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Improved prediction of blast-induced vibrations in limestone mines using Genetic Algorithm

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Abstract
Like most limestone mines, which produce the raw materials required for cement companies, the transportation cost of the raw materials used in the Shahrood Cement Company is high. It has been tried to build the crushing and grinding plant close to the mine as much as possible. On the other hand, blasting has harmful effects, and the impacts of blast-induced damages on the sensitive machinery, equipment, and buildings are considerable. In such mines, among the blasting effects, blast-induced vibrations have a great deal of importance. This research work was conducted to analyze the blasting effects, and to propose a valid and reliable formula to predict the blast-induced vibration impacts in such regions, especially for the Shahrood Cement Company. Up to the present time, different indices have been introduced to quantify the blast vibration effects, among which peak particle velocity (PPV) has been widely considered by a majority of researchers. In order to establish a relationship between PPV and the blast site properties, different formulas have been proposed till now, and their frequently-used versions have been employed in the general form of $PPV = K_1 W^{K_2} D^{K_3}$, where *W* and *D* are the maximum charge per delay and the distance from the blast site, respectively, and K_1, K_2, and K_3 describe the site specifications. In this work, a series of tests and field measurements were carried out, and the required parameters were collected. Then in order to generalize the relationship between different limestone mines, and also to increase the prediction precision, the related data for similar limestone mines was gathered from the literature. In order to find the best equation fitting the real data, a simple regression model with genetic algorithm was used, and the best PPV predictor was achieved. At last, the results obtained for the best predictor model were compared with the real measured data by means of a correlation analysis.

Keywords: *Blasting, Blast-Induced Vibration, PPV, Limestone Mine, Cement Company, Genetic Algorithm.*

1. Introduction

Companies using blasting operations are often faced with the necessity of limiting the vibration levels in order to minimize or eliminate the possibility of damage to the nearby structures. Therefore, proper blasting design is necessary to ensure both the safety of employees and the protection of nearby structures from the vibration effects [1]. Generally, a blasting project has four forms of concerns including fly rock, air blast, produced dust and fume, and vibration. The importance of each item depends on studying the case conditions and environmental aspects. In the case of the Shahrood Cement Company, due to the material transportation costs, it has been tried to make the factory and crushing plant close to the limestone mines as much as possible, and therefore, the blasting effects, mostly the vibrations, play the most important role in a blast design. An overview of the Shahrood Cement Company and one of its limestone mines is shown in Figure1.

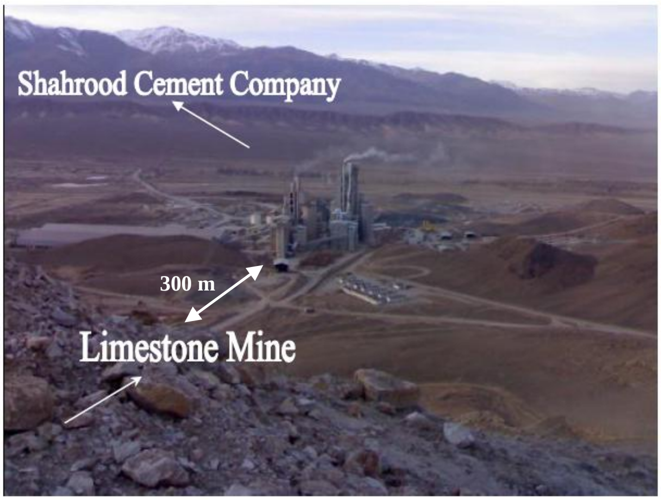

Figure 1. An overview of Shahrood Cement Company and one of its limestone mines.

The intensity of ground vibrations depends on various parameters. These parameters can be broadly divided into two categories, namely the controllable and uncontrollable parameters, as shown in Table 1. The controllable parameters can be changed by the engineers in charge, while the uncontrollable ones are natural and uncontrollable [2]. In order to establish a vibration predictor model, taking all these parameters in a single relation into account is impractical, and such an equation could not be used easily in practical situations. Engineering experiences show that the vibration level at any particular site is affected mostly by the maximum charge weight per delay (W), distance from the blast site (D), vibration frequency (*f*), and initiation method [3]. Among them, the vibration frequency is uncontrollable, and the initiation method is of less importance, and therefore, the analysis should be focused on the two controllable parameters (i.e. *D* and *W*). To simplify the relation between the blast-induced vibration impact and the blast and site parameters, two important enterprises should be attempted, as explained below.

First, to estimate the blast impacts and effects on the environment, buildings, and structures, an index or indicator should be defined, and this index should be a proper representative of the blast vibration impact, and yet, easy to use and measure. Actually, to estimate the damage level in the structures produced by blasting projects, a lot of studies have been conducted, and to determine the damage level, some parameters such as peak particle velocity (PPV), peak particle acceleration (PPA), peak particle displacement (PPD), scaled distance (SD), and energy ratio (ER) have been investigated. For estimating the damage of blast vibrations, the importance of different parameters has been considered by different sources and researchers, given in Table 2. For example, the US Bureau of Mines (USBM) has extensively studied the various aspects of the ground vibrations caused due to the open-cast blasting and damaging effects on different types of structures. They have found that PPV is the best index for use to determine the damage criteria for the structures [3]. Table 1 shows that, from the viewpoint of almost all researchers and sources, PPV is the best index for use to evaluate the blasting vibration effects, and so in this study, PPV was used as the vibration impact estimating the index or indicator.

Table1. Controllable and uncontrollable parameters affecting vibration intensity [2].

Controllable variables				Uncontrollable variables
Geometrical parameters	**Explosive- dependent parameters**	**Operational parameters**	**Others**	**Delay time scatter**
Hole diameter Burden Spacing Bench height Stemming Hole inclination Sub-drilling	Explosive type Total explosives Max. Charge/delay Explosive energy VOD P-wave in rock	Blast size Initiation point Delay sequence Delay intervals Firing method Confinement	Distance to object	Rock conditions Topography Geology Rock properties Weather Conditions

Table 2. Importance of different parameters used for estimating damage of blast vibrations [10-15].

Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Particle velocity				●	●	●		●	●	●	●	●	●	●
Frequency		●	●				●		●		●	●	●	
Damage type				●	●	●				●	●			
Structure type										●	●	●	●	
Rock type								●						
Acceleration			●				●							
Amplitude	●	●												
Distance		●												●
Vibration velocity							●							
Displacement							●							

1. United States Bureau of Mines (USBM),1942 [16]	8. Indian Standard Institute, 1973 [22]
2. Rockwell's Energy Formula, 1934 [17]	9. Medearis's Approach, 1976 [23]
3. Crandell's Energy Ratio Concept, 1949 [18]	10. Canmet, Bauer and Calder, 1977 [24]
4. Langefors, Kihlstrom and Westerberg, 1957 [19]	11. USBM's Criterion, 1980 [25]
5. Edwards and Northweed, 1959 [20]	12. German DIN Standard 4150, 1986 [26]
6. USBM's Criterion, 1971 [21]	13. Indian CMRI standards, 1993 [27]
7. Langefors and Kihlstrom's Chart, 1967 [6]	14. Rosenthal and Morlock, 1987 [28]

Secondly, a proper and reliable relation should be employed between the distance from the blast site (D) and the maximum charge per delay (W) as the most important controllable and effective parameters for the PPV intensity, and yet, it should be easy to use and analyze. During years, in different parts of the world, a lot of projects have been conducted to develop a suitable relationship between PPV, D, and W, and many scientists and engineers have investigated the PPV prediction and published their findings. The first significant PPV predictor equation was proposed by USBM [4]. There are also some modified predictors suggested by other researchers or institutions such as Langefors and Kihlstrom [5], Ambraseys and Hendron [6], Ghosh and Daemen [7], Roy [8], and Singh et al. [9]. However, the PPV predictor established by USBM is still the most widely used equation in the literature. In order to analyze the vibration data, some frequently-used PPV predictor models have been listed in Table 3. All these formulas were used to predict PPV and analyze the Shahrood Cement Company measured data, and in addition, in order to generalize these relations for a wide range of limestone mines, and also to increase the prediction precision, some related data from similar limestone mines was gathered from the literature. Next, to find the best fitted equation to the real data, a simple regression model associated with genetic algorithm (GA) optimization method was used, and the best PPV predictor was achieved.

Table 3. List of proposed predictor equations used for calculation of PPV.

Model	Name	Year	Equation	Reference
1	USBM(Duvall and Fogelson, 1962)	1962	$PPV = K_1\left(\frac{D}{\sqrt{W_{max}}}\right)^{-K_2}$	[4]
2	Langfors & Kihlstrom(1968)	1968	$PPV = K_1\left(\sqrt{\frac{W_{max}}{D^{2/3}}}\right)^{K_2}$	[5]
3	Ambrases & Hendron(1968)	1968	$PPV = K_1\left(\frac{D}{\sqrt[3]{W_{max}}}\right)^{-K_2}$	[6]
4	Indian standard predictor(1973)	1973	$PPV = K_1\left(\frac{W_{max}}{D^{2/3}}\right)^{K_2}$	[22]

2. Instrumentation and data measurement

Blast-induced vibrations were monitored by a Minimate Plus seismograph (made by M/s Instantel Inc). This seismograph has four channels, three of which are allocated to the vibration measurement in three directions, i.e. longitudinal (Lon.), vertical (Ver.), transverse

(Tran.), and the fourth one, which is an air phone, measures the air blast. This seismograph also records the dominant vibration frequency, peak particle acceleration (PPA), and peak particle displacement (PPD),and computes the peak vector sum (PVS) of vibration. PVS represents the resultant particle velocity magnitude, and is defined as follows:

$$PVS = \sqrt{V_L^{\ 2} + V_T^{\ 2} + V_V^{\ 2}} \quad (1)$$

Where V_L, V_T, and V_V are the longitudinal, transverse, and vertical components of vibration, respectively. The setup of the Minimate Plus seismograph in the Shahrood Cement Company is given in Figure 2.

The distances from the blasting site to the monitoring stations were measured precisely by means of a hand-held global positioning system (GPS) instrument, and the amount of charge weight per delay was recorded for each shot by controlling the hole charges. In determining the maximum charge per delay, the amount of dynamite used as priming was added to the amount of blasting agent. The required blasting design parameters and the measurement results are given in Table 4. In the blasting operations, ANFO (blasting agent) and gelatin dynamite (priming) were used as the explosives during the study. The blast holes were vertical and 64 mm in diameter. The holes length varied from 3.3 to 6m, with approximately 0.5 m of sub-drillings and one-third of hole length as stemming for all blast patterns. An electrical millisecond delay system was used to initiate the charge.

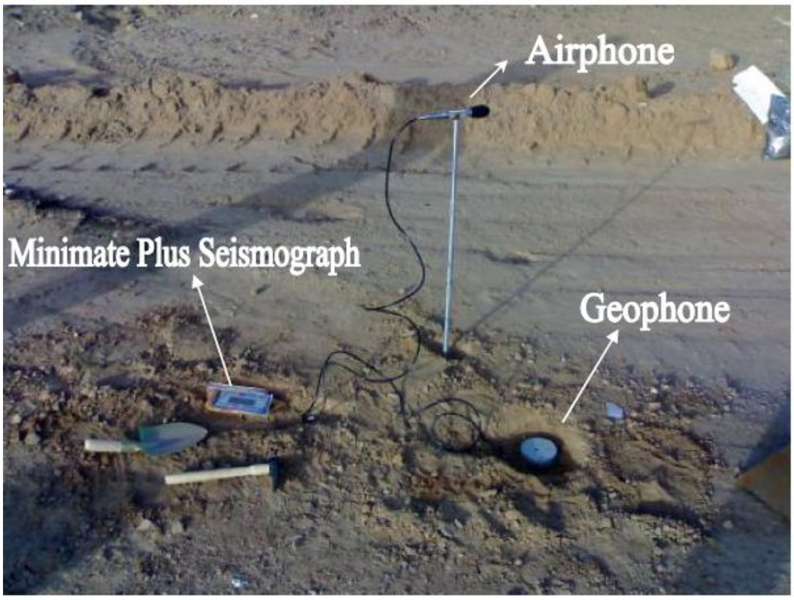

Figure2. Setup of Minimate Plus seismograph.

Table 4. Measured vibration data in Shahrood Cement Company limestone mines.

	Shot1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 7
W (kg)	945	665	810	810	270	63
D (m)	667.41	771.94	785.45	334.75	451.56	113.93
Tran (mm/s)	0.381(228Hz)	1.27 (5.4Hz)	1.40(15.3 Hz)	0.762 (11.5Hz)	0.508 (8.7 Hz)	6.22 (24.7 Hz)
Ver (mm/s)	0.508(205Hz)	0.762(4.0 Hz)	1.40(66 Hz)	0.508(10.6Hz)	0.381(15.6 Hz)	8.51(24.4 Hz)
Lon (mm/s)	0.508(128Hz)	0.762(3.7 Hz)	2.03(26.9 Hz)	0.762(26.3Hz)	0.508(26.3Hz)	10.0(30.1 Hz)
PPV (mm/s)	0.81	1.67	2.82	1.19	0.81	14.53
Mic (Pa)	<0.500	39.5(22Hz)	462(22.3 Hz)	50.3(15.8Hz)	52.0(49 Hz)	301(54 Hz)
PDT (mm)	0.0031	0.0407	0.0122	0.0116	0.00944	0.0384
PDV (mm)	0.00045	0.0266	0.00792	0.00778	0.00429	0.0559
PDL (mm)	0.00071	0.036	0.0146	0.011	0.0033	0.052
PAT(g)	0.053	0.053	0.106	0.053	0.053	0.212
PAV (g)	0.106	0.106	0.106	0.053	0.053	0.212
PAL(g)	0.053	0.053	0.106	0.053	0.106	0.212
PVS (mm/s)	0.762	1.28	2.05	1.09	0.568	11.5

3. Frequency analysis of blast vibration

Using the Minimate Plus seismograph, the dominant frequency and also the frequency range between 2 Hz and250 Hz were measured for each blasting sequence. The different frequency classifications based on the USBM standards are given in Table 5, and the recorded frequencies of blasting were classified in Figure 3 based on the USBM standards.

Since the same-value vibrations with different frequencies have different impacts on buildings and structures, a Fast Fourier Transform (FFT) analysis was used in this research work. In simple waveforms, which are not composed of many different frequencies, the dominant frequency may be at the peak particle velocity. In more complex waveforms, the dominant frequency is not necessarily the frequency at the peak particle velocity but at the frequency with the greatest amplitude. Whether or not this frequency actually contributed to the peak particle velocity value, it should be found by extrapolation of the closed original signal. The frequency at the peak of a complex wave is usually not a single frequency; rather it is a series of waves of different frequencies superimposed. It is intended that the frequency spectrum data be used as a tool in conjunction with the velocity versus time waveform. Burrus and Parks [29], Light hill [30], Oppenheim, [31], Rabinerand Gold [32], and Brigham [33] have widely worked on the FFT analysis.

In fact, the frequency of blast-induced waves is generally controlled by geological conditions and delay arrangements. There are geological forms and structures that are favorable to the formation of different types of frequency waves. When the incoming vibration has a frequency in the range of natural frequency of the structure, resonance occurs and the resultant amplitude of vibration on the structure is amplified [28]. Figure 4 shows the blast time history recorded in the Shahrood Cement Company. Figure 5 is the Fast Fourier Transform (FFT) analysis of the same blast event. It is evident from Figures 4 and 5 that the duration of the blast wave is very short, and that the dominant frequency of all channels falls into the 16-27 Hz range. In fact, the damage potentials in the low frequency range (<40 Hz) are considerably higher than those in the high frequency range (>40 Hz), especially due to a possible resonance effect in structures [35, 36].

Thus one of the important parameters involved in the damage of different frequencies is related to the closeness of the blast dominant frequency and natural frequency of the structures. Using the FFT diagrams, the blasting frequency distribution can be analyzed and also compared with the natural frequency of the structures, and then the damage level can be estimated properly.

In different standards for different frequency ranges, the acceptable levels of vibration velocities are different. For example, for a typical blast vibration time history and an FFT analysis, shown in Figures 4 and 5, the acceptable level of the blast-induced vibration velocities based on USBM RI8507, OSMRE, and CMRI, the proposed Indian standards are shown in Figure 6. It is obvious that the frequency ranges and the acceptable levels of vibration velocities are different in each standard.

As an individual wave passes through the ground, high frequencies will be attenuated, and just low frequencies would remain. A curve was estimated between the dominant frequency and distance of blast site, given in Figure 7. Instead of having a descending trend, this curve has an ascending trend because it is not for a single blasting sequence but in which the blast parameters such as the charge per delay vary for each shot.

Table 5. Different frequency classifications based on USBM standards [41].

Frequency range	0-4 Hz	5-12 Hz	12-40Hz	>40 Hz
Description	Lowest	Low	Medium	High

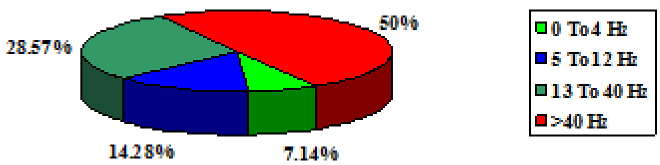

Figure 3. Frequency distribution resulting from Shahrood Cement Company blasting based on USBM standards.

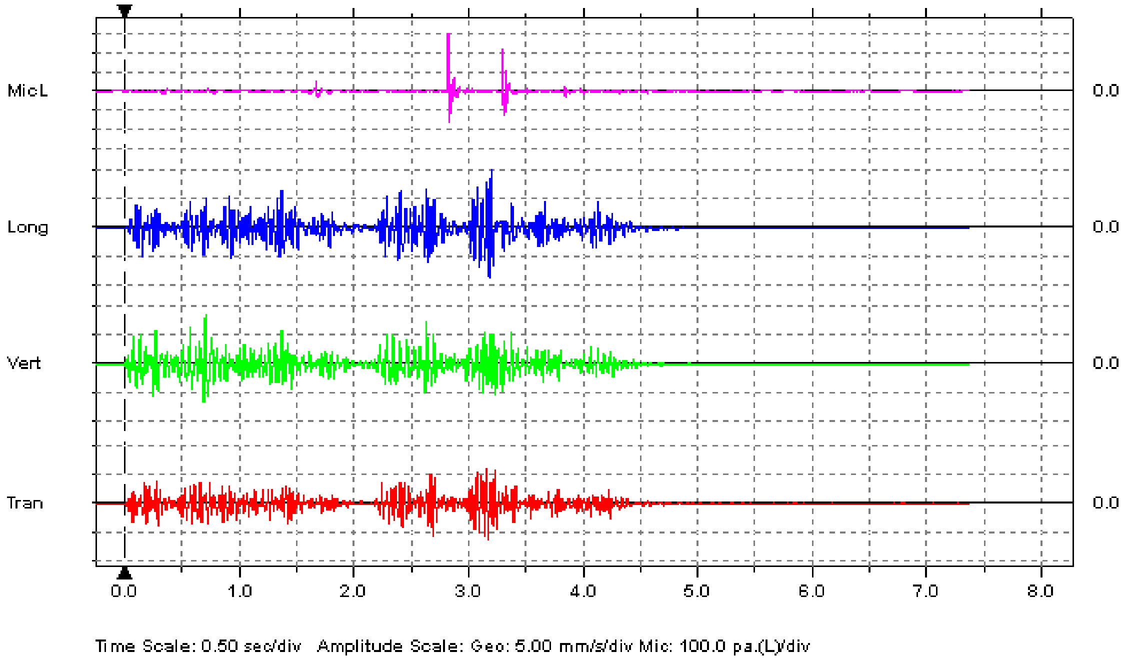

Figure 4.Typical blast vibration time history recorded in Shahrood Cement Company by MinimatePlus seismograph (T6.22 mm/s, F24.7 Hz; V8.51 mm/s, F24.4 Hz; L10.0 mm/s, F30.1 Hz).

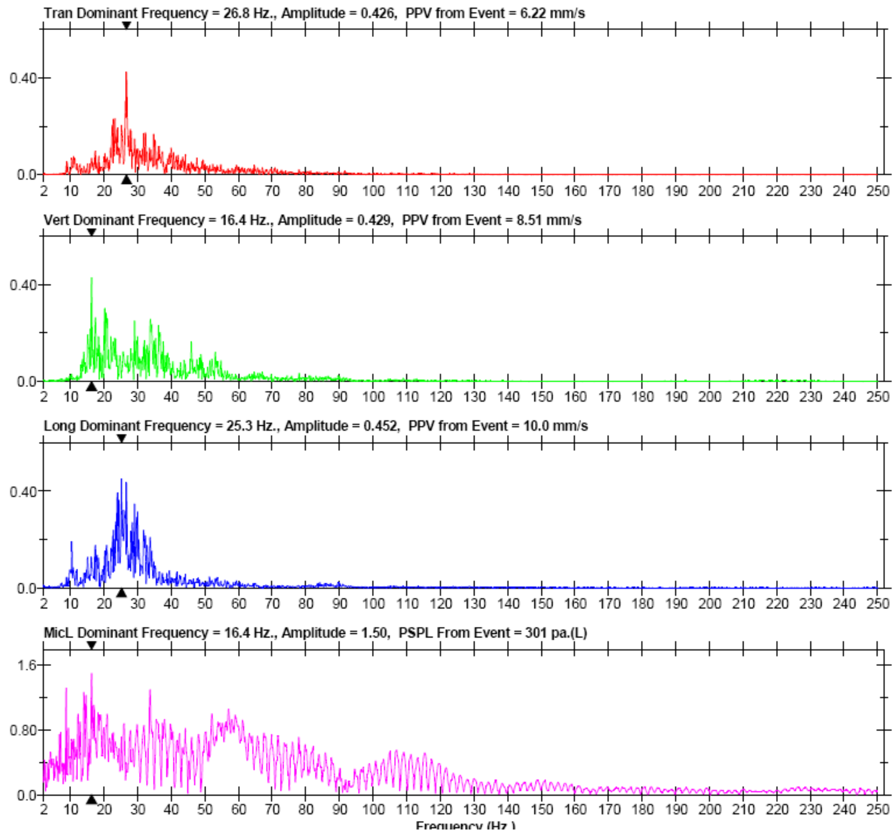

Figure 5. FFT analysis of frequencies of vibration recorded in Shahrood Cement Company limestone mine (dominant frequencies for Mic, T, V, and L are 16.4, 25.3, 16.4 and 26.8 Hz, respectively).

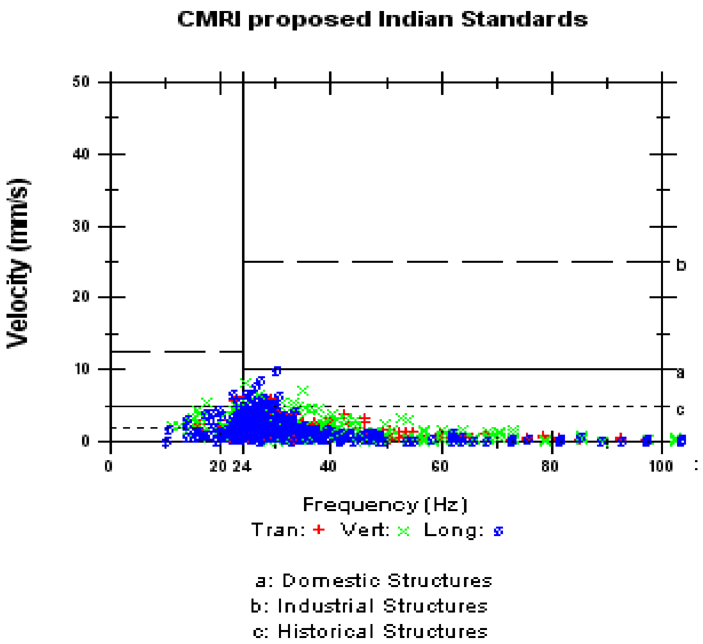

Figure 6. Acceptable level of blast-induced vibration velocities for typical FFT analysis shown in Figure 5 based on OSMRE and CMRI proposed Indian standards [22].

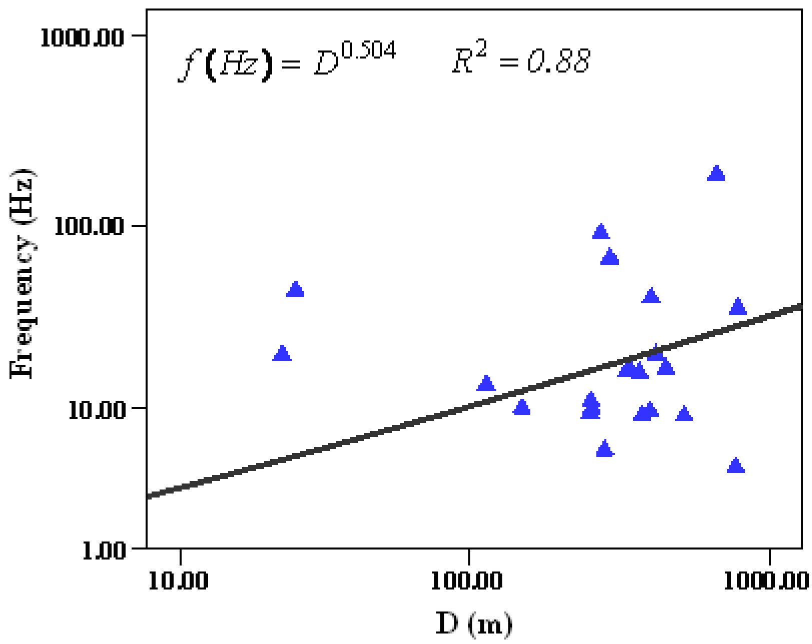

Figure 7. Frequency vs. distance from blast site.

4. Analysis of recorded data for Shahrood Cement Company

The vibration hazards of the sensitive machinery and buildings such as kiln, high buildings, fans, and grinders in the studied area have become an important concern. For this reason, a series of measurements were made in this field, and the required data was tabulate in Table 4.

Two important results can be extracted from Table 4, as follow.

First, PPA and PPD could not be such proper indicators to estimate the vibration damage level because their variations are not considerable in different locations.

Secondly, some researchers have included frequency along with PPV for the damage criteria [25, 37-39]. As it can be seen in their works, in addition to PPV, vibration frequency is an important index to indicate the damage level because, under approximately the same conditions, the vibration frequency is not the same in different directions (i.e. longitudinal, vertical, and transverse), and also a considerable amount of energy is transported by vibration, which has a low frequency [40].

After all, the predictors listed in Table 3 were used to analyze the data in Table 4 and the related curves given in Figure 8. The statistical summary of each model was brought in Table 6. The results of this table show that among of these models, the Langfors & Kihlstrom (1968) and Indian standard (1973) predictors, are comparatively suitable but not satisfactory and reliable. For this reason, and also to generalize the relationship between similar limestone mines, and also in order to increase the prediction precision, some related data for similar mines were gathered from several references, and the same analysis was followed.

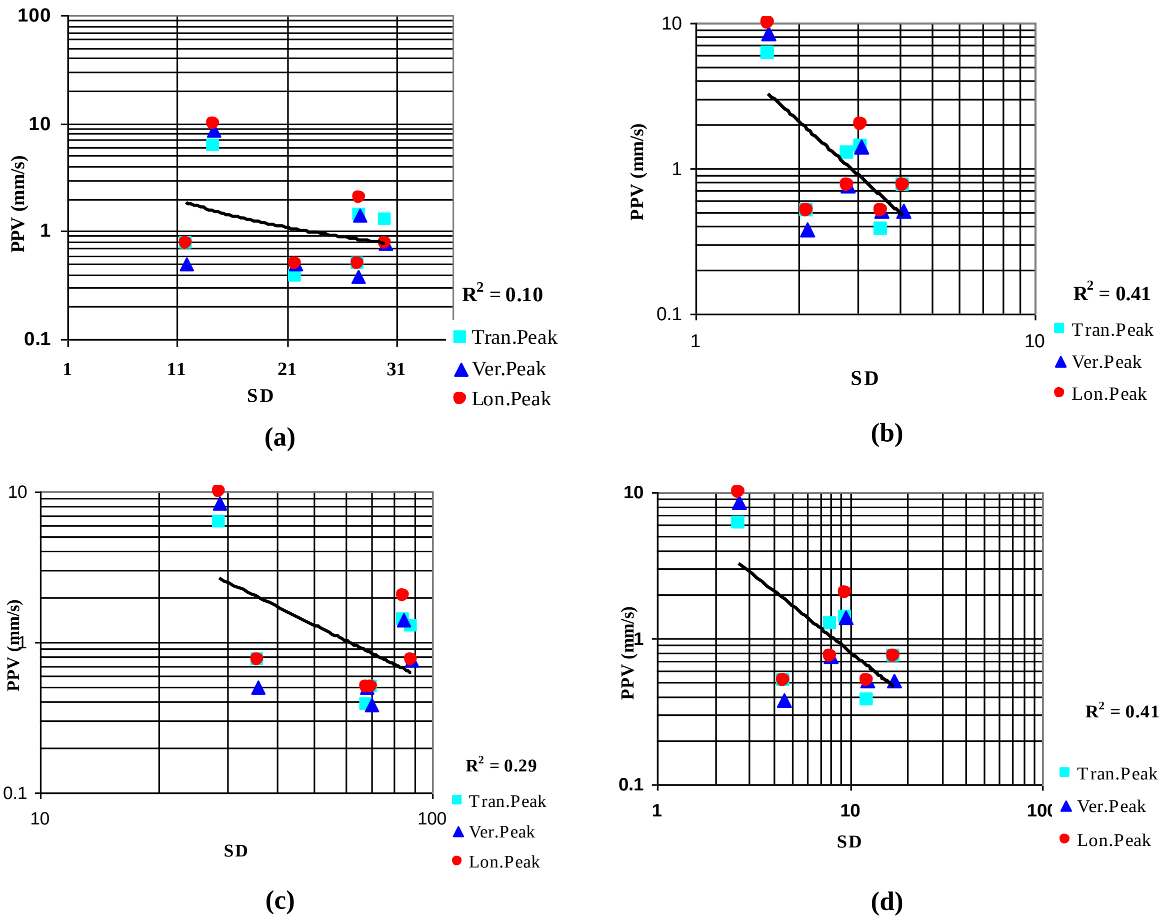

Figure 8. PPV prediction based on different predictors listed in Table 3 for recorded data in Shahrood Cement Company. a) USBM, b) Langfors & Kihlstrom (1968), c) Ambrases & Hendron (1968), and d) Indian standards.

Table 6. Statistical summary of PPV predictor models for Shahrood Cement Company data.

Predictor model	USBM	Langfors & Kihlstrom(1968)	Ambrases & Hendron(1968)	Indian standard
R^2	0.10	0.41	0.29	0.41
k_1	18.30	9.25	194.62	9.25
k_2	–0.92	–2.11	–1.28	–1.05

5. Establishing a general model for limestone mines

In order to establish a general model for limestone mines, a series of recorded data were gathered from different references, given in Tables 7-9. All these mines are located at cement companies. Like the data analysis carried out for the Shahrood Cement Company, all the frequently-used PPV predictors listed in Table 3 were employed to obtain a valid and reliable predictor to estimate the peak particle velocity. The results of this analysis are given in Figure 9, and also the statistical summary of each predicting model are given in Table 10. Considering the results tabulated in this table, the best model was found to be the USBM predictor with R square of 0.64 that is reliable to some extent. It can be seen that by using the additional recorded data, the estimation precision improved, and the R square of the best predictor was improved from 0.41 to 0.64, which is due to the extended database. In the next step, the general model would be used to estimate the PPV value in this extended database.

Table 7. Measured vibration data in Akcansa Cement Company limestone mines [42].

Row No.	PPV (mm/s)	Freq (Hz)	Total W (kg)	W (kg/delay)	D (m)
1	2.35	10	2102	538	257
2	1.2	10	1300	69	150
3	0.85	11	4390	81	255
4	0.95	5.6	3100	206	283
5	0.65	67	4165	93	295
6	0.70	91	3858	97	275
7	0.90	9.4	2225	175	254
8	144	20	180	180	23
9	0.25	9	4250	170	520
10	250	45	242	242	25.6
11	1.55	17	165	165	340
12	0.95	16	83	83	368
13	1.15	9.1	242	242	376
14	0.85	9.6	324	354	400
15	0.35	41	180	180	403
16	0.40	20	180	180	418

Table 8. Measured vibration data in Assiut Cement Company limestone mines [2].

Row No.	D (m)	W (kg/delay)	Lon (mm/s)	Tran (mm/s)	Vert (mm/s)	PPV (mm/s)
1	595	820	1.5	1.2	1.2	2.26
2	729	820	1.2	1.7	1.2	2.40
3	875	820	1.5	2.0	2.0	3.20
4	901	830	0.7	0.7	1	1.41
5	876	830	1.0	1.2	2.7	3.12
6	587	1525	1.7	1.7	3	3.84
7	767	1525	2.2	1.7	1.2	3.03
8	823	1525	2.0	2.0	2.0	3.46
9	585	1115	1.5	1.7	3.3	4.00
10	565	1115	2.2	1.7	3.0	4.09

Table 9.Measured vibration data in Egyptian Cement Company plant limestone mines [43].

Row No.	D (m)	W (kg/delay)	Long (mm/s)	Tran (mm/s)	Vert (mm/s)	PPV (mm/s)
1	544	661.5	1.4	2.23	0.9	2.78
2	770	975	0.93	1.33	0.7	1.77
3	778	874	1.73	2.29	1.5	3.24
4	538	400	1.51	1.71	1.44	2.70
5	864	535	1	1	1	1.73
6	536	164	1.18	1.22	1.12	2.03
7	732	330	1	1	1	1.73
8	608	378	1.34	1.98	1.5	2.82
9	824	367	1	1	1	1.73
10	494	228	1.2	1.5	1	2.17

Table 10. Statistical summary of PPV prediction models for all cement company data.

Predictor model	USBM	Langfors & Kihlstrom (1968)	Ambrases & Hendron (1968)	Indian standard
R^2	0.64	0.34	0.56	0.34
k_1	237.542	0.327	616.951	0.327
k_2	–1.537	1.954	–1.399	0.977

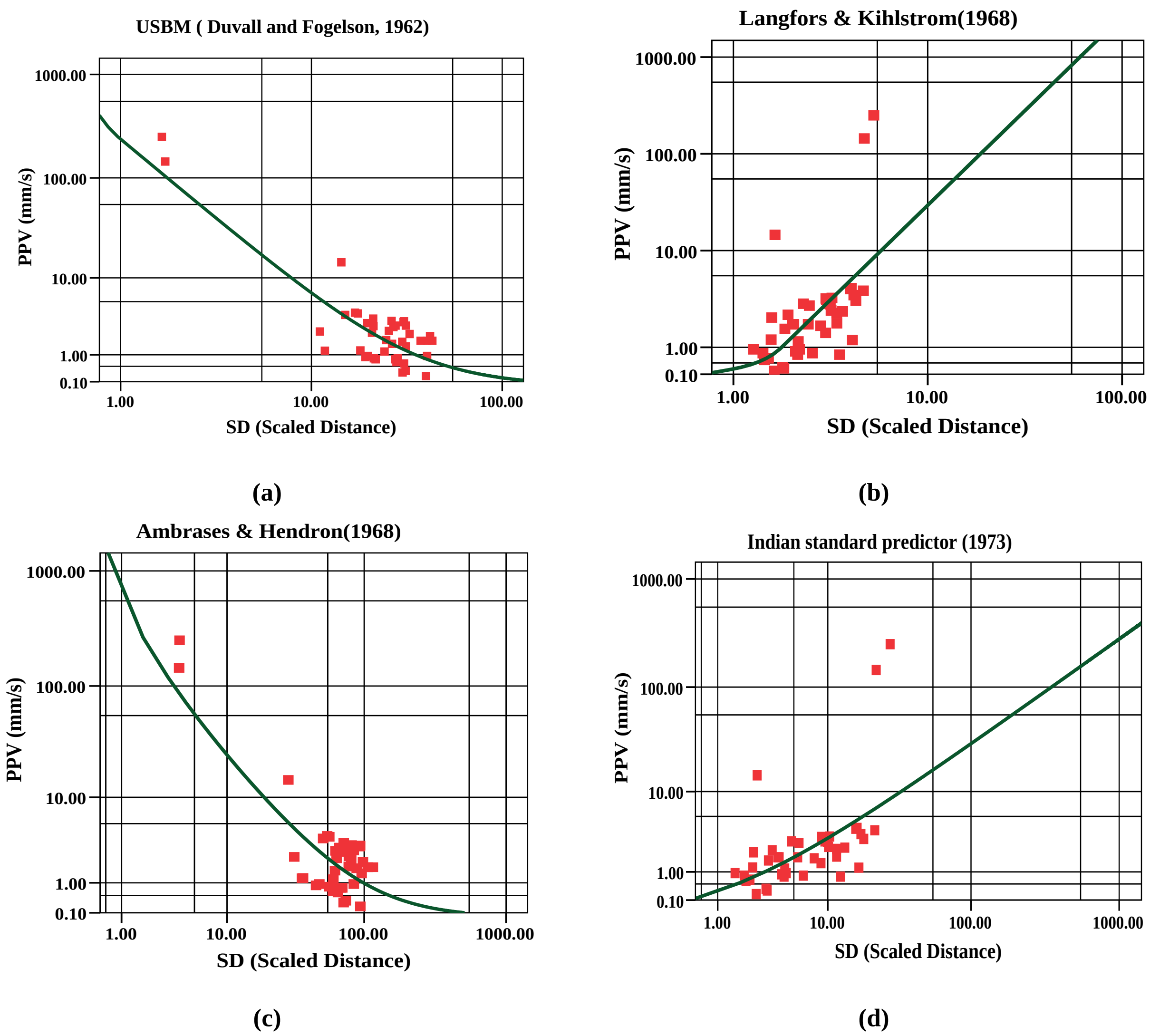

Figure 9. PPV prediction based on different predictors listed in Table 3 for extended database. a) USBM, b) Langfors & Kihlstrom (1968), c) Ambrases & Hendron (1968), and d) Indian standard.

5.1. Analyzing general model using genetic algorithm (GA)

All the formulas listed in Table 3 are the simplified and summarized forms of the general formula that was proposed by Davies et al. [8], as follows:

$$PPV = k_1.D^{-k_2}.W_{max}^{k_3} \qquad (2)$$

In all the reviewed literatures, they used the formulas which included two independent constants k_1 and k_2, describing the site specifications and characteristics. However, in this research work, there are three independent constants, k_1, k_2, and k_3, describing the blast-site properties. In fact, in the summarized formulas, in order to simplify the relationship between the blast-induced PPV and D (the distance between the blast face and vibration monitoring point, m), W (the maximum charge per delay, kg), a hybrid variable called SD (scaled distance) is defined, and in each relation, it has a pre-defined form, and so this form causes these relations not to establish a valid and reliable predictor for general situations. Each form is suitable for specific and particular conditions, and furthermore, even in an individual site, the two constants k_1 and k_2 in these relations cannot reflect the whole perspective of the geological and geotechnical conditions. To achieve a reliable predictor, the general forms of these predictors were employed, although finding such optimized values for the three constants involved (k_1, k_2, and k_3) in this relation could not be performed by a simple regression analysis. This problem was dissolved by the genetic algorithm (GA) optimization method, which was used to obtain the optimized constants k_1, k_2, and k_3, as explained below.

5.2. Genetic algorithm optimization method

Optimization is the process of trying to find the best solution to a problem that may have many possible solutions. Most problems involve many variables that interact based on the given formulas and constraints.

Genetic algorithm (GA) is a global search technique, modeled after the process of natural selection, which can be used to find the near optimal solutions to the highly non-linear optimization problems [43].

The following outline summarizes how GA works:

1. The algorithm begins by creating a random initial population.
2. The algorithm then creates a sequence of new populations. At each step, the algorithm uses the individuals in the current generation to create the next population. To create the new population, the algorithm performs the following steps:
   - Scores each member of the current population by computing its fitness value.
   - Scales the raw fitness scores to convert them into a more usable range of values.
   - Selects members, called parents, based on their fitness.
   - Some of the individuals in the current population that have lower fitness are chosen as elite. These elite individuals are passed to the next population.
   - Produces children from the parents. Children are produced either by making random changes to a single parent (mutation) or by combining the vector entries of a pair of parents (crossover).
   - Replaces the current population with the children to form the next generation.
3. The algorithm stops when one of the stopping criteria (such as maximum iteration and time criterion) is met.

Using this optimization method, the purpose is to find the optimized values for the constants K_1, K_2, and K_3, and then the optimized formula as $PPV = K_1.D^{K_2}.W^{K_3}$. From the data measurement Tables 4, 7, 8, and 9, the real values for the recorded PPV or a set of vectors are available as below:

$$(PPV_i, W_i, D_i) \quad \text{i = 1 to n} \tag{3}$$

Where n is the number of measured records, W_i and D_i are the maximum charge per delay and the observation station distance from blast-site in each blasting sequence, respectively.

On the other hand, the PPV value can also be predicted using the general form including simultaneously the three constants K_1, K_2 and K_3, and obtaining the predicted PPV. The aim is to find the best constants K_1, K_2, and K_3, so that the difference between the real and the predicted values for PPV should be minimized as much as possible by using the genetic algorithm optimization method. The predicted PPV values would be as:

$$PPV_j = K_1.D_i^{K_2}.W_i^{K_3} \quad \text{i, j = 1 to n} \tag{4}$$

Where PPV_j is the predicted PPV value by Equation (2).

The optimization method was used to minimize the error between PPV_M (measured PPV) and PPV_C (calculated PPV using $PPV_j = K_1.D_i^{K_2}.W_i^{K_3}$), and consequently, to increase the correlation between them, as follows:

$$ERROR_k = (PPV_j - PPV_i)^2 \tag{5}$$

$$\textit{Total error} = \sum_{i=1}^{n}\left(k_1.D_i^{k_2}.W_i^{k_3} - PPV_i\right)^2 \tag{6}$$

In fact, in the genetic model, the fitness function is the total error given by Equation (6), which should be minimized, and so it can be written as follows:

$$\text{Fitness Function} = \sum_{i=1}^{n}\left(k_1.D_i^{k_2}.W_i^{k_3} - PPV_i\right)^2 \tag{7}$$

In order to use the GA optimization method, in this work, the MATLAB program was used.

After optimizing with the GA, the optimized values were achieved for the constants, as follow:

k_1 = 5028.891, k_2 = –1.81523, k_3 = 0.524601,

and the final equation would be as follows:

$$PPV = 5028.89D^{-1.81}.W_{\max}^{0.52} \tag{8}$$

To evaluate the correlation level between the measured and calculated peak particle velocities, a linear regression was fitted (Figure 10). It could obviously be seen in this figure that the two data sets are close enough to each other. In fact, the slope of the fitted line was1.1, which can be rounded to 1, and its equation was given as Equation (9). After all, by considering a satisfactory engineering precision, this model is the best predictor of all. The statistical summary of this model was summarized in Table 11.

The equation for the linear fitted curve is as follows:

$$PPV_C = 1.1 \times PPV_M \qquad R = 0.92 \tag{9}$$

Where PPV_M and PPV_C are the measured and calculated values of peak particle velocities, respectively.

In a blasting design, there are several criteria that should be considered such as powder factor (specific charge) and fly rock. The maximum allowable PPV level is one of them, and this restrictor parameter controls and dictates the maximum amount of charge per delay for blast designers to prevent from excessive vibration occurrence. For this aim, the diagram of *W* (Maximum amount of charge per delay) versus *D* (distance) including different PPV levels was drawn (Figure 11).

As it can be seen in this figure, for any given distance from the blasting site and an allowable PPV, the amount of charge per delay can be estimated and determined using the curve of charge per delay *vs.* distance from blasting site.

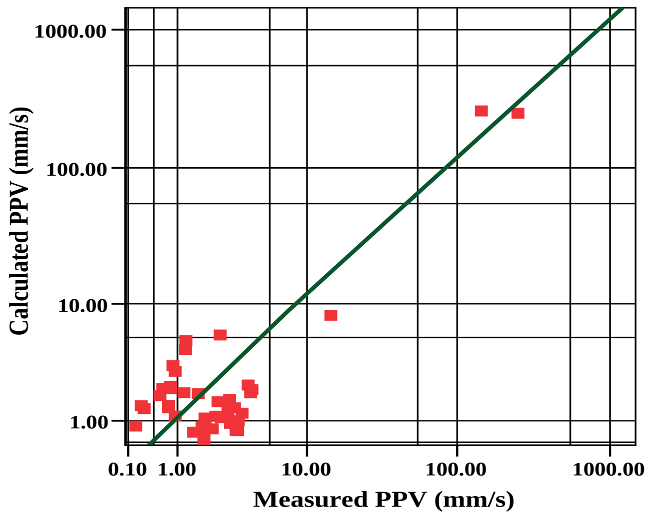

Figure 10. Correlation between PPV calculated by general formula and measured PPV.

Table 11. Statistical summary of PPV prediction.

Equation	R square (R^2)	Coefficient (Line slope)
Linear	0.92	1.192

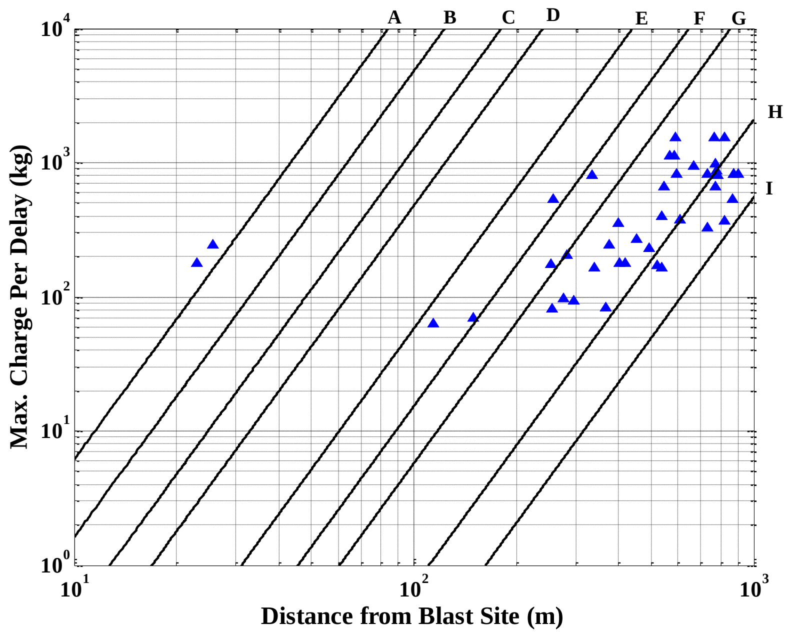

Figure11. Prediction of maximum charge per delay based on based acceptable level of PPV and distance form blast site (A=200 mm/s, B=100mm/s, C=50mm/s, D=30mm/s, E=10mm/s, F=5mm/s, G= 3mm/s, H=1 mm/s, and I=0.5 mm/s).

6. Conclusions

In this research work, the general aim was to propose a general blast-induced vibration predicting model for limestone mines. The work was focused on field observation and surveying the Shahrood limestone mines. After measuring the required data and parameters, the field measurement results were analyzed and interpreted using the frequently-used peak particle velocity predictors. Then the best predictor was chosen to estimate the PPV level in these mines. In this analysis, the best models were Langfors & Kihlstrom and Indian standard predictors with an R square of 0.41. In order to generalize the relationships between different limestone mines, and also to increase the prediction precision, some data related to similar limestone mine studies were gathered from several references, and then analyzed using the same predictors. The best predictor model for this stage was found to be the USBM predictor with an R square of 0.64. By adding additional databases, the prediction improvement was found to be significant.

Ultimately, the general PPV predication model was applied to the extended database, and then using the genetic algorithm (GA) optimization method, the constants of the model describing the geotechnical and other blast properties were obtained. The correlation between the values resulting from this model and the measured ones was 0.92, which is satisfactory and reliable.

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بهبود پیش‌بینی لرزش‌های ناشی از انفجار در معادن سنگ‌آهک با استفاده از الگوریتم ژنتیک

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چکیده:

مشابه بسیاری از معادن سنگ آهک که مواد خام مورد نیاز کارخانه سیمان را تأمین می‌کنند، هزینه انتقال مواد خام در کارخانه سیمان شاهرود بالا است. تلاش شده است که واحد سنگ‌شکن و آسیا در نزدیک‌ترین فاصله ممکن از معدن ایجاد شود. از سوی دیگر، انفجار اثرات منفی داشته و تخریب‌های ناشی از انفجار بر روی ساختمان‌ها و ماشین‌آلات قابل‌توجه است. در چنین معادنی از بین اثرات انفجار، لرزش‌های ناشی از انفجار جایگاه ویژه‌ای دارد. در این تحقیق اثرات انفجار مورد تحلیل قرار گرفته و یک رابطه معتبر برای پیش‌بینی اثرات لرزش‌های ناشی از انفجار در چنین مناطقی به ویژه شرکت سیمان شاهرود ارائه شده است. تاکنون شاخص‌های مختلفی برای ارزیابی اثرات لرزش‌های ناشی از انفجار معرفی شده است که در این بین حداکثر سرعت ذرات (PPV) توسط بسیاری از محققین مورد توجه قرار گرفته است. به‌منظور ایجاد رابطه بین PPV و ویژگی‌های منطقه انفجار، تاکنون روابط مختلفی ارائه شده است. قالب اکثر روابط ارائه شده به‌صورت $PPV = K_1 W^{K_2} D^{K_3}$ بوده است که در این رابطه W و D به ترتیب حداکثر خرج در هر تأخیر و فاصله از محل انفجار و K_1، K_2 و K_3 ویژگی‌های منطقه را تشریح می‌کنند. در این تحقیق مجموعه‌ای از آزمایش‌ها و برداشت‌های صحرایی انجام و پارامترهای لازم جمع‌آوری شده است. سپس به منظور قابلیت تعمیم رابطه ارائه شده و همچنین افزایش دقت، داده‌های معادن سنگ‌آهک مشابه نیز جمع‌آوری شده است. به منظور یافتن بهترین رابطه برازش شده روی داده‌ها، یک مدل برازش ساده با الگوریتم ژنتیک مورد استفاده قرار گرفته است و بهترین پیش‌بینی ارائه شده است. در انتها نتایج به دست آمده از مدل پیش‌بینی کننده با داده‌های واقعی با استفاده از تحلیل همبستگی مورد مقایسه قرار گرفته است.

کلمات کلیدی: انفجار، لرزش ناشی از انفجار، PPV، معدن سنگ‌آهک، کارخانه سیمان، الگوریتم ژنتیک.