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Research paper

Application of projection pursuit regression model for blasting vibration velocity peak prediction

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Abstract: Based on Projection Pursuit Regression Theory (PPRT), a projection pursuit regression model has been established for forecasting the peak value of blasting vibration velocity. The model is then used to predict the peak value of blasting vibration velocity in a tunnel excavation blasting in Beijing. In order to train and test the model, 15 sets of measured samples from the tunnel project are used as the input data. It is found that predicting results by projection pursuit regression model on the basis of the input data is much more reasonable than that predicted by the traditional Sodaovsk algorithm and modified Sodaovsk formula. The results show that the average predicting error of the projection pursuit regression model is 6.36%, which is closer to the measured values. Thus, the projection pursuit prediction model is a practical and reasonable tool for forecasting the peak value of blasting vibration velocity.

Keywords: blasting vibration, vibration velocity prediction, projection pursuit regression model, shallow tunnel, genetic algorithms

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1. Introduction

Blasting vibration has a significant destruction role in the surrounding environment[1-5]. Thus, accurate prediction and effective control of blasting vibration have essential theoretical and practical significance to ensure construction safety [6-10]. Most traditional blasting prediction methods are built on flat terrain, which did not reflect the impact of terrain elevation. However, the vast majority of blasting engineering conducts on undulating terrain venues. The change of topography causes a significant impact on the propagation of the wave. There is a large deviation for using traditional predicting methods in elevation areas. Therefore, to find a method of accurately predict the blasting vibration velocity under topography conditions is particularly important.

Projection Pursuit (PP) technology is an emerging statistical method, which is developed in the international statistical community in the middle of 1970s. Then it is used to process and analyze high-dimensional data, especially non-normality and nonlinear high-dimensional data[11-14]. PP technology is widely used in agriculture, water conservancy, meteorology, industry, and other fields. Using the pp technology, Ruyan improves the estimation accuracy of winter wheat chlorophyll density [15, 16]. Zheng Yuxin forecasted the industrial wastewater emissions of Tianjin city from 2010 to 2015 by projection pursuit regression [17]. Wu Chengming improved the projection and pursuit of two core issues of traditional projection pursuit technology [17-19]. Using projection pursuit regression technology, Peng Lihong created the prediction model of air pollutants SO2 concentrations and achieved better prediction results[20-22]. Based on projection dimensionality reduction, Gaoke established a genetic algorithm (GA) projection pursuit regression prediction method for predicting the gas emission quantity in the mining face [23]. Blasting vibration prediction is a complex nonlinear problem [24, 25].

This article introduced the powerful nonlinear prediction theory of Projection Pursuit, and established the Projection Pursuit regression model based on Hermite polynomial. Then it is employed to predict the blasting vibration velocity peak under elevation conditions, which provided a new research idea for blasting vibration hazard warning.

2. Prodection pursuit regression model based on hermite polynomials

2.1 The fundamental principle of projection pursuit

Projection Pursuit is a new statistical method for processing and analyzing high-dimensional data. The main purpose is to solve the regression problem of high-dimensional space, according to the given judging indexes, estimates the regression function.The idea of projection pursuit is to project the high-dimensional multi-factor special data to a line in the air, and to obtain the one dimension data. Then the relationship between the one dimension data and the dependent variable Y can be establish as the following equation.

$$Y = f(\sum_{j=1}^{m} a_j x_j) + \varepsilon \qquad (1)$$

Where $a = [a_1, a_2, ...a_m]^T$ is a column vector, represents a projection direction of m dimensional space, a is a unit vector. $\sum_{j=1}^{m} a_j x_j$ is the projection value of the observation vector $(X_1, X_2, ...X_m)$ in direction a formed by m factor variables.

2.2 The projection pursuit regression model based on Hermite polynomials

There are three common projection pursuit regression models, i.e. non-parametric projection pursuit regression model, based on Hermite polynomial projection pursuit regression model and spline smoothing projection pursuit model based on the kernel function. These models use modern statistical approximation theory to achieve the measured sequence points as a possible approximation, fitting, and the model's form is determined by measured data [26-28]. Hermite polynomial, which is widely used in engineering applications [29], belongs to parameter regression, The calculation for the Hermite polynomial is not complicated. The coefficients are determined in explicit formulas. It is helpful to application in practical engineering. The practices in other areas show that: Hermite polynomial calculation results are superior to the s function of BP network and the super smoother of the projection pursuit regression model [11]. When given a new sample point Z, the performance to insert or extension in the determined curve is superior to the piecewise linear regression curve in projection pursuit regression. Therefore, this paper selects the projection pursuit regression model based on Hermite polynomials, and the modelling steps are as follows:

(1) Assume the dependent variable y_i (i =1,2 , ⋯ , n) and p independent variables $\{x_1, x_2, \cdots, x_p\}$, then the projection value can be calculated as follows.

$$z_i = \sum_{j=1}^{p} a_j x_{ij}, i = 1,2,\ldots,n;\ \ j = 1,2,\ldots,p \tag{2}$$

Where $a_j (j = 1, 2,..., p)$ is the projection direction, x_{ij} is the data after the normalization processing.

(2) Fit the scatter points (z, y) by orthogonal Hermite polynomials and the projection pursuit regression model (see formula 3).

$$y = \sum_{i=1}^{m} \sum_{j=1}^{r} c_{ij} h_{ij}(z) \tag{3}$$

$$i = 1,2,\ldots m;\quad j = 1,2,\ldots, r$$

(3) Optimal projection index function. When optimizing the projection direction a, the optimization problem of polynomial coefficients c can be considered. And the optimal a , c value can be estimated by solving the minimization problem of the projection index function.

$$\min Q(a,c) = \frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y}_i)^2 \tag{4}$$

$$s.t. \sum_{j=1}^{p} a^2(j) = 1$$

This is a complex nonlinear optimization problem with c and a as the optimization variables. It is difficult to deal with the traditional optimization method, while the real coding based on accelerating genetic algorithms can solve high-dimensional global optimization problems.

(4) Calculate the first fitting residual error $r_1 = y - \bar{y}$, output the model parameters if they meet the requirements, otherwise conduct the next step calculations.

(5) Replace y by r_1 i, and go back to step 1 to start the optimization of the next ridge function until meeting certain requirements. Then stop increasing the number of ridge functions and output the final result. The calculation flow chart is shown in Fig.1.

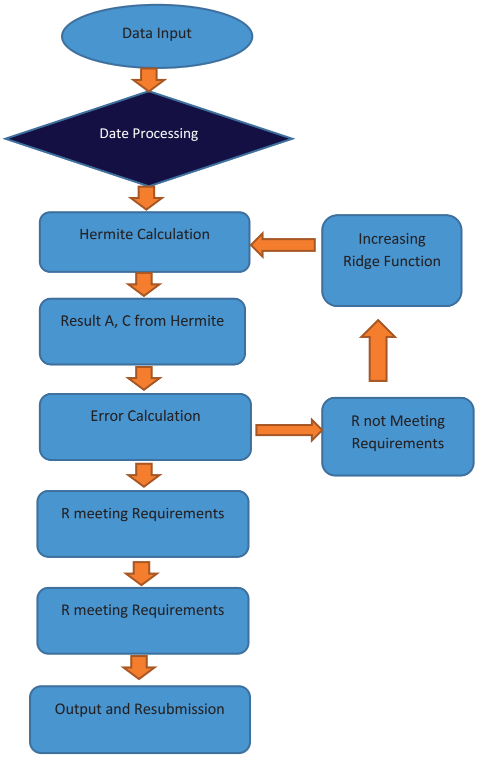


Figure 1 Calculation Flow Chart

In order to ensure the accuracy of parameter projection and avoid using the huge function table, the variable order orthogonal Hermite polynomial is used in step (2) to fit the one-dimensional ridge function.

$$h_r(z) = (r!)^{\frac{1}{2}} \pi^{\frac{1}{4}} 2^{-\frac{r-1}{2}} H_r(z) \varphi(z), \quad -\infty < z < \infty \tag{6}$$

Where $r!$ represents the factorial of r, $z = a^T X$, φ is the standard Gaussian equation, $H_r(z)$ is Hermite polynomials, $H_0(z) = 1$, $H_1(z) = 2z$, $H_r(z) = 2(zH_{r-1}(z) - (r-1)H_{r-2}(z))$.

2.3 Projection Pursuit Model prediction of blasting vibration velocity peak

Many factors affect the blasting vibration, including explosive performance, charging structure, rock properties and geological structure. In this study, the five parameters, i.e. total charge, maximum charge per interval, explosive distance, elevation difference and hole depth related to blasting vibration, were selected as influencing factors[28]. The model structure is shown in Fig.2. The projection pursuit regression model of peak velocity based on Hermite polynomial as shown in Equation (7).

$$Y = \sum_{i=1}^{m} c_i h_i (a_i^T X) \tag{7}$$

where c is the polynomial coefficient, h represents orthogonal Hermite polynomials, calculated according to the formula (6).

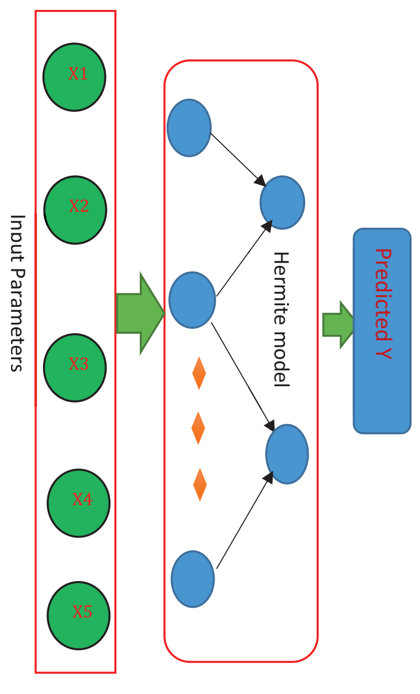


Figure 2 Projection pursuit regression model structure diagram of peak velocity

The information contained in the data can be expressed by polynomial coefficient c and order r. The key to the projection pursuit method to solve practical problems is to construct an effective algorithm to find the optimal projection direction. In this paper, the MATLAB genetic algorithm toolbox is used to solve the optimal projection direction by writing the objective function and constraint functions.

3. Projection Pursuit peak velocity prediction model used in Changping Tunnel

3.1 Project overview

The Churuchang tunnel locates in Changping District of Beijing City. Its plane position is shown in Figure 3. The excavation section tunnel by blasting under the roadbed of Beijing to Baotou highway. The roadbed is about 8.0m high, and the slope is 1:1.5. The tunnel section is 6.65m high, the width is 6.2m, the depth of the vault is about 6.2m

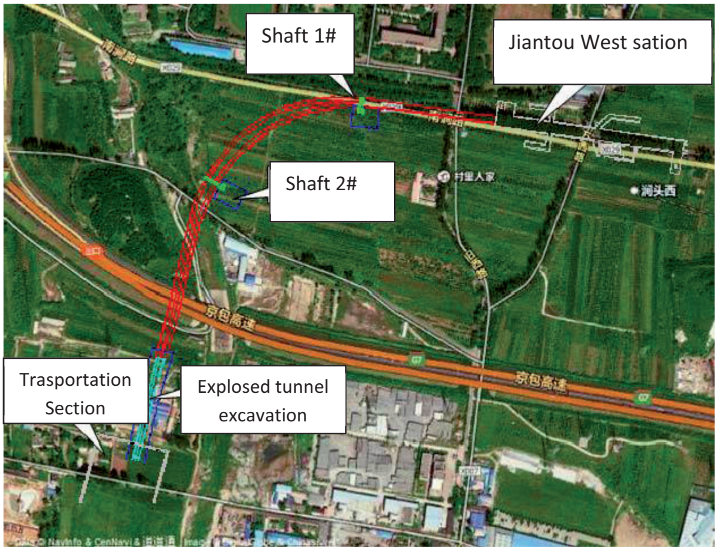


Figure 3 Map of Churuchang line interval tunnel

3.2 Arrangement of measuring points and results analysis

In order to analyze the propagation law of blasting seismic waves along the elevation direction, the highway roadbed above the blasting particles was selected as the test site. Then measuring points are arranged along the slope. The arrangement of measuring points is shown in Figure 4. In this research the Tc-4850 blasting vibration meter is used to measure the blasting vibration at each point during test as shown in Figure 5. Tc-4850 blasting vibration meter is a portable vibration monitor specially designed for engineering blasting. It is highly intelligent, with embedded computer module and LCD. It can directly set various acquisition parameters, preview vibration waveform, frequency and other parameters. Figure 6 shows the laryout the blasting vibration meter druring the blast testing. The parameters for the sensor of the blasting vibration meter can be found in Table 1.

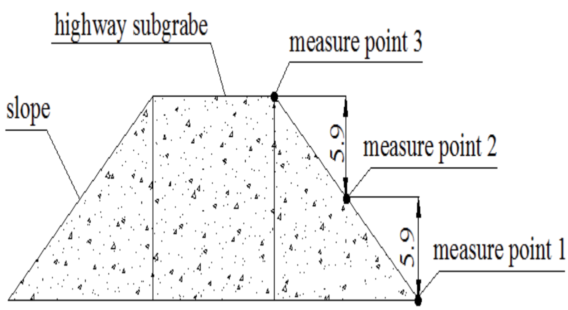


Figure 4 Arrangement of measuring points

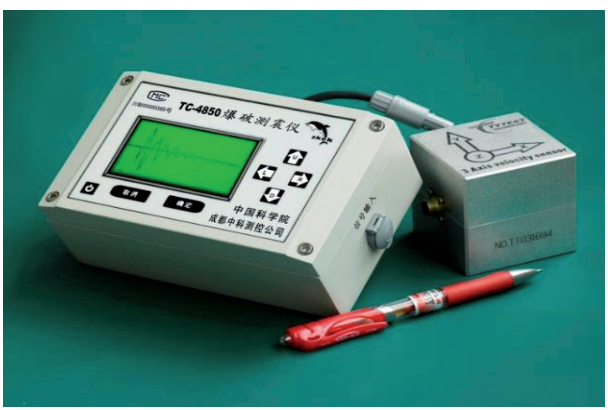


Figure 5 Tc-4850 blasting vibration meter

Figure 6 The playout of the blasting vibration during moniting

Table 1. Parameters for the Sensor of the blasting vibration meter

Parameters	Values
Frequency Response	1~500HX(g1db)
sensitivity	26.2v/m/s(±5%)
natural frequency	4.5±10%Hz
damping coefficient	0.6±20%
harmonic distortion	⩽0.2%
using temperature range	-20~75°C
size	72mm×72mm×72mm
Weight	65±5g

The measured results show in Table.

According to Table 2 and Figure 9-11, it is concluded that:

- Elevation magnification effect of the blasting vibration velocity occurs due to the increase in elevation. And the blasting vibration velocity increases rapidly from measuring point 1 to 2. In addition, the blasting vibration velocity grows slowed down from measuring point 1 to 2, but in general, it still increased significantly.
- According to the blasting vibration velocity changes of three directions of the situation, it found that (shown in Figure 10): the vertical and tangential velocity of the particles increases obviously with the increase of the elevation difference. Meanwhile, the radial velocity is increased inflection point when the elevation difference is equal to about 12.6m. As the growth rate

increases, the tangential and radial vibration velocity begins to decrease. The tangential velocity decay rate is higher than the radial velocity, and the radial velocity did not change much.

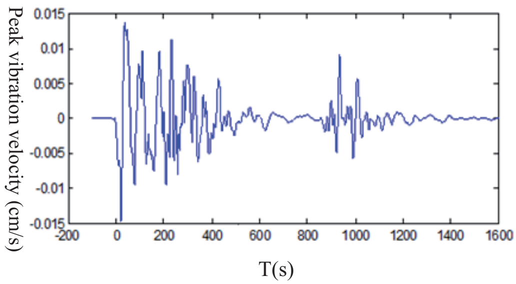
- From the relationship between blasting vibration velocity and blasting distance, it can be seen that: with the increase of explosive distance, the general trend of blasting vibration velocity is attenuated. Before the explosive distance is about 20.25m, with the increase of explosive distance, the three directions of the vibration velocity increased, and the vertical and tangential vibration velocity increased significantly. Then the tangential and radial velocity begins to decay, and the tangential velocity decay rate is more significant than The radial velocity.

Table 2. Field test results

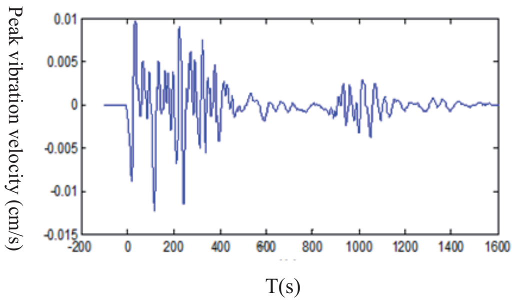
group	Measure point	Explosive distance/m	Elevation difference/m	Total charge/kg	Hole depth/m	Maximum charge per interval/kg	Peak vibration velocity/cm/s
1	1	35.68	9.45	72.00	2.20	1.50	0.61
	2	36.15	16.26	72.00	2.20	1.50	0.94
2	1	17.30	13.21	60.00	2.20	1.20	2.90
	2	17.87	17.00	60.00	2.20	1.20	3.53
3	1	34.02	13.17	66.00	1.70	1.20	0.89
	2	30.31	17.57	66.00	1.70	1.20	1.41
4	1	25.28	6.67	78.00	2.50	1.80	0.92
	2	26.91	12.17	78.00	2.50	1.80	1.17
	3	30.14	17.67	78.00	2.50	1.80	1.61
5	1	17.15	5.72	80.00	2.5	1.80	4.11
	2	17.64	11.22	80.00	2.50	1.80	2.88
	3	20.68	16.72	80.00	2.50	1.80	4.64
6	1	15.43	5.72	84.00	3.00	1.80	3.66
	2	16.78	11.22	84.00	3.00	1.80	3.54
7	1	14.25	5.72	54.00	2.00	1.20	3.07
	2	16.44	11.22	54.00	2.00	1.20	2.41
	3	20.91	16.72	54.00	2.00	1.20	4.79
8	1	34.70	14.06	72.00	2.50	1.20	0.71
	2	32.00	17.84	72.00	2.50	1.20	0.98
	3	39.01	16.86	72.00	2.50	1.20	1.27
9	1	35.85	14.16	27.00	1.50	0.90	0.67
	2	33.03	17.94	27.00	1.50	0.90	1.12
	3	39.85	16.94	27.00	1.50	0.90	0.74

The vertical velocity is still increasing after the explosive distance is more than 20.25m, the rate of increase slowed down, and from the overall trend, with the increase of the explosive distance, the vertical velocity decay will accelerate and eventually become smaller and smaller.

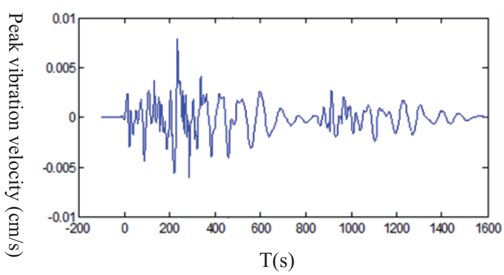
The empirical formula of Sodaovsk shows that the blasting vibration velocity decreases with the increase of explosive distance in flat terrain, but the application of the empirical formula of Sodaovsk is limited under the condition of undulating terrain. The experiment showed that it would occur elevation magnification effect of the blasting vibration velocity under the condition of undulating terrain, but the vibration velocity will not increase infinitely with the elevation difference, which is not in accordance with the laws of nature. The velocity of blasting size is not only related to elevation but also by the amount of charge, explosive distance, geological conditions and other factors. This experiment is limited by the field conditions, so along with the elevation direction arrangements, only 3 points, and the point of particle vibration velocity has not got after point 3. As for the relationship and the size of the influence factors of blasting vibration, velocity needs to be further studied, and the results of the study will be discussed in detail in the later literature.



(1) Radial direction

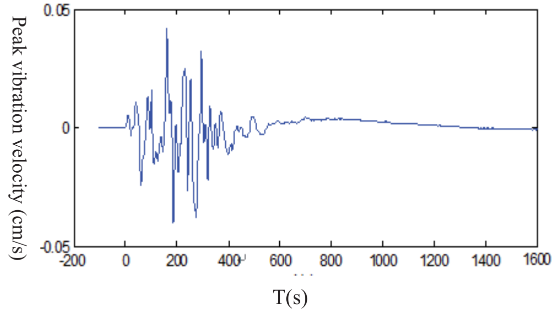


(2) Tangential direction

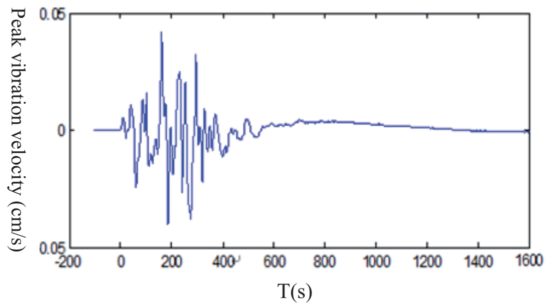


(3)Vertical direction

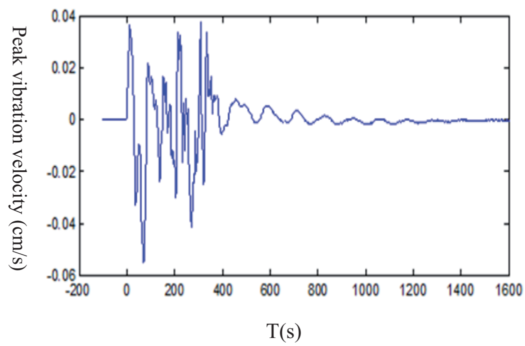
Figure 7 Time history curves of measuring point 1 in group 10



(1) Radial direction



(2) Tangential direction

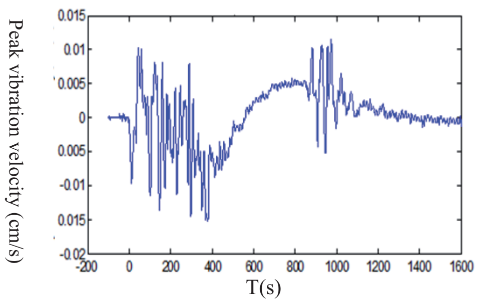


(3) Vertical direction

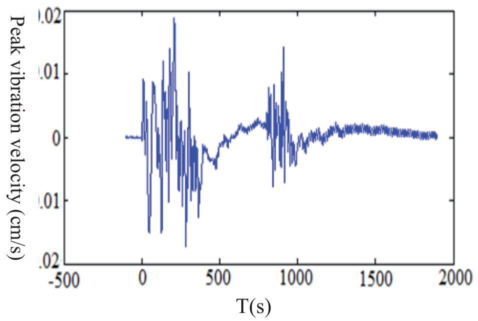
Figure 8 Time history curves of measuring point 2 in group 10

Combining with the data collected at the Changping exit-entry field line section tunnel, the projection pursuit regression model based on Hermite polynomials is used to predict the blasting vibration velocity and analyses the relationship between blasting vibration velocity and the elevation change. Field data are shown in Table 2, where the first 7 sets of data as training samples, the last four sets of data as a predictive test.

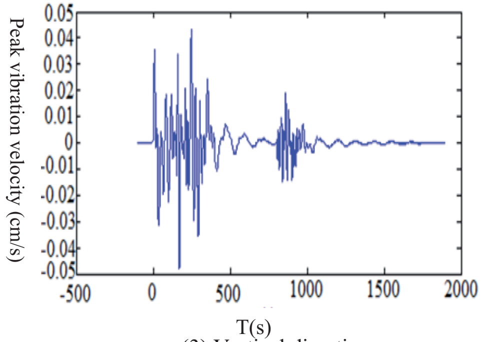
The empirical formula of Sodaovsk shows that the blasting vibration velocity decreases with the increase of explosive distance in flat terrain, but the application of the empirical formula of Sodaovsk is limited under the condition of undulating terrain. The experiment showed that it would occur elevation magnification effect of the blasting vibration velocity under the condition of undulating terrain, but the vibration velocity will not increase infinitely with the elevation difference, which is not in accordance with the laws of nature. The velocity of blasting size is not only related to elevation but also by the amount of charge, explosive distance, geological conditions and other factors. This experiment is limited by the field conditions, so along with the elevation direction arrangements, only 3 points, and the point of particle vibration velocity has not got after point 3. As for the relationship and the size of the influence factors of blasting vibration, velocity needs to be further studied, and the results of the study will be discussed in detail in the later literature.



(1) Radial direction



(2) Tangential direction



(3) Vertical direction

Figure 9 Time history curves of measuring point 3 in group 10

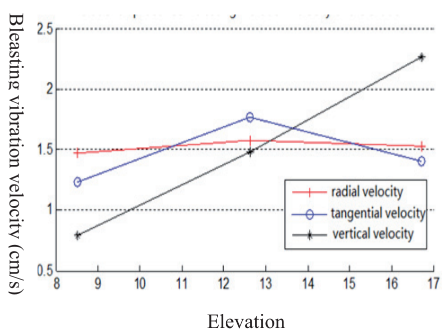


Figure 10 Relationship between blasting vibration velocity and elevation

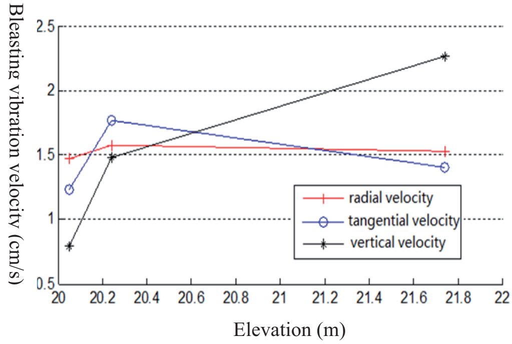


Figure 11 Relationship between blasting vibration velocity and explosion distance

Combining with the data collected at the Changping exit-entry field line section tunnel, the projection pursuit regression model based on Hermite polynomials is used to predict the blasting vibration velocity and analyses the relationship between blasting vibration velocity and the elevation change.

Field data are shown in Table 3, where the first 7 sets of data as training samples, the last four sets of data as a predictive test.

(1) Using the smaller, the better indicators with the measured data for normalization, in order to eliminate the dimension of each index value and unify the change range of each index:

$$x(i,j) = \frac{x_{\max}(j) - x^*(i,j)}{x_{\max}(j) - x_{\min}(j)} \quad (8)$$

where $x_{\max}(j)$ and $x_{\min}(j)$ are express the maximum and minimum values of the j index values, respectively. $x(i,j)$ is the normalization sequence of the indicators characteristic value. The treatment results are shown in Table 3:

(2) Using MATLAB software programming, the initial population N is chosen as 100, the crossover probability is 0.80, the number of outstanding individuals is 20, and the number of acceleration times is 25, so the best projection direction is obtained: $a^*(-0.815, 0.379, 0.202, 0.064, 0.383)$

(3) The normalized result is projected along the best projection direction. The projection values are: z=(0.33384 0.14169 -0.16957 -0.27076 0.34544 0.0949 -0.05623 -0.17788 -0.25063 -0.28664 -0.44289 -0.51364 -0.3708 -0.50006 0.00315 -0.1022 -0.1342).

Table 3. Data preprocessing results

Group	Measure point	x(1)	x(2)	x(3)	x(4)	x(5)
1	1	0.16	0.69	0.21	0.53	0.33
	2	0.14	0.14	0.21	0.53	0.33
2	1	0.85	0.39	0.42	0.53	0.67
	2	0.83	0.08	0.42	0.53	0.67
3	1	0.22	0.39	0.32	0.87	0.67
	2	0.36	0.03	0.32	0.87	0.67
4	1	0.55	0.92	0.11	0.33	0.00
	2	0.49	0.47	0.11	0.33	0.00
	3	0.37	0.02	0.11	0.33	0.00
5	1	0.86	1.00	0.07	0.33	0.00
	2	0.84	0.55	0.07	0.33	0.00
	3	0.72	0.10	0.07	0.33	0.00
6	1	0.92	1.00	0.00	0.00	0.00
	2	0.87	0.55	0.00	0.00	0.00
7	1	0.96	1.00	0.53	0.67	0.67
	2	0.88	0.55	0.53	0.67	0.67
	3	0.71	0.10	0.53	0.67	0.67

(4) For scatter points（z, y）are fitting with the projection pursuit regression model based on Hermite polynomials, this paper adopts a ridge function fitting, the specific parameters are shown in Table 4.

$$y=\sum_{j=1}^{r} c_j h_j(z)\,,\quad j=1,2,\ldots r \tag{9}$$

where y is blasting vibration velocity，r is the order of polynomials.

(5) For the other four sets of data are predicted by the projection velocity regression model of blasting vibration velocity, and the relevant data are brought into equation (9), the prediction results are shown in Table 5, and Fig. 10 is the comparison between the predicted value of the projection pursuit regression model and the measured value.

Comparing the prediction results of the projection pursuit regression model and the measured value, it is concluded that: the prediction results of the projection pursuit regression model based on Hermite polynomials are basically in agreement with the measured values, and the trend of the blasting vibration velocity increases with the increase of elevation; it will show that the blasting vibration amplification effect exists under the condition of terrain fluctuation. The average error of the projection pursuit regression model is only 6.36%, and the prediction error is within the allowable range, and the prediction accuracy is higher, which indicates that the projection pursuit prediction model can be used for the prediction of blasting vibration velocity.

Table 4. Correlation coefficient of regression analysis

Regression coefficient	Estimate of regression coefficient	Confidence interval of regression coefficient
C1	-23.743	[-25.650，10.585]
C2	-36.599	[-50.478，19.452]
C3	17.038	[-22.807，50.648]
C4	-17.139	[-60.354，68.548]
C5	4.169	[-10.456,18.795]
C6	-1.574	[-9.629，6.480]
C7	0.148	[-0.308，0.606]
C8	-0.033	[-0.213，0.146]
	R^2 =0.9315 F=2.4688 P<0.0001	

4. A Comparison between Projection Pursuit Prediction Model and Traditional Prediction

In this paper, in order to study the feasibility of the prediction method of projection pursuit, we use the traditional Sodaovsk formula (Equation .10), which does not consider the elevation, and the Sodaovsk expansion formula (Equation. 11). The method which introduces the elevation parameter to predict the blasting vibration velocity of the tunnel in the Changping district. The prediction results are compared with the prediction results of the projection pursuit regression model to explore the superior performance of the projection pursuit prediction method to predict blasting vibration velocity. Figure 13 shows the comparison between the measured values and the prediction results of Sodaovsk's empirical formula and projection pursuit model.Figure 14 shows the comparison between the measured values and the predicted results of the Sodaovsk expansion formula and the projection pursuit prediction model.

$$v = K\left(\frac{\sqrt[3]{Q}}{R}\right)^{\alpha} \tag{10}$$

$$v = k_1 k_2 [\frac{\sqrt[3]{Q}}{R}]^{\beta_1} [H]^{\beta_2} \tag{11}$$

where v is the particle vibration peak velocity, K is the medium coefficient, α is the attenuation coefficient, k_1 and k_2 are flat landform coefficient and convex landform influence coefficient, respectively, β_1 is the attenuation coefficient, β_2 is the elevation difference coefficient, Q is the explosive charge, R is the horizontal distance, and H is the elevation difference.

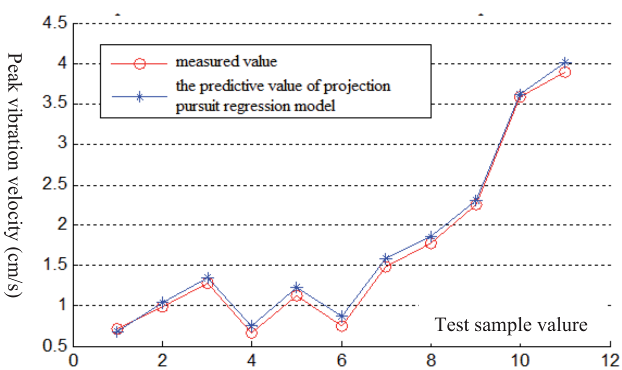


Figure 12 The comparison between the predicted value of the projection pursuit regression model and the measured value

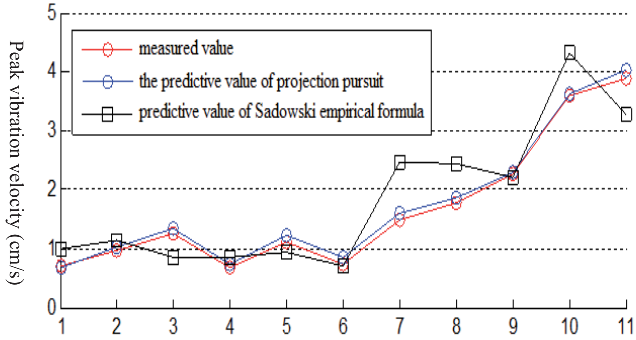


Figure 13 The comparison between the measured values and the prediction results of Sodaovsk's empirical formula and projection pursuit model

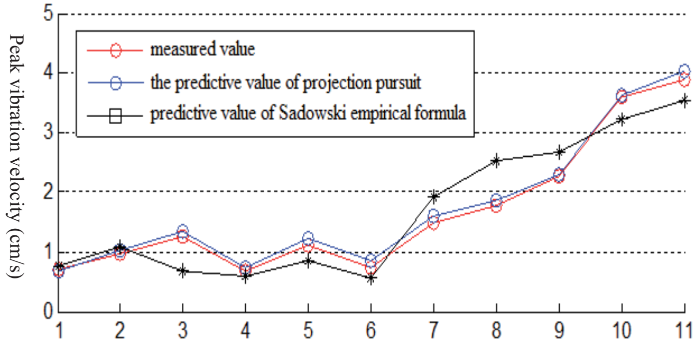


Figure 14 The comparison between the measured values and the predicted results of the Sadowski expansion formula and the projection pursuit prediction mode

We can draw the following conclusions by analyses Table4 , Figure 13 and Figure 14 that :

- The results show that the three prediction methods can basically reflect the overall variation trend of blasting vibration velocity, indicating that there is elevation amplification effect of blasting vibration under the condition of undulating terrain.
- The average error of Sadovsky formula is 25.32%, which indicates that Sadovsky formula can't predict blasting vibration velocity under the condition of topographic relief. The average error of Sadovsky extended formula is 21.68%, which is better than the traditional Sadovsky formula, but the error is still too large. The average error of the prediction result is 6.36%,

which is better than the former two prediction methods. The average error is smaller, the fitting curve is closer to the measured value, and the prediction result is more accurate. Therefore, the projection pursuit prediction model can be used to predict the blasting vibration velocity under the condition of terrain elevation difference, and the prediction accuracy is high.

5 Conclusion

The elevation amplification affects the blasting vibration under topographic fluctuation conditions. The traditional blasting vibration prediction method often neglects the influence of topography fluctuation, and the result of prediction is quite different. In this paper, a projection pursuit regression model of blasting velocity projection based on Hermite polynomials is established. The peak value of blasting vibration velocity is predicted under the condition of elevation and achieved good prediction results. The main conclusions are as follows:

- The elevation amplification effect appears when the blasting vibration of a shallow tunnel is propagated along the elevation direction, and the effect of vertical vibration velocity is the most obvious.
- Many factors are affecting blasting vibration, and only five prediction indexes are selected in this study due to the limitation of engineering site conditions. For the projection pursuit method, the more the prediction factors are, the higher the prediction accuracy is. Therefore, we should be based on the actual situation and select more factors to consider for predicting the blasting vibration velocity in future research.
- In this study, the projection pursuit prediction model is introduced into the prediction of blasting vibration velocity, which provides a new approach to the early warning of the blasting vibration. And the research results are helpful to guide the engineering practice.

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