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NEW PREDICTION MODEL OF BLAST-INDUCED PPV BASED ON EMPIRICAL APPROACH IN SEDIMENTARY ROCK

*Supandi Sujatono[1]

[1]Department of Mining Engineering, Institut Teknologi Nasional Yogyakarta, Indonesia

*Corresponding Author, Received: 16 July 2023, Revised: 01 Nov. 2023, Accepted: 04 Nov. 2023

ABSTRACT: Prediction models of peak particle velocity (PPV) in blasting operation have been developed by many researchers, but all the previous researches mostly referred to the concepts of waves and rocks. There is not much development of PPV prediction model based on empirical approach that is specific in sedimentary rock blasting. This study aims to build a PPV prediction model in sedimentary rocks based on empirical and statistical approaches. The study was conducted on sedimentary rocks which have hardness ranging from 1 MPa to 5 MPa. The analysis used the monitoring result of PPV from blasting operation and statistical method to develop the PPV model. PPV model based on the U.S. Bureau of Mines (USBM) as a theoretical model was compared with PPV model based on field data as a proposed model. The PPV obtained from USBM model did not fit the rock characteristics based on the actual data, so a new model was proposed. The new model considers the distance between observation point and blast hole (D) and the quantity of explosive charge (Q) as independent variables. The new model has mean absolute percentage error (MAPE) of 25.50%, 1.72% better than that of the USBM model. By considering the explosive charge (Q) and the distance to observation point (D) in modeling with regression analysis, seismic velocity and rock mass density can be represented by site-specific condition constants. The site-specific constants refer to rock constant and propagation constant, which are 5670.882 and 0.6269 in the new model that has been built.

Keywords: Peak particle velocity (PPV), Blasting, Site coefficient, Regression analysis

1. INTRODUCTION

Minimizing blasting impacts in mining activity is necessary to protect the environment. The impacts of blasting operation include ground vibration, air blast, flyrock, dust, and noise. Ground vibration is particles movement due to the propagation of seismic waves, and air blast is rising air pressure wave resulting from the detonation process of explosives. Ground vibration occurs because the stress due to blasting received by the material is smaller than the strength of the material, so it only causes change in shape and volume and undergoes displacement with a certain velocity and acceleration. The displacement causes an increase in forces that drive landslides and breaks down the landslide resisting forces. The change in shape and volume occurs depending on the elastic properties of the material and it will return to its original state after the stress is removed.

Ground vibration is seismic waves induced by blasting. Seismic waves are waves that propagate through the solid earth. A propagating wave is a disturbance of the medium which can proceed by itself from one point to another carrying energy and momentum. Mechanical waves are waves that propagate through a medium which can be air, soil, or rock. Mechanical waves occur when a part of the medium is disturbed in its equilibrium position. Propagation of stress in elastic zone yields elastic waves, called seismic waves. Seismic waves are generally classified into two types: body waves and surface waves.

Body waves propagate energy through rock mass and pass through the interior of the rock mass. Pressure waves and shear waves are two types of body waves. Pressure waves produce pressure or expansion in the same direction as the direction of wave propagation. Pressure waves are also referred to as longitudinal waves. On the other hand, shear waves are transverse waves that move perpendicular to the direction of wave propagation.

Surface waves are waves that propagate on a surface which can be soil or rock. Two types of surface waves are Love waves and Rayleigh waves. Love waves move like transverse waves and are polarized horizontally. Meanwhile, Rayleigh waves are waves where the particles move backwards in a circular motion and the direction of the waves travel is vertical.

Research on prediction of vibration values have been proposed by many previous researchers, but each of the studies has the same specific characteristics of geological conditions and has not been verified in the field or studied empirically. Prediction of peak particle velocity (PPV) values in a location is influenced by the geological conditions of the location; therefore, the prediction model does not necessarily match the characteristics of the other location [1]. Several numerical equations for predicting PPV proposed by previous researchers are in Table 1 [2,3]. In the Table 1, PPV is peak particle velocity, Q is maximum charge per delay (kg), D is distance between observation point and blast hole (m), while k, β, and α are site constants.

Table 1 Previous research on PPV model

Name	Year	Equation
USBM	1959	$PPV = k\left(\frac{D}{\sqrt{Q}}\right)^{-\beta}$
Langefors–Kihlstrom	1963	$PPV = k\left(\sqrt{\frac{Q}{D^{3/2}}}\right)^{\beta}$
Ambraseys–Hendron	1968	$PPV = k\left(\frac{D}{Q^{1/3}}\right)^{-\beta}$
Holmberg and Persson	1978	$PPV = \frac{kQ^{\alpha}}{D^{\beta}}$
Bureau of Indian Standard	1973	$PPV = k\left(\frac{Q}{D^{2/3}}\right)^{\beta}$
Just-Free	1980	$PPV = k\left(\frac{D}{Q^{1/3}}\right)^{\beta} e^{\frac{-\alpha D}{Q^{1/3}}}$
Gosh-Daeme	1983	$PPV = k\left(\frac{D}{\sqrt{Q}}\right)^{-\beta} e^{-\alpha D}$
CMRI	1993	$PPV = n + k\left(\frac{D}{\sqrt{Q}}\right)^{-1}$

Vibration in rock will decrease by 37% when it passes through soil [4]. Quantity of explosive charge has a very important role in vibration due to blasting [5]. Free surface also has a significant role in vibration [6], in addition to charge length, velocity of denotation, and lithology [7]. Peak particle velocity (PPV) values from main boreholes based on smooth blasting are higher than that based on presplit blasting [8]. Besides being influenced by explosive charge [9-12], PPV is also influenced by step topography [13].

The impact of blasting is closely related to the material property, which in this case is uniaxial compressive strength (UCS) [14]. Peak particle velocity (PPV) will be well-calculated when the calculation is developed based on not only empirical approach, but also detailed site characteristics [15]. Evaluation of PPV by comparing the theoretical and the actual data must be carried out using statistical approach in order to obtain results in accordance with the geological conditions [16,17]. PPV obtained from empirical approach will be smaller than its theory because of geological control and rock structure that are not homogeneous and cannot be included in the analysis model [18,19].

Monitoring and measuring vibration are mandatory when operating blasting [20,21].

The monitoring can be done by applying artificial neural network (ANN), where this method shows a very strong correlation [22-24]. The position of monitoring device against the source of vibration must be recorded accurately [25]. To reduce vibration, it can be done by setting the delay and powder factor [26].

Estimation of ground vibration due to blasting operation can be done by connecting the parameters of the distance between observation point and blast hole (D) and the quantity of explosive charge (Q). U.S. Bureau of Mines (USBM) states the relationship in the concept of peak particle velocity (PPV) and scaled distance (SD) in the following equation (Eq. (1)):

$$PPV = k\left(\frac{D}{\sqrt{Q}}\right)^{-\beta} = k\, SD^{-\beta} \quad (1)$$

where:

PPV = Ground vibration as peak particle velocity (mm/s)
D = Distance between observation point and blast hole (m)
Q = Maximum explosive charge per delay (kg)
k = Rock mass condition constant
β = Vibration decay coefficient
SD = Scaled distance, a ratio of the distance to the quantity of explosive charge

Peak particle velocity (PPV) is related to the explosive charge, the distance from the blast to the protected area, and the rock mass parameter at the location. This relationship can be determined by building a model using a regression method.

It is very important to understand that most of the factors that affect vibration in blasting design are interrelated or interactive. It means that a change in one factor will have an impact on the others. Therefore, if one of the influencing factors can be corrected, then the others will be affected and the vibration effect can be minimized properly.

Waves that have higher frequency will dissipate faster than that have lower frequency because the waves lose energy in each cycle. Factors that affect vibration are divided into two:

1. Factors that can be controlled by human ability in designing a blasting operation in order to obtain the expected blasting result, such as: explosive type, total explosive charge per delay, tie-up design, distance between ground vibration measurement point and blast location
2. Factors that cannot be controlled by human ability because the process occurs naturally, such as geological conditions and geological structures

2. RESEARCH SIGNIFICANCE

This research builds a mathematical equation to predict PPV for low-hardness sedimentary rocks. With the equation, better accuracy is obtained than the other equation. The calculation has taken into account the distance between observation point and blast hole and the quantity of explosive charge, so it is more valid. The theoretical PPV obtained from the equation is closer to the actual PPV. It is expected that with better accuracy, slope stability analysis process can be more accurate so that mining optimization can be improved. The equation can be useful for geological characteristics described in the material and method section.

3. GEOLOGICAL CONDITION

The research area lies on the geographical coordinate of 0°39'15” S to 0°40'30” S latitude and 117°3'33” E to 117°4'30” E longitude. It belongs to the Balikpapan Formation in the Kutai Basin, East Kalimantan. Quartz sandstone, claystone, silt inserts, limestone, and coal dominate the research area. The quartz sandstone is yellowish white with 1-3 m thick layer, inserted by coal layer with a thickness of 5-10 cm. The claystone is blackish gray and it contains plant residue, iron oxide which fills the cracks, and sandstone lenses. The clay sandstone contains large foraminifera and molluscs, showing the age of lower Late Miocene to upper Middle Miocene [27]. The rock hardness in this formation is around 1.5 MPa [28].

Sedimentary rocks have low rock hardness and will experience degradation of mechanical properties when exposed [29]. The sandstone consists of fine-to-coarse quartz mineral with rupture angle of 53° [30]. The presence of clay mineral in the claystone is very small because the clay-sized material in the claystone is clay-sized quartz mineral [28]. The clay mineral contains about 15% kaolinite and 8% illite [31] because the provenance of quartz mineral is recycled orogenic rock from older formation.

4. MATERIAL AND METHOD

Lithological distribution in the research area varies from claystone to sandstone with density of 18-22.2 kg/cm³, cohesion of 18.2-225 kPa, and friction angle of 12.49-38.44°. The rock hardness ranges from 1.16 MPa to 5.84 MPa with Geological Strength Index (GSI) varying around 66-70. The detail of material properties can be seen in Table 2. Blasting design during the study used parameters in Table 3.

Ground vibration was measured by using Blastmate III. This tool can automatically interpret transverse, vertical, and longitudinal waves in numerical form. Blastmate III has two functions to capture and record the effect of residual energy from blasting operation. The two functions include recording vibration due to seismic waves conduction in rock body, with the vibration propagation in longitudinal, transverse, and vertical directions. The data of vibration generated by Blastmate III are peak particle velocity (PPV), peak particle acceleration (PPA), peak displacement, and frequency (f).

Table 2 Material properties

Lithology	Density (kg/cm^3)	Cohesion (kPa)	Friction angle (°)
Top soil	20.7	40	12.70
Coal	19.6	212	38.44
Claystone	21.2	161	21.42
Siltstone	20.5	155	18.2
Shaly coal	20.9	-	-
Carbonaceous	20	0	12.49
Sandstone	22.2	225	32.65
Overburden	18	18.2	15.14
Lithology	**UCS (MPa)**	**GSI**	
Top soil	-	-	
Coal	-	-	
Claystone	5.01	70	
Siltstone	5.84	70	
Shaly coal	1.16	66	
Carbonaceous	-	-	
Sandstone	3.37	50	
Overburden	-	-	

Table 3 Blasting design

Parameter	Value	Unit
Hole diameter	171.45	mm
Hole depth	6.45	m
Burden	6	m
Spacing	9	m
Subdrill	0.5	m
Stemming	2.9	m

This study used data from monitoring result on coal mine blasting operations that have been carried out since last year. Table 4 shows a total of 30 samples of peak particle velocity (PPV) obtained in two ways: from direct measurement in the field (actual PPV, stored in the "PPV actual" column in Tabel 4) and from theoretical calculation based on scaled distance (theoretical PPV, stored in the "PPV theory" column in Tabel 4). Both data were analyzed to obtain theoretical PPV that is relatively close to the actual PPV.

Table 4 Actual and theoretical PPV

Sample	PPV actual	PPV theory
1	4.50	5.71
2	3.38	6.33
3	8.40	5.75
4	5.59	5.20
5	4.60	5.78
6	4.06	6.14
7	4.39	6.20
8	5.27	5.52
9	9.73	7.04
10	5.95	5.57
11	6.56	6.06
12	6.38	6.24
13	6.61	5.82
14	7.27	5.99
15	9.18	6.42
16	6.71	5.92
17	8.05	5.89
18	5.26	5.96
19	7.36	5.84
20	3.31	5.57
21	6.86	6.54
22	7.48	6.15
23	8.84	5.92
24	5.79	5.85
25	6.66	5.99
26	10.08	6.35
27	5.53	6.23
28	3.58	6.39
29	3.83	6.73
30	9.25	6.76

The theoretical peak particle velocity (PPV) data in Table 4 were obtained from the relationship between PPV and scaled distance (SD) based on the U.S Bureau of Mines (USBM) model (Eq. (1)). By applying the model concept to the actual data, the rock mass condition constant and the vibration decay coefficient and obtained were 25.754 and 0.354, and thus the model was as follows:

$$PPV = 25.754\ SD^{-0.354} \quad (2)$$

This model (Eq. (2)) will be reviewed through the model significance and diagnostic checks to assess the quality of the model against data. Apart from statistically significant model, a good model will also show the following diagnostic plots [32]:

1. In Residual vs Fitted plot, there is no particular pattern of residuals along with change in fitted values
2. Residuals in Normal Q-Q plot are more or less on the line, indicating that the residuals follow a normal distribution
3. In both Scale-Location plot and Residual vs Leverage plot, the data are in one group and not too far from the center. The Residual vs Leverage plot effectively detects influential points [33].

5. RESULT

The actual peak particle velocity (PPV) ranges from 3.31 mm/s to 10.80 mm/s with average of 6.35 mm/s. The actual PPV values are more spread out than the theoretical PPV whose values range from 5.20 mm/s to 7.04 mm/s with average of 6.06 mm/s, and it can also be seen from the variance of actual PPV which is much higher than the variance of theoretical PPV (Table 5). This is corroborated by the visualization of the actual PPV data distribution which is wider than that of the theoretical PPV in Fig. 1. From Fig. 1, it can be said that the actual PPV values less than 5 mm/s and more than 7 mm/s are not covered by the model in Eq. (2). Therefore, it is necessary to examine the built model.

Table 5 Summary statistics of actual and theoretical PPV

	PPV actual	PPV theory
Mean	6.35	6.06
Variance	3.81	0.16
Minimum	3.31	5.20
Maximum	10.80	7.04

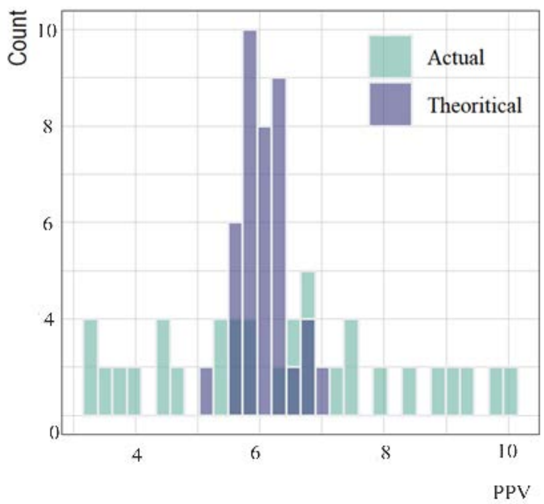

Fig.1 Histogram of actual and theoretical PPV

5.1 Checking The Model

The peak particle velocity (PPV) model in Eq. (2) is equivalent to a simple linear regression model of PPV and scaled distance which have been transformed into natural logarithmic form:

$$\ln PPV = \ln 25.754 - 0.354 \ln SD \quad (3)$$

This model (Eq. (3)) was examined by checking the model significance as a first step. The examination of model significance was carried out by testing the regression coefficient as an indicator of the scaled distance significance in predicting PPV, with the result shown in Table 6. Based on the p-value in Table 6, with a significance level of 5%, the scaled distance variable is not significant. Scaled distance as the only variable in the model does not have a significant role in determining PPV.

Table 6 Regression test result

	Estimate	Std. Error	t	p-value
Intercept	3.2486	1.3153	2.470	0.0199
Scaled distance	-0.3539	0.3210	-1.103	0.2796

Next, diagnostic checks on residuals of the model (Eq. (3)). Residual is the difference between the actual value and the predicted value, or also known as fitted value, by a model. In this study, the predicted/fitted value is referred to as the theoretical value. Residual value that is close to zero indicates that the theoretical value is close to the actual value. The results of diagnostic checks are as follows (Fig. 2):

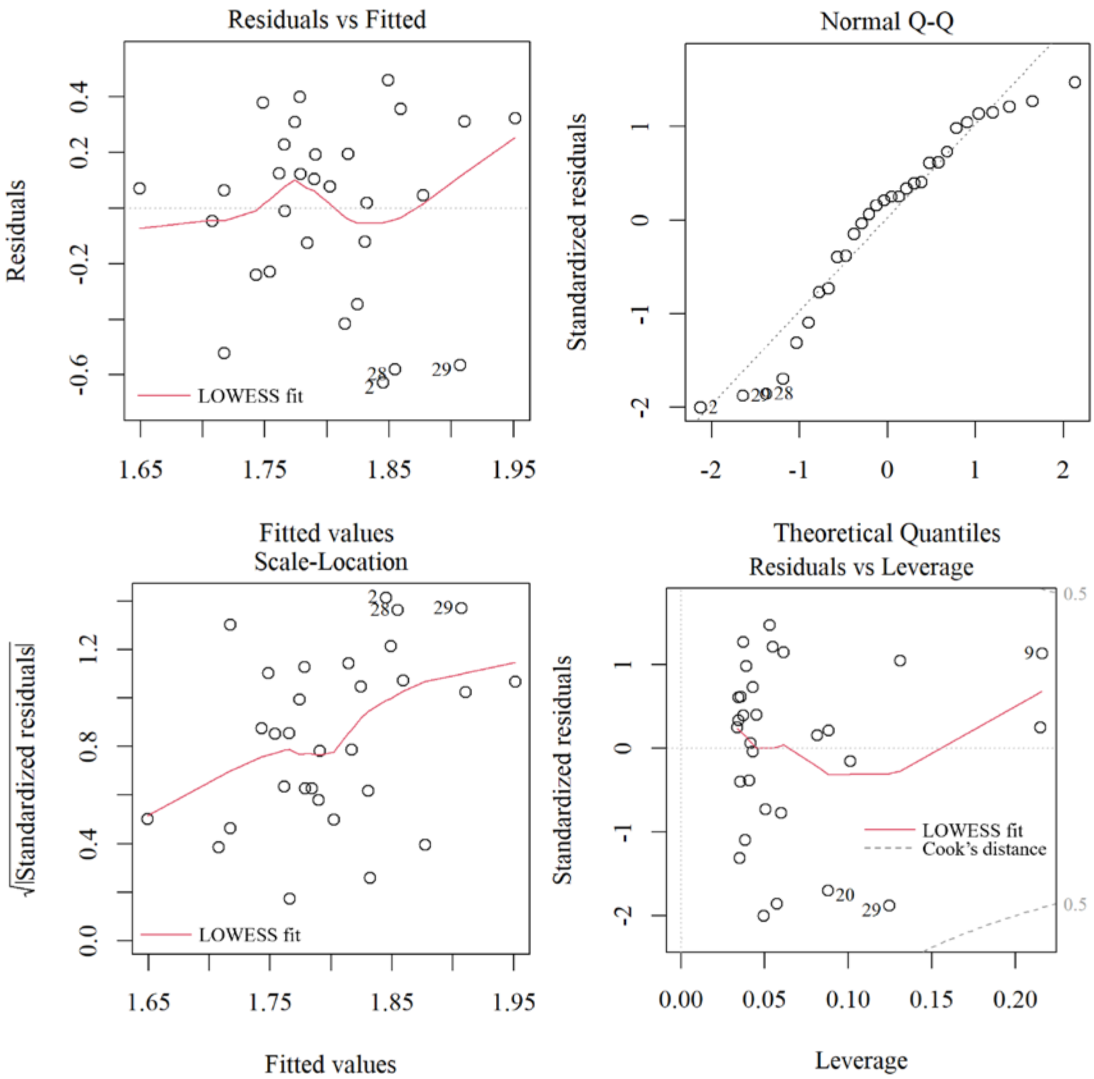

Fig.2 Regression diagnostic plots

1. In the Residual vs Fitted plot, it can be seen that there is a pattern of residual values that spread along with the increase in the fitted values. This is an indication that the variance of residual is not constant, while the constant variance (homoscedasticity) is one of the assumptions that must be met in regression. This result is corroborated by a test for homogeneity of variance using the Glejser method which produced p-value of 0.04. Violation of assumptions may result in the model built from the sample cannot be used to draw a conclusion for the population.
2. In the Normal Q-Q plot, the residuals are more or less on the line, indicating that the residuals follow a normal distribution. The result of Shapiro-Wilk test confirmed this indication by the p-value of 0.06.
3. In both Scale-Location plot and Residual vs Leverage plot, the data are not in one group and some data are too far from the center.

From the review which has been carried out, it can be concluded that the theoretical model (Eq. (1)) did not fit the data. Therefore, a new model was proposed to fit the existing data.

5.2 The Proposed Model

Looking at the theoretical model (Eq. (1)), basically there are two variables used to determine the peak particle velocity (PPV), namely the distance between observation point and blast hole (D) and the maximum explosive charge per delay (Q). By transforming the model to its natural logarithmic form, the theoretical model (Eq. (1)) is equivalent to Eq. (4):

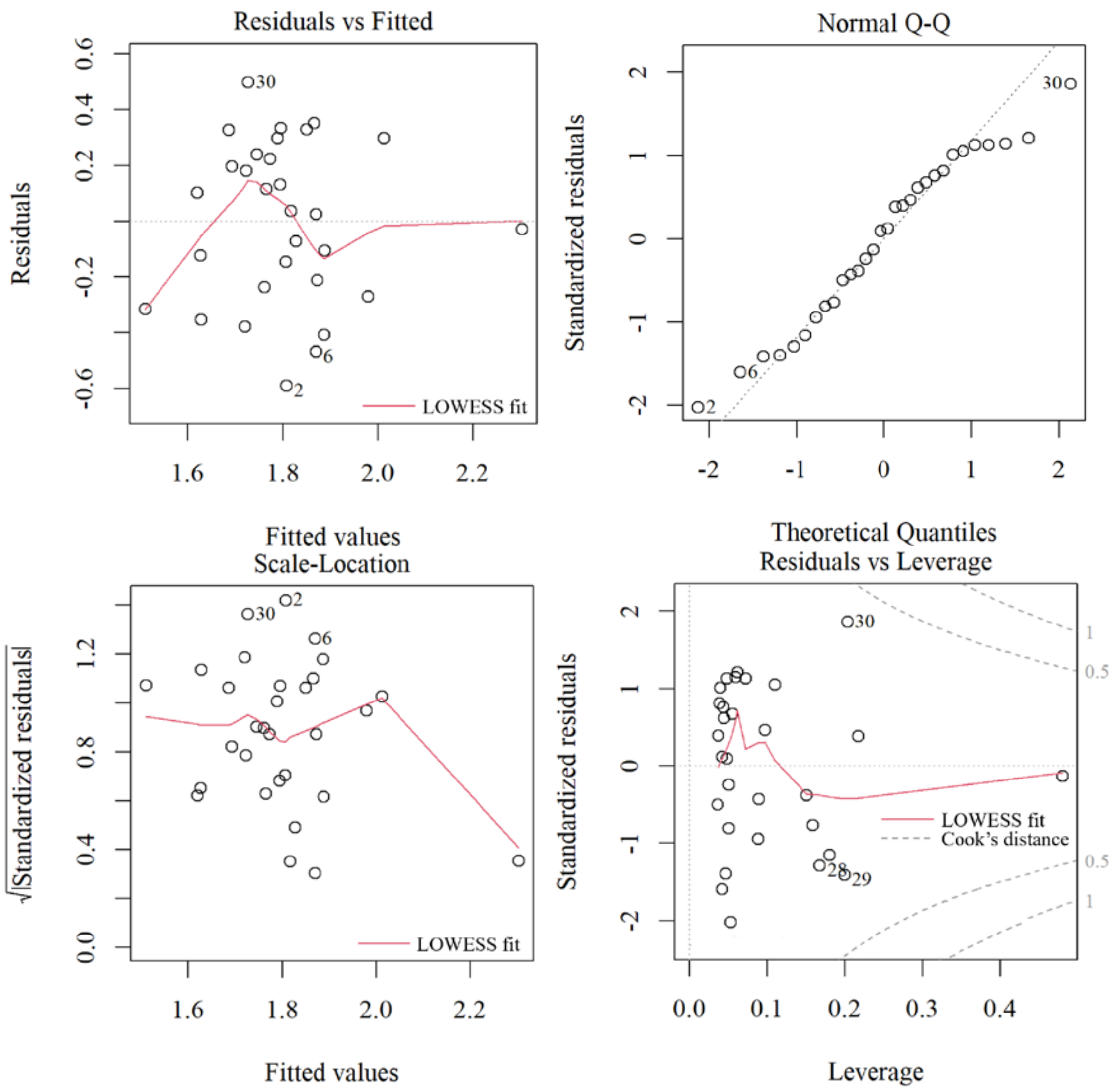

Fig.3 Diagnostic plots of the new model

$$\ln PPV = \ln k - \beta(\ln D - 0.5 \ln Q) \tag{4}$$

Multiple regression analysis was applied to the data that had been natural-log transformed, where PPV as the dependent variable and D and Q as independent variables, with the result in Table 7.

Table 7 The result of regression analysis

	Estimate	Std. Error	t	p-value
Intercept	8.6431	2.6596	3.250	0.00309
Distance (D)	-0.6269	0.3222	-1.946	0.06214
Quantity of explosive charge (Q)	-0.7306	0.4243	-1.722	0.09654

Based on the analysis result in Table 7, with a significance level of 10%, it was found that there is a significant relationship between distance (D) and quantity of explosive charge (Q) with PPV. In addition, the diagnostic plots (Fig. 3) are better than before (Fig. 2). In Fig. 3, there is no particular pattern of residuals along with change in fitted values, the residuals are more or less on the line, as well as the data are in one group and not too far from the center.

With the estimated values in Table 7, the following model was obtained:

$$PPV = 5670.882(DQ^{1.1654})^{-0.6269} \tag{5}$$

This new theoretical model (Eq. (5)) produced a different scaled distance (SD) formula, which was previously $D/\sqrt{Q}$ to $DQ^{1.1654}$. Theoretically, PPV should be directly proportional to Q and inversely proportional to D. However, the data shows that the relationship between Q and PPV tends to be non-directly proportional (Fig. 4).

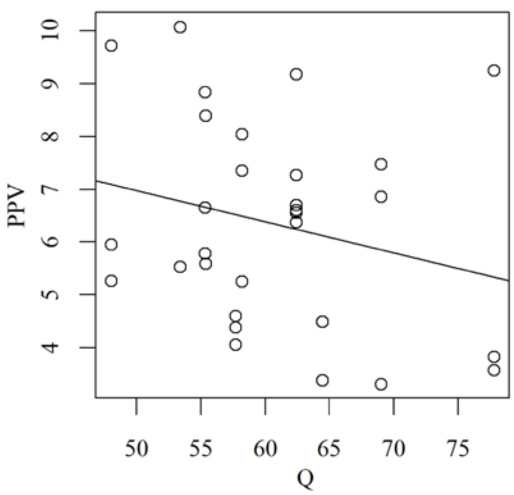

Fig.4 Plot of the relationship between quantity of explosive charge (Q) and peak particle velocity (PPV)

With the new scaled distance (SD) formula from Eq. (5), the relationship model between SD and peak particle velocity (PPV) becomes significant, seen from the p-value in Table 8.

Table 8 The result of regression analysis on the new model

	Estimate	Std. Error	t	p-value
Intercept	8.6431	2.6117	3.309	0.00258
Scaled distance	-0.6269	0.2392	-2.621	0.01402

5.3 Comparison Between The Old And The New Models

Fig. 5 shows a plot of the relationship between scaled distance (SD) and peak particle velocity (PPV) for the old and the new models.

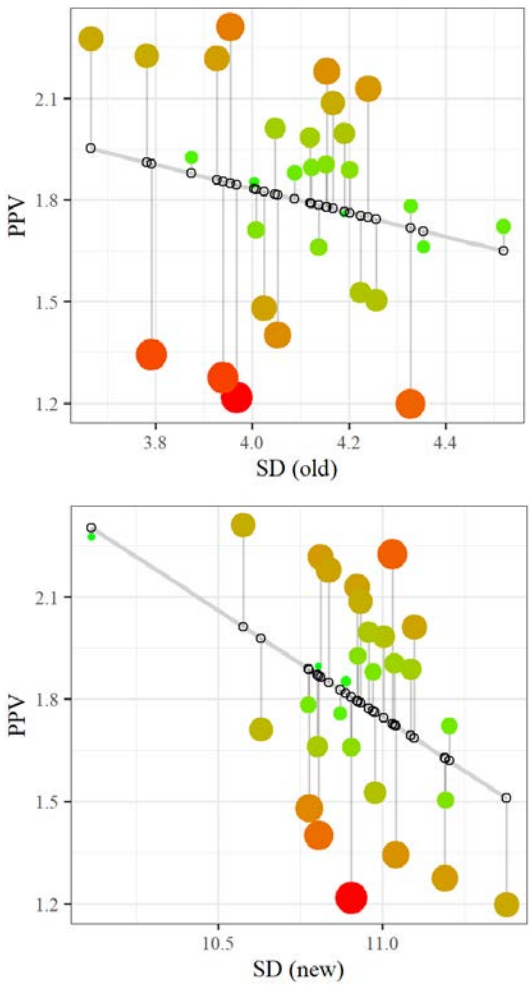

Fig.5 Plot of the relationship between scaled distance (SD) and peak particle velocity (PPV) for the old (top) and the new (bottom) models

The gray line across the data points represents a regression line of the relationship between SD and PPV. The data points are plotted with different sizes and colors, depending on magnitude of the residual value. The smaller the residual value, the smaller the point size and the closer the color is to green. The larger the residual value, the larger the point size and the closer the color is to red. The thin lines connecting each of data points to the regression line show the distance between the actual PPV value (colored dot) and the theoretical PPV value produced by the model (black circle). The shortest distance has the smallest residual, which means that the two values are the most similar.

The theoretical PPV produced by the new model has a relatively wider range than that of the old model (Fig. 6). The old model has mean absolute percentage error (MAPE) of 27.22%, while the new model is 25.50%.

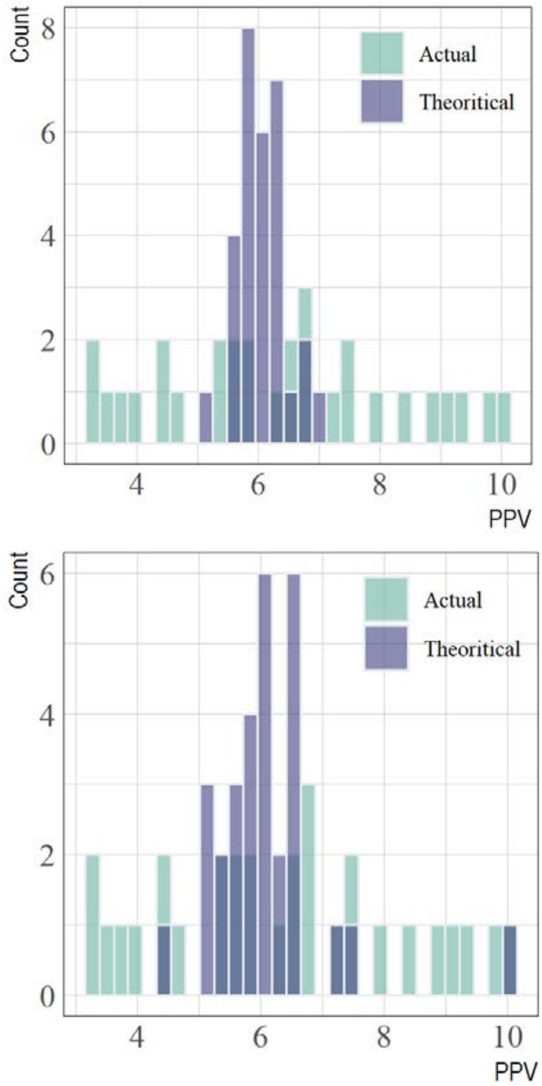

Fig.6 Theoretical PPV histograms of the old (top) and the new (bottom) models

6. CONCLUSION

The results of the analysis show that the peak particle velocity (PPV) model by U.S Bureau of Mines (USBM) did not fit the data. Therefore, a new model was proposed to fit the characteristics of the existing geological condition, as follows:

$$PPV = 5670.882(DQ^{1.1654})^{-0.6269}$$

where D is distance between observation point and blast hole, and Q is maximum explosive charge per delay. This model has mean absolute percentage error (MAPE) of 25.50%, 1.72% better than that of the previous model.

It should be noted that the data shows an inverse relationship between quantity of explosive charge (Q) and peak particle velocity (PPV). This is contrary to the theory stating that the larger the Q, the greater the PPV (directly proportional relationship). Besides being affected by distance (D) and quantity of explosive charge (Q), PPV is also affected by seismic velocity and rock mass density. By considering D and Q in modeling with regression analysis, seismic velocity and rock mass density can be represented by site-specific condition constants [34]. The site-specific constants refer to rock constant and propagation constant, which are 5670.882 and 0.6269 in the new model that has been built. It could be possible that the relationship between Q and PPV, which is not directly proportional, has something to do with the seismic velocity and rock mass density which are actually not homogeneous.

7. ACKNOWLEDGMENTS

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