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Original Paper

Assessment of Blast-Induced Ground Vibration at Jinduicheng Molybdenum Open Pit Mine

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Ground vibration generated from blasting activities is a major problem in mine open-pit slopes and nearby properties, and it can endanger the inhabitants in the surrounding environment. To understand better the influence of blasting activities in the open-pit mine, it is important to determine the propagation and attenuation of the blast-induced vibration in open-pit slope. This paper presents a predictive model based on the Sadovsky equation for determining blast-induced ground vibration in the Jinduicheng open-pit mine, Shaanxi province, China. The field observation focused on providing measurements and data collected for the wave propagation with the influence of blasting activities. Empirical models were also used for predicting blast-induced ground vibration for comparison with the Sadovsky model. Blast design parameters such as maximum charge per delay and distance were considered as input parameters for prediction of blast-induced vibration. Site constants for different empirical equations were taken into consideration when determining the peak particle velocities in the Jinduicheng north slope. The performance indices of R^2 (correlation coefficient), MSE (mean square error), RMSE (root mean square error), MAPE (mean absolute percentage error) and MEDAE (median absolute error) were calculated for the empirical models and the Sadovsky model. The results showed that the Sadovsky model is a more satisfactory model for predicting blast-induced vibration as compared to empirical models.

KEY WORDS: Peak particle velocity, Empirical models, Sadovsky model, Ground vibration, Blasting parameters.

INTRODUCTION

The economic growth of the People's Republic of China has led to a continuous demand for development of transport system, infrastructure, power generation (such as hydropower and nuclear power stations), mining and other related industries. Industries such as mining, hydropower station and nuclear power station require a usage of explosives during the developmental stage. Chinese blasting operations utilize approximately 300,000 tons of explosives and 2.5 billion detonators per year (Lu et al. 2012; Zhou et al. 2019). The mining industry utilizes explosives as a mode of rock breakage and rock fragmentation; the Jinduicheng molybdenum (Mo) open-pit mine is being excavated using drilling and blasting procedures. However, despite the positive aspects of blasting, some negative elements also exist such as flyrock, air blast, noise, dust, and blast-induced earthquakes.

Several scholars have studied the impact related to ground vibration, flyrock and air blast, which are

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mostly induced by blasting (Armaghani et al. 2014). The first ground vibration predictor was introduced by the United States Bureau of Mines (USBM); then, several ground vibration predictors were proposed and put into use (Duvall and Petkof 1959; Langefors and Kihlström 1963; Davies et al. 1964; Ambraseys and Hendron 1968; Bureau of Indian Standards 1973; Ghosh and Daemen 1983; Roy 1993). Programs such as artificial neural network (ANN), adaptive neuro-fuzzy inference system (ANFIS), multivariate regression analysis (MVRA), gene expression programming (GEP) and other regression analysis are being utilized for the prediction for blast-induced ground vibration (Faradonbeh et al. 2016). ANN can calculate the peak particle velocity (PPV) with higher-level precision than empirical models, and ANFIS presents better result than artificial neural network and empirical models (Zhou et al. 2016; Armaghani et al. 2016). GEP was introduced to determine the peak particle velocity using input and output parameters such as maximum explosive charge, distance between the blasting point and explosive source. GEP have lead to number of blast design parameters being explored during peak particle velocity prediction. Most techniques are dependent on the dataset; the output and input parameters from the blast design parameters and geological conditions of the given area are essential (Zhou et al. 2019). The majority of these empirical equations consider the maximum explosive charge per delay and the distance between the blasting source point and monitoring point as influential parameters for PPV prediction (Hajihassani et al. 2015). Blast design parameters, such as blasthole depth, explosive charge, stemming and bench geometry, play a critical role in the occurrence of blast-induced ground vibration in open-pit mine. It is, therefore, important to optimize the blast design parameters in order to reduce ground vibration with respect to the geological condition of a given mine area.

The relationship between blasting activities and mine slope requires a clear understanding of the geological and hydrogeological condition of the excavation, mine operation scale and mine productivity (Kesimal et al. 2008). Furthermore, the transmission of ground vibration depends on the type of rock, its density, rock layers, condition of the terrain, blasthole condition and presence or absence of water (Iphar et al. 2008). In addition, wave propagation during blasting process is influenced by the discontinuities and rock bridges in the rock mass (Mortazavi and Sharafisafa 2012). The Jinduicheng north slope is highly fractured, which makes it vulnerable to landslides, earthquakes and blast-induced vibration.

The intensity of blast-induced vibration is defined by factors such as amplitude, PPV, frequency, acceleration, material properties of rock or soil and attenuation characteristics of the field (Ekanayake et al. 2014; Armaghani et al. 2015). PPV is considered to be the principal factor during ground vibration measurement, and it has been widely applied by various scholars (e.g., Hasanipanah et al. 2017). In addition, PPVs are recorded in three directional ways such as radial, tangential and vertical components per explosive charge weight and distance. The type of blast vibration monitor helps determine the blast wave characteristics and structural damage. Blast monitoring depends on the type of instrument being used and the locations of monitoring points for blast-induced vibration. Slope monitoring is necessary, and it is important that slope movements remain within acceptable limit (Bye and Bell 2001).

This paper seeks to understand the propagation characteristics of the blast-induced ground vibration in the case study. Field observation and effective measurements of blast-induced ground vibration were conducted in the study area, and the blast design parameters for the Jinduicheng north slope were clearly stated. The paper aims to establish a soft computing technique using Sadovsky model from blast-induced ground vibration data obtained from the mine site. With the availability of the field investigation data, the datasets of input and output parameters obtained from the Jinduicheng north slope were employed for prediction of PPV using Sadovsky modeling and empirical techniques. The results of the PPV prediction using the Sadovsky model and empirical models were interpreted and compared. Finally, mitigation and controlling measures were developed to reduce blast-induced ground vibration occurring in Jinduicheng open-pit mine.

The Jinduicheng molybdenum (Mo) open-pit mine, founded in 1958, is located in Huaxian County, Shaanxi Province, People's Republic of China (Fig. 1). It is one of the largest producers of Mo in Asia; its life span is expected to be more than 100 years. The mine's operation involves drilling, blasting, haulage and loading. Because blast-induced vibration can destroy buildings, equipment and other infrastructures around the mine, protecting of inhabitants and communities around the mine from the blast impact is important. The north slope of the mine (Fig. 2) was chosen as the site for study.

GEOLOGICAL SETTING

The Huaxian County, in the Jinduicheng mine area, consists of four different Mo deposits, namely Balipo, Huanglongpu, Shijiawan and Jinduicheng. These deposits are hosted in the Xiong'er Group and the Guandaogou Group. The Xiong'er Group comprises Neoproterozoic sandstone, mudstone and slate, while the Guandaogou Group is made up of Mesoproterozoic andesite (Table 1).

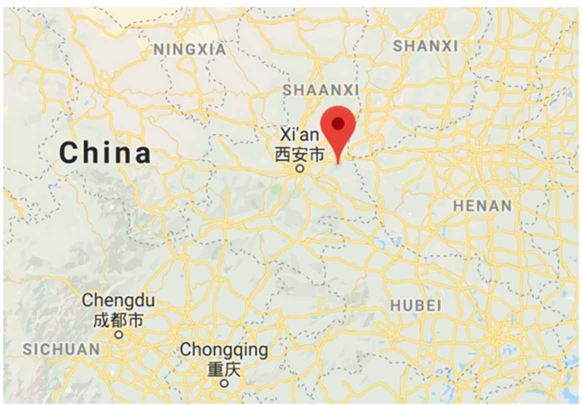

Figure 1. Locality map of the Jinduicheng Mo open-pit mine, Shaanxi Province, China (Google earth map).

The Jinduicheng deposits can be described as a classical porphyry style of structurally controlled or oriented veins of Mo mineralization. The Jinduicheng Mo deposits are dominated by discontinuities (fault, joints and tension cracks), which extend from east to west. The Neoproterozoic quartz sandstone of the Guandaogou group can be found along the Ludongou fault at the southern boundary of the Yanmen fault, whereas the Xiong'er andesite rock can be found at the northern boundary of the Yanmen fault. Moreover, the Jinduicheng and Huanglongpu anticlines are derived from a fault cluster running from north to west, which is mainly characterized by two tectonic activity phases. The north slope is characterized by one dominant joint set with dip directions between 320° and 360° and dip angles ranging from 60° to 80°. Between 2001 and 2003, the north slope experienced a large gully deformation; the crack was identified in 1230 level stope with a length of approximately 100 m. Several discontinuities and faults zone existing on the north slope require special attention (Fig. 2).

METHODOLOGY

Establishment of the Sadovsky Modeling

The main objective of this research was to develop a predictive model for PPV using Sadovsky

Figure 2. Jinduicheng north slope composed of multiple discontinuities and fault zones.

Table 1. Mechanical properties of the dominant rock mass at the Jinduicheng open-pit mine

Rock type	Density (kg/m^3)	Cohesion (MPa)	Internal friction angle (°)
Biotite andesite	27.5	0.253	38.2
Chlorite andesite	27.4	0.211	37.3
Granite porphyry	27.2	0.174	27.12
Tectonic breccia	27.1	0.234	36.3
Tectonic cataclastic	28.4	0.213	38.0
Biotite andesite	29.1	0.459	40.1
Granite porphyry	27.5	0.322	38.2
Sliding soil zone	21.9	0.017	34.1

model and empirical models. Empirical models such as the USBM by Duvall–Petkof, the Langefors–Kihlstrom, a general predictor, the Ambraseys–Hendron, the Bureau of Indian Standard (BIS) and the Central Mining Research Institute (CRMI) models were selected for prediction of PPV. These empirical models were compared with the Sadovsky model. In most research conducted on blast-induced ground vibration, PPV considers the relationship between maximum explosive charge per delay and distance between explosive source and monitoring point. Sadovsky modeling was considered as the main criterion for blast-induced vibration, and it was utilized to examine wave propagation and attenuation of the PPV. The Sadovsky model for PPV can be defined as:

$$v = k\left(\frac{\sqrt[3]{Q}}{R}\right)^{\sigma} \tag{1}$$

where v is PPV (mm/s), Q is explosive charge mass (kg) per delay, R is distance between the explosive source and the monitoring points, k represents the constant parameters in the site related to rock mass characteristics and geological conditions from the blasting point to the monitoring station, and σ indicates the blast design parameters such as spacing, charge weight, explosion source, burden design and stemming length (Ainalis et al. 2016). The PPV varies from one area to another with respect to the lithological, geological and structural conditions of a given area. Blast-induced vibration must continuously be monitored around the testing site.

Blasting Practices at the Jinduicheng Open-Pit Mine

Blast design parameters such as bench height, blasthole diameter, blasthole depth, spacing, burden and explosive charge must be taken into account during mine excavation. The generation of ground vibration, flyrock, air blast and rock fragmentation depends on the charge weight per delay (Kesimal et al. 2008). In this study, the maximum explosive charge per delay time and the distance from the blast face were considered as input parameters, and so both controllable and uncontrollable blast design parameters were incorporated to predict PPV. The bench was blasted with a 400 ms in-hole delay time, and 65 ms was used for initiating the blast. The benches were blasted for 25 ms in the rows or the free face, 42 ms was used in between the rows, and 65 ms for the last rows. The outline of the input data used for modeling analysis in the case study is presented in Table 2.

Blasting Vibration Monitoring

Blast-induced vibration in the Jinduicheng north slope was monitored using EXP3850, which has the advantage of multi-acquisition, storage and analysis. The instrument was connected to a set of speed sensors and acceleration meter. The instrument and sensors were placed at different elevation points to obtain and record blast-induced vibration events at different times. Furthermore, the Jinduicheng north slope is composed of multiple discontinuities; thus, arranging the monitoring points on both sides of the fault or fracture zones is necessary.

Empirical Methods

Over the years, researchers have developed and established empirical equations for predicting PPV (Table 3). According to Vasović et al. (2014), most empirical equations were elaborated on the assumption that the amount of energy of the ground motion created by a blast differs directly proportional to the weight of the explosive detonated and

Table 2. Blast design parameters used at the Jinduicheng Mo open-pit mine

Name (unit)	Values
Burden (m)	6.5–7.5
Spacing (m)	8.5–9.5
Blasthole depth (m)	11.5–13.5
Bench height (m)	12
Sub-drilling (m)	1.5
Hole diameter (mm)	250
Initiation system	Non-electric delay detonator
Type of explosive (explosive quantity per hole) (kg)	Emulsion (2000–2050 kg)
Stemming (m)	3
Detonation sequence	Hole by hole detonation
Initiation pattern	Staggered
Hole inclination	Vertical
Timing sequence (ms)	400/65/25

Table 3. Empirical equations used for predicting PPV

Empirical Predictors	Equations	Year
USBM model by Duvall–Petkof	$v = k\left[R/\sqrt{Q_{\max}}\right]^{\beta}$	1959
Langefors–Kihlstrom	$v = k\left[\sqrt{Q_{\max}/R^{3/2}}\right]^{\beta}$	1963
General predictor	$v = k\,R^{-B}\,(Q_{\max})^{\alpha}$	1964
Ambraseys–Hendron	$v = k\left[R/\sqrt[3]{Q_{\max}}\right]^{-\beta}$	1968
Bureau of Indian Standard (BIS)	$v = k\left(\frac{Q_{\max}}{R^{2/3}}\right)^{\beta}$	1973
Central Mining Research Institute (CRMI)	$v = n + k\left[R/Q_{\max}\right]^{-1}$	1993

inversely proportional the squared distance from the blasting point. The existing empirical equations were used here to determine blast-induced vibration against the proposed model for assessing ground vibration. The calculated site constant values for each empirical equation measured using multiple regression analysis are given in Table 4. Site constants are represented by *k, β, α* and *n*, which are useful for vibration monitoring.

The Sadovsky model (Eq. (1)) was used to determine the wave propagation law of the open-pit mine slope. PPV was calculated in vertical, radial and tangential direction. *k* and *Q* were calculated from the monitoring data captured from the Jinduicheng Mo open-pit mine. To derive a competent relationship among PPVs, maximum charge per delay and scaled distance in the mine slope, a regression analysis for the propagation rule was implemented. PPV predictive modeling in the Jinduicheng north slope was implemented in three directions with varying site constants as shown in Table 5.

The values of *k* and *α* in the Jinduicheng north slope are dependent on blasting mode, weathering condition, fault zones, multiple cracks and testing site condition. For the Jinduicheng north slope, *k* value ranges from 133.765 to 235.174, and *α* values are between 1.679 and 1.963. Because this slope is composed of large faults and multiple fissures, these cause the velocity of particles from the blasting to be greater, which affect the height of amplification. The vertical direction correlation coefficient is higher than the longitudinal and transverse directions with the correlation coefficients ranging from 0.933 to 0.963.

PERFORMANCE OF THE SADOVSKY MODEL AND EMPIRICAL MODELS

The capabilities of the different empirical models were assessed against the Sadovsky model. The statistical assessments were based on R^2 (correlation coefficient), root mean square error (RMSE), mean absolute percentage error (MAPE)

Table 4. Site constants established using empirical models in the Jinduicheng north slope

Empirical equations	k	β	α	n
USBM model by Duvall–Petkof	133.765	1.261		
Langefors–Kihlstrom	64.65	1.478		
General predictor	215.27	1.09	0.402	
Ambraseys–Hendron	311.221	− 1.0215		
Bureau of Indian Standard (BIS)	4.1	0.456		
CRMI (Central Mining Research Institute)	136.92	− 1.553		− 0.451

Table 5. Site constants generated by the Sadovsky equation for the Jinduicheng north slope

Slope	Direction	Equations	Correlation coefficients
North slope	Vertical	$v = 235.174\left(\frac{\sqrt[3]{Q}}{R}\right)^{1.963}$	0.963
	Longitudinal	$v = 201.947\left(\frac{\sqrt[3]{Q}}{R}\right)^{1.847}$	0.955
	Transverse	$v = 133.765\left(\frac{\sqrt[3]{Q}}{R}\right)^{1.679}$	0.933
	Radial	$a = 15341.32\left(\frac{\sqrt[3]{Q}}{R}\right)^{1.67}$	0.979

Table 6. Performance indices for assessment of PPV prediction

Statistical parameters	Equations
R^2	$R^2 = \frac{\left[\sum_{i=1}^{n}(x_i - x_{\text{mean}})^2\right] - \left[\sum_{i=1}^{n}(x_i - y_i)^2\right]}{\left[\sum_{i=1}^{n}(x_i - x_{\text{mean}})^2\right]}$
RMSE	$\text{RMSE} = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n}\left\lvert(y_i - x_i)^2\right\rvert}$
MAPE	$\text{MAPE} = \frac{1}{n} \times \left[\sum_{i=1}^{n}\left\lvert\frac{y_i - x_i}{y_i}\right\rvert\right] \times 100$
MEDAE	$\text{MEDAE} = \text{median}(y_i - x_i)$

and median absolute error (MEDAE). These were implemented based on the following equations given in Table 6, where y_i, x_i and x_{mean} are measured, predicted and mean values of the prediction models, respectively; and n represents the total number of the datasets.

RESULTS AND DISCUSSION

This research was carried out to evaluate blast-induced ground vibration in the Jinduicheng north slope. PPV was recorded in the vertical, longitudinal and transverse directions from the monitoring points during blasting activities. The PPVs in the longitudinal direction tend to be generally larger than in the vertical and transverse directions. The PPV in the longitudinal direction reduces when the distance of the explosive source increases. In the Jinduicheng north slope, the maximum charge per delay and distance from the blast face were considered as input parameters and PPV as output parameter. To validate the use of the Sadovsky model for predicting PPV, the results of blast-induced vibrations were characterized mainly by four parameters, namely amplitude (A), frequency (F) and acceleration (a) as presented in Table 7.

Frequency was utilized to assess the damage caused by blast-induced ground vibration to the mine slope or other structures within the mine area. Frequency characteristics during blast-induced ground vibration are dependent on factors such as blasting method, explosive charge, topography and geological condition of a given area. The frequency of blast vibration in the Jinduicheng north slope ranged between 5 and 35 Hz, and the average frequency was 23.44 Hz. The Jinduicheng north slope has a lower frequency as compared to the other slopes in the mine area, which is due to weathering that is deemed to pose potential risks to the slope and infrastructure in the mine area. Lower frequency vibrations have greater potential of causing damage than high-frequency vibrations (Siskind et al. 1987; Zeng et al. 2018).

EVALUATION AND COMPARISON OF THE MODELS PERFORMANCES

The R^2 for the empirical models in the Jinduicheng north slope ranges between 0.808 and

Table 7. Detailed blast-induced ground vibration test results conducted at the Jinduicheng north slope

Event no.	Detonation distance	Scaled distance	Height	Charge per delay (kg)	Maximum explosive charge (kg)	PPV (mm/s)		Acceleration (mm/s^2)	Vibration speed (mm/s)	Frequency (Hz)	Vibration duration (s)
1	120	26.96	23.5	19.80	2000	Vertical	26.80	3012.5		23.44	0.711
						Longitudinal	32.37	3335.1	46.80	19.65	0.841
						Transverse	21.96	2987.6		15.36	0.624
2	200	44.9	60		2000	Vertical	10.34	1481.3		12.36	0.841
						Longitudinal	14.31	1564.3	20.50	9.56	0.762
						Transverse	9.88	1320.1		10.36	0.815
3	230	51.6	69		2000	Vertical	8.57	104.2	13.65	12.69	0.872
						Longitudinal	10.63	1194.5		8.69	0.796
						Transverse	–			–	–
4	250	56.2	80		2000	Vertical	7.44	1021.1	13.50	10.25	0.779
						Longitudinal	9.29	1043.4		7.68	0.873
						Transverse	6.37	785.3		8.51	0.914
5	340	76.4	125		2000	Vertical	3.49	412.6		7.65	0.812
						Longitudinal	5.29	620.4	7.46	9.45	1.060
						Transverse	3.94	521.4		11.30	1.065
1	100	18.56	25	29.00	2050	Vertical	40.61	3941.6	81.17	16.39	0.814
						Longitudinal	57.07	5344.6		17.68	0.792
						Transverse	41.01	4217.6		8.96	0.814
2	165	30.6	58		2050	Vertical	14.92	1689.5	28.90	7.56	0.716
						Longitudinal	20.25	2068.3		7.89	0.802
						Transverse	13.75	1398.6		9.86	0.796
3	195	36.21	70		2050	Vertical	11.06	1018.3	21.20	10.56	0.915
						Longitudinal	15.36	1608.5		11.23	0.998
						Transverse	10.44	1236.8		7.68	0.956
4	215	39.9	82		2050	Vertical	9.21	1024.3	18.20	6.43	1.102
						Longitudinal	12.98	1376.5		9.12	1.156
						Transverse	8.81	1056.3		8.63	1.068
5	300	55.7	125		2050	Vertical	–	581.1		8.61	1.065
						Longitudinal	6.84	770.3	8.30	7.76	1.025
						Transverse	4.72	614.2		9.12	1.025

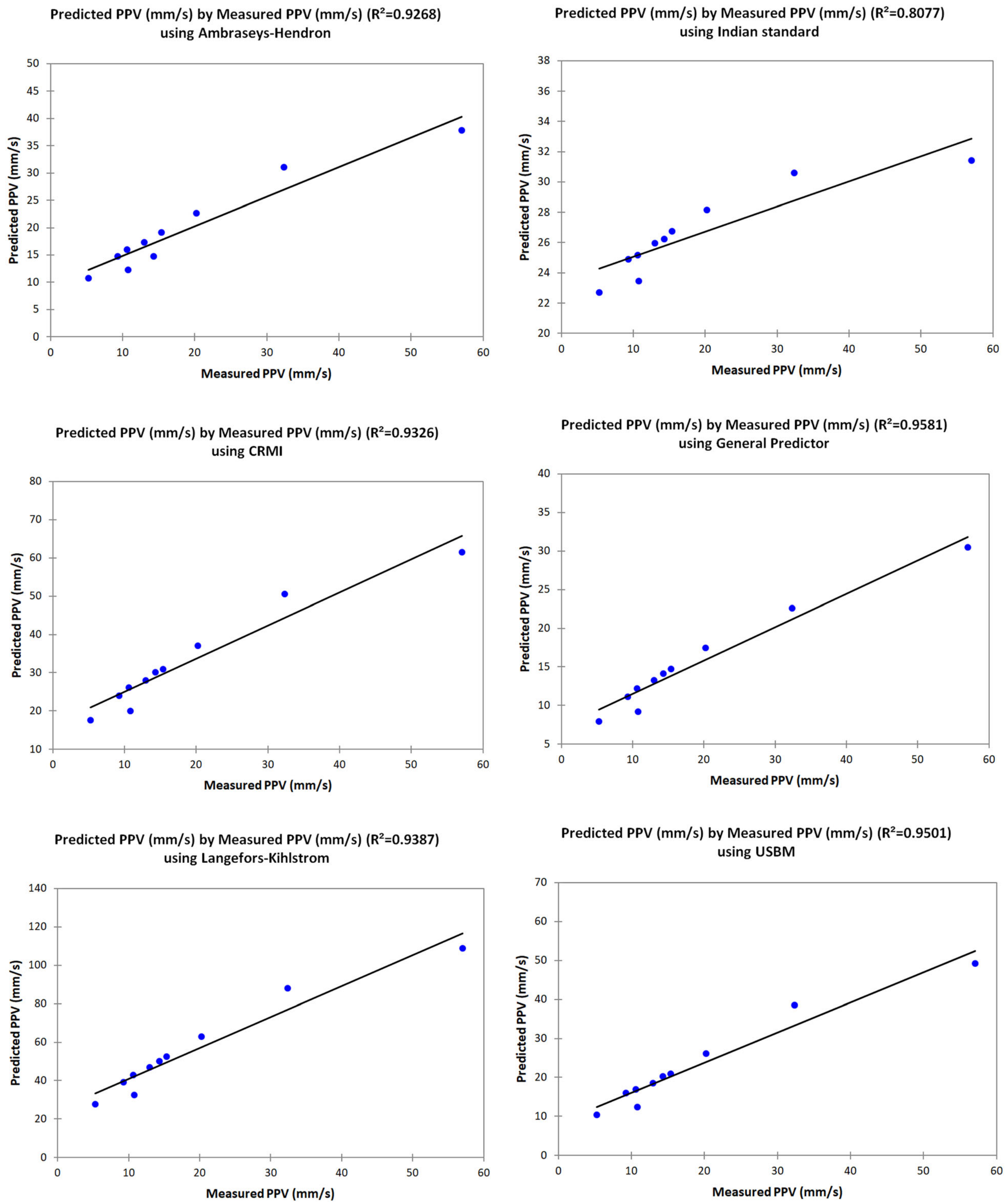

Figure 3. Measured PPVs vs. predicted PPVs at Jinduicheng north slope by empirical models: (i) Ambraseys–Hendron; (ii) BIS; (iii) CRMI, (iv) general predictor; (v) Langefors–Kihlstrom; and (vi) USBM.

Table 8. Statistical performance indices for models

Model	Statistical performance criteria				
	R^2	RMSE	Adjusted R	MSE	MAPE
Langefors–Kihlstrom	0.939	6.681	0.931	44.63	24.77
United States Bureau of Mines (USBM) by Duvall–Petkof	0.950	2.884	0.944	8.31	4.22
Bureau of Indian standards (BIS)	0.808	1.315	0.784	1.73	10.98
General predictor	0.958	1.471	0.953	2.16	1.96
Ambraseys–Hendron	0.927	2.470	0.917	6.13	2.90
Central Mining Research Institute (CRMI)	0.933	3.799	0.924	14.43	10.96

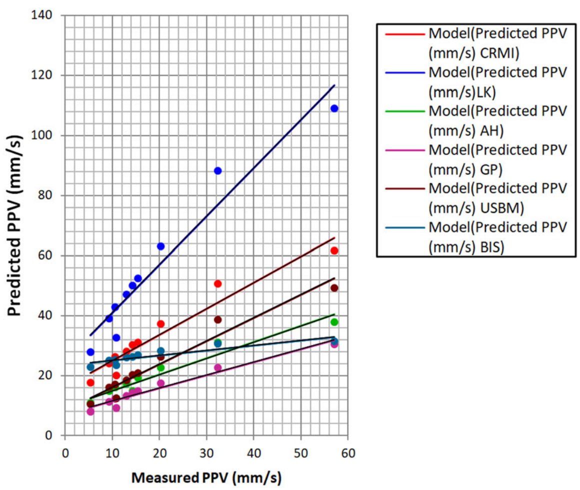

Figure 4. Comparison of predicted and measured PPV using empirical methods.

0.958 (Table 8, Fig. 3). Furthermore, the RMSE values for the PPVs predicted by the empirical models vary between 1.315 and 6.681, and the MAPE values range from 2.90 to 24.77 (Table 8). Comparisons of the empirical models with respect to the measured and predicted PPVs are illustrated in Figure 4.

The Sadovsky model was developed to predict the PPV generated from the blasting operation. For comparison with the empirical models, the Sadovsky model was developed using input parameters such as maximum charge per delay and distance, while the output was set as PPV values. The Sadovsky model is capable of predicting the measured datasets quite accurately (Fig. 5). The R^2 (correlation coefficient) ranges from 0.968 to 0.998. Furthermore, the RMSE values for the Sadovsky model are between 0.026 and 0.057 and the MAPE values ranged from 8.70 to 9.165. In several instances, the required values of RMSE and R^2 are within the range of 0 and 1 (Taheri et al. 2017). The results indicate that the Sadovsky model yielded better prediction performance for determining PPV as compared to the empirical models.

The control of blast-induced ground vibration depends on the maximum charge per delay and distance from the blast area to the sensitive receiver. The type of explosive charge (2000 kg) and the blasthole diameter (200–300 mm) are some of the blast design parameters that can be optimized to reduce possible hazards associated with blast-induced ground vibration, and the delay time that is suitable for the reduction of blast-induced ground vibration is 15 m/s. Furthermore, the design of the initiation sequence must also ensure sufficient delay time between blastholes to minimize blast-induced ground vibration. Millisecond blasting is widely utilized in the mining industries to alleviate blast-induced ground vibration. Additional field observations, laboratory experiments and numerical simulations are required to understand better the potential implication of PPV in the mine area.

CONCLUSIONS

In this study, the Jinduicheng north slope was considered for the investigation of the PPV using the Sadovsky model and empirical models. Jinduicheng north slope consists of highly jointed rock mass, which is vulnerable to blast-induced ground vibration. The Sadovsky model was used to determine wave propagation characteristics in the vertical, tangential and radial directions. The Sadovsky model produces results that are more accurate than the empirical models. The Sadovsky equation proved to be efficient for helping to solve the blast-induced vibration problem in the mine area. Furthermore, blast design parameters such as maximum charge per delay, spacing, burden, number of holes

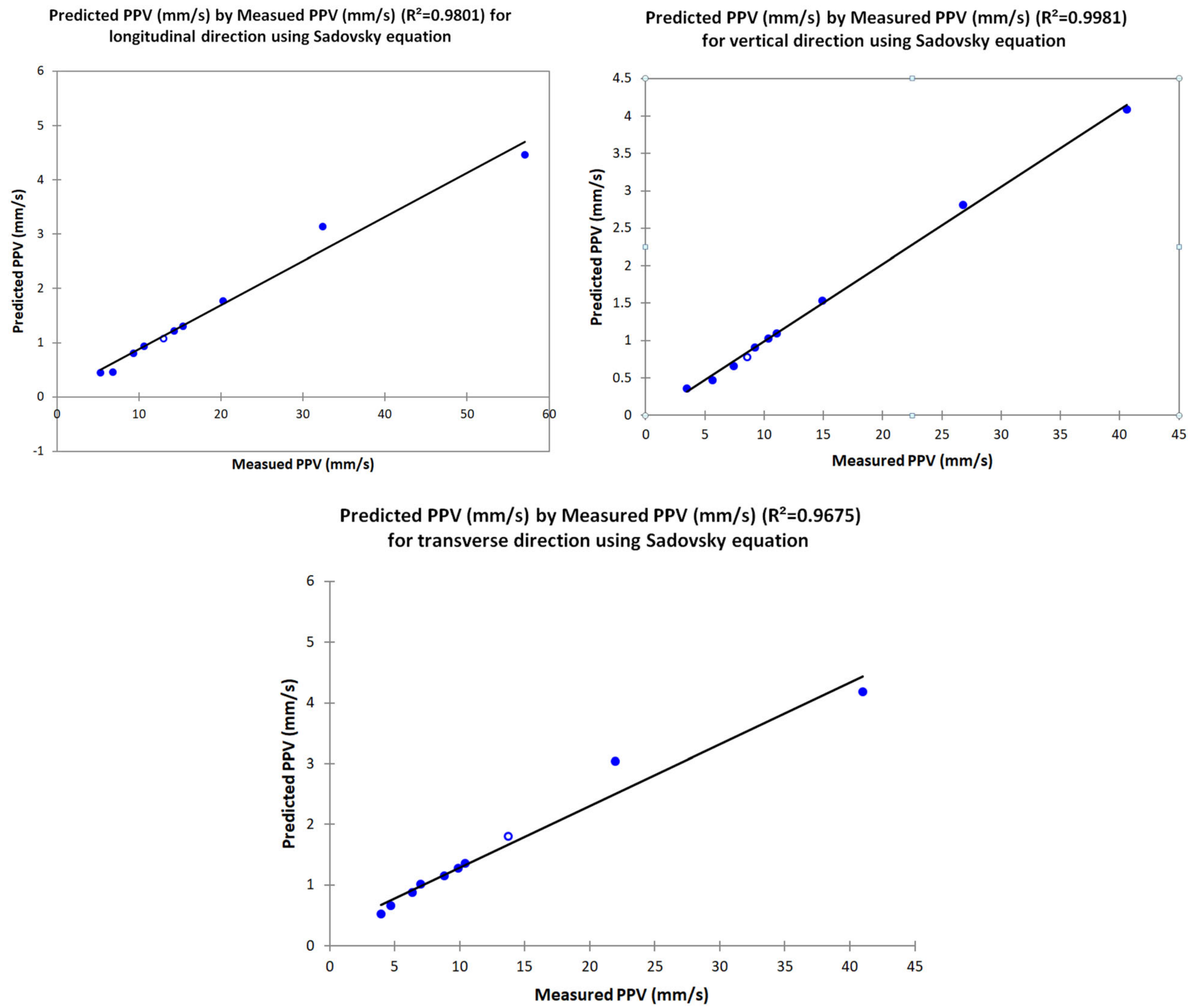

Figure 5. PPV prediction results generated for the different monitoring points using the Sadovsky equation.

per delay and delay time per rows were observed as critical influencers of blast-induced vibration. The acquired data from the measured PPVs and the predicted PPVs by the empirical models and Sadovsky model can be used to reduce and control environmental impact associated with blasting activities in the open-pit mine. Continuous assessment and monitoring of ground blast-induced ground vibration in the open-pit mine will be necessary. Finally, the Sadovsky model was deemed useful for predicting blast-induced ground vibration.

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REFERENCES

Ainalis, D., Kaufmann, O., Tshibangu, J.-P., Verlinden, O., & Kouroussis, G. (2016). Assessing blast source pressure modelling approaches for the numerical simulation of ground vibrations. In *23rd international congress on sound & vibration*.

Ambraseys, N. N., & Hendron, A. (1968). *Dynamic behaviour of rock masses*. New York: Wiley.

Armaghani, D. J., Hajihassani, M., Mohamad, E. T., Marto, A., & Noorani, S. (2014). Blasting-induced flyrock and ground vibration prediction through an expert artificial neural network based on particle swarm optimization. *Arabian Journal of Geosciences, 7*(12), 5383–5396. https://doi.org/10.1007/s12517-013-1174-0.

Armaghani, D. J., Mohamad, E. T., Hajihassani, M., Abad, S. A. N. K., Marto, A., & Moghaddam, M. (2016). Evaluation and prediction of flyrock resulting from blasting operations using empirical and computational methods. *Engineering with Computers, 32*(1), 109–121. https://doi.org/10.1007/s00366-015-0402-5.

Armaghani, D. J., Momeni, E., Abad, S. V. A. N. K., & Khandelwal, M. (2015). Feasibility of ANFIS model for prediction of ground vibrations resulting from quarry blasting. *Environmental Earth Sciences, 74*(4), 2845–2860. https://doi.org/10.1007/s12665-015-4305-y.

Bureau of Indian Standards. (1973). Criteria for safety and design of structures subjected to underground blast. New Delhi, India: Bureau of Indian Standards(Bulletin No: IS-6922).

Bye, A., & Bell, F. (2001). Stability assessment and slope design at Sandsloot open pit, South Africa. *International Journal of Rock Mechanics and Mining Sciences, 38*(3), 449–466. https://doi.org/10.1016/s1365-1609(01)00014-4.

Davies, B., Farmer, I., & Attewell, P. (1964). Ground vibration from shallow sub-surface blasts. *Engineer*, *217*(5644), 553–559.

Duvall, W. I., & Petkof, B. (1959). *Spherical propagation of explosion-generated strain pulses in rock* (Vol. 5481–5485). Washington: US Department of the Interior, Bureau of Mines.

Ekanayake, S. D., Liyanapathirana, D., & Leo, C. J. (2014). Attenuation of ground vibrations using in-filled wave barriers. *Soil Dynamics and Earthquake Engineering, 67,* 290–300. https://doi.org/10.1016/j.soildyn.2014.10.004.

Faradonbeh, R. S., Armaghani, D. J., Majid, M. A., Tahir, M. M., Murlidhar, B. R., Monjezi, M., et al. (2016). Prediction of ground vibration due to quarry blasting based on gene expression programming: a new model for peak particle velocity prediction. *International Journal of Environmental Science, 13*(6), 1453–1464. https://doi.org/10.1007/s13762-016-0979-2.

Ghosh, A., & Daemen, J. J. (1983). Simple new blast vibration predictor (based on wave propagation laws). In *The 24th US symposium on rock mechanics (USRMS)* (Vol. 2, pp. 151–161). TX: American Rock Mechanics Association. https://doi.org/10.1016/0148-9062(84)91486-4.

Hajihassani, M., Armaghani, D. J., Monjezi, M., Mohamad, E. T., & Marto, A. (2015). Blast-induced air and ground vibration prediction: a particle swarm optimization-based artificial neural network approach. *Environmental Earth Sciences, 74*(4), 2799–2817. https://doi.org/10.1007/s12665-015-4274-1.

Hasanipanah, M., Golzar, S. B., Larki, I. A., Maryaki, M. Y., & Ghahremanians, T. (2017). Estimation of blast-induced ground vibration through a soft computing framework. *Engineering with Computers, 33*(4), 951–959. https://doi.org/10.1007/s00366-017-0508-z.

Iphar, M., Yavuz, M., & Ak, H. (2008). Prediction of ground vibrations resulting from the blasting operations in an open-pit mine by adaptive neuro-fuzzy inference system. *Environmental Geology, 56*(1), 97–107. https://doi.org/10.1007/s00254-007-1143-6.

Kesimal, A., Ercikdi, B., & Cihangir, F. (2008). Environmental impacts of blast-induced acceleration on slope instability at a limestone quarry. *Environmental Geology, 54*(2), 381–389. https://doi.org/10.1007/s00254-007-0825-4.

Langefors, U., & Kihlström, B. (1963). *The modern technique of rock blasting*. New York: Wiley.

Lu, W.-B., Luo, Y., Chen, M., & Shu, D.-Q. (2012). An introduction to Chinese safety regulations for blasting vibration. *Environmental Earth Sciences, 67*(7), 1951–1959. https://doi.org/10.1007/s12665-012-1636-9.

Mortazavi, A., & Sharafisafa, M. (2012). A study of the effect of rock bridges on blast-induced wave propagation in jointed media. *Rock Fragmentation by Blasting*. https://doi.org/10.1201/b13759-38.

Roy, P. (1993). Putting ground vibration predictions into practice. *Colliery Guardian, 241*(2), 63–67. https://doi.org/10.1016/0148-9062(93)92499-g.

Siskind, D. E., Stachura, V. J., & Nutting, M. J. (1987). Low-frequency vibrations produced by surface mine blasting over abandoned underground mines (Trans., Vol. 25, 9078). US Department of the Interior, Bureau of Mines.

Taheri, K., Hasanipanah, M., Golzar, S. B., & Majid, M. Z. A. (2017). A hybrid artificial bee colony algorithm-artificial neural network for forecasting the blast-produced ground vibration. *Engineering with Computers, 33*(3), 689–700. https://doi.org/10.1007/s00366-016-0497-3.

Vasović, D., Kostić, S., Ravilić, M., & Trajković, S. (2014). Environmental impact of blasting at Drenovac limestone quarry (Serbia). *Environmental Earth Sciences, 72*(10), 3915–3928. https://doi.org/10.1007/s12665-014-3280-z.

Zeng, Y., Li, H., Xia, X., Liu, B., Zuo, H., & Jiang, J. (2018). Blast-induced rock damage control in Fangchenggang nuclear power station, China. *Journal of Rock Mechanics and Geotechnical Engineering, 10*(5), 914–923. https://doi.org/10.1016/j.jrmge.2018.04.010.

Zhou, J., Li, C., Arslan, C. A., Hasanipanah, M., & Amnieh, H. B. (2019). Performance evaluation of hybrid FFA-ANFIS and GA-ANFIS models to predict particle size distribution of a muck-pile after blasting. *Engineering with Computers*. https://doi.org/10.1007/s00366-019-00822-0.

Zhou, J., Shi, X., & Li, X. (2016). Utilizing gradient boosted machine for the prediction of damage to residential structures owing to blasting vibrations of open pit mining. *Journal of Vibration and Control, 22*(19), 3986–3997. https://doi.org/10.1177/1077546314568172.