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Research Article

A New Mathematical Model for Predicting the Surface Vibration Velocity on the Step Topography

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In order to control production blasting and optimize mining operation, it is important to study the step topography vibration amplification and attenuation effect in the open-pit mine. Surface particle vibration velocity attenuation characteristics, the formation, and change rules of the terrain effect were studied by analyzing the field measured data. Results show that local amplification effect and local attenuation amplification effect of particle vibration velocity are obvious. Amplification effect associates with bench height, and the attenuation effect is closely related with the distance from the vibration source and distance from the top. With the increase of elevation, vibration magnification of the particle on the top was 1.1~1.4. Because of the influence of the terrain effect, particle vibration velocity on the slope toe was obviously inhibitory. Based on the measured data, elevation amplification factor and clamping effect factor which influence blasting vibration velocity are put forward, and a new mathematical model considering the attenuation coefficient, the elevation amplification coefficient, and the clamping effect coefficient for predicting the blasting vibration velocity of the step topography is further improved. The regression analysis results show that the fitting coefficient of determination of the new prediction model is 0.8152 in horizontal and 0.8902 in vertical, respectively, and the prediction error is less than 20%, which is much better than other formulas. This new model provides effective reference for blasting seismic wave propagation law research of slope engineering.

1. Introduction

With the exploitation and utilization of mineral resources, a large number of open mining pits have been formed on the surface, and some mines have entered the deep mining stage. Blasting is still the main method for exploiting the resource; however, only 20%~30% of the explosive energy is used for breaking rock, and the rest is wasted in negative areas such as ground vibration, air blast, and fly rock [1–6]. Ground vibration induced by blasting is the major hazard for the structural safety of surrounding buildings and for the stability of the high slope. Because of the complexity of blasting and the difference of propagation medium, the prediction of blasting vibration velocity is always the technical problem urgently needed to be solved [7]. To ensure the smooth operation of the slope engineering and avoid social and economic problems created by blasting, predictive and preventive measures are the essential components [8]. Thus, it is imperative to predict the vibration level and put forward the blasting parameters prior to the operations for better safety and productivity [9].

Many researchers have devoted to the study of blasting vibration propagation law and suggested various methods to forecast the ground vibration and minimize the hazard level. Ground vibration is directly related to the quantity of explosive, distance between blast hole and monitoring point, and the geological conditions. Topographic condition especially terrain elevation becomes one of the important factors affecting the vibration velocity in the slope terrain [10–14]. Peak particle velocity used as the measure index of blasting vibration effect had been estimated based on two main and commonly used parameters (maximum charge per delay and the distance between blast hole and monitoring point) [15–21]. However, a lot of field monitoring data displayed that terrain elevation has a marked impact on PPV. The amplification of vibration velocity can be 1.5~3 times [22–25]. Elevation amplification effect is very important to study the propagation characteristics of blasting seismic wave and the slope safety protection measures. A few predictors took the elevation into consideration; it agrees that positive elevation increases the velocity, on the contrary will reduce [26–29]. There have been few researchers focusing on the clamping effect of step topography, although it exists and always appears.

Over the past few years, artificial intelligent (AI) techniques such as artificial neural networks (ANN) and support vector machine (SVM) which had put total charge, distance, max charge per delay, frequency, blasting parameters, etc, into the prediction model have been used in mining and civil engineering [30–32], but the clamping effect has been not considered. And the recent field monitoring data showed that on the step surface blasting vibration, velocity was influenced by the height of the step and the clamping effect controlled by the distance from the step top.

In the past, the study of vibration amplification effect mainly focuses on the field of earthquake. Since the 1970s, researchers had observed the vibration amplification effect on the ridge top or cliff top in many earthquake events such as San Fernando earthquake in 1971, Central Chile earthquake in 1985, Loma Prieta earthquake in 1989, Northridge earthquake in 1994, and Wenchuan earthquake in 2008, and the amplification effect of topography had been found by experts in the analysis of seismic data [33–37]. Generally, buildings at the top of the steep slope suffered more serious damage. Experts had began a long-term theoretical and field study on the topographic amplification effect of earthquake events and had obtained some qualitative results; however, it is still insufficient in quantitative research, the topographic effects of vibration could not be predicted accurately, and efficient mathematical prediction models were not be established yet.

In recent years, Chinese researchers are beginning to pay more attention to the topographic effects of artificial blasting seismic waves. Vibration observation data had been obtained from the open-pit mine. The researchers arranged the monitoring points on the different steps to obtain the influence law of elevation on vibration velocity, but the vibration velocity data on the same step were not obtained and analyzed [27–29]. The vibration velocity prediction formulas were very limited and not suitable for every position of the step topography. Therefore, previous relevant studies could not describe the attenuation law of vibration velocity of step topography and could not effectively provide the protection suggestions and guide the equipment installation.

In the paper, different empirical formulas have been used to predict PPV, and a new multifactor vibration velocity prediction model with high accuracy has been established.

2. Case Study

The vibration monitoring test was carried out at the Sijiaying Iron Mine which belongs to Hebei Iron and Steel Group Mining Co., Ltd. and locates to the east of Hebei province, in 118°45′30″ longitude and 39°38′~39°42′ latitude and at 30 m above sea level. It has been extracting six million tons of raw iron per year. The rocks in that area comprise granulite, schist, and quartzite. Granulite is the main ore-bearing rock. The area belongs to the southwest edge of Yanshan folded belt, which is principally composed of Sinian and Quaternary. The main mineral of the deposit is magnetite, and the proved reserve is approximately 2.348 billion tons with an average grade of 31.09%. The mine is exploited by open-pit mining in the early stage and covers an area of 2.7797 million square meters with 1630 m long from north to south and 1500 m wide from east to west. The height and slope of working benches are 12 m~15 m and 65°, respectively. The maximum height of final slope is about 432 m.

Vibration monitoring instrumentation was TC-4850, as shown in Figure 1, and it was made up of acquisition equipment and three vector speed sensor. The main technical indicators are the frequency range X/Y: 1~300 Hz, Z: 1~500 Hz, the sensitivity 28 V/m/s, and the harmonic distortion ≤0.1%.

The monitoring test was conducted twice in Figure 1; the total amount of explosive, respectively, was 14200 kg and 16710 kg, the maximum charge per delay was 750 kg, and the remaining parameters are listed in Table 1. Measuring points are located at the toe and the top of adjacent steps. The blasting vibration observation results are shown in Table 2.

3. Prediction by Conventional Predictors

Table 3 illustrates the various conventional vibration prediction formulas widely used in different countries or put forward by different researchers. The attenuation coefficient and site coefficient can be obtained from the data regression analysis, and the calculated values of site and attenuation coefficient in different formulas are shown in Table 4 and in Figure 2.

However, in the slope engineering, the above empirical formula results have large errors and low reliability. Field monitoring data show that the elevation of the terrain has obvious amplification effect on the vibration velocity. Zhu and Zhou [28, 29] had partially corrected the empirical formula, introducing the elevation variable and established the vibration velocity prediction model with terrain elevation shown in Table 5.

The formulas which add the elevation H as the variable in Table 5 are based on Sadaovsk formula, the effect of terrain elevation on vibration velocity is reflected, and the terrain effect of vibration velocity can be described more accurately.

Figure 3 shows the relationship between scaled distance and PPV described by the different empirical formulas. The CoD is minimum for Japan formula, in which the scale distance is linear with PPV, and the constant term is zero. According to the formulas in Table 5, the data are analyzed with binary regression, and the fitting results are shown in Table 6.

(a) (b)

Figure 1: Field monitoring of blasting vibration velocity.

Table 1: Blasting design parameters.

Item	Parameter	
Bench height (m)	12~15	
Hole depth (m)	14~17.5	
Hole diameter (mm)	310	
Subdrilling (m)	2~2.5	
Filling length (m)	7~8	
Row spacing (m)	Mineral	7~8
	Rock	5~9
Hole spacing (m)	Mineral	6~7
	Rock	4~8
Explosive type	ANFO	
Detonation mode	Hole-by-hole initiation	
Detonator	Millisecond nonel detonator	
Charge structure	Interval charging	

Table 2: Vibration monitoring results.

Explosive source	Charge weight (kg)	Monitoring point	Distance from Blast-face (m)	Elevation (m)	Distance from the top (m)	Horizontal PPV (cm/s)	Frequency (Hz)	Vertical PPV (cm/s)	Frequency (Hz)	Measuring point location
I	750	1	141.3	53.5	15.0	4.117	24.2	2.927	31.7	Slope toe
		2	171.6	65.9	0	5.411	25.8	4.060	28.8	Slope top
		3	192.5	65.9	20.9	4.186	22.1	1.871	29.3	Slope toe
		1	275.2	52.5	15.2	2.288	24.8	0.608	21.7	Slope toe
		2	304.9	65.1	0	2.633	21.9	0.737	21.2	Slope top
		3	329.0	65.1	24.1	1.272	29.9	0.486	29.8	Slope toe
II	750	1	237.1	52.3	14.9	3.256	24.4	1.238	27.3	Slope toe
		2	266.3	65.0	0	4.102	28.9	1.595	20.9	Slope top
		3	290.2	65.0	23.9	1.786	23.4	0.651	29.9	Slope toe
		1	220.8	54.1	15.0	2.189	24.1	1.750	23.6	Slope toe
		2	265.7	67.1	0	2.719	26.6	2.272	20.1	Slope top
		3	284.1	67.1	18.4	1.890	25.7	0.586	20.0	Slope toe

Table 3: Different prediction models.

Name of models	Formula
Sadaovsk	$V = K \cdot (Q^{1/3}/R)^{\alpha}$
USBM	$V = K \cdot (Q^{1/2}/R)^{\alpha}$
Indian	$V = K \cdot (Q/R^{2/3})^{\alpha}$
Sweden	$V = K \cdot (Q/R^{2/3})^{\alpha/2}$
Ambraseys–Hendron	$V = K \cdot (Q^{0.33}/R)^{\alpha}$
Attewell	$V = K \cdot (Q/R^{2})^{\alpha}$
Japan	$V = K \cdot (Q^{0.75}/R^{2})$

Note. V is the PPV, cm/s; Q is the maximum charge per delay, kg; R is the distance between blast hole and measuring point, m; K is the site coefficient; and α is the attenuation coefficient.

Table 4: Calculated values of K and α.

Formula	Velocity direction	K	α	CoD
Sadaovsk	Horizontal	176.77	1.2686	0.5724
	Vertical	2581.6	2.3271	0.6994
USBM	Horizontal	43.604	1.2686	0.5724
	Vertical	198.06	2.3271	0.6994
Indian	Horizontal	0.0098	1.9029	0.5724
	Vertical	$4e^{-5}$	3.4007	0.6994
Sweden	Horizontal	0.0098	3.8058	0.5724
	Vertical	$4e^{-5}$	6.8014	0.6994
Ambraseys–Hendron	Horizontal	181.78	1.2686	0.5724
	Vertical	2717.6	2.3271	0.6994
Attewell	Horizontal	43.604	0.6343	0.5724
	Vertical	198.06	1.1636	0.6994
Japan	Horizontal	920		0.0371
	Vertical	543.9		0.6171

Note. CoD is the fitting coefficient of determination.

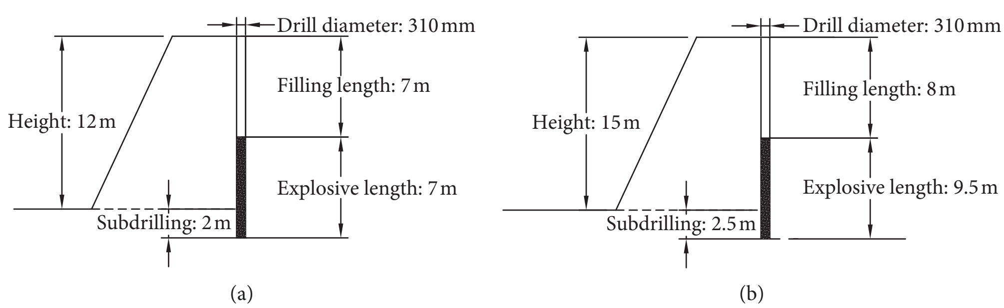

Figure 2: General blasting parameters for Sijiaying Iron Mine.

Table 5: Prediction models with terrain elevation.

Name of models	Formula
ZHU Chuantong	$V = K \cdot (Q^{1/3}/R)^{\alpha} \cdot (Q^{1/3}/H)^{\beta}$
TANG Hai	$V = K \cdot (Q^{1/3}/R)^{\alpha} \cdot (H/R)^{\beta}$
ZHOU Tongling	$V = K \cdot (Q^{1/3}/R)^{\alpha} \cdot H^{\beta}$
MA Anshan	$V = K \cdot (Q^{1/3}/R)^{\alpha} \cdot e^{\beta \cdot H}$

Note. H is the terrain elevation, m; β is a coefficient related to terrain elevation difference. When the location of measuring point is higher than the explosion source, beta is positive; on the contrary, it is negative.

The fitting coefficients of determination in Table 6 are higher than that in Table 4. To some extent, the models with elevation factor demonstrate the amplification effect of terrain elevation on vibration velocity, the value of β obtained by fitting also indicates that the terrain elevation has an enhancement effect on the vibration velocity. But the prediction accuracy of vibration velocity has not improved significantly, and the CoD is still low. According to the field monitoring data in Table 2, the propagation of the PPV along the step surface is not only influenced by the distance attenuation effect and elevation amplification effect. The PPV at the toe position of the same elevation attenuates rapidly. The measurement point 1 is compared with point 3, and PPV of point 3 with higher elevation is lower; therefore, it can be obtained that PPV at the toe of slope is restricted by rock mass, and amplitude of PPV drops sharply.

4. Prediction by New Model

Considering the PPV changing characteristics of the top and toe of the steps, the clamping effect factor and elevation amplification factor were introduced in the new prediction model, and it is as follows:

$$V = K_0 \cdot \frac{1}{\varepsilon^r} \cdot \left(\frac{Q^{1/3}}{R}\right)^{\alpha} \cdot \left(\frac{H}{R}\right)^{\beta}, \quad (1)$$

where V is the PPV, cm/s; Q is the maximum charge per delay, kg; R is the distance between blast hole and measuring point, m; K_0 is the site coefficient; α is the attenuation coefficient, $\alpha > 0$; β is the elevation amplification coefficient, $\beta > 0$; r is the distance between measuring point and the top of step at the same elevation; and ε is the clamping effect coefficient, $\varepsilon > 1$.

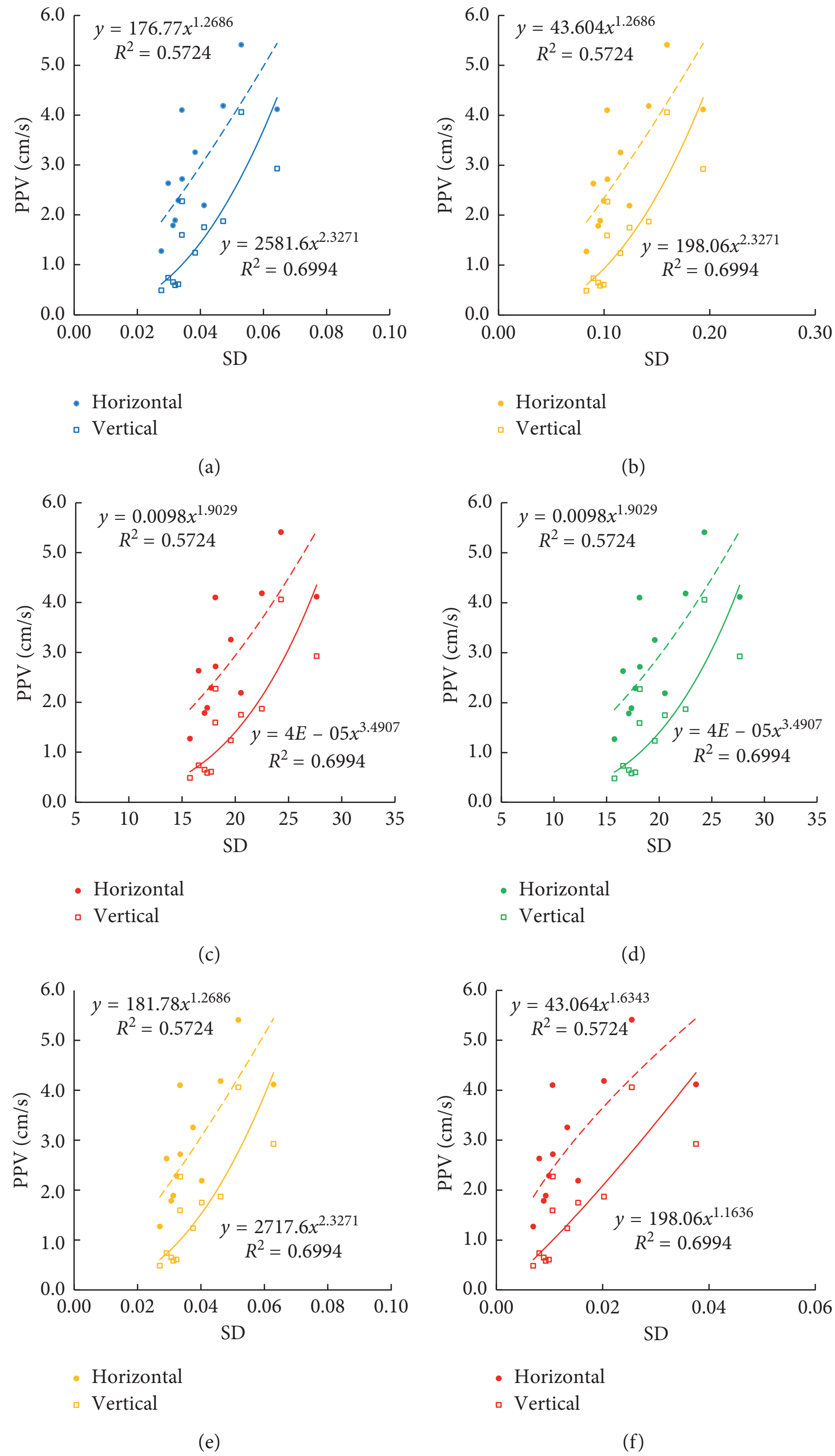

FIGURE 3: Data fitting results of different formulas. (a) By Sadaovsk formula. (b) By USBM formula. (c) By Indian formula. (d) By Sweden formula. (e) By Ambraseys–Hendron formula. (f) By Attewell formula. SD is the scaled distance; $\ln V$ means the logarithm of PPV; and lnSD is the logarithm of SD.

The fitting results of the new prediction model are shown in Table 7.

The PPV mathematical prediction model containing the elevation amplification factor and clamping effect factor can respond the propagation rule of the surface vibration velocity more accurately, the CoD is higher than 0.8, and predicting results are more reliable and more consistent with the monitoring data. Six more sets of vibration data have been selected for comparison with the calculation results of the new formula. The new data and comparison results are shown in Tables 8 and 9.

Table 6: Fitting results of PPV considering the elevation.

Name of models	Horizontal PPV	CoD	Vertical PPV	CoD
ZHU Chuantong	$V = 51.83 \cdot (Q^{1/3}/R)^{1.385} \cdot (Q^{1/3}/H)^{-0.8434}$	0.6119	$V = 272.6 \cdot (Q^{1/3}/R)^{2.541} \cdot (Q^{1/3}/H)^{-1.546}$	0.7476
TANG Hai	$V = 51.83 \cdot (Q^{1/3}/R)^{0.5418} \cdot (H/R)^{0.8434}$	0.6119	$V = 272.6 \cdot (Q^{1/3}/R)^{0.9951} \cdot (H/R)^{1.546}$	0.7476
ZHOU Tongling	$V = 8.06 \cdot (Q^{1/3}/R)^{1.385} \cdot H^{0.8434}$	0.6119	$V = 9 \cdot (Q^{1/3}/R)^{2.541} \cdot H^{1.546}$	0.7476
MA Anshan	$V = 107.55 \cdot (Q^{1/3}/R)^{1.386} \cdot e^{0.01434 \cdot H}$	0.6124	$V = 1043.15 \cdot (Q^{1/3}/R)^{2.542} \cdot e^{0.02617 \cdot H}$	0.7478

Table 7: Fitting results of PPV by the new model.

Velocity direction	Model	CoD
Horizontal	$V = 113.87 \cdot (1/1.021^{r}) \cdot (Q^{1/3}/R)^{0.9238} \cdot (H/R)^{0.3179}$	0.8152
Vertical	$V = 813.79 \cdot (1/1.029^{r}) \cdot (Q^{1/3}/R)^{1.526} \cdot (H/R)^{0.8154}$	0.8902

Table 8: Six more sets of vibration data.

Explosive source	Charge weight (kg)	Monitoring point	Distance from Blast-face (m)	Elevation (m)	Distance from the top (m)	Horizontal PPV (cm/s)	Frequency (Hz)	Vertical PPV (cm/s)	Frequency (Hz)	Measuring point location
III	750	1	237.1	81.3	14.6	3.256	24.4	1.438	27.3	Slope toe
		2	242.2	93.7	0	4.502	18.9	2.595	20.9	Slope top
		3	266.3	94.0	24.1	2.375	19.9	1.210	45.2	Slope toe
		1	364.6	79.5	14.2	1.561	18.9	0.625	20.2	Slope toe
		2	370.2	92.9	0	2.186	23.4	1.051	19.9	Slope top
		3	392.4	92.5	22.2	1.254	25.3	0.480	19.3	Slope toe

Table 9: Comparison of the performance of new formula with the other related studies.

Model	Velocity direction	Average error (%)
$V = K_0 \cdot (1/\varepsilon^{r}) \cdot (Q^{1/3}/R)^{\alpha} \cdot (H/R)^{\beta}$	Horizontal	9.80
	Vertical	10.34
$V = K \cdot (Q^{1/3}/R)^{\alpha}$	Horizontal	17.49
	Vertical	29.07
$V = K \cdot (Q^{1/2}/R)^{\alpha}$	Horizontal	17.49
	Vertical	29.07
$V = K \cdot (Q/R^{2})^{\alpha}$	Horizontal	17.49
	Vertical	29.07
$V = K \cdot (Q^{1/3}/R)^{\alpha} \cdot (Q^{1/3}/H)^{\beta}$	Horizontal	29.54
	Vertical	25.45
$V = K \cdot (Q^{1/3}/R)^{\alpha} \cdot e^{\beta \cdot H}$	Horizontal	40.52
	Vertical	32.26

Obviously, prediction by new model is closer to the measured velocities, the PPV errors of these common formulas are about 17%~41% in horizontal and about 29%~33%% in vertical, and by contrast, the errors respectively are about 9.8% and 10.34%; the comparative results are shown in Figure 4.

In conclusion, the new prediction model can fully describe the topographic elevation effect and the clamping effect and accurately predict the PPV propagating along the surface on the steps. The new formula can evaluate the vibration of the step topography at Sijiaying Iron Mine. The new formula is more suitable for prediction of blasting vibration in this area than other formulas.

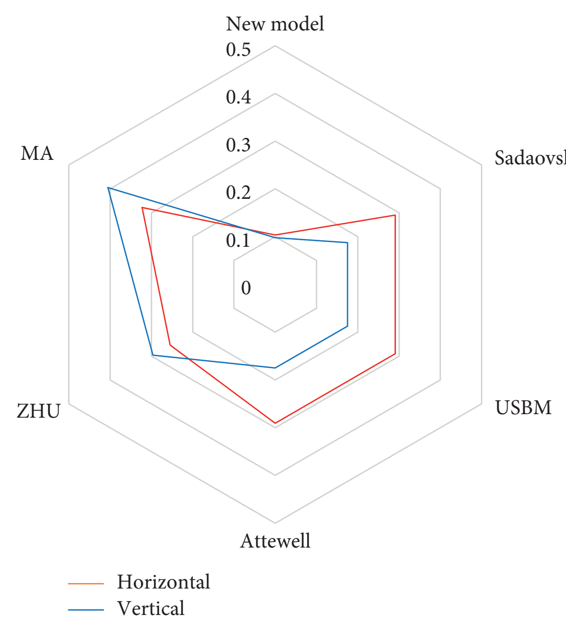

Figure 4: Comparative results between measured and predicted horizontal and vertical PPV.

5. Conclusions

The vibration velocity of the surface on the steps is related to the topographic elevation, the blasting distance, and the distance between measuring point and the top of slope. The PPV on the top has obvious amplification effect, and the magnification factor is 1.15~1.39 times, and oppositely, the PPV which is limited on the toe of step decreases rapidly. So, vibration velocity is a complex product of multiple factors.

PPV prediction formulas are compared and analyzed based on the measured data, and the fitting results show that the new model can get the higher CoD and the minimum error.

The new prediction model is aimed at the step topography, and it is more intuitive and accurate to reflect the elevation amplification effect and the rock clamping effect on the step terrain. The new prediction model is more consistent with the change rule of the measured data, and the guiding significance of the slope blasting operation is more targeted.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

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