration sensor is shown in Figure 12. The parameters of test prototype of "machine-pavement" vibratory system and test pavement are shown in Table 4.

Figure 11. Field test of test prototype of "machine-pavement" vibratory system.

Figure 12. Installation position of acceleration sensor of vibrating drum.

Table 4. Parameters of test prototype and test pavement structure.

Parameters of Test Prototype		Parameters of Pavement Structure				
Mass of Vibrating Drum (kg)	100		Pavement Structure 1		Pavement Structure 2	
Width (mm)	600		Materials	Thickness (cm)	Materials	Thickness (cm)
Diameter (mm)	425	**Surface layer**	Asphalt mixture	110	Asphalt mixture	150
Excitation force (N)	650	**Substratum**	Cement stabilized macadam	200	Cement stabilized macadam	300
Excitation frequency (Hz)	65	**Subbase layer**	Cement stabilized soil	200	Cement stabilized macadam	200
Thickness of rubber pad (mm)	3	**Soil matrix**	Sandy soil	—	Sandy soil	—

Pavement structure 1 was selected for field test and the test results were compared with the simulation results of "machine-pavement" system with parameters of E = 1700 MPa, f = 60 Hz, and F = 650 N, as shown in Figure 13.

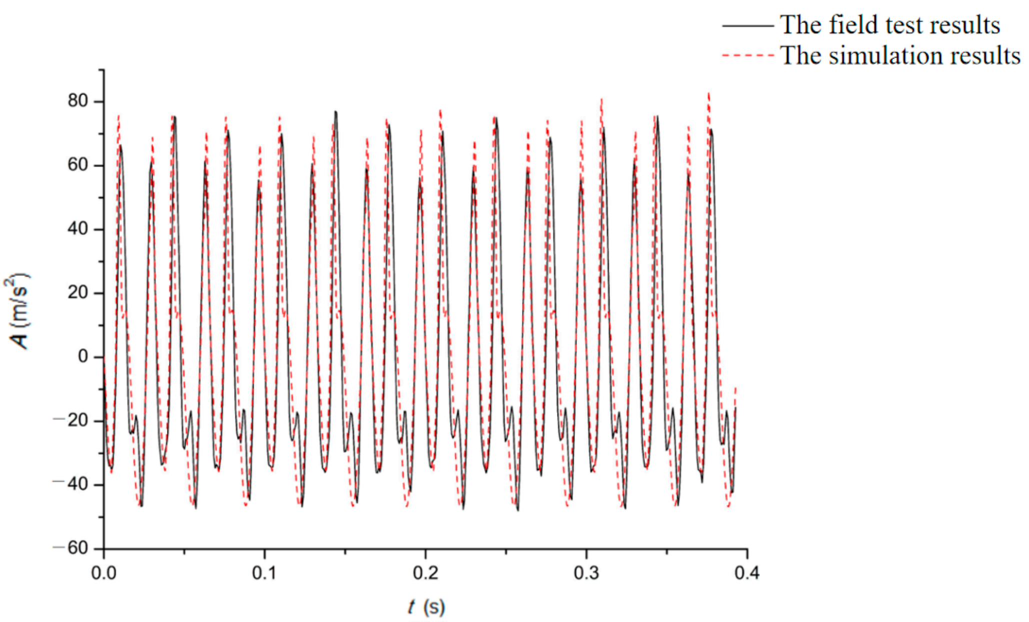


Figure 13. Comparison between field test results and simulation results.

Figure 13 shows that the curves of simulation results and test results show a law of large amplitude and small amplitude, and each has a small fluctuation in the downward section, which may be caused by the fact that the sensor is arranged on the right side of the vibrating drum and there is a certain deflection due to incomplete symmetry between the left and right when the vibrating drum jumps up and lands. As this phenomenon is mild in simulation, the fluctuation of simulation results is small, but the fluctuation of field test is large. Therefore, the simulation model of "machine-pavement" system is reasonable.

4.2. Verification of Correctness of Relationship between A and Composite Modulus of Pavement Structure

In order to verify the correctness of Equation (7), the pavement structure 1 and the pavement structure 2 in Table 3 were tested using the test prototype for continuous testing device of pavement structure bearing capacity.

When detecting the deflection value of pavement structure, the surface temperature was 5 °C, and the average temperature was 2 °C five days before the test. According to reference [2], the temperature correction coefficient is 1.11, and the deflection test result of

Benkelman beam can be converted into the composite modulus of pavement structure by Equation (8), which was compared with the test result of the test prototype.

$$E_1 = \frac{200p\delta}{L_1}\left(1-\mu^2\right)a \quad (8)$$

where,

E_1 = the composite modulus of pavement structure, MPa;
p = the vertical load of the wheel, MPa;
δ = the equivalent circle radius of single wheel pressure transmission surface with double circular load of test vehicle, mm;
μ = the equivalent Poisson's ratio of pavement material;
a = the deflection coefficient;
and L_1 = the calculated representative deflection value, 0.01 mm.

The vertical load p on the wheels of the test vehicle for testing was 0.702 MPa; the equivalent circle radius δ of the single wheel pressure transmission surface was 106.451 mm; the pavement material was dense asphalt concrete with Poisson's ratio μ of 0.25; the deflection coefficient a was 0.712; the calculated representative deflection values of pavement structure 1 and pavement structure 2 were measured separately and converted into the composite modulus of pavement structure according to Equation (8), and compared with the test results of the test prototype, as shown in Table 5.

Table 5. Comparison between deflection test results of Benkelman beam and test prototype.

Test Pavements	Detected Deflection Value /0.01 mm	Converted Composite Modulus /MPa	Detected Acceleration Value /m·s^{-2}	Interpolation Result /MPa	Error/%
Pavement structure 1	8.01	1263.3	65.8941	1701.1	25.7
Pavement structure 2	4.5	2217.7	77.7688	2688.7	17.5

As shown in Table 5, the composite modulus converted from the deflection value detected by the Benkelman beam has a good correspondence with the acceleration value A of the vibrating drum detected by the test prototype. The composite moduli of the two pavement structures calculated by the interpolation of the vibration wheel acceleration maximum A are higher than the composite modulus converted from the deflection value detected by Benkelman beam, because the Benkelman beam detection method is a static detection method, and the test prototype used a dynamic detection method, and the error between the two was about 20%, which basically met the engineering requirements. Therefore, the continuous testing device for pavement structure bearing capacity can be used to continuously test the bearing capacity of pavement structure.

5. Discussion

Asphalt pavement structure is a multi-layer structure with different materials combined according to a certain thickness. According to the theory of multi-layer elastic half-space, the elastic modulus of multi-layer structure can be converted into comprehensive modulus. In the current evaluation methods of pavement structural bearing capacity, the pavement deflection value is taken as the evaluation index of pavement structural bearing capacity. The traditional pavement deflection detection equipment applies static or dynamic loads to the pavement structure and uses displacement sensors to detect the changes of pavement structure displacement during loading and unloading. The maximum pavement deflection value or deflection basin information of the pavement structure under a certain load is obtained. The detection speed of this traditional detection equipment is very slow, and will affect traffic while doing the detection.

According to the maximum pavement deflection value or deflection basin information of the pavement structure, we can use some specific algorithms to back-calculate the elastic modulus of pavement structure, but details of the pavement structure information, such as the pavement temperature during detection, the material characteristics of each layer of pavement structure, thickness, etc. is needed, and these details are hard to know. Moreover, the solution results are not unique in the back-calculation process [4,5].

These shortcomings above limited the use of Benkelman beam deflectometer, Lacroix automatic deflectometer, laser automatic deflectometer, and falling weight deflectometer for pavement bearing capacity testing. The traffic speed deflectometer uses the Doppler method to measure the velocity of pavement structure displacement change in the process of pavement loading and unloading, and then calculates the maximum deflection and deflection basin data through the calculation program. The traffic speed deflectometer can be used to detect the bearing capacity of the pavement structure in normal traffic speed, but the measurement accuracy is greatly affected by the roughness of the pavement and the vibration of the vehicle, and the test results also have the problem that the reverse calculation results are not unique.

In this study, the method of jumping vibration is proposed to apply a pulse load on the pavement surface, which can accurately simulate the real traffic load. By collecting the acceleration feedback signal of the vibration wheel, the relationship between the acceleration feedback signal of the vibration wheel and the comprehensive modulus of the pavement structure is established, and the acceleration signal can be directly transformed into the comprehensive modulus of the pavement structure, and continuous detection can be realized. Parameters of the vibration equipment were optimized by finite element method, and the test prototype of the testing equipment was made. The test results of the prototype are compared with those of the Benkelman beam deflectometer, which can basically meet the engineering requirements.

6. Conclusions

In this paper, a new continuous testing method for the bearing capacity of pavement structure is proposed, and a test prototype is completed. The field testing results of the test prototype are compared with those of the traditional pavement bearing capacity testing equipment, and the following main conclusions are obtained:

(1) A dynamic model of “machine-pavement” system with two-stage jumping was established and the numerical solution of the model was deduced. Moreover, through the solution of the model, the main factors that affect the acceleration of the steel wheel in the process of the system jumping were determined as the steel wheel mass, vibrating weight, equivalent stiffness and damping of the rubber pad and the pavement structure, the amplitude and frequency of the excitation force, etc.

(2) A finite element model of “machine-pavement” system was established. Compared with the existing literature, it is proposed for the first time to study the relationship between the acceleration feedback signal of the vibrating drum and the composite modulus of the pavement structure by analyzing the mean value A of the maximum acceleration signal of vibrating drum and the coefficient of variation a_{cv} of the maximum acceleration signal when statistical time was 0.4 s. According to the analysis, when the excitation frequency f of the “machine-pavement” system was 60 Hz and the excitation force F was 650 N, the acceleration signal of the vibrating drum could keep a relatively stable state with the change of the bearing capacity of the pavement structure.

(3) The pavement structure with composite modulus ranging from 100 MPa to 2900 MPa was simulated, and the relationship between composite modulus E of pavement structure and the maximum value A of vibrating drum acceleration signal was obtained by quadratic polynomial fitting. The goodness of fit was greater than 0.99, indicating that there was a good fitting relationship between them.

(4) The test prototype for continuous detection device of pavement structure bearing capacity was made to test the bearing capacity of two pavement structures. The

test results were compared with the composite modulus converted from deflection value detected by Benkelman beam. The error between the two was about 20%, which basically met the engineering requirements. In summary, the continuous testing device for pavement structure bearing capacity can be used to continuously test the bearing capacity of pavement structure.

The continuous detection method of pavement structural bearing capacity proposed in this study can be used to evaluate the pavement structural bearing capacity, but the detection accuracy is still low, and the pavement structural model needs to be further optimized. In the future research, the influence of detection speed and pavement structure temperature on detection results should be considered.

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