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Studying Peak Particle Velocity Due to Blast in Development Tunnels' Face in Coal Stoping

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ABSTRACT

The impact of blast-driven shocks on the safety and stability of the underground coalmines has been well established. The seismic imperfections resulting from blasting depend on the total explosive energy released during the blasting and the closeness of the development tunnel's face to the stope face. In addition, the quality of the rock mass wherein the whole stope face is located might pose considerable effects on the damages from blasting operations. Peak particle velocity is the main criterion for the evaluation of the damage caused by blast vibrations. Twenty-nine logs were recorded of three indicators, namely the longitudinal, transverse and vertical, assessed in 29 blasting in the Alborz-e-Sharghi underground coal mine and twenty datasets extracted thereof were subjected to a series of statistical analyses. The remaining data was applied to validate the equations proposed herein. The present study analyzes and evaluates the common equations used in predicting the ground vibrations. The results of the analyses indicated that the vibrations prediction scale, based on the cube root of the amount of the applied charge, is a better predictor of the vibrations in this underground mine. Studies demonstrated that the scaled distance based on the square or cubic root of the delay charge mass might not be very appropriate for the prediction of PPV (peak particle velocity) in underground situations. Accordingly, the present study performed an alternative analysis based on multivariate fitness estimation. Finally, a PPV equation with an appropriate correlation coefficient was suggested for predicting the ground vibrations in the area of interest.

Keywords : *Explosion, Ground vibration, Peak particle velocity, Predictive equation, Statistical analysis*

1. Introduction

Blasting is usually the method of choice in the advancing faces of the coalmines. Ground vibration, air vibration (air blast), rock emission, and the shockwave created by the explosion are inevitable and they cannot be completely eliminated, but mitigated to a permissible level for avoiding the damage to the peripheral environment. Ground vibration, amongst all these adverse effects, is the major concern of the blast engineers and designers. Some researchers have proposed various methods for alleviating the ground vibration intensity during the blasts. Ground vibration is directly correlated with the amount of the charge mass used and the distance between the stope face and the monitoring point, i.e. the development tunnel face, as well as the geological and geotechnical conditions of the rock unit within the excavation area. Geological conditions are uncontrollable but the distance to the blasting zone and the amount of the charge used per delay are controllable. There are numerous empirical equations proposed for the prediction of the peak particle velocity (PPV) based on controllable factors, namely the distance to the blasting site and the charge weight per delay. These equations are scaled based on the distance, i.e. the distance from the blasting site divided by the power of the maximum charge weight used per delay, the most important of which have been summarized in Table 1. Prediction and control of the ground vibration is necessary for selecting the method with the highest fitting to serve this.

Hosseini and Baghikhani [12] studied 78 blasting events in an open-pit limestone mine and concluded that the square-root equation pertaining to the amount of used charge introduced by the American Bureau of Mines (USBM) gives a better estimation of the existing conditions. In an evaluation of the blasting vibrations in a coalmine, Jha and Deb [14] concluded that the variable power of the used charge is more efficient for any type of mine due to its more accurate estimation of the ground vibrations stemming from the blasts. Dey and Murthy [6] investigated the effect of vibrations resulting from the blasts in four underground coal mines in India on the corridors' stability and concluded that for evaluating the damages, the PPV range, among different factors, changes from mine to mine based on the rock mass rating (RMR) value. In a similar conclusion [23], it was recommended that the underground gallery vibration threshold should be determined based on the rock mass's RMR value. Moreover, it was observed that although some the considerable damages occur immediately after the blasting operation, the roof's fall-down height significantly increases over the time. First, 29 data records were collected in the present study. Then, the efficiency of the empirical equations for predicting the ground vibration was evaluated by the use of 20 data records and the best equation was figured out. Afterward, a multivariate nonlinear regression was applied to offer the best new equation followed by a validation procedure, which was conducted on the nine remaining data.

2. Study Region

The study region was the seam K12 of the Tazareh Coal Mine located within 85 kilometers to the west of Shahrood in Northern Iran. The blasting operations were carried out on three levels of this seam, i.e. 2110, 2175 and 2240 horizons on which the active galleries are situated (Fig. 1). The geotechnical properties of the rocks in these three levels are almost identical (Table 2). The extraction operations were undertaken based on the longwall development fronts and the slope of the coal seam varying from 40 to 45 degrees. In the development faces, drilling and blasting are the methods of choice. The explosive used in the

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development tunnel face was Amatol (Ammonite) and the blasts followed a delay trend, and copper electrical detonators were applied for providing the delays. Detonations occurred from the center towards the walls because of which a hollow hole was created in the center of the tunnel's face. The middle blast-holes are drilled to a depth of one-meter vertical to the tunnel's face. Besides, the holes closer to the floor and the walls are drilled inclined. The number of the blast holes and the amount of applied charge for excavating a complete cross-section differs depending on the blasting conditions and design. Seismic records were taken by using a four-channel Instantel Blastmate device.

Table 1. Scales of predicting ground vibration used in the present study.

Predictive Equation	Source
$PPV = K\left(\frac{D}{\sqrt{Q_{max}}}\right)^{\beta}$	USBM (Duvall and Fogelson, 1962)
$PPV = K\left(\frac{D}{\sqrt[3]{Q_{max}}}\right)^{\beta}$	Ambraseys-Hendron, 1968
$PPV = K\left(\sqrt{\frac{Q_{max}}{D^{2/3}}}\right)^{\beta}$	Indian Standard, 1973
$PPV = K\left(\sqrt{\frac{Q_{max}}{D^{3/2}}}\right)^{\beta}$	Longefors and Kihlstrom, 1973
$PPV = K\left(\frac{D}{\sqrt{Q_{max}}}\right)^{\beta} e^{\alpha \times D}$	Ghosh and Daemon, 1983
$PPV = K\left(\frac{D}{\sqrt[3]{Q_{max}}}\right)^{\beta} e^{\alpha \times D}$	Ghosh and Daemon, 1983
$PPV = K \times R^{\alpha} \times Q_{max}{}^{\beta}$	Birch and Chaffer, 1983
$PPV = K\left(\frac{Q_{max}}{D^{3/2}}\right)^{\beta} e^{\alpha \times D}$	Gupta et al, 1987
$PPV = K\left(\frac{Q_{max}^{2/3}}{D}\right)^{\beta} e^{\alpha \times D}$	Gupta et al, 1987
$PPV = K\left(\frac{D}{\sqrt{Q_{max}}}\right)^{\beta} e^{\alpha \times \frac{D}{Q_{max}}}$	Gupta et al, 1988
$PPV = K\left(\frac{D}{\sqrt[3]{Q_{max}}}\right)^{-1} + \beta$	Roy P.P., 1991
$PPV = K\left(\frac{D}{\sqrt[3]{Q_{max}}}\right)^{-1} + \beta$	CMRI, 1993
$PPV = K \times D^{\beta} \times Q_{max} \times e^{\alpha}$	Rai and Singh, 2004
$Q_{max} = K\,(PPV \times D^2)^{\beta}$	Rai et al, 2005

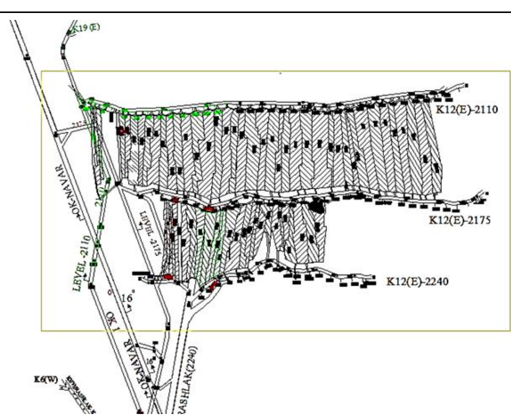

Fig. 1. The position of the development tunnels and the stope face in the seam K12 of the Alborz-e-Sharghi coal mine.

In addition, the other required parameters were recorded and transferred to the corresponding software, named Blastware. The seismic monitoring tool has been illustrated in Fig. 2, and the recorded particle velocity indicators and the contrastive frequency rates are presented in Table 3. Fig. 3 shows the time history of the particle velocity and the air vibrations for one of the recorded data. Totally, four delay blasts are clearly visible in the figure.

Table 2. Rock mass geotechnical specifications (shockwave radiation space).

Level	Wall type	Status	UCS (MPa)	RQD (%)	RMR
2110	Sandstone	Damp	53.2	58	52
2175	Sandstone	Semi-damp	51.4	54	50
2240	Sandstone	Dry	48.8	50	54

Fig. 2. Monitoring tool of the blasting vibrations and a geophone installed on the stope's roof.

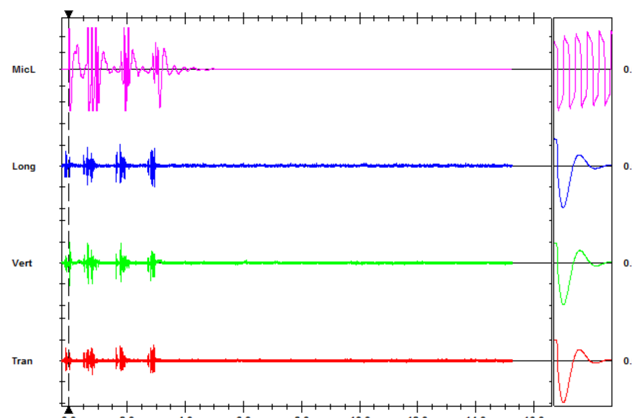

Fig. 3. A sample of triple-indicator particle velocity and the sound intensity histogram for data no.12 from Table 3.

3. Predicting the Ground Vibration

3.1. Empirical Models

In order to predict the ground vibrations resulting from the blasting operations, first, the existing experimental models were used. Based on this approach, the empirical formulas provided in Table 1 were applied on the collected data, and the results of the empirical formulas' fitness estimation are summarized in Table 4.

As is observed in Figs. 4 and 5, as well as from the one-way variance analysis (Table 5), the exponential and power fitness possess the highest correlation coefficient. It is worth mentioning that 20 sets of data from Table 3 were used in the analyses and the remaining nine sets were used to compare the performance of the best determined empirical equation and the best offered regression equation. Their corresponding degrees of freedom and F-value and the significance level are given in Table 5. The table indicates that whether or not the regression model is capable of predicting the dependent variable variations in a significant, and appropriate, manner. Since the significant (sig.) values are smaller than 0.05 in the entire models, all of the regression models are considered statistically significant, and thus, enable a proper prediction of PPV. But, the largest differences are seen for the exponential and the power cases considering the F-values. Numerous research works are at hand in the area of estimating the ground vibration because of the blasting operations and prediction of the peak particle velocity depending on the scale distance. Disregarding α, the best data fitness belongs to the equation defining the cubic root of the delay charge (Eq. 1).

Table 3. The data recorded from seismic monitoring of the study region.

No	Distance (m)	Charge weight (kg)	Transverse		Vertical		Longitudinal	
			F (Hz)	PPV (mm/s)	F (Hz)	PPV (mm/s)	F (Hz)	PPV (mm/s)
1	20.5	4.2	85	5.84	57	15.61	39	9.65
2	22	5	171	4.62	146	4.67	146	4.29
3	28	4.8	85	2.29	146	4.44	146	2.41
4	27.9	3.6	73	2.86	85	1.65	93	1.78
5	32.5	4	135	4.21	65	4.07	120	3.21
6	35	3	141	1.44	118	2.14	112	3.36
7	37.2	3.2	85	1.77	112	2.15	128	1.82
8	40.8	3	141	1.66	114	2.09	151	1.85
9	50	4.8	73	3.38	85	5.01	108	2.97
10	45.4	3.2	126	0.56	117	0.81	85	1.32
11	48.1	2.8	174	1.17	156	1.85	73	1.26
12	60	4.4	110	0.36	24	0.54	85	0.52
13	50	2.4	131	0.62	109	1.19	85	1.13
14	53.5	2.6	209	0.46	94	0.56	110	0.73
15	49	2	171	1.05	79	0.98	102	0.49
16	54.4	2.4	28	0.89	30	1.65	105	1.02
17	59.4	3	171	1.51	128	1.01	128	0.81
18	55	2.2	200	0.15	205	0.29	171	0.54
19	60	2	171	0.48	102	0.56	102	0.97
20	74.8	2.4	171	0.73	128	0.51	114	0.57
21	36	4.6	166	2.1	109	4.21	132	3.12
22	26.5	4	174	2.34	146	6.76	156	4.23
23	50	2.2	194	0.67	98	1.19	88	0.88
24	52	1.8	121	0.58	79	0.66	85	0.76
25	48.8	2.6	135	1.2	118	1.79	92	1.28
26	55.2	2.2	187	0.78	124	1.19	105	0.85
27	56.5	3.4	98	1.31	108	2.45	115	1.62
28	62	2	131	0.55	37	0.68	76	0.61
29	36.5	3.4	200	0.96	124	2.22	143	1.81

$$PPV = K\left(D/\sqrt[3]{Q_{max}}\right)^{\beta} \qquad \text{(Eq. 1)}$$

There are numerous studies that reflect the superiority of the cubic root in underground excavations [7, 18, and 25]. However, it should be noted that these equations do not lead to a correlation coefficient surpassing 69.68. Taking the attenuation effect (α) into consideration decreases the correlation coefficient to some extent. The detrimental effect of the shock waves on the rock at the periphery of the galleries in underground mining is not only influenced by the source energy emission and their failure, but it also depends on the complexity of the rock mass structure [4, 21, and 24]. Rock mass quality is a parameter affecting PPV, but there was no possibility herein to deliver an equation based on the rock mass qualitative specifications due to the lack of sufficient data. The effect of the rock mass conditions on PPV can be investigated by the use of an empirical model and considering the attenuation. The high correlation coefficient of the fitness estimation and a high accuracy in the ground vibration prediction are of the benefits of these models. Encompassing a wide spectrum of the rocks with different geological properties and estimation of the vibration parameters resulted from the blast operations for rocks with various rock engineering attributes are the other advantages of these models. On the other hand, the variability of the blast conditions is a part of the blasting operations. Therefore, the operator should be aware of this potential variability in the intensity of the explosions due to the blasting operation conditions and the performance to be able to control the vibrations.

3.2. Mathematical Models

Common extant empirical equations for the prediction of the ground vibration were studied in the previous section. However, it should be highlighted that there have always been uncontrollable factors in every region that make these equations fall short of appropriate accuracy in estimating the vibrations. The research works have shown that the distance scaled on the square or cubic root of the delay charge might not be so much appropriate for the prediction of PPV in underground situations. Accordingly, in the this research, another analysis was carried out based on the "distance variable power" and the applied "charge" amount by the use of multivariate nonlinear regression method, which is presented as below:

$$y = c + a_1x_1 + a_2x_2 + \ldots a_nx_n \qquad (2)$$

$$y = c * \left(x_1^{a_1}\right) * \left(x_2^{a_2}\right) * \ldots \left(x_n^{a_n}\right) \qquad (3)$$

$$\log y = \log c + a_1 \log x_1 + a_2 \log x_2 + \ldots a_n \log x_n \qquad (4)$$

$$y^* = c^* + a_1x_1^* + a_2x_2^* + \ldots a_nx_n^* \qquad (5)$$

$$y = 10^c * x_1^{a_1} * x_2^{a_2} * \ldots x_n^{a_n} \qquad (6)$$

$$y^* = c_{constant} * a_1D^* * a_2W^* \qquad (7)$$

$$y = 10^{constant} * D^{a_1} * W^{a_2} \qquad (8)$$

According to the above equations and using the SPSS software and performing a linear regression between the logarithmic amounts obtained for the 20-recorded datasets, the following equation is resulted for predicting the peak particle velocity:

$$PPV = 452.89 \times D^{-1.636} \times W^{0.725} \qquad (9)$$

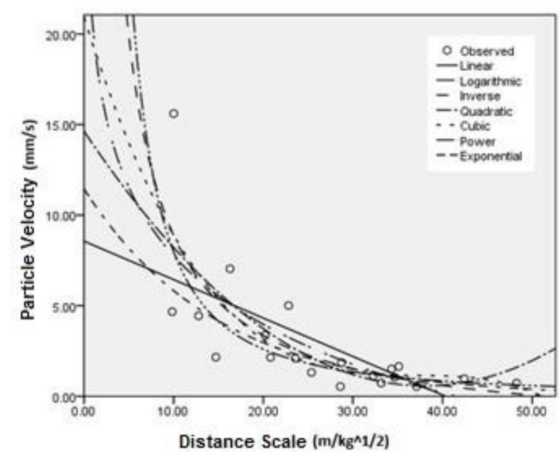

Fig. 4. Collected data and common mathematical fitness estimations by the use of the square root.

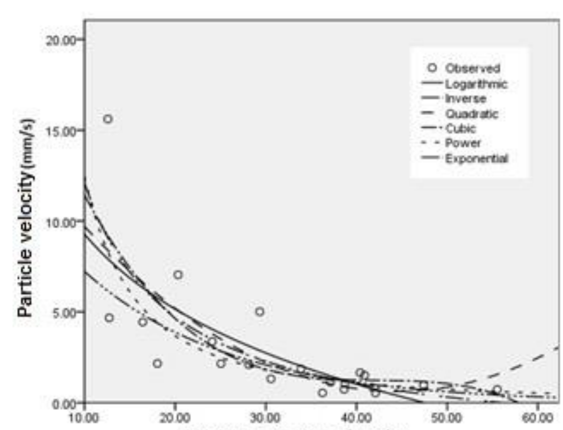

Fig. 5. Collected data and common mathematical fitness estimations by the use of the cubic root.

Table 4. Ground vibration prediction criteria used in the present study.

Predictive equation	R2	β	α	K	SOURCE
USBM (Duvall and Fogelson, 1962)	69.6	-	-1.617	330.67	$PPV = K\left(D/\sqrt{Q_{max}}\right)^{\beta}$
Ambraseys-Hendron, 1968	69.68	-	-1.758	713.27	$PPV = K\left(D/\sqrt[3]{Q_{max}}\right)^{\beta}$
Indian Standard, 1973	64.83	-	2.9962	14.784	$PPV = K\left(\sqrt{Q_{max}/D^{2/3}}\right)^{\beta}$
Longefors and Kihlstrom, 1973	57.7	-	2.015	202.942	$PPV = K\left(\sqrt{Q_{max}/D^{3/2}}\right)^{\beta}$
Ghosh and Daemon, 1983	60.1	-0.048	-0.574	99.532	$PPV = K\left(D/\sqrt{Q_{max}}\right)^{\beta} e^{\alpha \times D}$
Ghosh and Daemon, 1983	61	-0.008	-1.66	774.522	$PPV = K\left(D/\sqrt[3]{Q_{max}}\right)^{\beta} e^{\alpha \times D}$
Birch and Chaffer, 1983	69	-3.687	-1.716	1.1*107	$PPV = K \times R^{\alpha} \times Q_{max}{}^{\beta}$
Gupta et al, 1987	59.7	0.0018	0.3976	149.85	$PPV = K\left(Q_{max}/D^{3/2}\right)^{\beta} e^{\alpha \times D}$
Gupta et al, 1987	60.1	-0.121	-0821	24.049	$PPV = K\left(Q_{max}{}^{2/3}/D\right)^{\beta} e^{\alpha \times D}$
Gupta et al, 1988	59.4	0.915	-0.995	736.5	$PPV = K\left(D/\sqrt{Q_{max}}\right)^{\beta} e^{\alpha \times \frac{D}{Q_{max}}}$
Roy P.P., 1991	59.1	-	-2.632	147.263	$PPV = K\left(D/\sqrt[3]{Q_{max}}\right)^{-1} + \beta$
CMRI, 1993	58.4	-	-2.152	110.319	$PPV = K\left(D/\sqrt{Q_{max}}\right)^{-1} + \beta$
Rai and Singh, 2004	58.3	5.325	-1.769	2.305	$PPV = K \times D^{\beta} \times Q_{max} \times e^{\alpha}$
Rai et al, 2005	8	-	0.17	0.806	$Q_{max} = K\,(PPV \times D^2)^{\beta}$

Table 5. Common fitness estimation models based on the cubic root and their corresponding F-tests.

Equation	R2	Sum of Squares	DF	F	Sig.
Logarithmic	53.4	122.04	1	20.629	0.000
Inverse	59.1	134.996	1	25.981	0.000
Quadratic	55.7	127.323	2	10.694	0.001
Cubic	58.3	133.183	3	7.45	0.002
Power	69.7	10.634	1	41.376	0.000
Exponential	66.6	10.167	1	35.929	0.000

Table 6. Common fitness estimation models based on the square root and their corresponding F-tests.

Equation	R2	Sum of Squares	DF	F	Sig.
Logarithmic	53	121.119	1	20.298	0.000
Inverse	458.4	133.397	1	25.242	0.000
Quadratic	55.5	126.825	2	10.6	0.001
Cubic	57.7	131.904	3	7.281	0.003
Power	69.7	10643	1	41.49	0.000
Exponential	65.8	10.043	1	34.644	0.000

To investigate the performance of Eq. 9, four scales of performance assessment including the correlation coefficient (R2), the root-mean-square error (RMSE), the variance accounted for (VAF) and the mean absolute percentage error (MAPE) were used based on the following equations:

$$R^2 = 100\left[\frac{\left(\sum_{i=1}^{N}\left((y_{meas} - \bar{y}_{meas})(y_{pred} - \bar{y}_{pred}\right)\right)^2}{\sqrt{\sum_{i=1}^{N}(y_{meas} - \bar{y}_{meas})^2 \sum_{i=1}^{N} y_{pred} - \bar{y}_{pred}{}^2}}\right] \quad (10)$$

$$RMSE = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N}\left(y_{meas} - y_{pred}\right)^2\right)} \quad (11)$$

$$VAF = 100\left[1 - \frac{var\left(y_{meas} - y_{pred}\right)}{var\left(y_{meas}\right)}\right] \quad (12)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_{meas} - y_{pred}}{y_{meas}}\right| \times 100 \quad (13)$$

To investigate the performance of the obtained equations, nine out of the twenty-nine recorded vibration datasets were selected from the beginning as the test data. Therefore, based on the nine sets, the above-mentioned parameters were computed once more for the equation selected from the empirical equations (Eq. 1) and once again for the equation we have obtained (Eq. 9). accordingly, the superiority of the obtained equation will be proven. The data fitness estimation led to the following results.

As it is evident from the comparative diagram of the particle velocity that was measured and calculated from the empirical and proposed models, the correlation coefficients obtained for the proposed and empirical equations are equal to 92.63 and 92.09, respectively.

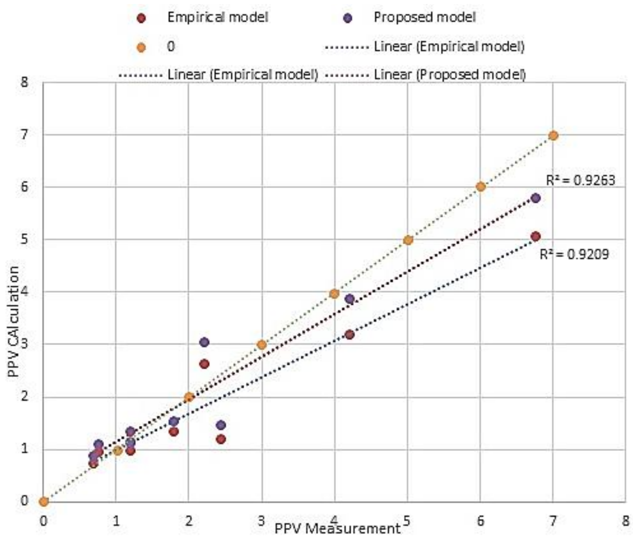

Fig. 6. Comparison of the peak particle velocity measured and calculated from the experimental and suggested models.

Table 7. Correlation coefficient (R2), root-mean-square error (RMSE), variance accounted for (VAF), mean absolute percentage error (MAPE) measured by the empirical and the proposed equation.

Scale	PPV measured by the empirical relation	PPV measured by the proposed relation
R^2	92.09	92.63
RMSE	0.807356	0.56021
MAPE	22.26495	22.01781
VAF	86.69921	91.30229

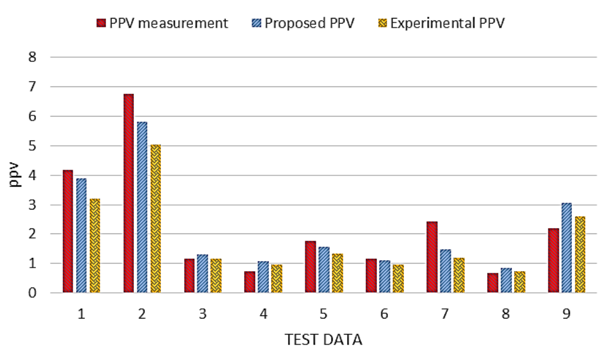

Fig. 7. comparative diagram of PPV calculated by the empirical equation, proposed equation, in-situ measurement values.

This comparison justifies the proposed equation's superiority. Based on the values calculated for the mean-square errors of the proposed equation, 0.56021, and for the empirical equations, 0.807356, and based on the fact that the smaller this index, the better the equation, it can be seen that the proposed equation outperforms the empirical ones. The amount of the mean error percentage for the proposed equation was found to be 22.01781, and the mean error percentage for the empirical equations was 22.26495. Moreover, based on the fact the smaller values for this index are deemed better, it can be stated that the proposed equation exhibits a better performance.

In terms of the value calculated for the variance accounted for (VAF), the amount obtained for the proposed equation was 91.30229, and the amount obtained for the empirical equations was 86.69921. In addition, according to the fact that the smaller values for this index are preferred, then it can be asserted that the proposed equation outperforms the empirical ones.

In Fig. 7, the comparative diagram of the calculated PPV from the empirical and proposed equations and the in-situ measurements are contrasted in a columnar manner. Comparison of the values obtained from the in-situ measurement data with the values obtained for the peak particle velocity via the empirical and proposed relations proved that the values obtained from the proposed relation are very close to the values measured from the empirical equation.

4. Conclusion

Ground vibration resulted from the mining activities might influence the adjacent structures. Therefore, measuring these vibrations is of a great importance for controlling and mitigating such problems. The patricel velocity is still one of the major scales for recording and predicting the vibrations. The present study analyzed the results of a number of vibrations recorded in advancing tunnels' blasting operations to provide for a better control on the environmental damages of the coal extraction galleries in the Alborz-e-Sharghi Mine. The use of the well-known empirical equations featuring as the acceptable correlation coefficients in predicting the vibrations was analyzed. As it was expected, the cubic root of the used charge was realized as an acceptable equation due to its higher data consistency. More precise evaluation of the phenomenon led to the presentation of another particle velocity model characterized by an appropriately higher accuracy in estimating the ground vibration, and thus, it can be applied in similar situations with similar geotechnical parameters.

However, the fact that the present study did not consider the rock mass qualitative specifications is a limitation constraining the results to the specific conditions outlined herein. Therefore, the scale proposed in the current research for underground excavations should be applied through paying attention to the given considerations, and further adjustments are necessary as well upon the advances made in the tunnels.

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