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Characteristic Parameters Analysis of Rockfall Movement for Rock Slope and LM-BPNN Forecasting Model

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Abstract:

Rockfall movement is influenced by many factors. Aiming at the rockfall movement characteristic parameters including horizontal movement distance, bounce height and motion energy, the orthogonal experimental method is introduced to study the sensitivity and unfavorable level combination of factors. Then the top five factors affecting the rockfall movement characteristic parameters are selected to establish the data set and the rockfall forecasting system for rock slope is established by Back-Propagation Neural Network, which can predict the characteristic parameters of rockfall movement. Finally, the forecasting system is verified by an engineering example. The results show that the orthogonal test method can determine the primary and secondary factors of rockfall movement characteristic parameters and the unfavorable level combination. Besides, forecasting system based on BPNN can easily estimate the parameter of rockfall movement without modeling and computing with Rockfall software.

Keywords*: Rockfall, Influencing factors, Orthogonal test, Back-Propagation neural network, Parameter forecasting.*

I. INTRODUCTION

Rockfall disasters along slopes or dangerous rocks occur from time to time on roads such as railways and highways of mountainous and remote areas in China where geological and terrain conditions are very different from other places and hills on both sides of such roads are easy to be damged by various factors. In May 2007, rock mass collapse suddenly occurred on a slope of 108 National Highway Sichuan section. A bus which was travelling from west to east was smashed by the rockfall and it rolled to the slope on the south side of the highway, leaving ten people dead and more than ten people injured. In July 2013, rock slope collapse happened on Zhangzhuo Expressway Zhangjiakou section in Hebei Province. Rockfall rolled over the guardrail and brought violent hit to the road, leading to two weeks of traffic disruption and

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an economic loss of 8 million Yuan. In 2016, a total of 9710 geological disasters occurred in China, including 1484 collapse cases, accounting for 15.3%, resulting in hundreds of deaths and economic losses of billions[1] .

With the rapid development of China's infrastructure construction and the construction of a large number of high-speed railways, the loss caused by slope rockfall disaster is becoming more and more serious. Therefore, the accurate judgement of the slope rockfall energy level movement distance, bounce height and movement characteristic parameters and the factors of influence of the three sports [2-5] research analysis, to determine the final motion characteristics of the rock fall, can decrease the cost of the slope engineering design, which will provide a scientific basis for engineering design of retaining structure, the cut slope engineering busywork and specific implementation work, It makes the engineering design of retaining structure targeted.

II. CHARACTERISTIC PARAMETERS ANALYSIS OF ROCKFALL MOVEMENT FOR ROCK SLOPE

Scholars at home and abroad have carried out a lot of research work on the characteristics of rockfall movement in slope, and achieved relatively effective research results [6-14]. Professor Ni Mi Roini [7] Shvili was one of the early scholars who studied the trajectory of rockfall movement, and he proposed a formula for calculating the velocity of rockfall movement on slopes of different material types. On this basis, Hu Houtian [3] derived the formula for calculating the horizontal movement distance, speed and jump height of rockfall in four different states of straight fall, cross fall, roll fall and slide, established the trajectory equation of rockfall movement, and proposed the calculation method of retaining structure size. Yang Haiqing [6-8] studied several common forms of rockfall movement, and believed that the elastic-plastic deformation of slope should be considered when rockfall collided with slope in the process of movement, and obtained the velocity calculation equation of these common forms of movement and slope reduction coefficient calculation formula related to slope material, velocity before impact and rockfall shape. Azzoni [9] developed a computer software model to study the characteristics of rockfall movement, and discussed and studied the influencing factors of rockfall movement speed, energy and bounce height, etc., and also studied the rockfall forces under different slope morphology in the process of rockfall movement. Paolo Paronuzzi [10-11] believes that in the process of rockfall movement, even on the slope covered by vegetation, as long as the tangential recovery coefficient Rt of the slope surface is not less than 0.8, the rockfall will bounce and its tangential recovery coefficient must not be less than 0.8, otherwise the rockfall can be in a rolling state. Lv Qing [15-16] divided the main motion forms of rockfall into sliding, rolling, collision, bounce and flying, and established physical equations corresponding to the four main motion forms respectively, and focused on studying the influence of normal recovery coefficient Rn and tangential recovery coefficient Rt and rolling friction coefficient on the motion characteristics of rockfall. Based on the contact theory, C. Thomton [12-14] assumes that slope surface materials and rockfalls meet the ideal elastic-plastic characteristics, and gives the calculation formula of normal recovery coefficient after collision. Huang Runqiu [17-20], based on the kinematics and mechanical analysis methods of theoretical mechanics, calculated the calculation formula of rockfall collision with slope surface. Field tests were

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carried out to collect relevant rockfall movement data [35-42], and the influence of friction coefficient on rockfall movement characteristics was analyzed. It was concluded that the coverage of slope and vegetation played a decisive role in the normal and tangential recovery coefficients of slope. It is concluded that the order of factors affecting the acceleration of rockfall motion is slope slope, rockfall shape, slope surface characteristics, slope length, rockfall mass and initial rockfall motion mode.

The above methods have achieved relatively effective results [20-26], but in the process of calculation, there are many parameters and the calculation is complicated, and sometimes it takes several tests to obtain more effective results [27-34]. Therefore, based on the orthogonal experimental design method, this paper takes the three characteristic variables of slope rockfall horizontal movement distance, bounce height and movement energy as the design objective to analyze the contribution degree of influencing factors of rockfall motion characteristics and the combination analysis of risk level. On this basis, Rockfall software was used to obtain the data sample set of Rockfall motion characteristics, and LM-BP was introduced to establish the prediction system of Rockfall motion characteristic variables, in order to provide scientific basis for retaining structure engineering design.

2.1 Orthogonal Test Analysis

We take a pure rock slope for example. Six factors such as Slope Height H, Slope Angle α , Normal Recovery Coefficient R_n, Tangential Recovery Coefficient Rt, Friction Angle φ, Initial Velocity V and Mass M are selected to do orthogonal test analysis with the purpose of studying their sensitivity to rockfall motion parameters one by one and finding a level combination of favorable influencing factors. As there is a clear correlation [18-19] between Rn value and Rt value, we just select Rt as an influencing factor but do not regard Rn as an independent factor during the process of rockfall motion analysis on rock side slopes.

If sensitivity analysis on influencing factors is done one by one according to the six factors mentioned above, times of analysis and calculation may increase in power exponent as each factor has a different influence on rockfall motion parameters. Therefore, it’s necessary to introduce orthogonal test analysis to select several representative sample points (a level combination of influencing factors) to form an orthogonal level table for the test analysis. As each factor and level in the orthogonal level table owns the exactly the same probability to take part in the orthogonal test, interference of imbalance between other factors and levels can be cleared away to the greatest extent on level probability of test combination. Those test combinations that adopt orthogonal level tables can not only help us to reduce the workload of test data, but also lead us to gain each influencing factor’s sensitivity [22,26] to rockfall motion parameters.

Test level of each influencing factor, that is range of value (See Table I), has been defined in this paper according to features of side slopes in a natural state (rockfall are of small volume, light mass and slow initial velocity) on both sides of highways in mountainous areas.

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TABLE I. Factors level table of orthogonal test

Factor	*H*/(m)	*α* /(°)	*Rn/Rt*	*φ*/(°)	*V*/(m/s)	*M*/(kg)
Level 1	5	29	0.29/0.79	19	0.1	0.5
Level 2	10	37	0.32/0.82	22	0.2	1
Level 3	18	45	0.35/0.85	25	0.5	2
Level 4	25	53	0.38/0.88	28	1	5
Level 5	35	61	0.41/0.91	31	2	10

2.2 Analysis on Rockfall Motion Parameters

This article adopts Rockfall software to do numerical simulation [29-30]. Based on probability statistics analysis, Rockfall is such a software that can do a great deal of probability simulation and statistical analysis on sliding calculation, contact calculation and collision calculation when rockfall are falling in a random way by considering types of slope surfaces and self-owned parameters as well as motion state of rockfall to obtain relatively stable high probability statistical results. Meanwhile, rockfall' motion tracks, motion state during their falling process, and rockfall motion parameters can all be obtained with the help of computer simulation and stochastic simulation method.

As for a case with six influencing factors and five levels, 5^6 test analyses are usually needed according to orthogonal test design theory. Fortunately, 25 test analyses are enough if orthogonal test table is used. Rockfall software can be used to randomly trigger a hundred times of simulative calculation so as to get rockfall motion parameters corresponding to each time of test [5,22] (See Table II). Results of range analysis, variance analysis and effect curve can also be reached to know well each influencing factor's sensitivity and contribution rate to rockfall motion parameters, get a level combination of less favorable influencing factors, and study change rules of rockfall motion parameters under different levels of each factor (See Table III, Table IV, Fig 1 to Fig 3).

TABLE II. Orthogonal test scheme and test results table

Factor	*H*	*α*	R_n/R_t	*φ*	*V*	*M*	Horizontal movement distance /(m)	Bouncing height /(m)	motion energy /(J)
Test 1	5	29	0.29/0.79	19	0.1	0.5	11.44	0.09	10.60
Test 2	5	37	0.32/0.82	22	0.2	1	9.87	0.18	26.64
…	…	…	…	…	…	…	…	…	…
Test 9	10	53	0.41/0.91	19	0.2	2	15.63	1.32	139.89
…	…	…	…	…	…	…	…	…	…
Test 25	35	61	0.38/0.88	25	0.2	0.5	39.39	4.02	122.86

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TABLE III. Range analysis

Factor	*H*	*α*	R_n/R_t	*φ*	*V*	*M*
Horizontal movement distance /(m)	45.01	15.34	6.38	3.73	4.97	7.21
Bouncing height /(m)	1.949	2.081	0.674	0.954	0.960	0.831
Motion energy/(J)	685.16	442.95	371.410	475.720	461.992	1048.01

The range analysis shows that the greater the range, the higher the sensitivity of the influencing factors. It helps to get a sensitivity ranking of influencing factors and a level combination of favorable (or less favorable) influencing factors. As each rockfall motion parameter does not lie on the same order of magnitude, an effect curve (See Fig 1) for range analysis of rockfall motion parameters can be obtained as soon as a normalization of values of range analysis is completed.

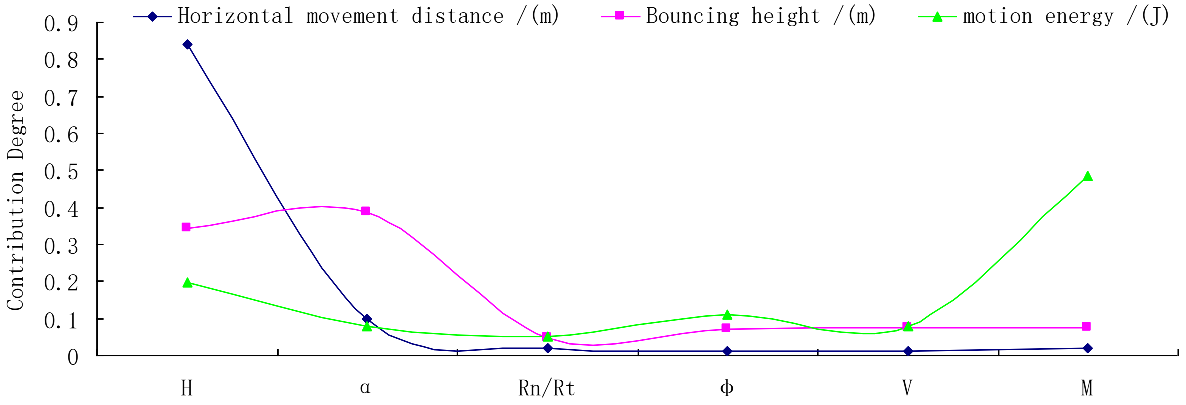

Fig 1: Range effect curve of rockfall motion characteristic parameters

Both F ratio and contribution rate to rockfall motion parameters by influencing factors can be obtained through variance analysis.

TABLE IV. Variance analysis

Factor	Horizontal movement distance /(m)		Bouncing height /(m)		Motion energy/(J)	
	F	Contribution degree	F	Contribution degree	F	Contribution degree
H	110.28	0.84	7.324	0.344351	3.983	0.198475
α	13.48	0.10	8.251	0.387935	1.548	0.077138
R_t	2.15	0.02	1.000	0.047017	1.000	0.049831
φ	1.00	0.01	1.523	0.071607	2.206	0.109926
V	1.33	0.01	1.601	0.075274	1.573	0.078383
M	2.74	0.02	1.570	0.073816	9.758	0.486247

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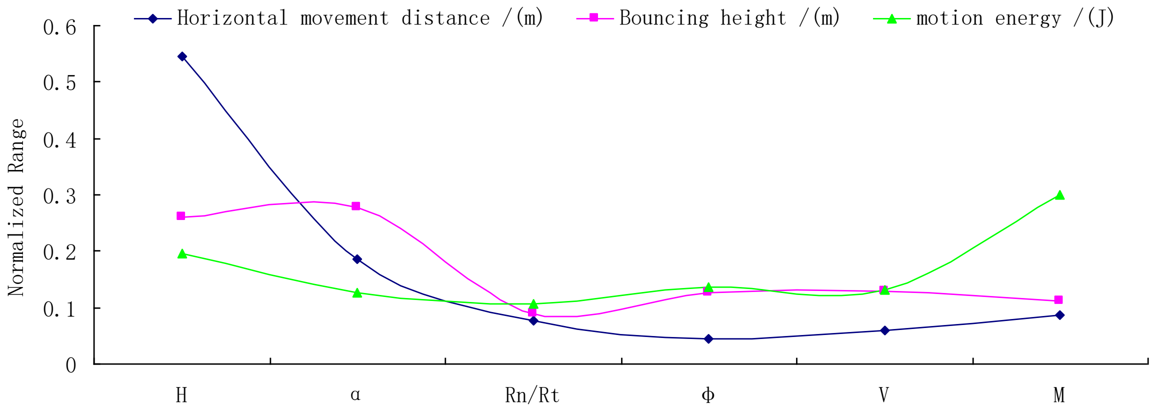

Fig.2 Contributions curve of influence factors of rockfall on motion characteristic parameters

Table II to Table IV and effect curves of Fig 1 and Fig 2 tell us that, within the value range of each influencing factor, the more scattered the points on the curves, the more sensitive the influencing factor is. That is to say, results are the same from range analysis and variance analysis. It's easy to find how each influencing factor affects rockfall motion parameters in a regular way and obtain a sensitive range in which each influencing factor works on rockfall motion parameters.

1) Ranking of influencing factors' sensitivity to rockfall' horizontal moving distance shall be: Slope Height>Slope Angle>Side Slope Recovery Coefficient>Rock Mass>Initial Velocity>Friction Angle. The cumulative contribution rate from top two (Slope Height and Slope Angle) has reached to 94%, which tell us that all that to be considered are the top two influencing factors when we are studying influencing factors of rockfall' horizontal moving distance, while other influencing factors left can be ignored. In addition, a favorable data combination for rockfall' horizontal moving distance can be Slope Height: 5m; Slope Angle: 61°; Friction Angle: 31°; Tangential Recovery Coefficient: 0.82; Initial Velocity: 0.1m/s; Rock Mass: 0.5kg.

2) Ranking of influencing factors' sensitivity to rockfall' bounce height shall be: Slope Angle>Slope Height>Initial Velocity>Rock Mass>Friction Angle>Side Slope Recovery Coefficient. The cumulative contribution rate from top two (Slope Angle and Slope Height) has reached to 73.2%, which tell us that all that to be considered are the top two influencing factors when we are studying influencing factors of rockfall' bounce height, while other influencing factors left can be ignored. In addition, a favorable data combination for rockfall' bounce height can be Slope Height: 5m; Slope Angle: 29°; Friction Angle: 31°; Tangential Recovery Coefficient: 0.91; Initial Velocity: 0.5m/s; Rock Mass: 1kg.

3) Ranking of influencing factors' sensitivity to rockfall' motion energy shall be: Rock Mass>Slope Height>Friction Angle>Initial Velocity>Slope Angle>Side Slope Recovery Coefficient. The cumulative contribution rate from top three (Rock Mass, Slope Height and Friction Angle) has reached to 79.5%, which tell us that all that to be considered are the top three influencing factors when we are studying influencing factors of rockfall' motion energy, while other influencing factors left can be ignored. In

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addition, a favorable data combination for rockfall' motion energy can be Rock Mass: 0.5kg; Slope Height: 5m; Friction Angle: 31°; Initial Velocity: 1m/s; Slope Angle: 29°; Tangential Recovery Coefficient: 0.91.

4) It can be seen from analyses listed above that initial velocity under a natural state has an insignificant influence on three rockfall motion parameters. As a result, initial velocity can be ignored in the following studies.

In a word, the level combination of less favorable influencing factors which is got referring to the orthogonal test analysis can provide scientific basis for the scheme design of safe slope cutting, selection of covering materials for slope surfaces, green vegetation selection and retaining structures design according to specific situation of prevention and control measures for rock slopes whenever necessary.

III. ESTABLISHMENT OF A FORECASTING SYSTEM

It can be known from the analyses mentioned above that rockfall modeling calculation is needed to get exact values for rockfall motion parameters. However, as for a rock side slope that is known to us, there will be no doubt that it has an important guiding significance to the disaster prevention design against rockfall if their rockfall motion parameters can be estimated at the very beginning of such design. Therefore, introduction of LM-BP helps to establish a forecasting system to forecast the three rockfall motion parameters based on analysis results got in previous section. Values of these three parameters can be easily obtained as soon as values for the influencing factors of a rock side slope are input to the forecasting system. And then they can be used for the reference of designers in making design plans.

BP Neural Network is short for Error Back Propagation Multilayer Feedforward Neural Network. The learning rule of BP Neural Network is steepest descent method which realizes error reduction by adjusting weights and thresholds of internal connections through error's back propagation (Atlas Khan. 2013; Duan X J. 2005). Improved from Gauss - Newton method, LM algorithm not only owns Newton method's optimization direction of local fast convergence, but also has the global features of gradient method with the fastest descent. LM-BP algorithm runs upon the principle of constant error reduction to adopt a second-order approximate derivative calculation method when approaching to the optimum point and adjust network weights and thresholds via built-in parameter μ so as to reach the optimal goal. LM-BP algorithm has both rapid convergence speed and stable performance.

3.1 Establishment of Sample Set

Five influencing factors which have significant influences on rockfall motion parameters are selected here after removing the factor of initial velocity that has insignificance influence on the basis of orthogonal test analysis mentioned before. Three hundred groups of sample data (See Table VI) can be obtained from a permutation and combination calculation by selecting an appropriate level value (See Table V) aiming at artificial design and prevention slope on both sides of highways of mountainous areas according to influencing factors' sensitivity degree considering simulation test times that may be needed by the sample set.

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TABLE V. Factor level of sample set

Factor	H	α	M	φ	R_n/R_t
Level 1	8	35	0.5	23	0.33/0.83
Level 2	16	40	1.0	30	0.37/0.87
Level 3	24	45	5.0	——	——
Level 4	32	50	——	——	——
Level 5	40	55	——	——	——

TABLE VI. Data sample set

Test number	H	α	M	φ	R_n/R_t	Horizontal movement distance /(m)	Bouncing height /(m)	motion energy /(J)
1	8	35	0.5	23	0.33/0.83	15.71	0.2746	19.11
2	8	35	0.5	23	0.37/0.87	15.67	0.2624	18.72
3	8	35	0.5	30	0.33/0.83	13.30	0.1274	13.22
…	…	…	…	…	…	…	…	…
120	16	55	5	30	0.37/0.87	21.23	1.571 0	526.27
…	…	…	…	…	…	…	…	…
300	40	55	5	30	0.37/0.87	50.16	4.0897	1231.30

3.2 Analysis on Forecasting Results

Firstly, establish a forecasting system for parameters of rockfall' horizontal moving distance, select 280 groups of uniformly distributed sample sets under univariate test simulation for data normalization, take use of BPNN method to do egression training, and make grid search to determine BPNN parameters through Bayesian Regularization Method. Next do the test using 20 groups of uniformly distributed sample data. Please find training results in Fig 4 and forecasting results in Fig.3. Mean square error of the forecasting result for rockfall' horizontal moving distance is 1.9844e-004 with a square correlation coefficient reaching to 0.9994.

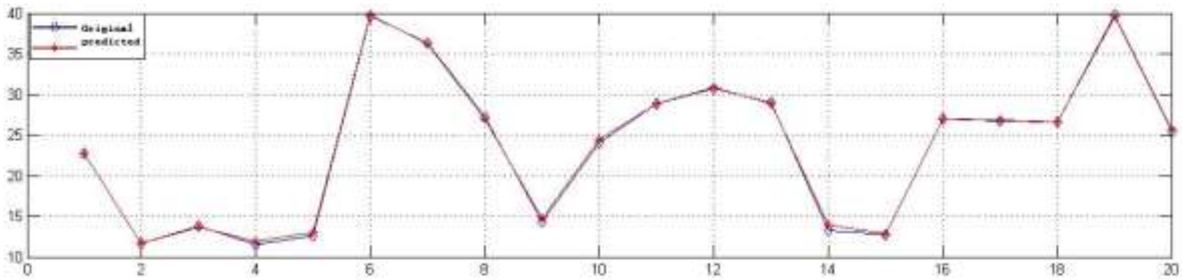

Fig 3: Prediction of test sample of horizontal movement distance

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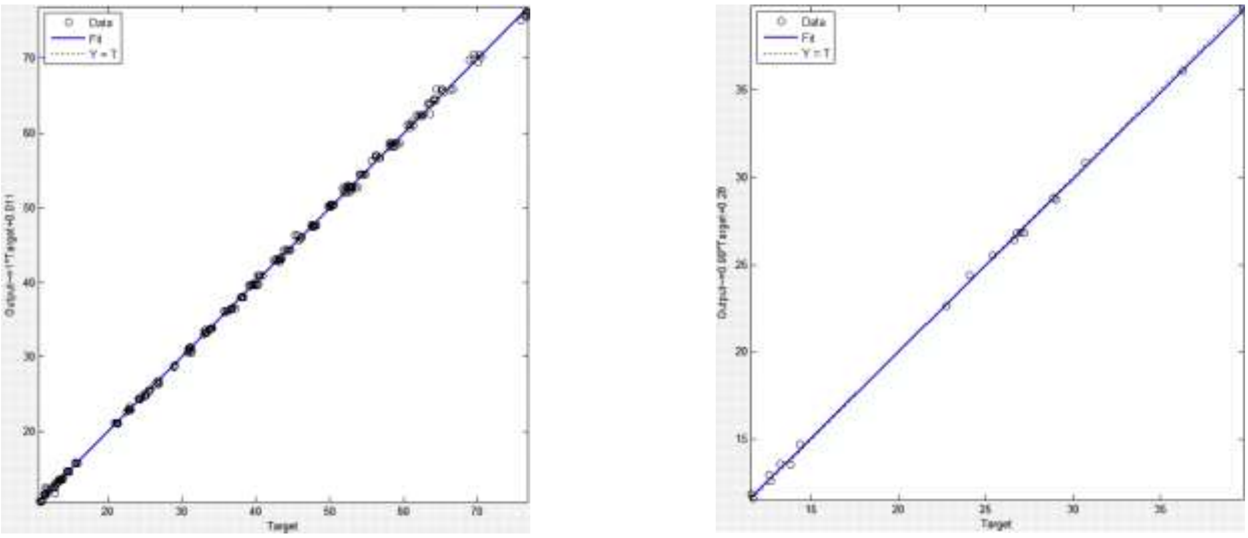

Fig 4: BP regression curve of horizontal movement distance

Forecasting systems for parameters of both bounce height and motion energy of rockfall can be established in the same way as previous section. Parameter training results and forecasting results for bounce height forecasting system can separately be checked in Fig 5 and Fig 6. Mean square error of the forecasting result for rockfall' bounce height is 0.0041 with a square correlation coefficient reaching to 0.9889. Parameter training results and forecasting results for motion energy forecasting system can separately be checked in Fig 7 and Fig 8. Mean square error of the forecasting result for rockfall' motion energy is 0.0973 with a square correlation coefficient reaching to 0.8727. Errors not exceeding 15% exist in all of the three forecasting systems. These errors that go within the allowable error range of the project show that forecasting accuracy can meet our needs and these forecasting systems can be deemed as qualified and successful.

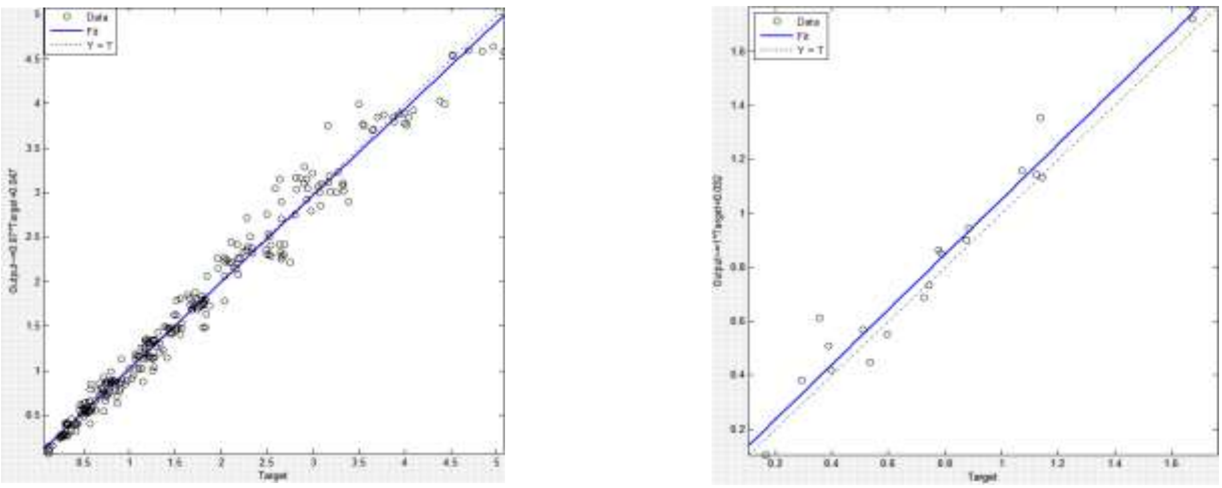

Fig 5: BP regression curve of bounce height

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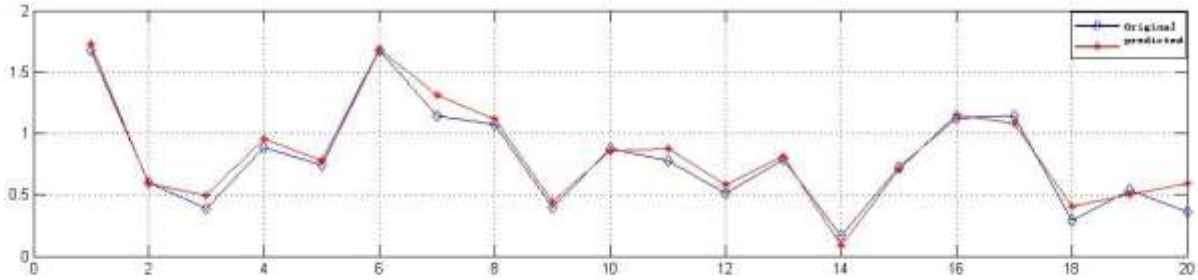

Fig 6: Prediction of test sample of bounce height

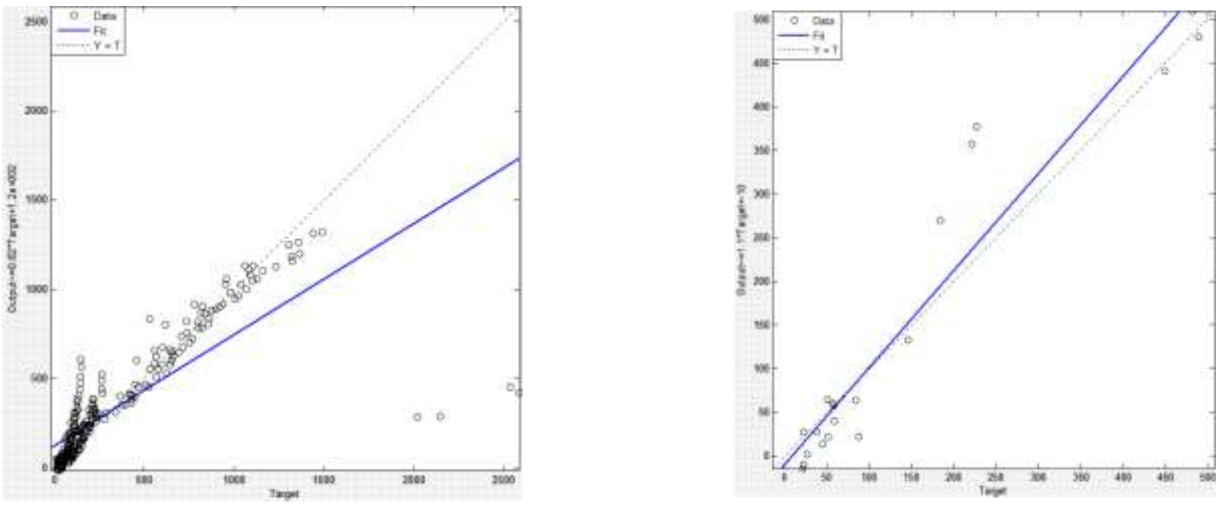

Fig 7: BP regression curve of motion energy

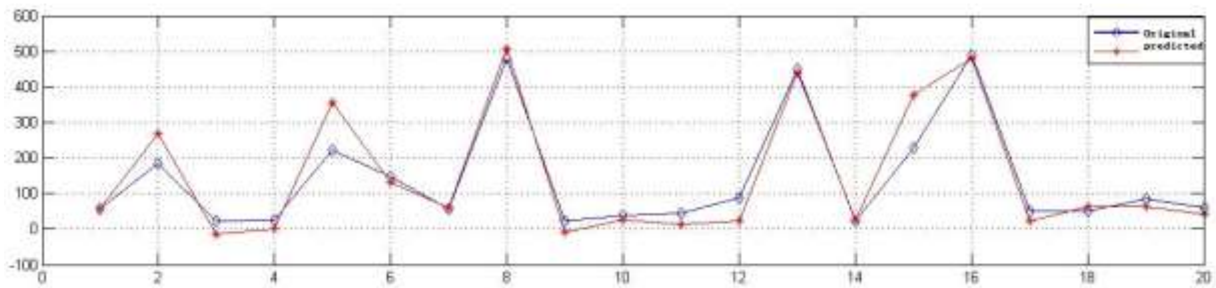

Fig 8: Prediction of test sample of motion energy

IV. CASE STUDY

In July 2013, a large scale slope rock falling and local collapse geological disaster occurred on a side slope on Zhangzhuo Expressway *K19+500--K19+710* section in Zhangjiakou in China because of a continuous rainstorm (See Fig 9). The highway where the side slope collapsed went towards S110°～100°E with a slope aspect of 195°. Total length of the side slope reached to 210 meters, slope relative height difference reached to about 40 meters, and angle of slope wall reached to about 55°. Slope lithology

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was mainly boulders, gravels and blocks with petrochemical compositions of dolomites and siltrocks. The slope surface was covered by a small amount of vegetation and partially hard soil. There were collapse and slope weathering residues with the thickness of about 2 meters in slope toe. According to the field survey results, we defined Rock Mass as 5kg, Initial Velocity as 0.6m/s, Slope Surface Recovery Coefficient as 0.35/0.85, Fiction Angle as 30°. And then we got a result (See Table VII) after making a comparative analysis by using Rockfall software and the forecasting system based on BPNN.

Fig 9: The status of rockfall

TABLE VII. Comparison of calculation results

Data / Parameter	*Rockfall*	LM-BPNN	Error
Horizontal movement distance /(m)	50.16	49.47	1.8142%
Bouncing height /(m)	4.09	3.82	8.8020%
Motion energy/(J)	1231.30	1115.02	9.4437%

The result showed that contrast errors for three rockfall motion parameters before slope cutting were 1.8142%, 8.8020% and 9.4437%, none of which exceeded 10%. It proved that the forecasting system based on LM-BPNN could be used for the forecasting of rockfall motion parameters.

V. DISCUSSIONS AND CONCLUSIONS

The prediction system of characteristic parameters of rockfall movement can help designers to estimate the characteristic parameters of rockfall movement easily and quickly in the stage of preliminary design or daily protection, so as to reduce field workload and improve work efficiency. Although the prediction model is given for the engineering examples of good prediction effect have been achieved, but as a result of the orthogonal test analysis and forecast system in the process of the establishment of the part has carried on the simplification and assumption, and the influencing factors of rockfall movement characteristic parameters, also there is a coupling relationship between, therefore, the next step we will work further research with the combination of experiment.

1) Orthogonal test analysis can help to get sensitivity rankings, influence rules and cumulative contribution rates of influencing factors to parameters of each type of rockfall motion and also a level combination of less favorable (or favorable) influencing factors by studying rockfall's horizontal moving distance, bounce height and motion energy.

2) Accuracy ranking of forecasting systems for rockfall motion parameters based on LM-BP shall be horizontal moving distance, bounce height and motion energy, in which forecasting effect on motion energy shall be poorer than that of the other two types.

3) Mean square deviation of the forecasting system based on LM-BP does not exceed 10%, an error that goes within the allowable error range of the project. It helps designers to easily estimate rockfall motion parameters at the very beginning of scheme design or during daily maintenance.

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