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Research Article

Field Measurement of Dynamic Compressive Stress Response of Pavement-Subgrade Induced by Moving Heavy-Duty Trucks

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This paper presents the dynamic compressive stress response of pavement-subgrade induced by moving heavy-duty trucks. In order to study the distribution characteristic of dynamic pressure of pavement-subgrade in more detail, truck loadings, truck speeds, and dynamic pressure distributions at different depths were monitored under twenty-five working conditions on the section of Qiqihar-Nenjiang Highway in Heilongjiang Province, China. The effects of truck loading, truck speed, and depth on dynamic compressive stress response can be concluded as follows: (1) increasing truck loading will increase the dynamic pressure amplitude of subgrade-pavement and dominant frequencies are close to the characteristic frequencies caused by heavy-duty trucks at the speed of 70 km/h; (2) as truck speed increases, the dynamic pressure amplitudes of measuring points have an increasing tendency; the dynamic pressure spectrums are also significantly influenced by truck speed: the higher the truck speed, the wider the spectrum and the higher the dominant frequencies; (3) as depth increases, the dynamic pressure amplitudes of measuring points decrease rapidly. The influence of the front axle decreases gradually until disappearing and the compressive stress superposition phenomenon caused by rear double axles can be found with increasing depth.

1. Introduction

The stress state of pavement-subgrade has a significant effect on evaluating the stability of pavement-subgrade. However, with the rapid economic development, heavy-duty trucks which are the main cause of subgrade diseases and pavement damage in highway transportation are quite common. A large number of field investigations show that 35%–67% of heavy-duty trucks are overloaded in Jiangsu Province, China [1]. Furthermore, the axial loading of heavy-duty trucks approaches 22 t on Xuanhua-Datong Highway [2]. Therefore, it is of importance to evaluate the dynamic stress of pavement-subgrade for improving the service performance of highways.

There is already growing evidence, on the basis of ongoing researches, that field measurement is an effective method to investigate the dynamic stress response of pavement-subgrade induced by moving heavy-duty trucks [3–16]. The Engineering and Physical Sciences Research Council of the United Kingdom [17] built a full-scale experimental road for testing the mechanical and subsidence properties of roads under traffic loading. Hyodo et al. [18, 19] investigated the vertical pressure of subgrades induced by a 10 t car at different speeds (0 km/h, 10 km/h, 20 km/h, and 35 km/h). Mateos et al. [20] carried out a field test on six sections of a circular road in Spain. The results showed that when the speed of moving vehicles increased, the compressive stress of the subgrade decreased gradually. Timm et al. [21] built eight test sections in the NCAT for testing the dynamic stress response of subgrade-pavement induced by heavy-duty trucks. The test data of the NCAT obtained by Immanuel and Timm [22] showed that temperature had a certain influence on the compressive stress response of subgrade and pavement. The compressive stress of pavement-subgrade decreased in winter and increased in summer because the stiffness of hot mix asphalt (HMA) pavement was higher in winter and lower in summer.

In China, Ling et al. [23] pointed out that the vertical stress on the top of the subgrade was between 5 kPa and 10 kPa. Zha et al. [24] tested the vibration acceleration and

Table 1: Geomechanical parameters of soil.

Specific gravity	Cohesion force	Friction angle	Dynamic elastic modulus
2.61	94 kPa	37°	490 MPa

Figure 1: Monitoring section of Qiqihar-Nenjiang Highway in Heilongjiang Province, China.

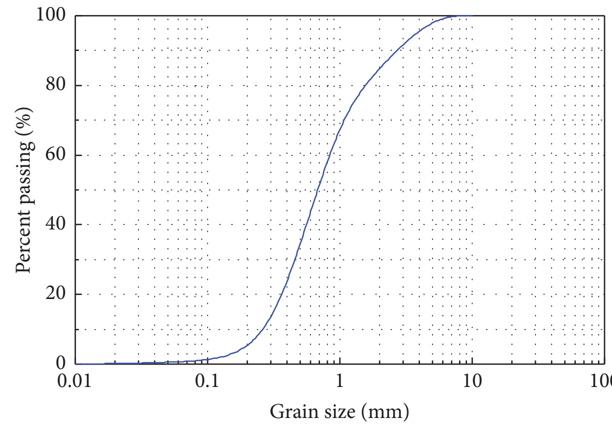

Figure 2: Grain size distribution of subgrade soil.

dynamic pressure of pavement induced by Dongfeng Trucks and Jinbei buses. The results showed that the dynamic pressure amplitude of pavement was 38.6 kPa for trucks and only 3.78 kPa for buses. Wang et al. [25] found that the dynamic pressure of subgrade-pavement decreased with increasing vertical depth and increased with increasing truck loading. Wang et al. [26] discussed the effects of axle loading, road roughness, and truck speed on the additional stress induced by traffic loading. Zhao et al. [27] tested the dynamic stress and dynamic displacement of subgrade induced by 2 t and 20 t trucks. The results showed that the dynamic pressure and dynamic displacement of subgrade increased with increasing truck speed. Shi et al. [28] measured the dynamic stress of subgrade induced by trucks and suggested that the stress amplitude was from 0 to 100 kPa on the top of the subgrade. Cui et al. [29] found that the cumulative settlement of subgrade obviously increased with increasing wheel load.

In this paper, in situ tests on the section of Qiqihar-Nenjiang Highway in Heilongjiang Province, China, are presented. The main objective of this paper is to get a better understanding of the dynamic compressive stress response of pavement-subgrade induced by moving heavy-duty trucks. The effects of truck loading, truck speed, and depth on the dynamic compressive stress response are analyzed. In addition, this paper would be helpful to provide a series of test data that researchers can use for further investigation and for the validation of numerical prediction models.

2. Measurement Details

2.1. Test Section and Materials of Subgrade

2.1.1. Test Section. As shown in Figure 1, field measurement site is the K46+732 section of Qiqihar-Nenjiang Highway in Heilongjiang Province, China.

The Qiqihar-Nenjiang Highway is a bidirectional, four-lane highway. The asphalt concrete pavement is composed of three layers as follows: the up layer of asphalt concrete (AC16) with a thickness of 0.05 m, the middle layer of asphalt concrete (AC20) with a thickness of 0.06 m, and the bottom layer of large-size asphalt macadam (ATB25) with a thickness of 0.08 m. The thickness of the base course of cement-stabilized macadam is 0.2 m and the thickness of the subbase course of cement-stabilized gravel is 0.23 m.

2.1.2. Materials of Subgrade. According to the Test Methods of Soils for Highway Engineering (JTG E40-2007) issued by the Ministry of Transport, China, the grain size distribution of subgrade soil is shown in Figure 2.

The uniformity coefficient C_u and curve coefficient C_c are calculated as 3.2 and 1.013, respectively. The maximum dry-unit weight is 2010 kg/m^3 at the optimum water content of 8.63%. A series of unconsolidated-undrained triaxial compression tests and dynamic triaxial tests on the remolded subgrade soil with optimum water content and maximum dry-unit weight are performed to obtain the geomechanical parameters which are shown in Table 1.

2.2. Test Points and Sensor Installation. To investigate the vertical dynamic stress of pavement-subgrade induced by moving heavy-duty trucks, ten test points were chosen according to the Specifications for Design of Highway Subgrade (JTGD30-2004) issued by the Ministry of Transport, China. These test points were located on the top of the base course, the top of the roadbed, the top of the up-embankment, the top of the subembankment, and the bottom of the subembankment. Figure 3 shows the layout of the dynamic soil pressure cells. During the construction process of subgrade and pavement, ten dynamic soil pressure cells with a diameter of 180 mm and a height of 22 mm were buried at different depths (0.19 m, 0.62 m, 1.42 m, 2.12 m, and 3.12 m). The horizontal distance of dynamic soil pressure cells (1.83 m) was close to the rear wheel distance of normal heavy-duty trucks in China.

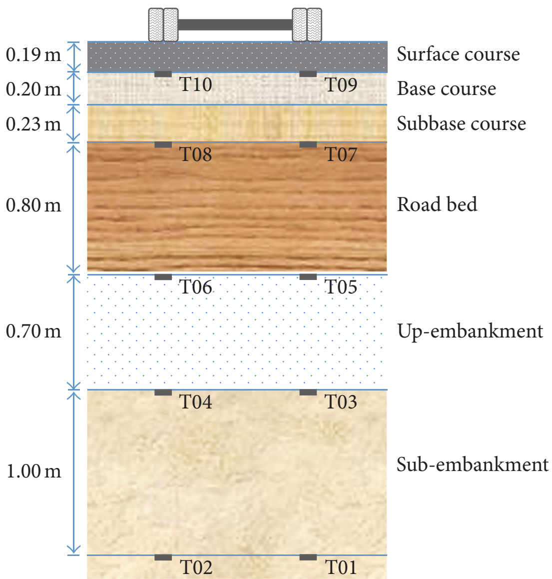

Figure 3: Location and placement of soil pressure cells (units: m).

The dynamic soil pressure cells (BY-1) used in the field tests were produced by Dandong Qiulong Sensor Manufacturing Co., Ltd. The measurement range of the sensor was from 0 to 200 kPa and the sensitivity was 1 mv/v dimension. The operating temperature of the sensor was from −30°C to 60°C.

To avoid the damage of data line during the construction process of subgrade and pavement, cable lines were firstly protected by a soft plastic pipe and the joint between cells and the plastic pipe was twined with waterproof adhesive tape. Then, the sensors were put in a predug groove and covered by soil or asphalt. Figure 4 shows the installation process of sensors.

2.3. Heavy-Duty Truck. A three-axle heavy-duty truck manufactured by FAW Group Corporation is chosen, as shown in Figure 5(a). The dimensions of the test truck are shown in Figures 5(b)–5(d). The length of the whole truck is 8.9 m and the width is 2.5 m. The front axle distance is 3.5 m and the rear axle distance is 1.35 m. The front wheel distance is 2.02 m and the rear wheel distance is 1.83 m.

When the truck runs on the road, the periodic loading is applied on the pavement and subgrade. The periodic frequency is related to the dimensions and speed of the heavy-duty truck. The characteristic frequency can be calculated by

$$f_i = \frac{v}{L_i} \quad i = \mathbf{1}, \mathbf{2}, \mathbf{3}, \tag{1}$$

where f_i is the characteristic frequency of pavement-subgrade generated by moving heavy-duty trucks (Hz), v is the heavy-duty truck's speed (m/s), and L_i is the characteristic distance of the heavy-duty truck. For three-axle heavy-duty trucks, there are three kinds of characteristic distances as follows: the distance of the front axle to the center of the rear double axles ($L_1 = 3.5 + 1.35/2 = 4.175$ m), the distance between the left and the right rear wheel groups ($L_2 = 1.83$ m), and the distance between the rear double axles ($L_3 = 1.35$ m).

Table 2: Field tests under twenty-five working conditions.

Working condition	Truck loading (kN)	Truck speed (km/h)
1		5
2		10
3		20
4		30
5	140	40
6		50
7		60
8		70
9		80
10		5
11		10
12		20
13		30
14	328.9	40
15		50
16		60
17		70
18		80
19		10
20		20
21		30
22	533.8	40
23		50
24		60
25		70

2.4. Test Procedure and Data Acquirement. Before field test, the front axle load and rear two-axle loads were measured by wagon balance. There were three whole truck loadings as follows: 533.8 kN (76.6 kN of front axle and 457.2 kN of rear axles), 328.9 kN (92.4 kN of front axle and 236.5 kN of rear axles), and 140 kN (51.1 kN of front axle and 88.9 kN of rear axles). In addition, the heavy-duty truck speeds were 80 km/h, 70 km/h, 60 km/h, 50 km/h, 40 km/h, 30 km/h, 20 km/h, 10 km/h, and 5 km/h.

A DH3840 signal amplifier instrument and DH5932 signal acquisition system (manufactured by Donghua Testing Technology Co., Ltd.) were adopted to measure the dynamic stress. The sampling frequency was set to 200 Hz. The response of the dynamic stress of pavement-subgrade was recorded by the monitoring system.

Field tests under twenty-five working conditions were performed to investigate the distribution characteristic of dynamic pressure of pavement-subgrade induced by moving heavy-duty trucks. The working conditions are listed in Table 2. The general situation of field tests is shown in Figure 6.

Figure 4: Installation process of the sensor.

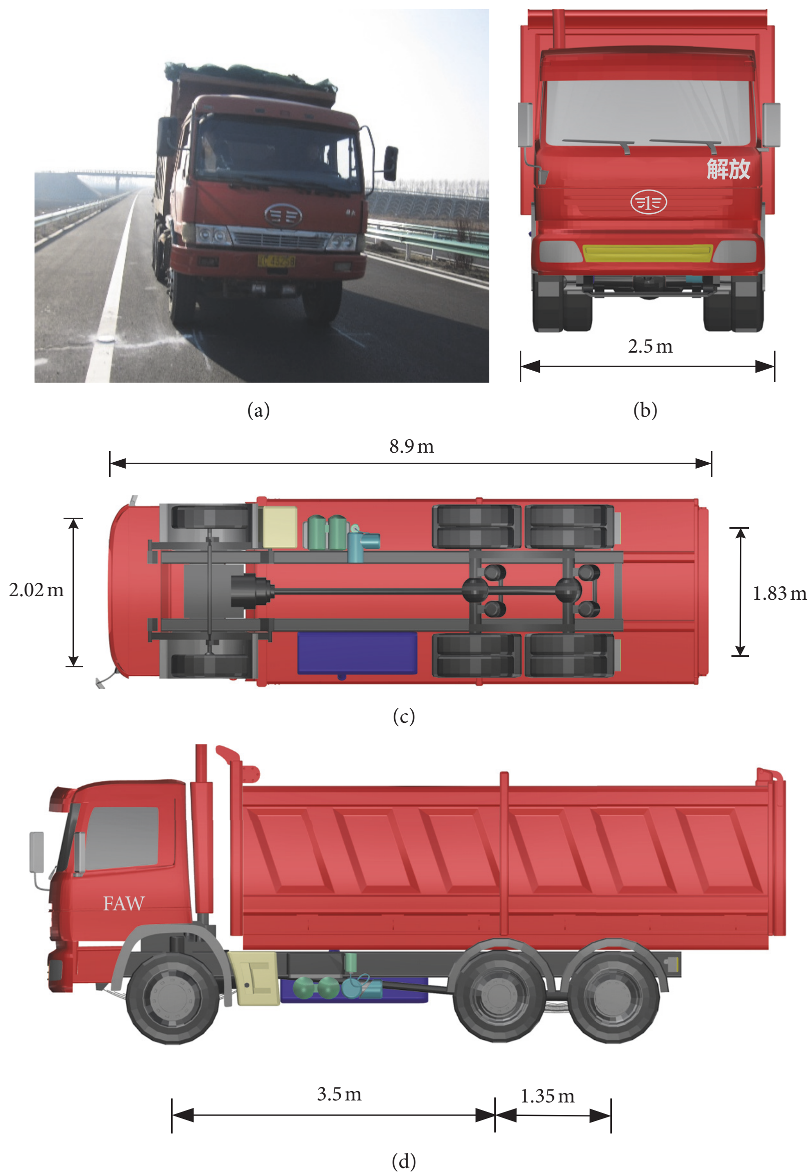

Figure 5: Dimensions of the test truck.

(a) (b) (c)

(d) (e) (f)

Figure 6: General situation of field monitoring.

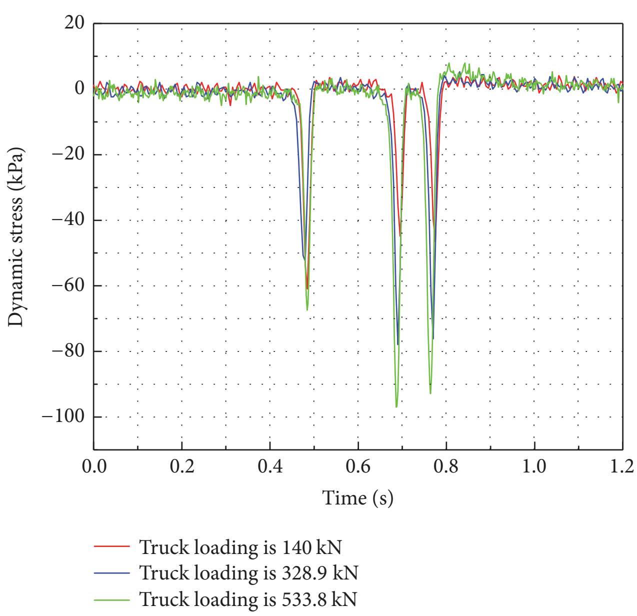

Figure 7: Time history curves of dynamic pressure on the top of the base course under different truck loadings.

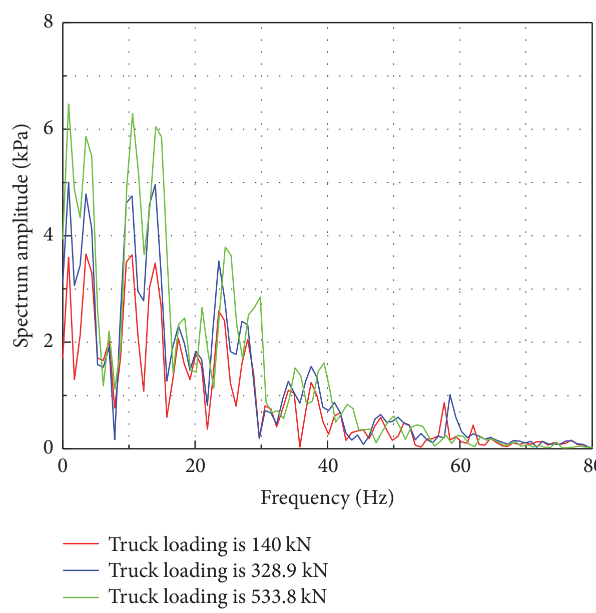

Figure 8: Spectrum curves of dynamic pressure on the top of the base course under different truck loadings.

3. Results and Analysis

3.1. Effect of Truck Loading. Figure 7 shows the time history curves of dynamic pressure on the top of the base course at the truck speed of 70 km/h under different loadings (140 kN, 328.9 kN, and 533.8 kN). It can be seen that there are three compressive stress peaks which are induced by the three axles of heavy-duty trucks and the compressive stress peaks caused by the rear double axles are almost equal. When the whole truck loading is 140 kN, the dynamic compressive stress amplitude caused by the front axle is greater than that caused by the rear double axles. However, when the whole truck loading is 328.9 kN or 533.8 kN, the compressive stress amplitude caused by the front axle is weaker than that caused by the rear double axles. One reason which can explain this phenomenon is that the gravity center of the test truck moves backward as the whole truck loading increases.

As shown in Figure 8, time history curves are converted to spectrum curves by the fast Fourier transformation to

Table 3: Maximum dynamic stress at different truck speeds.

Truck loading (kN)	Depth (m)	Truck speed (km/h)								
		80	70	60	50	40	30	20	10	5
328.9	0.19	−74.9	−79.7	−62.2	−81.9	−75.7	−66.2	−54	−73.9	−72.9
	0.62	−25.3	−27.5	−26.2	−24.8	−24.3	−24.1	−20.9	−20.5	−13.2
	1.42	−24.2	−20.8	−19.7	−19.4	−18.8	−19.7	−18	−18.4	−9.4
	2.12	−15	−12	−15.9	−16.8	−14.7	−14.1	−13.7	−9	−6
	3.12	−9.6	−7.9	−6.3	−8.3	−9.6	−7.6	−7.6	−6.3	−3.6

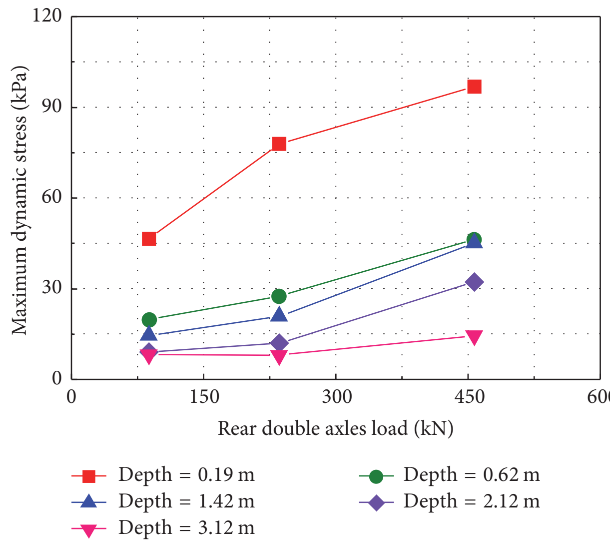

Figure 9: Relationship between rear double axles load and maximum dynamic stress.

analyze the frequency-domain characteristics. The significant frequency components are between 0 and 50 Hz. Figure 8 also indicates that the first dominant frequency is 0.83 Hz. The second dominant frequency is 3.9 Hz and it is close to the characteristic frequency ($f_1 = 4.65$ Hz) caused by L_1 of heavy-duty trucks. The third dominant frequency is 10.16 Hz and it is close to the characteristic frequency ($f_2 = 10.63$ Hz) caused by L_2 of heavy-duty trucks. The fourth dominant frequency is 14.06 Hz and it is close to the characteristic frequency ($f_3 = 14.4$ Hz) caused by L_3 of heavy-duty trucks. The reason why the three dominant frequencies are smaller than the three characteristic frequencies caused by heavy-duty trucks is that some of the vibration components are absorbed by asphalt concrete pavement. Furthermore, it can be observed that dominant frequencies are identical while the spectrum amplitude is different when the whole truck loading increases from 140 kN to 533.8 kN.

Figure 9 shows the relationship between the maximum dynamic stress and the rear double axles load at a truck speed of 70 km/h at different depths. It can be seen that the rear double axles load plays a significant role in the dynamic stress of pavement-subgrade and the maximum dynamic stress increases with the increase of truck loading for a certain depth. In addition, when the rear double axles load increases from 88 kN to 457 kN, the maximum dynamic stress amplitude increases from 46.6 kPa to 96.9 kPa which means a 107 percent growth can be found.

3.2. Effect of Truck Speed. Figure 10 shows the time history curves of dynamic stress on the top of the base course at the speeds of 5 km/h, 10 km/h, 20 km/h, 30 km/h, 40 km/h, 50 km/h, 60 km/h, 70 km/h, and 80 km/h when the truck loading is 328.9 kN. The three obvious dynamic stress peaks are induced by the three axles of heavy-duty trucks. In addition, the maximum dynamic stress is caused by the front axle for the truck speeds of 5 km/h, 10 km/h, 20 km/h, 50 km/h, and 80 km/h. It seems that the pitching motion of moving heavy-duty trucks can account for this phenomenon. During the pitching down process, the gravity center of the test truck moves forward and the front wheels have bigger dynamic stress.

Table 3 shows the maximum dynamic stresses at different truck speeds. It could be seen that truck speed has a certain effect on dynamic pressure. The dynamic pressure amplitudes of measuring points in up-embankment and subembankment increase with the increase of truck speed. Park et al. [30], Xia et al. [31], and Feng et al. [32] also found that dynamic pressure exhibited an increasing tendency with increasing truck speed. The possible reason is that high frequency vibrations are absorbed by soil and the vibrations with low frequency become the dominant vibrations gradually as the truck loading transfers from top to bottom.

Figure 11 shows the spectrum curves of dynamic stress on the top of the base course at different speeds (5 km/h, 10 km/h, 30 km/h, 50 km/h, and 70 km/h) when truck loading

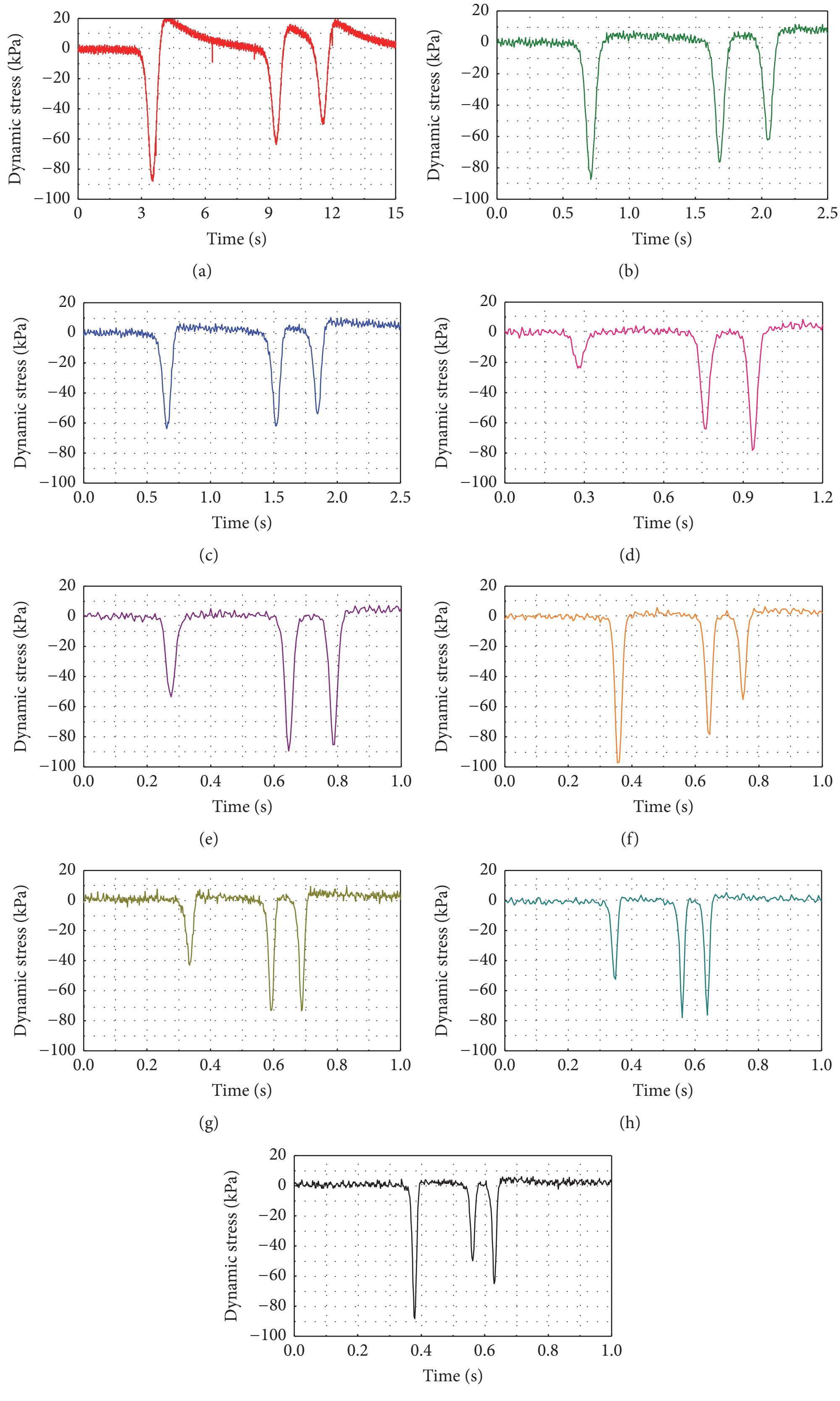

Figure 10: Time history of dynamic pressure on the top of the base course at different truck speeds: (a) 5 km/h, (b) 10 km/h, (c) 20 km/h, (d) 30 km/h, (e) 40 km/h, (f) 50 km/h, (g) 60 km/h, (h) 70 km/h, and (i) 80 km/h.

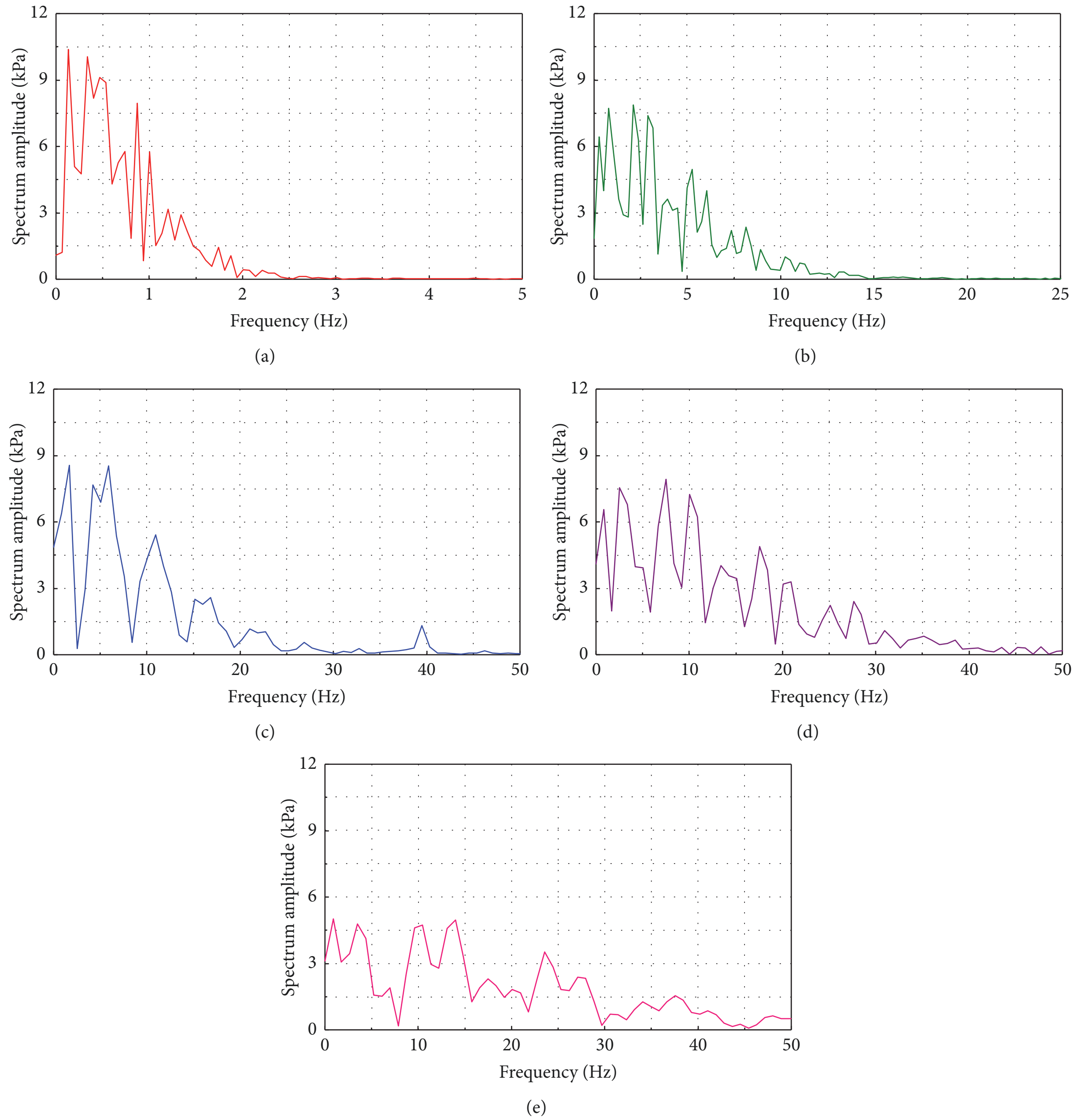

Figure 11: Spectrum curves of dynamic stress on the top of the base course when the truck's speed is (a) 5 km/h, (b) 10 km/h, (c) 30 km/h, (d) 50 km/h, and (e) 70 km/h.

is 328.9 kN. It is evident that the frequency range increases with increasing truck speed and the dominant frequency with a range of 0 to 2 Hz at the speed of 5 km/h becomes that with a range of 0~50 Hz at the speed of 70 km/h. Figure 12 shows the relationship between truck speed and dominant frequency of dynamic stress on the top of the base course. The first three dominant frequencies increase with the increase of truck speed. When the truck speed is 5 km/h, the first three dominant frequencies are 0.13 Hz (f_1), 0.33 Hz (f_2), and 0.47 Hz (f_3), respectively. When truck speed is 70 km/h, the first three dominant frequencies increase to 3.49 Hz (f_1), 10.48 Hz (f_2), and 13.97 Hz (f_3), respectively.

3.3. Effect of Depth. Figure 13 shows the dynamic pressure time history curves and spectrum curves at different depths when truck loading is 533.8 kN and truck speed is 60 km/h. The dynamic pressure time history curves show that the influence of the front axle decreases gradually until disappearing and the compressive stress superposition phenomenon caused by rear double axles can be found with increasing depth. The maximum dynamic stress decreases from 84.6 kPa to 10.9 kPa as depth increases from 0.19 m to 3.12 m. Besides, high frequency vibrations are absorbed by soil with increasing depth. Therefore, the dominant frequency is only 1 Hz when depth is 3.12 m.

Table 4: Maximum dynamic stresses under different truck loadings.

Truck loading (kN)	Depth (m)	Truck speed (km/h)								
		80	70	60	50	40	30	20	10	5
533.8	0.19	-	−81.9	−84.6	−82.7	−86.1	−83.7	−80.7	−94.6	-
	0.62	-	−46.4	−48	−50.7	−44.3	−36.8	−34.6	−28.4	-
	1.42	-	−45.1	−41.4	−42.5	−39.4	−39.4	−33.9	−31.7	-
	2.12	-	−32.3	−21.3	−21	−23.7	−22.8	−16.5	−18.6	-
	3.12	-	−14.6	−10.9	−11.3	−13.9	−16.9	−12.9	−12.9	-

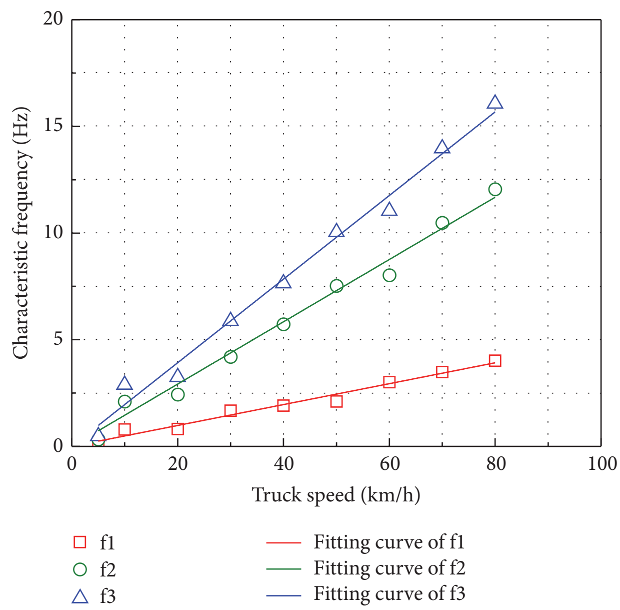

Figure 12: Relationship between truck speed and dominant frequency on the top of the base layer.

Table 4 shows the maximum dynamic stresses under different truck loadings. In general, dynamic pressure amplitude decreases dramatically with the increase of depth. This conclusion is consistent with the results of Park et al. [30], Xia et al. [31], and Feng et al. [32]. Table 4 also demonstrates that the greatest attenuation ratio of dynamic pressure is 87% as depth increases from 0.19 m to 3.12 m. The dynamic pressure amplitudes are between 30 kPa and 50 kPa on the top of the up-embankment and are between 10 kPa and 20 kPa when the depth is 3.12 m.

4. Conclusions

Field experiments were carried out with the purpose of investigating the dynamic compressive stress response of pavement-subgrade induced by moving heavy-duty trucks. The effects of truck loading, truck speed, and depth on amplitude and frequency of dynamic stress were analyzed. Based on measured results, the salient findings are summarized as follows.

(1) The dynamic pressure amplitude of each measuring point is strongly influenced by truck loading. The rear double axles load plays a significant role in the dynamic stress of pavement-subgrade and the maximum dynamic stress increases with increasing truck loading for a certain depth. Furthermore, dominant frequencies are identical while the spectrum amplitude is different when the whole truck loading increases from 140 kN to 533.8 kN.

(2) Truck speed has a certain effect on dynamic pressure. The dynamic pressure amplitudes of measuring points in the up-embankment and subembankment increase with the increase of truck speed. Moreover, the frequency range increases with increasing truck speed and the dominant frequency with a range of 0 to 2 Hz at the speed of 5 km/h becomes that with a range of 0 to 50 Hz at the speed of 70 km/h.

(3) The dynamic pressure amplitudes are between 30 kPa and 50 kPa on the top of the up-embankment and are between 10 kPa and 20 kPa when depth is 3.12 m. The dynamic pressure amplitude decreases dramatically with the increase of depth and the greatest attenuation ratio of dynamic pressure is 87%. The dominant frequency is only 1 Hz when depth is 3.12 m because high frequency vibrations are absorbed by soil with increasing depth.

Conflicts of Interest

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

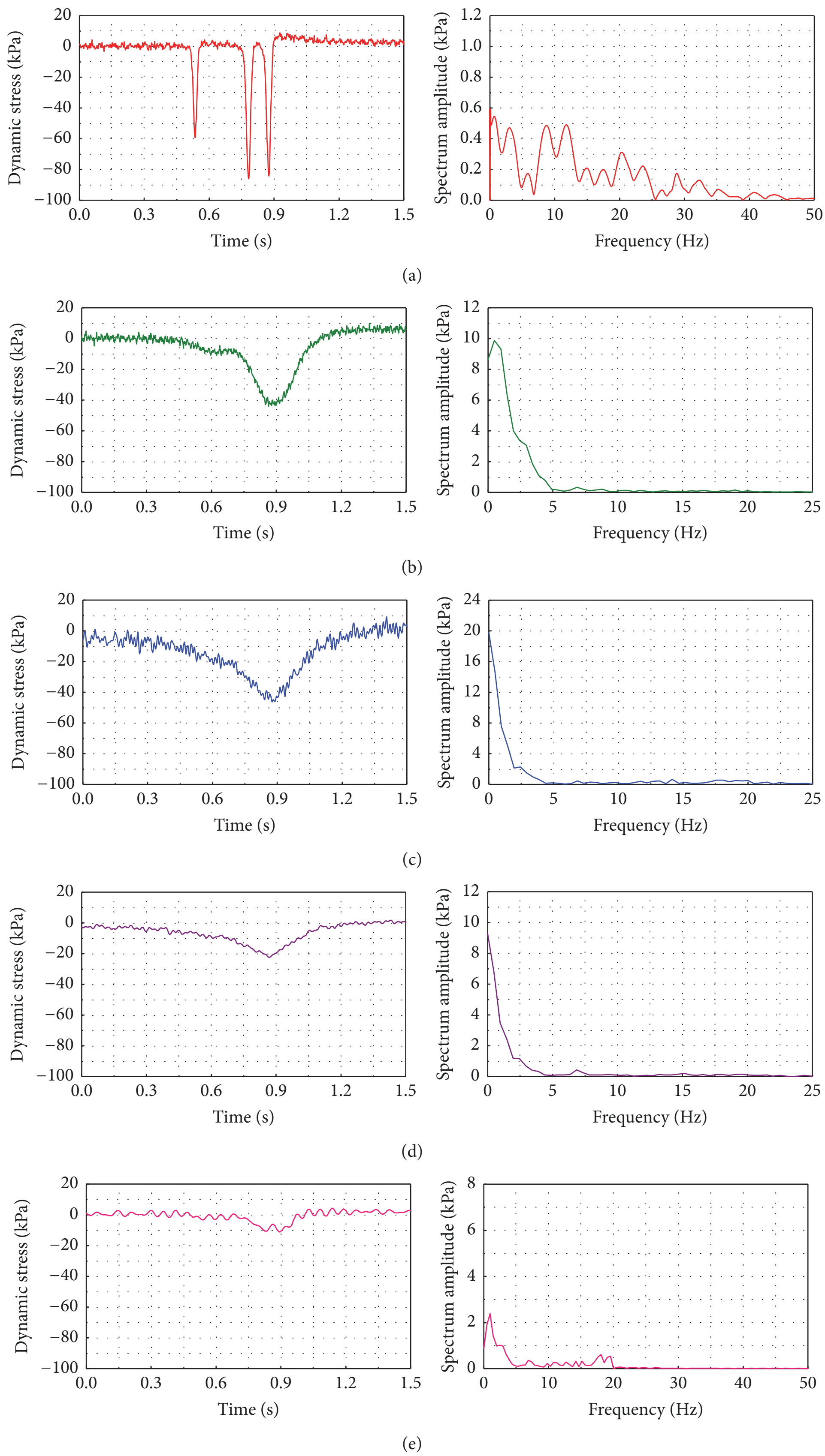

Figure 13: Dynamic pressure time history and spectrum curves when the depth is (a) 0.19 m, (b) 0.62 m, (c) 1.42 m, (d) 2.12 m, and (e) 3.12 m.

Acknowledgments

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