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Roughness evaluation of three-dimensional asphalt pavement based on two-dimensional power spectral density

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Abstract: To solve the problem of the lack of comprehensive evaluation of three-dimensional (3D) asphalt pavement roughness, a method for evaluating the asphalt pavement roughness is proposed based on two-dimensional (2D) power spectral density (PSD). By calculating the 2D PSD of a 3D asphalt pavement and converting it into the longitudinal average asphalt pavement PSD, the relationship between the evaluation method of the 3D asphalt pavement roughness and the current evaluation standard of roughness is established. Combined with the road-fitting formula used in international standards, the elevation data of the A, B, C, and D grades of the 3D asphalt pavement are simulated by the harmonic superposition method. According to the proposed method, the longitudinal PSD of each level of simulated asphalt pavement is calculated and compared with the standard spectral line of each pavement level. This approach verifies the effectiveness of the proposed method in evaluating the roughness of the 3D asphalt pavement. Compared with the PSD of a certain horizontal profile elevation, it is verified that the fluctuation amplitude of the spectral line calculated by the proposed method is greatly improved. The results show that the proposed method can evaluate the roughness of asphalt pavements more comprehensively and accurately and has strong practicability.

Key words: roughness; power spectral density; three-dimensional asphalt pavement

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Roughness is one of the main technical indicators for evaluating the quality of asphalt pavements and ensuring driving safety and comfort. The American Society for Testing and Materials defines road roughness as the vertical deviation of the road surface from the ideal plane[1]. Studies have shown that the deterioration and uneven distribution of asphalt pavement quality causes several crash accidents[2], affects driving speed, increases the rolling resistance of driving, accelerates the degradation of automobile parts, and increases automobile maintenance costs[3]. Additionally, uneven asphalt pavement surfaces stimulate vehicles to produce vertical dynamic loads, which are reflected on the asphalt pavements, aggravating the occurrence of asphalt pavement disease.

Among many indicators for evaluating asphalt pavement roughness, the international roughness index (IRI) is the most widely used. Other indicators include the power spectral density (PSD), profile index, and vertical acceleration root mean square[4]. Since asphalt pavement profiles comprise short, medium, and long waves with different characteristics, the roughness characteristics of asphalt pavement profiles can be investigated by analyzing the elevation, velocity, and acceleration variations under different frequencies[5].

Generally, roughness detection technology can be divided into reaction and section types according to the detection principle[6]. It mainly includes the three-meter ruler method, the continuous roughness meter, the hand-push roughness meter, the vehicle-mounted bump accumulator, and the vehicle-mounted laser roughness meter.

With the development of information technology, machine vision has been widely used in several fields, such as robotics and automation, with the advantages of rich information, good timeliness, small size, and low energy consumption[7]. RGB-D sensors[8], binocular vision technology[9], and other technologies are used to obtain more comprehensive three-dimensional (3D) information on asphalt pavement. The transverse and longitudinal sections of 3D asphalt pavements have height changes. Compared with the traditional detection methods, these new detection technologies can obtain the longitudinal and transverse elevation data of asphalt pavement. Conventionally, the calculation method of asphalt pavement roughness is mainly for the longitudinal.

Herein, a new method for calculating the elevation longitudinal roughness of 3D asphalt pavements based on the 2D PSD is proposed. The rest of this manuscript is arranged as follows: Firstly, the roughness index of the PSD and the 3D harmonic superposition simulation method of asphalt pavements are introduced. Next, a new calculation method for evaluating the longitudinal roughness of 3D asphalt pavement elevation is proposed. Further-

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more, the 3D asphalt pavements from grade A to D are simulated, and the effectiveness of the proposed method is verified by experimental comparison.

1 Basic Theory

1.1 PSD evaluation of pavement roughness

Several measured data have shown that the elevation of road profiles is generally considered a random phenomenon. In the time domain, it is a stationary random process of all states[10]. As the input of vehicle vibration, the statistical characteristics of road roughness are mainly described by the road PSD. According to the random process theory, the road PSD can be used to analyze the road profile and represent the variations in the variables at different frequencies (wavelengths). Therefore, the unevenness of the road profile can be analyzed by the variations in elevation, velocity and acceleration under different frequencies (wavelengths).

In the 1970s, the International Standard Organization (ISO) proposed the PSD index, which realized the evaluation of road surface profile texture at different scales. According to the road surface spectrum frequency index, road surface roughness is divided into eight grades from A to H in the international standard. In the Road Surface Roughness Representation Method Draft [11] proposed by ISO/TC108/SC2N67, the PSD of the road roughness $G_q(n)$ is expressed as

$$G_q(n) = G_q(n_0)\left(\frac{n}{n_0}\right)^{-\omega} \tag{1}$$

where $n_0 = 0.1\ \mathrm{m}^{-1}$ is the spatial reference frequency; $G_q(n_0)$ is the roughness coefficient corresponding to the road grade; ω is the frequency index, which determines the frequency structure of the road PSD under general conditions, and n is a frequency in the space-frequency effective band. The spatial frequency bandwidth is $[n_1, n_2]$.

The PSD curve is a spectral density curve with spatial frequency as the horizontal axis and the finite mean square value within the range of unit spatial frequency or spatial angular frequency as the vertical axis. It can represent the distribution of road roughness energy in the spatial frequency domain and describe the structure of road waves. Therefore, it is called the road vertical displacement PSD, or road spectrum for short.

The range and geometric mean values of grade A to H road roughness coefficients are presented in Tab. 1, and the frequency index of the graded pavement spectrum $\omega = 2$. The grading diagram of road roughness is shown in Fig. 1; the graph is expressed in double logarithmic coordinates. The logarithmic coordinates expand the dynamic range of the expression, and the low-power part of the high-frequency end is graphically amplified, whereas the high-frequency power is an important part of the road excitation.

Tab. 1 Classification standard for road roughness

Road grade	$G_q(n_0)/\mathrm{cm}^3$ ($n=0.1\ \mathrm{m}^{-1}$) Lower limit	Geometric mean	$\sigma_q/10^{-3}\ \mathrm{m}^2$ ($0.011<n<2.83\ \mathrm{m}^{-1}$) Upper limit	Geometric mean
A	8	16	32	3.81
B	32	64	128	7.61
C	128	256	512	15.23
D	512	1 024	2 048	30.45
E	2 048	4 096	8 192	60.90
F	8 192	16 384	32 768	121.80
G	32 768	65 536	131 072	243.61
H	131 072	262 144	524 288	487.22

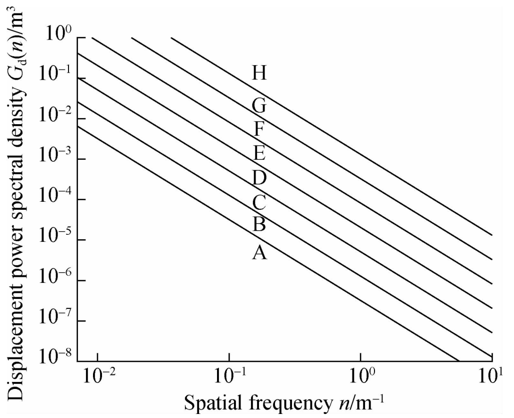

Fig. 1 Grading diagram of road roughness

1.2 Harmonic superposition method for 3D asphalt pavement simulation

The transverse and longitudinal sections of 3D asphalt pavement have height changes (see Fig. 2), which have an impact on the assessment of roughness. According to the statistical characteristics of the road spectrum, road elevation is a Gaussian process of smooth traversal with a mean of zero. Therefore, different forms of trigonometric series can be used for simulation.

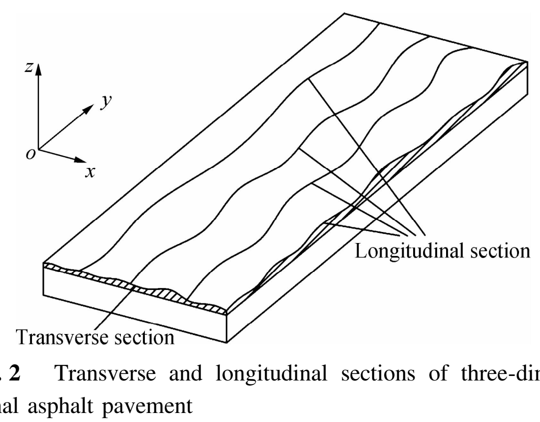

Fig. 2 Transverse and longitudinal sections of three-dimensional asphalt pavement

The standard asphalt pavement roughness within a limited range of spatial frequencies can be obtained by the superposition of harmonic components of the asphalt pavement roughness at the central frequency between each partition, as follows[12]:

$$q(x) = \sum_{i=1}^{m} \sqrt{2G_q(n_{\text{mid}-i})\Delta n}\sin(2\pi n_{\text{mid}-i}x + \theta_i) \quad (2)$$

where $n_{\text{mid-}i}$ is the central frequency between each cell, where $i = 1, 2, \ldots, m$; $\theta_i \in [0, 2\pi]$ is a random number with interval uniform distribution; Δn is the sampling interval of the spatial frequency.

To build a random 3D asphalt pavement and increase the elevation distribution of the transverse profile, Eq. (2) needs to be extended, as follows [13]:

$$q(x, y) = \sum_{i=1}^{m} \sqrt{2G_q(n_{\text{mid}-i})\Delta n} \cdot \sin\left(2\pi n_{\text{mid}-i}\sqrt{x^2 + y^2} + \theta_i(x, y)\right) \quad (3)$$

where x is the longitudinal position of the random asphalt pavement, y is the transverse position of the random asphalt pavement, and $\theta_i(x, y)$ is the random number between $[0, 2\pi]$ of any line y on the asphalt pavement.

2 Evaluation Method of 3D Asphalt Pavement Roughness

2.1 Two-dimensional PSD of 3D asphalt pavement

In the Euclidean coordinate system, the three-dimensional asphalt pavement can be represented by a function $z(x, y)$ of two variables x and y, where z is the vertical coordinate of the actual surface relative to the theoretical surface height at position (x, y). The two-dimensional Fourier transform of $z(x, y)$ is given as follows:

$$Z(f_x, f_y) = \int_0^{L_x}\int_0^{L_y} z(x, y) \cdot \exp\left[-\text{j}2\pi(xf_x + yf_y)\right]\text{d}x\text{d}y \quad (4)$$

where f_x and f_y are the spatial frequencies in the x and y directions; and L_x ad L_y are the lengths of the 3D asphalt pavements in the x and y directions, respectively.

The collected asphalt pavement elevation is discretized. Thus, sampling is performed with sampling pitches Δx and Δy in the spatial region in the x and y directions, respectively, to obtain a spatial surface with a lattice size of $M \times N$. Then, the spatial frequencies in the x and y directions of the spatial surface are discretized as $f_p = p/(M\Delta x)$ $(p = 0, 1, 2, \ldots, M-1)$, and $f_q = q/(N\Delta y)$ $(q = 0, 1, 2, \ldots, N-1)$, respectively. Its 2D discrete Fourier transform is given as follows:

$$Z(f_p, f_q) = \Delta x\Delta y\left|\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} z(m, n) \cdot \exp\left[-\text{j}2\pi\left(\frac{p}{M}m + \frac{q}{N}n\right)\right]\right|$$
$$0 \leqslant p \leqslant M-1, \quad 0 \leqslant q \leqslant N-1 \quad (5)$$

Its 2D PSD calculation equation is expressed as

$$\text{PSD}(f_q, f_q) = \frac{\Delta x\Delta y}{MN}\left|\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} z(m, n) \cdot \exp\left[-\text{j}2\pi\left(\frac{p}{M}m + \frac{q}{N}n\right)\right]\right|^2$$
$$0 \leqslant p \leqslant M-1, \quad 0 \leqslant q \leqslant N-1 \quad (6)$$

To solve the problem of the side lobe leakage in the PSD spectrum, the Hanning window was used for preprocessing. The definition of the 2D Hanning window (normalized window energy) is given as follows:

$$w_{2h}(m, n) = \frac{2}{3}\left[1 - \cos\left(\frac{2\pi m}{M-1}\right)\right]\left[1 - \cos\left(\frac{2\pi n}{N-1}\right)\right]$$
$$0 \leqslant m \leqslant M-1, \quad 0 \leqslant n \leqslant N-1 \quad (7)$$

The 2D PSD of the 3D asphalt pavement elevation processed by the Hanning window is given as follows:

$$\text{PSD}(f_q, f_q) = \frac{\Delta x\Delta y}{MN}\left|\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} z(m, n)\,w_{2h}(m, n) \cdot \exp\left[-\text{j}2\pi\left(\frac{p}{M}m + \frac{q}{N}n\right)\right]\right|^2$$
$$0 \leqslant m \leqslant M-1, \quad 0 \leqslant n \leqslant N-1 \quad (8)$$

2.2 Longitudinal mean PSD

The roughness index mainly reflects the roughness of the longitudinal profile curve. Therefore, it is necessary to convert the 2D PSD into a 1D PSD for the longitudinal pavement evaluation. When the spectrum varies only in a fixed direction, the 1D PSD can be calculated from the 2D PSD. Assuming that the x-direction is the direction of the frequency change, the specific equation is given as follows:

$$\text{PSD}_{\text{1D}}(v_x) = \int_{-x}^{x} \text{PSD}_{\text{2D}}(v_x, v_y)\,\text{d}v_y \quad (9)$$

The discrete form is given as follows:

$$\text{PSD}(v_m) = \sum_{m=0}^{M-1} \text{PSD}(v_m, v_n)\,\Delta v_n \quad (10)$$

Therefore, after the conversion to the longitudinal 1D PSD, the equation is given as follows:

$$\text{PSD}(f_q) = \sum_{m=0}^{M-1}\left(\frac{\Delta x\Delta y}{MN}\left|\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} z(m, n)\,w_{2h}(m, n) \cdot \exp\left[-\text{j}2\pi\left(\frac{p}{M}m + \frac{q}{N}n\right)\right]\right|^2\right)\frac{1}{N\Delta y}$$
$$0 \leqslant p \leqslant M-1, \quad 0 \leqslant q \leqslant N-1 \quad (11)$$

3 Experimental Verification

3.1 Three-dimensional asphalt pavement simulation

The roughness of the road displacement can be expressed as $q = q(l)$, where the independent and dependent variables are the length and height, both of which are unit dimensions of length. Also, $q(l)$ is the infinite signal in the time domain. In engineering, a section of asphalt pavement with length L is usually selected for research. The value of L should ensure the spatial frequency resolution. The spatial frequency of the road roughness signal is between 0.011 and 2.83 m^{-1}, so the minimum identification frequency is $\Delta n = 1/L \leqslant 0.011$, that is, $L \geqslant 91$ m.

According to the sampling theorem, the sampling frequency satisfies the condition when $n_s \geqslant 2n_{max}$. Then, the sampling intervals Δx and Δy in the x and y directions should meet the following condition:

$$\frac{1}{\Delta x} \geqslant 2n_{max}, \quad \frac{1}{\Delta y} \geqslant 2n_{max} \tag{12}$$

Therefore, $\Delta x \leqslant 0.1767$ m and $\Delta y \leqslant 0.1767$ m. Herein, $\Delta x = 0.1$ m, $\Delta y = 0.1$ m, $L_x = 160$ m, and $L_y = 6$ m.

According to Tab. 1, the geometric mean value of the grade A road roughness coefficient is selected, and the elevation of grade A 3D asphalt pavement is simulated according to the harmonic superposition method of Eq. (3). Similarly, the corresponding roughness coefficients of grades B, C, and D are selected to simulate the corresponding level of the 3D asphalt pavement elevation according to Eq. (3). The 3D elevation of grades A-D asphalt pavement is shown in Fig. 3.

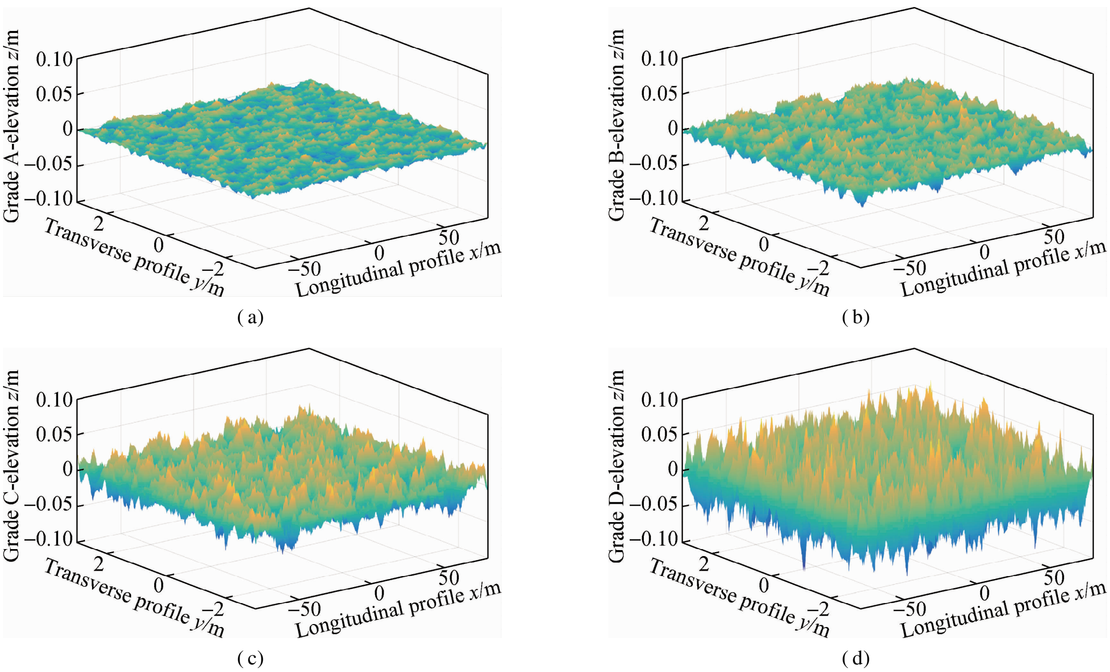

Fig. 3 Three-dimensional elevation of grades A-D asphalt pavements. (a) Grade A; (b) Grade B; (c) Grade C; (d) Grade D

3.2 Validity verification

The steps to verify the effectiveness of the method herein are as follows:

1) The 2D PSD is calculated using the 3D elevation data. According to the elevation data of grades A-D 3D asphalt pavement simulated in Section 3.1, Eq. (8) is used to calculate the 2D PSD of the corresponding elevation data. The 2D power spectral densities of grades A-D asphalt pavements are shown in Fig. 4.

2) The 2D PSD of the 3D road surface is converted into the 1D longitudinal PSD. Since the current roughness index reflects the roughness of the longitudinal profile curve, Eq. (11) is used to calculate the longitudinal 1D power spectral densities of grades A-D.

3) The power spectrum calculated by this method is compared with the standard road spectrum. The 1D power spectrum density spectrum is compared with the corresponding standard pavement spectrum. The comparison results under grades A-D asphalt pavements are shown in Fig. 5.

According to Fig. 5, in the space-frequency range, the PSD lines of grades A-D 3D asphalt pavements calculated by the method herein are very consistent with the standard spectral lines of the corresponding grades. Therefore, the method presented herein is feasible for evaluating the roughness of 3D asphalt pavements.

3.3 Comparison with traditional methods

According to the national standard [14], the roughness is usually tested using the eight-wheel instrument or the laser roughness profiler as an interval every 100 m to calculate the PSD or IRI of a longitudinal profile. Therefore, the traditional method is used to evaluate the roughness of a profile. Then, to verify the advantages of this method over the traditional method, the PSD of a horizontal profile is calculated and compared with the results of this method.

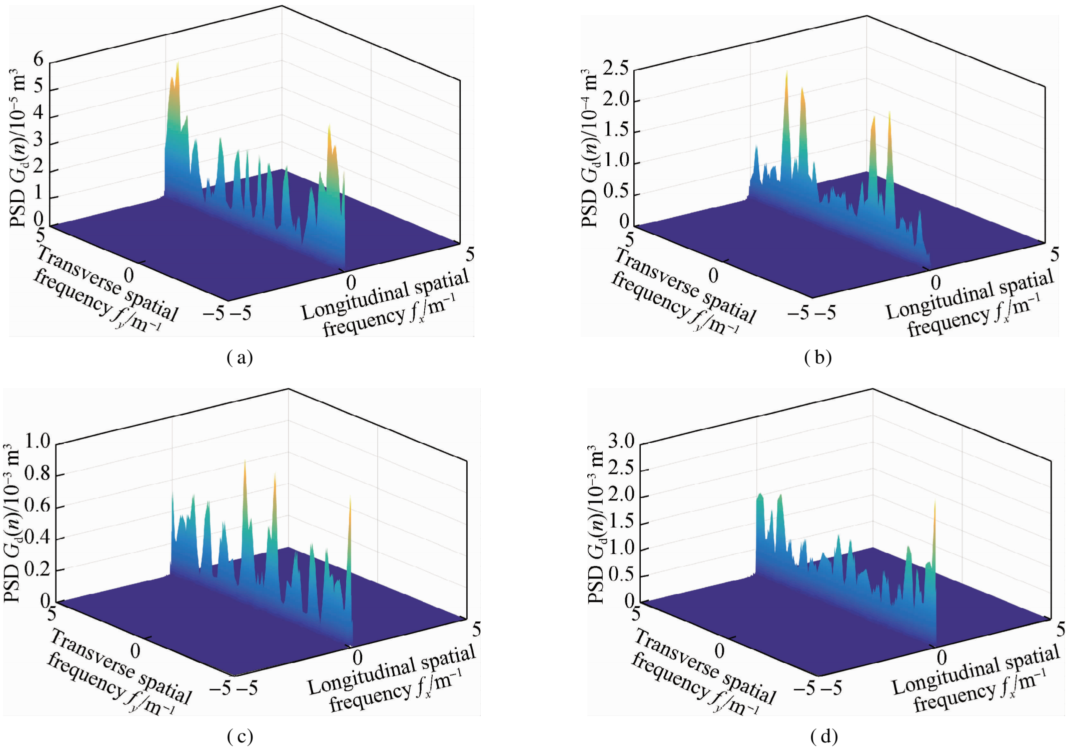

Fig. 4 Two-dimensional power spectral densities of grades A-D asphalt pavements. (a) Grade A; (b) Grade B; (c) Grade C; (d) Grade D

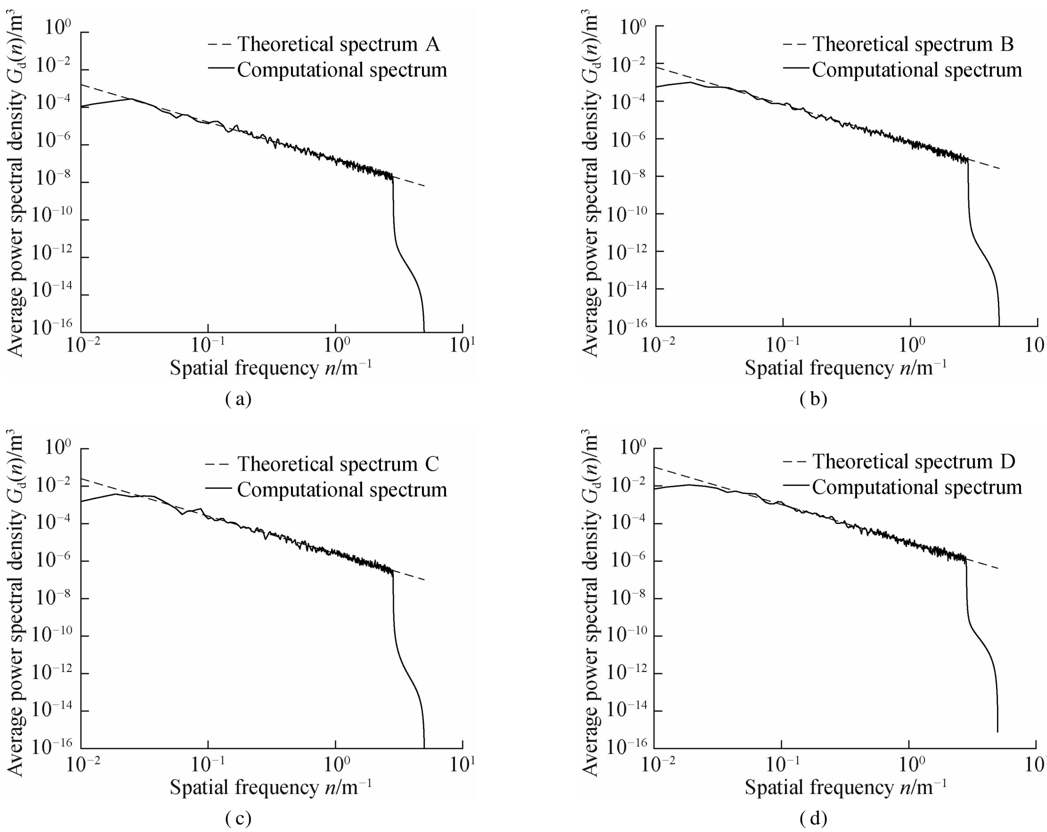

Fig. 5 Comparison diagram with standard spectrum under grades A-D asphalt pavements. (a) Grade A; (b) Grade B; (c) Grade C; (d) Grade D

The comparison steps between the method herein and the traditional method are as follows:

1) The 3D asphalt pavement simulation data in Section 3.2 was selected for experimental verification.

2) The longitudinal 1D PSD of the 3D asphalt pavement is calculated by the method herein.

3) The longitudinal section elevation data is selected at the transverse 2 m ($y=2$ m) of the simulation pavement at all levels, and the corresponding PSD is calculated.

The comparison results with the method herein are shown in Fig. 6.

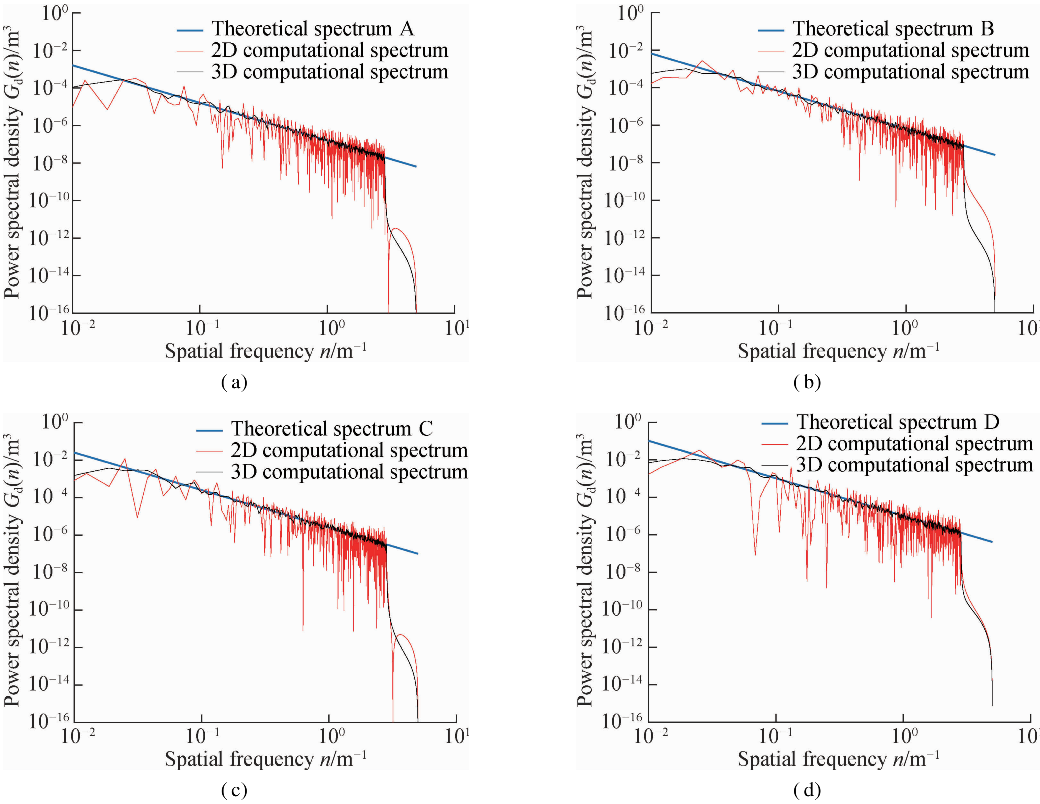

Fig. 6 Comparison with traditional method under grades A-D asphalt pavements. (a) Grade A; (b) Grade B; (c) Grade C; (d) Grade D

Tab. 2 Performance comparison between the proposed and traditional methods

Road grade	Gradient/m⁴			Standard deviation/m³		
	Standard Spectrum	Traditional method	Proposed method	Standard spectrum	Traditional method	Proposed method
A	−2.00	−1.935 6	−1.988 7	0	0.939 0	0.244 2
B	−2.00	−2.138 2	−1.987 9	0	0.822 2	0.239 2
C	−2.00	−2.148 7	−1.991 5	0	0.967 7	0.255 2
D	−2.00	−1.793 8	−1.973 6	0	0.950 5	0.235 8

The PSD calculated from the elevation data of the transverse and longitudinal profiles fluctuates greatly (see Fig. 6). The PSD spectrum of each grade obtained by this method is very consistent with the standard spectrum of the corresponding grade, and the fluctuation of the spectrum is reduced. The gradient of the standard spectral line is −2. Assuming that the variance of the standard spectral line is zero, the performance index obtained by correcting the spectral line calculated by the traditional and proposed methods is shown in Tab. 2. The method proposed herein has a certain degree of improvement compared with the traditional method of calculating the spectral line slope (see Tab. 2). In terms of the spectral line fluctuation, the standard deviation calculated by the traditional method is generally 0.8 to 0.9, and the standard deviation calculated by the method proposed herein is ~0.24, with a significant improvement. Therefore, it can be proved that the method presented herein can better evaluate the roughness of 3D asphalt pavements and has high evaluation accuracy.

4 Conclusions

1) Based on the elevation data of simulated 3D asphalt pavements, this study finally deduces the equation of the longitudinal average PSD of 3D asphalt pavement by studying the 2D PSD of 3D asphalt pavements to adapt to the evaluation standard of the pavement roughness in the current standard.

2) The simulation case shows that the spectral lines calculated by the method herein are consistent with the standard spectral lines. Besides, the evaluation of the roughness of 3D asphalt pavements is more comprehensive and accurate.

3) The 2D PSD contains the frequency information of

the 2D surface and reflects the influence of different wavelengths in different directions. This information is important for evaluating the roughness of asphalt pavements.

References

[1] Zamora Alvarez E J, Ferris J B, Scott D, et al. Development of a discrete roughness index for longitudinal road profiles[J]. *International Journal of Pavement Engineering*, 2018, **19**(12): 1043 - 1052. DOI: 10.1080/10298436.2016.1237180.

[2] Lee J, Abdel-Aty M, Nyame-Baafi E. Investigating the effects of pavement roughness on freeway safety using data from five states[J]. *Transportation Research Record: Journal of the Transportation Research Board*, 2020, **2674**(2): 127 - 134. DOI: 10.1177/0361198120905834.

[3] Sime M, Bailey G, Hajj E Y, et al. Impact of pavement roughness on fuel consumption for a range of vehicle types[J]. *Journal of Transportation Engineering, Part B: Pavements*, 2021, **147**(3): 04021022. DOI: 10.1061/jpeodx.0000272.

[4] Zhou X Q, Sun L J, Yan L. Development and trend of pavement evenness evaluation [J]. *Highway Transportation Technology*, 2005(10): 18 - 22. (in Chinese)

[5] Wang D W, Wang C H, Bernhard S, et al. Overview on evaluation methods of pavement evenness for pavements without speed limitations in Germany[J]. *China Journal of Highway and Transport*, 2019(4): 105 - 113, 129. (in Chinese)

[6] Zhang Z, Zhang H L, Xu S, et al. Pavement roughness evaluation method based on the theoretical relationship between acceleration measured by smartphone and IRI [J]. *International Journal of Pavement Engineering*, 2022, **23**(9): 3082 - 3098. DOI: 10.1080/10298436.2021.1881783.

[7] Yu H. Mechanical parts defect detection method based on computer vision technology[C]//2015 *Seventh International Conference on Measuring Technology and Mechatronics Automation*. Nanchang, China, 2015: 630 - 633. DOI: 10.1109/ICMTMA.2015.158.

[8] Mahmoudzadeh A, Golroo A, Jahanshahi M R, et al. Estimating pavement roughness by fusing color and depth data obtained from an inexpensive RGB-D sensor[J]. *Sensors* (*Basel, Switzerland*), 2019, **19**(7): 1655. DOI: 10.3390/s19071655.

[9] Dong X D, Lou P, Yan J W, et al. A detection method for pavement roughness with binocular vision[C]//*Proc SPIE* 11373, *Eleventh International Conference on Graphics and Image Processing* (*ICGIP* 2019). Hangzhou, China, 2020, 11373: 613 - 619. DOI: 10.1117/12.2557811.

[10] Sun L. Simulation of pavement roughness and IRI based on power spectral density[J]. *Mathematics and Computers in Simulation*, 2003, **61**(2): 77 - 88. DOI: 10.1016/S0378-4754(01)00386-X.

[11] Papagiannakis A T, Raveendran B. International standards organization-compatible index for pavement roughness[J]. *Transportation Research Record: Journal of the Transportation Research Board*, 1998, **1643**(1): 110 - 115. DOI: 10.3141/1643-14.

[12] Niu K, Li C. Simulation of pavement roughness based on time domain model [J]. *Journal of Southeast University* (*English Edition*), 2010, **26**(3): 475 - 479. DOI: 10.3969/j.issn.1003-7985.2010.03.021.

[13] Huang Z Q, Zheng W H. Modeling of ADAMS 3D random road with Matlab[J]. *Modern Defence Technology*, 2018, **46**(3): 165 - 170. (in Chinese)

[14] Zhou J. Study on field test procedures for highway subgrade and pavement [J]. *Building Materials and Decoration*, 2018, (47): 274. (in Chinese)

基于二维功率谱密度的三维沥青路面平整度评估

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摘要:为了解决全面评估三维沥青路面平整度的问题,基于二维功率谱密度提出了评估三维沥青路面平整度的方法.通过计算三维沥青路面的二维功率谱密度,再转化为纵向平均路面功率谱密度,建立了三维沥青路面平整度评价方式与现行平整度评价标准的联系.利用国际标准中采用的幂函数道路拟合公式,通过谐波叠加法仿真出 A、B、C 和 D 级三维沥青路面的高程.根据所提方法计算出各级仿真路面的纵向功率谱密度,并与各级路面标准谱线进行对比,验证了该方法评估三维沥青路面平整度的有效性.通过与横向某一纵断面高程的功率谱密度谱线进行比较,验证了该方法谱线的波动幅度有很大的改善.结果表明,所提方法可以更加全面且准确地评估沥青路面的平整度,并且具有较强的实用性.

关键词:平整度;功率谱密度;三维沥青路面

中图分类号:U416.2