Research Article BEU Fen Bilimleri Dergisi 15(2): 630-646 (2026) DOI: 10.17798/bitlisfen.1804250

BİTLİS EREN UNIVERSITY
FEN BİLİMLERİ DERGİSİ
ISSN: 2147-3129 / e-ISSN: 2147-3188

AN APPROACH TO THE PREDICTION OF AIR SHOCK CAUSED BY BLASTING OPERATIONS IN LIMESTONE QUARRIES

Serdar ERCİNS

Department of Mining and Mineral Extraction, Sivas Cumhuriyet University, Sivas Technical Sciences Vocational School, Sivas, Türkiye
sercins@cumhuriyet.edu.tr

Article Info

Received: *October 15, 2025*
Revised: *December 20, 2026*
Accepted: *April 5, 2026*

Keywords
Air Shock,
Air Shock Prediction Model,
Blasting,
Environmental Impacts,
Statistical Analysis.

ABSTRACT

While blasting operations provides fast and efficient extraction of material, it also has environmental impacts. In particular, effects such as air shock, vibration, dust and noise have the potential to disrupt the environmental balance. Therefore, minimizing the environmental impact of blasting operations, especially in quarries, and managing them in accordance with sustainable mining principles is of great importance for the future of the sector and the protection of the health and safety of society.

The study used data from 75 blasting operations carried out in three different limestone quarries. The measurement results obtained were evaluated using a statistical program and the impact of blasting practices on environmental sustainability was investigated. In particular, a new model was developed to minimize the effects of air shock. This prediction model achieved a high success rate of 90.42%. However, the fundamental assumptions of regression analysis were also evaluated in the study. The model can be used as a valuable guide in the management and planning of blasting operations.

Predicting the effects of air shock is becoming an important element of environmental protection efforts. The prediction model includes the parameters of instantaneous charge, burden, spacing, hole length and measurement distance.

At the end of the study, the air shock measurement results of 6 blasting operations carried out in different limestone quarries were interpreted by comparing them with the values determined by the prediction model and calculation method.

1. INTRODUCTION

Almost all limestone quarries continue to operate using the open-pit method. The open-pit method is a common method used to extract underground resources in areas close to the surface. Blasting operations are at the forefront of the most commonly used operations in these operations.

Drilling and blasting methods are widely used in rock excavations, tunnel and road construction, and open pit mining [1-4].

Rapid urbanization has caused mines and limestone quarries to remain within urban areas. The blasting aggregate production process has increased environmental and occupational safety risks. This is because blasting is the main method of breaking rock. This method has environmental impacts such as vibration, noise and dust and fly rock [5].

One of the most important of these effects is the production of air shock waves that are temporary during blast operations, lasting a few seconds and similar to earthquakes [6].

Explosion-induced ground vibrations, whose formation mechanism differs from that of earthquakes, exert their effects through the propagation of elastic waves (P, S, and surface waves) in the ground. These waves exhibit similar propagation characteristics in the same physical medium as the waves generated during earthquakes. Therefore, explosion-induced ground vibrations and earthquakes exhibit comparable behaviors in terms of structure-soil interaction and vibration response.

License: CC BY-NC 4.0

For this reason, the resulting air shock has become an important problem in mines and limestone quarries, but it also causes discussion between operators and those affected [7,8].

The existing environmental effects mentioned also bring security concerns. During the planning and realization of blasting operations, it is very important to minimize the effects by making some predictions and calculations before the implementation.

Different approaches used since the mid-1900s to reduce blast vibrations, which were considered successful with the knowledge and technology of the time, are now inadequate in most cases to minimize blast vibrations in vibration-sensitive environments, especially in residential areas and slopes near mining areas [9].

Today, new approaches and models are being used to predict blast induced vibration using a variety of parameters [10-12].

Modern statistics has become a more computational science today [13,14]. In today's understanding of statistics, computational methods focused on data analysis are often required to understand many prominent concepts [15].

Statistical analysis helps to understand complex data sets and to obtain meaningful results. The statistical analysis and data modeling capabilities of the program allowed for the analysis of blasting data sets and meaningful conclusions to be drawn from these data.

In this study, the measurement results of blasting operations performed with different bench parameters in different open pits, measured with vibration measurement devices, were evaluated.

These data were processed into the Minitab program, which is widely used in the field of statistics, and a new approach that goes beyond traditional methods for the prediction of air shock value, which is one of the important environmental effects, has been realized. This program is powerful statistical software used for analyzing data, creating models and drawing conclusions.

Minitab statistical analysis program is used in areas such as industry, production and healthcare. In particular, the fact that it provides the necessary tools to check assumptions as well as statistical tools and supports its users with an assistant makes this program very important. It provides great convenience to its users in systematically choosing appropriate statistical techniques when analyzing data and interpreting the results [16].

In the analysis of collected data, the concept of 'P-value' is of great importance from a statistical perspective. It also serves as a fundamental component of many statistical tests and hypothesis testing. In statistical analyses, a small probability value indicates a probability that is too low to be attributed solely to chance [17]. Therefore, for a result to be considered statistically significant, the “P-value” must be between a predetermined limit value (critical value) and 1. When an observed difference or relationship between data meets the significance level, it defines the statistically significant threshold [18].

The smaller the P value, the more statistically significant the results obtained. In this case, comments can be made about the effect of independent variables on the dependent variable.

In the basic principle of the approach, it is aimed to predict the air shock value by using the relationships between the amount of explosive per delay, burden, spacing, hole length and blast point/target distance parameters determined before the blasting operation. While "amount of explosive per delay," used during the blasting process refers to the amount of explosive material (kg) that explodes in a hole during the blast, "Burden" refers to the distance (m) of the holes opened for the blasting process to the free surface. While "Spacing" expresses the distance (m) between the blast holes, "Hole Length and Measuring Distance" defines the relationship between the depth of the blast holes (m) and the distance between the blasting point and the measurement distance (m).

With the use of the program, the relations between the parameters were determined and the formation of the air shock was expressed with a mathematical model. With the innovation brought by this approach, more precise and predictable results can be obtained during the pre-planning phase of blasting operations. With the use of the new prediction model, the air shock impacts from blasting practices in

open-pit mines will become better predictable and manageable. During the planning phase of blasting operations, parameters such as the amount of explosive and the hole pattern will be optimally selected to minimize the effects of air shock. Furthermore, the timing of the blasting can be adjusted more precisely. At the same time, security concerns can be reduced.

This new approach in the study is an important step towards increasing the sustainability of the mining industry, especially in a more environmentally predictable way. It will also enable the development of safer and more environmentally friendly blasting practices in the future.

Sustainability objectives in mining and quarrying are generally related to reducing environmental impacts and increasing energy and material efficiency. These relationships are supported by optimization techniques supported by numerical modelling and artificial intelligence-based algorithms, smart blasting methods supported by electronic capsules, drone and sensor technologies.

Cheng P et al., aimed to promote the sustainable use of resources by optimizing the blasting technology of underground rock in alpine regions. As a result of the optimization, they increased the mining efficiency by improving the blasting parameters [19].

In his study, Fissha Y, looked at the use of sustainable blasting techniques to reduce the environmental impact of mining. He found that the use of precision blasting, in particular, plays an important role in reducing negative environmental and social impacts [20].

In her thesis, Kılıç B, analyzed two different risk assessment methods in an open pit mine to minimize the environmental impact of drilling and blasting in mining activities, and made proposals to minimize the environmental impact in line with sustainable goals [21].

Field studies were carried out in three different limestone quarries fields at different times and patterns. The measuring devices used in blasting operations are installed in the direction of the firing and at different distances. Data from 75 blasting operations carried out in 3 different limestone fields were used to develop the air blast prediction model presented in the study. This number of data is a very good sample size for predicting the strength of the relationship between independent and dependent variables more precisely. Because in studies carried out through statistical programs, a large number of operations or data allows generalizations and predictions to be more accurate.

Loading, transport and mine production capacity are closely related to blasting efficiency. Research shows that 7-22% of the energy used during blasting is spent on fragmentation of rock, and the remaining is spent on factors such as blasting vibrations, air shock waves, flying stones and noise [22]. Such low-efficiency blast can have negative consequences, such as damage to nearby structures, equipment damage and personnel injuries. It can also negatively affect biodiversity. For this reason, it is of great importance to increase the efficiency of blasting and minimize its environmental effects in open pit mining [23].

Air shock is among the most important problems arising from blasting operations in limestone quarries that produce with open pit mining. The gases formed as a result of the reaction during blasting quickly escape to the outside atmosphere through the cracks in the rock and create a significant level of noise. If the measures to be taken are insufficient, the noise level reaches high levels and turns into air shock waves [24].

Air shock waves have a very wide frequency range ranging from 0.1 to 200 Hz. Shock waves with a frequency above 20 Hz are audible and considered noise, while sound waves with a frequency below 20 Hz are inaudible. If shock waves are large enough, they can cause damage to buildings in both frequency ranges [25].

The following measures should be taken to prevent air shock [26]:

- Bench blasting technique is applied and the explosive material is distributed as evenly as possible into the rock and compacted.
- The hole geometry is determined with the most suitable parameters.
- Nonel or electronic ignition system is used.
- The size and type of stemming material should be chosen correctly.

Before drilling, it is examined whether there is a cutting slope to be blasted and whether there is a geological structure that will cause gas escape. If such a structure exists, less explosives are placed in that area [27].

When the air shock level reaches certain values, problems and disturbances may occur in the environment presented in Table 1.

Table 1. Environmental impacts of air shock levels [24]

Sound Intensity, dB	Sound Pressure, psi	Effect
180	3.0	Damage to buildings
170	0.95	Most windowpanes are broken
160	0.30	
150	0.095	Some broken window glass
140	0.030	Maximum level for impulse sound
128	0.0070	Safe level
120	0.0030	Annoying continuous volume limit
110	0.00095	
100	0.00030	
90	0.000095	8 hours of continuous sound discomfort
80	0.000095	

In the assessment of noise, it is recommended to adhere to the L scale and the limit values provided in the US Regulation, in accordance with scientific and technical principles and regulations. In the US Federal Regulation, the highest allowable noise levels, depending on the device's ability to measure low frequencies, are given in Table 2.

Table 2. Highest noise levels allowed under US Federal Statutes

Low frequency limit of the measuring system (Hz)	Maximum noise level (dB)
2 Hz or lower	Highest 133
Less than 6 Hz (up to 2 Hz)	Highest 129

Depending on the frequency measurement ability of the measuring device presented in Table 2, no damage or glass breakage occurs in buildings at the permitted air shock levels of 129 dB or 133 dB. 140 dB value is accepted as the limit of no damage. When the air shock reaches 148 dB, it is seen that some window glasses are broken [28].

As a result of measurement, monitoring and statistical studies conducted in the USA and other countries, different approaches have been presented for blast-induced air shock prediction. These approaches are associated depending on distance and amount of explosive per delay. In 2018, T.R. In the "Blasting Designs and Environmental Impacts Due to Blasting Guide" published by the Ministry of Environment and Urbanization, the general formula in Eq. 1 is presented for the prediction of air shock [29].

$$P = k\left(D/\sqrt[3]{W}\right)^{-\beta} \quad (1)$$

Here;

P: The highest measured air shock level, (Pa). Air shock (or air high pressure) is expressed in Pascals (Pa or N/m^2), a unit of pressure, or in other units of pressure, millibars (mb) or pounds per $inch^2$ (psi).

k: It is a coefficient related to the propagation of sound pressure waves resulting from blasting in the relevant area (atmosphere). The value where the line determined in the logarithmic graph drawn by statistical analysis intersects the y-axis gives the "k" coefficient.

D: Physical distance between the blasting point and the measurement point, (m).

W : Amount of Explosive Per Delay, (kg). The cube root is taken when inserting it into the formula.

β: It is the slope of the line determined as a result of statistical analysis.

The scaled distance (Scaled Distance, SD) definition is obtained by dividing the physical distance (D) by the cube root of the instantaneous charge (W) in practice. In short, it is denoted by the symbol SD and Eq. 2 [29,30].

$$SD = {}^{D}/_{\sqrt[3]{W}} \tag{2}$$

If you pay attention; $\sqrt{W}$ in vibration calculation and $\sqrt[3]{W}$ in air shock calculation. This issue is important.

The formula used in predicting the air shock resulting from quarry blasting, which is also relevant to the study area, is presented in Eq. 3 [31]. The given formula is valid for the metric measurement system. Because the "k" and "β" coefficients in the formulas are adapted to the metric system [32].

$$P = 37.1 * SD^{-0.97} \tag{3}$$

To convert the air shock measured in millibars to decibels, "$SPL_{dB} = 20$ x Log $P_{mb} + 134.1$"

To convert the air shock measured in pascals into decibels, the formulas "$SPL_{dB} = 20$ x Log $P_{N/m^2} + 94$" can be used [33].

High air pressure caused by blasting; can be expressed as sound equivalent. Its unit is decibel and its symbol is dB and it can be calculated with the formula given in Eq. 4.

$$P_s = 20 * \log\left({}^{P}/_{P_o}\right) \tag{4}$$

Here,

P_0: Reference sound pressure (20×10^{-6} Pa or 2.9×10^{-9} lb/in^2)

2. MATERIAL AND METHOD

Measurements for this study were performed using a ground vibration and air shock monitoring device, shown in Figure 1. The Instantel Micromate vibration measuring device can measure three-dimensional vibrations (PPV; mm/s). It can also calculate the vector sum of Longitudinal (L), Transverse (T), and Vertical (V) movements. On the resulting measurement graph, it also presents the vector resultant particle velocity (VS) and peak particle velocity (PPV) values. The geophone used in the study has a frequency of 4 Hz.



Figure 1. Instantel Micromate vibration measuring device

The device's measurement limits are 100-148 dB for noise and 0.127 - 253.9746 mm/s for particle velocity. The desired ranges within these values can be adjusted via the digital display. User information,

including event duration, study area, recording format (single or continuous), and desired units, can be programmed in a pre-defined manner [34].

Blasting operations were carried out on days with clear weather conditions, taking meteorological reports into account. For the 75 measurements, the measurement locations were determined according to field conditions, focusing particularly on areas where the effects of blasting within the mine were most likely to be observed. In this way, suitable conditions were provided in terms of both weather conditions and equipment placement, and the measurements were taken.

The path followed on the statistical program in the modeling of air shock by analyzing the measurement results obtained from the fields where blasting operations are carried out is as follows.

A. Data Collection and Sample Selection: As a first step, all data and air shock measurements of blasting operations carried out in different limestone quarry and patterns were collected. Operations such as statistical analysis, histograms, regression analysis and variance analysis can be performed in the program. On the program, regression analysis was made using the data obtained from the blasting operation, the relationship between blast pattern parameters and air shock was defined and the effects of these parameters on air shock were examined.

B. Prediction and Optimization: With the data obtained, a prediction model was created for the air shock that occurs during blasting operations. This model was created to predict the expected air shock when blasting is performed with variable parameters. The same time, it can also be used to optimize pattern combinations that will minimize air shock impacts. In addition, through the obtained model, different scenarios can be simulated and optimized to achieve the lowest air shock values.

C. Validation and Application: The created prediction model was used in different blasting operations and the predictions were compared with real measurements.

This new approach, which aims to pre-calculate the air shock measured in blasting operations in limestone quarry, can increase environmental sustainability and ensure safety at a high level. While making forecasting more precise and reliable with the data analysis carried out on the program, it will support efforts to minimize the air shock impacts of blasting operations carried out in open-pit mining operations.

There are five independent variables (X) in the approach to forecasting the air shock (Y, the dependent variable). The main purpose of the study is to create a regression model with these variables and optimize the dependent variable. In response to the dependent variable, the independent variables are amount of explosive per delay, burden, hole distance, hole length and blast-point/target distance.

There are two parameters taken into account in the air shock calculation before blasting operations using Eq. 3. Considering the increasing complexity of the methods used in blasting operations today, situations forced by non-linear natural conditions, etc., it has been thought that more independent variables should be included in air shock calculations.

As a matter of fact, Blair in his study emphasized the importance of developing new operations by moving away from classical approaches due to the non-linear behavior of blasts [35].

For this reason, in the study, it was examined whether 5 different independent variables were related to air shock, first individually (Figure 2) and then with the multiple regression method (Figure 3).

Even when the hole distance is kept constant, an increase in the total number of holes, an increase in the instantaneous charge amount, and a decrease in measurement distances lead to an increase in the intensity of the air shock. In this context, an increase in the energy per hole and the total energy amount increases the measured intensity of the air shock.

When the graphs presented in Figure 3 for each parameter associated with air shock are examined based on the data obtained after blasting operations, it is observed that none of the parameters are directly related to air shock at a sufficient level and cannot be meaningfully interpreted on their own.

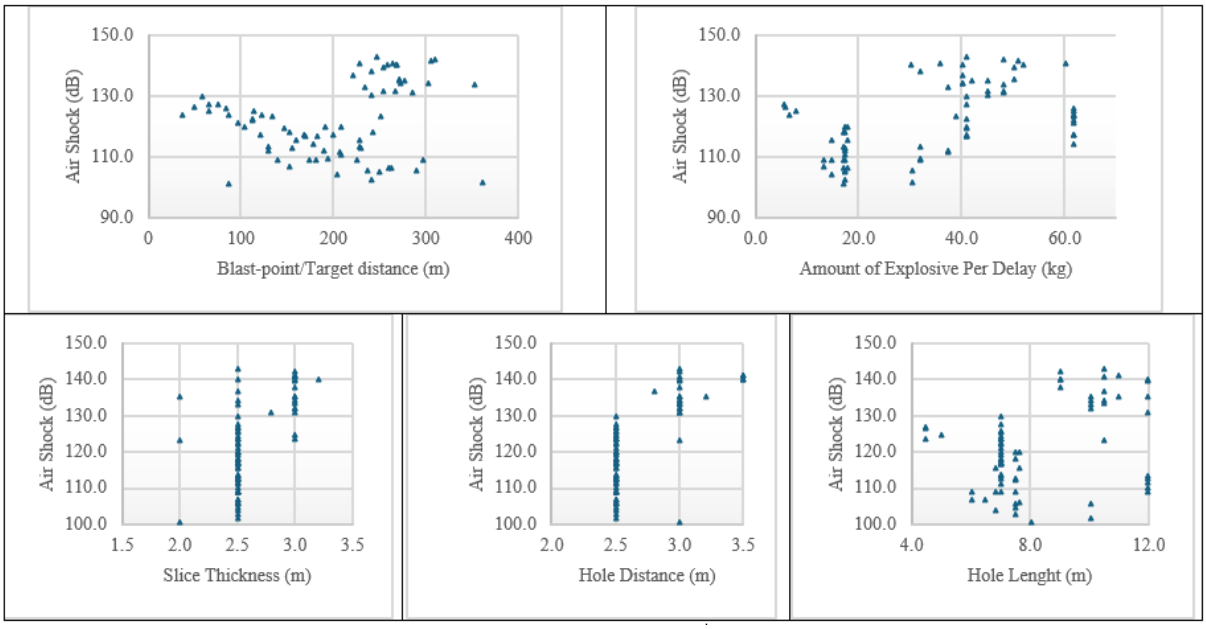


Figure 2. Relationships between post-blast air shock and other measurement parameters

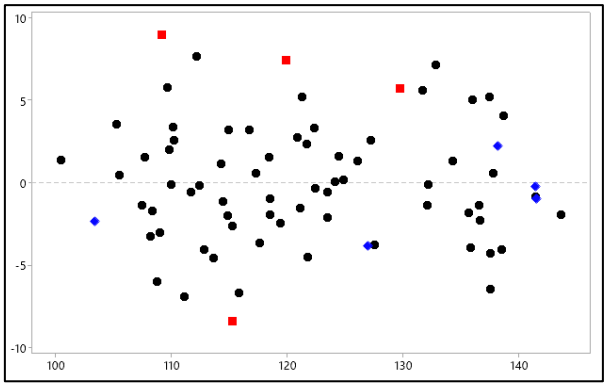


Figure 3. Multiple regression plot for air shock

In the model developed for the prediction of air shock, values that are not suitable for the model are defined as different colored dots compared to the suitable values. It is very important to check the residual (red) points in the figure to verify the model. Which parameter these points belong to can be determined through the program.

Here;

MP : Blast-point/Target distance (m), (X_1)

AEPD : Amount of Explosive Per Delay (kg), (X_2)

ST : Burden (m), (X_3)

HD : Hole Distance (m), (X_4)

HL : Hole Lenght (m), (X_5)

AS : Air Shock (dB)

6 different blasting operations were carried out to test and verify the model created to prediction the air shock value using the multiple regression method (Figure 4). These blastings differ from the original data set. The blastings belong to 6 different blasting operations carried out in the limestone field at different times. In addition, the blasting measurements in the field were carried out in sunny and clear weather, there are no environmental factors that could affect the air shock.



Figure 4. An image of blasting operations

To evaluate the performance of the prediction model with the obtained values, the commonly used statistical criteria Mean Absolute Deviation (MAD), Mean Squared Error (MSE) and Mean Absolute Percentage Error (MAPE), whose calculation methods are given in Eq. 5-7, were used [36]. These metrics help understand how well or poorly the model predicts.

$$\mathrm{MAD} = \frac{1}{n}\sum_{i=1}^{n}|G_i\text{-}T_i| \tag{5}$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{G_i\text{-}T_i}{G_i}\right| *100 \tag{6}$$

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(G_i\text{-}T_i)^2 \tag{7}$$

In the given equations, "n" is the number of blasting operations, Gi refers to the actual air shock value, while Ti refers to the air shock values calculated from Eq. 3 with the prediction model.

MAD is an accuracy model of the mean absolute deviation by evaluating the method obtained by averaging the prediction errors of the absolute error rate of the errors [37].

MSE is an accuracy model obtained by squaring each error result and measuring the overall prediction error level [38].

According to studies, a MAPE value below 10% means that the measured performance value is high [39].

The predictive power and accuracy of the model were evaluated using MAD, MSE, and MAPE performance criteria. Then, descriptive statistics including mean, standard deviation, skewness, and kurtosis were calculated to reveal the distribution characteristics and basic statistical structure of the data. Based on the results obtained, the applicability of regression analysis was evaluated, and multiple linear regression analysis was performed. To examine the assumptions of the regression model, multicollinearity was tested using tolerance and VIF values. Autocorrelation between residuals was evaluated using the Durbin–Watson scale. Furthermore, the homoscedasticity assumption was checked using graphical methods, and the normality of the residuals was examined through residual distribution graphs. Finally, the statistical significance of the regression model was evaluated, and the R^2 value, indicating the explanatory level of the model, was presented.

3. RESULTS AND DISCUSSION

In the study, the equation of the regression model for the prediction of air shock based on the data obtained during the blast is given in Eq. 8.

$$AS\ (dB) = -353 - 0.453X_1 + 1.196X_2 + 48.0X_3 + 283.2X_4 - 1.326X_5 - 0.00604X_2^2 - 25.11X_3^2 - 73.3X_4^2 + 0.1529X_1*X_4 - 1.078X_2*X_3 + 0.826X_2*X_4 + 42.8X_3*X_4 \quad (8)$$

In the presented model, it is stated that, for example, only an increase in AEPD will probably increase the air shock by 1.196.

When the model is examined for MP, another independent variable, it is observed that the coefficient of the MP variable is negative. This is interpreted as an increase in MP causing a decrease in the AS level. Accordingly, a one-unit increase in MP reduces the AS value by approximately 0.45 dB. Therefore, it can be stated that MP has a suppressive effect on AS.

In the resulting regression model, the ST variable has a positive and strong effect on AS. A one-unit increase in ST causes an increase in the AS value of approximately 48 dB. This result shows that ST is a determining parameter in the formation of air shock.

This model can be used to predict air shock in order to prevent environmental and psychological negativities that may occur during blasting operations in limestone quarries producing with open pit method.

The results of MAD, MSE and MAPE statistical measures of the air shock prediction model, which was validated using the measurement results obtained from blasting operations, are as shown in Table 3.

Table 3. Statistical analysis of air shock values predicted from model and calculated from the Eq. 3

Measured Value (dB) (1)	Predicted Value From The Model (dB) (2)	Calculated by Equation-3 (dB) (3)	(MAD) Between		(MSE) Between		(MAPE) Between	
			(1)-(2)	(1)-(3)	(1)-(2)	(1)-(3)	(1)-(2)	(1)-(3)
127.3	130.00	131.01	2.70	3.71	7.29	13.76	2.12	2.91
127.8	126.62	134.25	1.18	6.45	1.39	41.60	0.92	5.05
92.49	87.11	126.42	5.38	33.93	28.94	1151.24	5.82	36.69
126.28	124.83	132.55	1.45	6.27	2.10	39.31	1.15	4.97
113.6	123.98	128.93	10.38	15.33	107.74	235.01	9.14	13.49
118.7	120.54	131.92	1.84	13.22	3.39	174.77	1.55	11.14
AVERAGE VALUE			3.82	13.15	25.14	275.95	3.45	12.37

MAD represents the average of the absolute differences between the values predicted by the model and calculated from Eq. 3 for each measured air shock value. A high MAD value indicates that the deviation between predictions and actual values is larger. A low MAD value indicates that predictions are closer to the actual values, while a high MAD value indicates that the predictions are less accurate.

Accordingly, the average MAD value of the data obtained from the model is lower (3.82). This shows that the predictive ability of the model is better. In other words, the model made predictions closer to the real data.

The average MAD value of the data obtained with Formula-3 is higher (13.15). This indicates that the formula's predictions deviate more from the actual data. The accuracy of the formula is lower.

As a result, based on this information, it can be concluded that the model used to predict the measurement results of blasting operations has a better performance than Formula-3 and offers a relative improvement.

MSE represents the mean value of the squared differences between each measured air shock value and the values determined from the model and calculated through Eq. 3. MSE gives more weight to large

errors and increases the impact of high errors. A low MSE value indicates that predictions are more accurate, while a high MSE value indicates less accurate predictions.

The difference between the model given in Table 3 and the MSE values of Eq. 3 is quite large, and this difference reflects a significant difference between the success levels of the two approaches.

The average MSE value of the data obtained with the model is quite low (25.14). This indicates that the model's predictions are very close to the real data and the model has a good predictive ability.

The average MSE value of the data obtained with Formula-3 is quite high (275.95). This means that the formula's predictions deviate greatly from the actual data, and the formula makes less accurate predictions.

As a result, based on this information, it can be concluded that the model used to predict the measurement results of blasting operations has a much better performance than Formula-3.

MAPE represents the average value of the absolute percentage errors between each measured air shock value and the values determined from the model and calculated through Eq. 3. A low MAPE value indicates that the prediction is generally close to the actual values. However, situations where MAPE is high indicate that predictions may contain large biases.

When Table 3 is examined, it is seen that there is a quite significant difference between the model and the MAPE value of Eq. 3. This difference reflects a significant difference between the levels of success of the two approaches.

The average MAPE value of the data obtained with the model is quite low (3.45). This indicates that the model's predictions are very close to the real data and the model has a good predictive ability.

The average MAPE value of the data obtained with the formula is quite high (12.37). This means that the formula's predictions deviate greatly from the actual data, and the formula makes less accurate predictions.

Table 4 presents the descriptive statistics of the parameters examined from 75 measurements. Kurtosis and skewness values within the ±3 range indicate that the data show a normal distribution [40-43].

Table 4. Descriptive statistics values

Parameters	n	Mean	Std. Deviation	Kurtosis	Skewness
ST	75	2.6	0.24878	.452	.492
HD	75	2.6867	.29561	.819	1.349
HL	75	8.496	2.23561	-.805	.481
AEPD	75	34.538	16.97148	-1.148	.061
MP	75	197.69	76.37366	-.730	-.245
PPV	75	3.7337	2.02172	2.196	1.343
AS	75	121.776	11.93173	-1.096	.173

When Table 4 is examined, it is determined that the kurtosis and skewness values for the presented parameters are in the range of -3 and +3, and the data show a normal distribution. Therefore, the general distribution characteristics of the data reveal that parametric statistical analyses are applicable.

To assess the presence of multicollinearity between variables, it is necessary to examine the Tolerance and VIF (Variance Inflation Factor) values (Table 5). According to Kline (2005), a VIF coefficient below 10 and a tolerance value above 0.01 indicate that there is no multicollinearity problem [44].

When the VIF and Tolerance values of the independent variables in our study are examined from Table 5, it is seen that the VIF values are less than 10 and the Tolerance values are greater than 0.01. This indicates that there is no multicollinearity between the variables.

In addition to these results, a Durbin-Watson value close to 2 indicates the absence of an autocorrelation problem [45]. In this study, this value was found to be 1.663. Therefore, there is no autocorrelation problem among the error terms of the data in this study.

Table 5. Multicollinearity statistical values

Model	Multicollinearity Statistics	
	Tolerance	VIF
ST	.711	1.407
HD	.451	2.215
HL	.398	2.514
AEPD	.504	1.986
MP	.537	1.863

The homocedasticity assumption was evaluated using the graph given in Figure 5, comparing the residuals against the values predicted by the model.

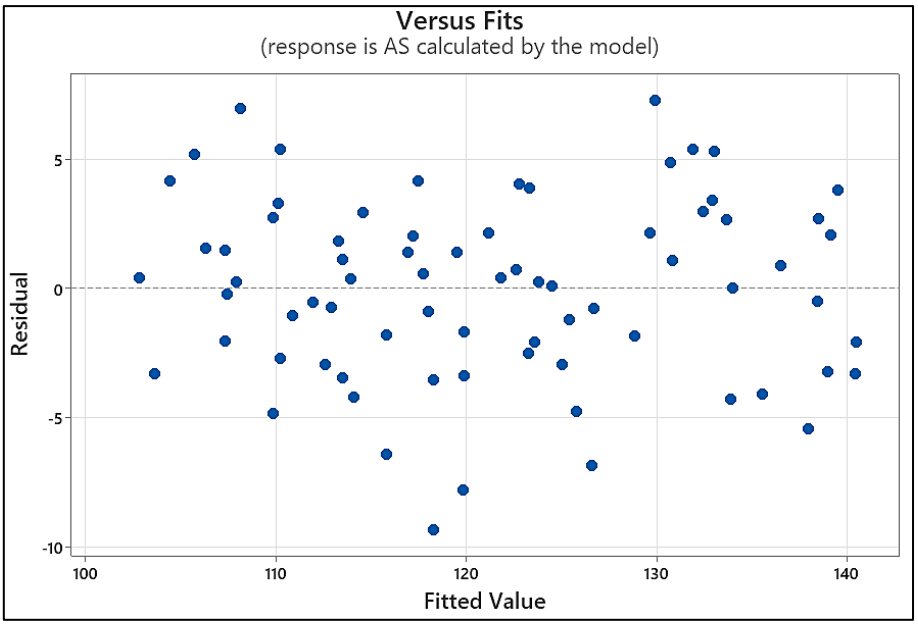


Figure 5. Graph Related to the Assumption of Homoscedasticity

Residuals are defined as the differences between the measured AS values and the values predicted by the model. The graph shows that the residuals exhibit a symmetrical and random distribution around the zero line. No significant increase or decrease in the distribution of residuals is observed along the predicted values. This indicates that the regression model satisfies the homoscedasticity assumption.

The normality of the residuals was assessed using the graph given in Figure 6.

The graph shows that the residuals are largely aligned along the reference line, with limited deviations only at extremes. This indicates that the residuals are approximately normally distributed and that the normality assumption in regression analysis is reasonably satisfied.

The overall significance of the model was evaluated using the Anova test (Table 6). The results indicate that the model is statistically significant.

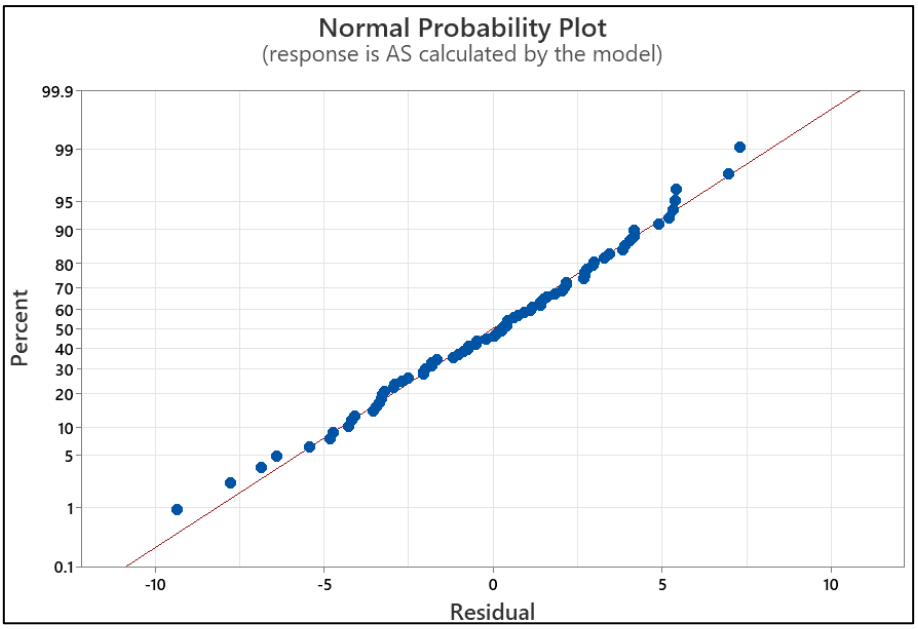


Figure 6. Normality graph of residues

Table 6. Significance of the Regression Model

Anova					
Model	Sum of Squares	df	Mean Square	F	p
Regression	7914.771	6	1319.129	34.233	.000
Residual	2620.322	68	38.534		
Total	10535.094	74			

When Table 6 is examined, the significance level (p) corresponding to the F value for the regression model was calculated as .000. Therefore, since the model is significant ($p < 0.001$), this indicates that the independent variables used in the model significantly explain the dependent variable (AS). Furthermore, when the sum of squares values of the regression and residual are examined, it is seen that the model generally exhibits a good fit and that the independent variables make a significant contribution to explaining the air shock.

Analysis of the measurement results related to blasting operations of the data used in the study, it has been observed that R-squared value of 90.42% (Figure 7).

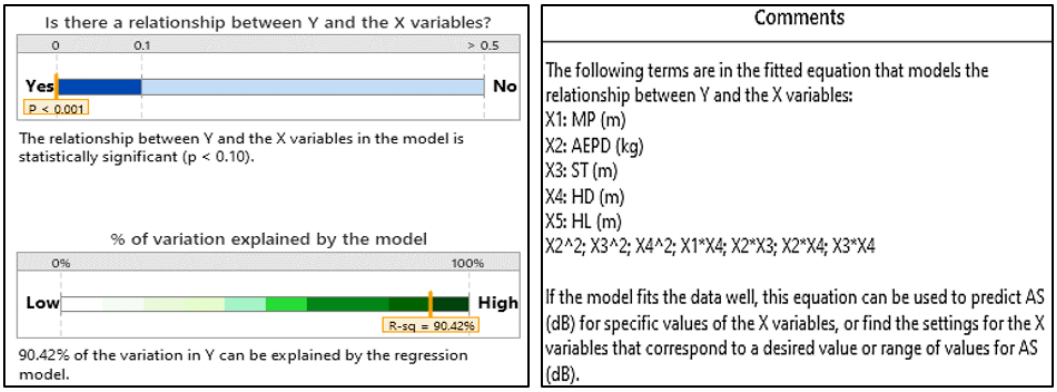
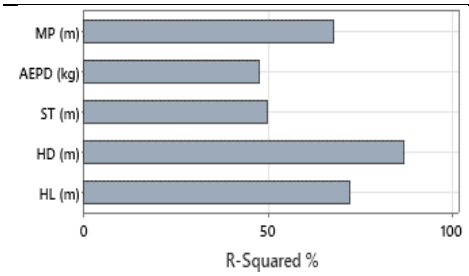


Figure 7. Program output of P-value and R-squared values

An approach generally seen in multiple regression analyzes is expressed graphically in Figure 8.



Variable	Value
MP	67.9963
AEPD	47.9281
ST	50.1219
HD	87.2847
HL	72.5856

Figure 8. Effect of independent variables on the R^2% change of air shock

Figure 8 shows the extent to which each independent variable affects the change in the R^2% value of the air shock. This approach is very useful to understand the effect of independent variables in the model on each other and to see clearly the effect of each independent variable on the dependent variable. In this way, the contribution of each independent variable to the dependent variable can be better understood by purging it from the effects of other variables.

The graph obtained from the model and showing the relationship between the measurement distance and other independent variables in determining the air shock is given in Figure 9. The prediction value of the air shock can be practically determined by matching the relationships of the measurement distance with the other 4 independent variables on the graph.

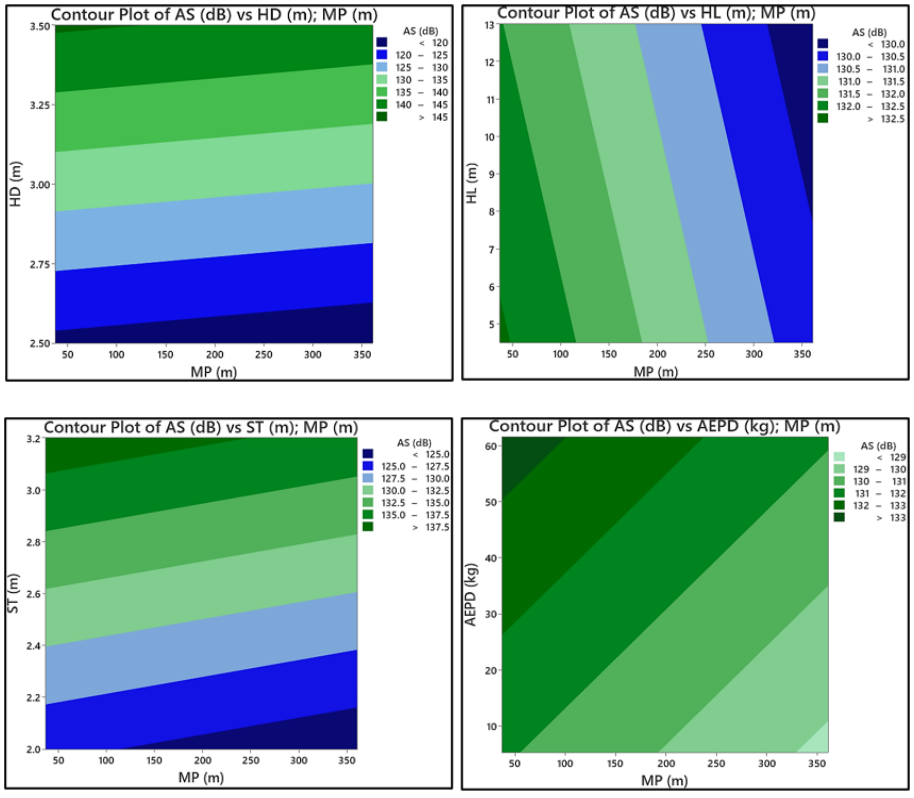


Figure 9. Relationships between measurement distance and other independent variables in determining air shock

Generally, the hole lenght and the deeper the blast, the greater the impact of the blast, and consequently, the intensity and propagation distance of the resulting shock wave. Longer holes generally provide more controlled blasting and better energy dissipation. This leads to higher energy density and gas dispersion velocity, increasing the intensity of the air shock as the measurement distance decreases. Therefore, this relationship between hole length and measurement distance directly affects the impact of the blast and the intensity of the air shock.

The effectiveness of the predictions made through the model can be evaluated according to a possible optimization target or purpose. Thus, it is possible to examine the sample points where the predictions are closest to the optimal values. In this context, the predicted values of the independent parameters obtained from the model for the 100, 129, 133 and 140 dB air shock values determined as examples are presented in Table 7. Of course, the same air shock value can be obtained by changing the values of the independent parameters.

Table 7. Sample points with predicted Y values closest to the optimal solution

Predicted Y (dB)	X_1 (m)	X_2 (kg)	X_3 (m)	X_4 (m)	X_5 (m)
100	361	30.5	2.5	2.5	10
129	271	45	2	3.2	12
133	254	50	3	3	12
140	220	52	2.7	3	11

The model created by the multiple regression method was verified with the values obtained from air shock measurements with 6 different blasting operation data. The air shock measurement results obtained from blasting operations were calculated from the model and Eq. 3, and the values are presented in Table 8.

Table 8. Values of blasting measurement results calculated from the model and formula

No	MP (X_1)	AEPD (X_2)	ST (X_3)	HD (X_4)	HL (X_5)	Measured Value (dB)	Predicted Value From The Model (dB)	Calculated by Equation-3 (dB)
1	191	32.5	2.5	2.8	10	127.3	130.00	131.01
2	128	31	3.5	3.0	9.0	127.8	126.62	134.25
3	375	48	2.0	4.0	12	92.49	87.11	126.42
4	163	35	3.5	3.0	9.0	126.28	124.83	132.55
5	286	52	3.5	3.2	12	113.6	123.98	128.93
6	174	34	2.5	3.5	9.0	118.7	120.54	131.92

It can be seen in Table 8 that the air shock values calculated with the model presented in the study are very close to the values measured during blasting, the deviations between the actual and predicted values from the model are minimal and the modeling is successful. In addition, the R^2 graphs of the air cannon values determined from the model and the Eq. 3 against the measured air cannon values of the blasting operations carried out in the field are given in Figure 10.

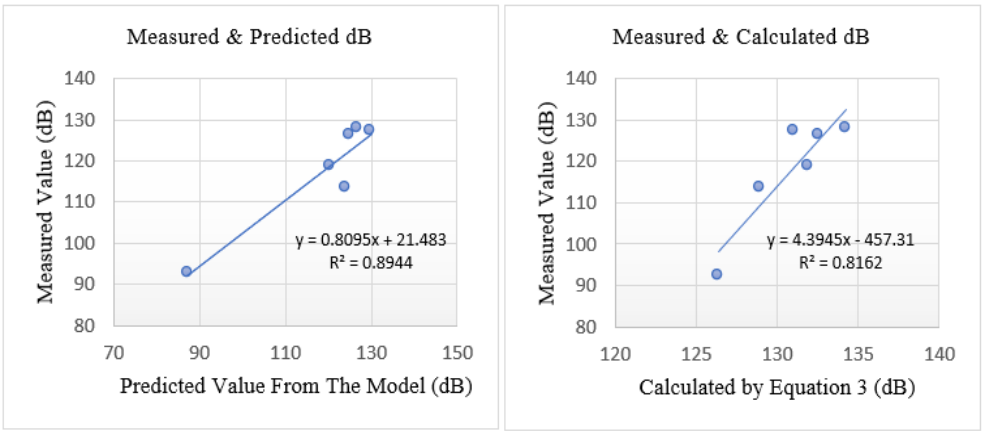


Figure 10. R^2 graph of air shock measurement results determined by model and calculation

As a result, based on this information, it can be concluded that the model used to predict the measurement results of blasting operations has a much better performance than Formula-3.

4. CONCLUSION AND SUGGESTIONS

In this study, as a result of the statistical analysis of data obtained from 75 different blasting operations, a prediction model was created to be used in the prediction of air shock. Using the obtained model, 6 different blasting operations were carried out and the reliability of the model was tested. This model shows the ability to successfully predict weather shock with a rate of 90.42%. This high prediction success achieved is extremely important in terms of evaluating the air shock impacts of blasting operations and identifying potential risks in advance.

In addition, the values of MAD, MSE and MAPE statistical criteria were determined and interpreted to evaluate the performance of the prediction model with the obtained measurement values.

Furthermore, statistical analyses revealed that the model is statistically significant, and the data distribution and basic statistical properties conform to a normal distribution. Tolerance and VIF values indicated no problems in terms of multicollinearity. It was also determined that homoscedasticity was achieved and the residual normality graph was consistent. In light of these findings, it can be concluded that the obtained model is more reliable than Formula-3 and represents a relative improvement.

The model's high predictive accuracy can be an important tool for field practitioners, engineers, and environmental managers who want to minimize the air shock effects of blasting activities and anticipate problems that may arise in the near future. This model can guide the planning and management stages of blasting processes, so that possible air shock effects can be predicted and necessary precautions can be taken.

Additionally, the results of this study may contribute to the development of strategies to design future blasting operations in a more sustainable and environmentally friendly manner. The high prediction success highlights the potential of statistical models to assess the environmental impacts of industrial processes and may enable increased research in this field to be carried out and advanced in the future.

The current model may be capable of making even better predictions with a larger number of data. This can be tested to see how the model can make predictions under different formations.

Approaches that have been widely used from past to present in minimizing the air shock effect caused by detonation and have produced successful results are being reintroduced with different variables today, where data science and computer programs are used more effectively. This model, created with data from limestone fields, can also be improved with data from different mining fields and a different model that generalizes all fields can be created.

Conflict of Interest Statement

The author declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the author.

REFERENCES

[1] L. X. Xie, W. B. Lu, Q. B. Zhang, Q. H. Jiang, G. H. Wang, and J. Zhao, "Damage evolution mechanisms of rock in deep tunnels induced by cut blasting," *Tunnelling and Underground Space Technology*, vol. 58, pp. 257–270, 2016. https://doi.org/10.1016/j.tust.2016.06.004

[2] K. Liu, Q. Li, C. Wu, X. Li, and J. Li, "A study of cut blasting for one-step raise excavation based on numerical simulation and field blast tests," *International Journal of Rock Mechanics and Mining Sciences*, vol. 109, pp. 91–104, 2018. https://doi.org/10.1016/j.ijrmms.2018.06.019

[3] S. Li, S. Liang, C. Li, and D. Liu, "Current status and development trend of deep hole bench blasting technology in open-pit mines," *Journal of Mining Science and Technology*, vol. 6, no. 5, pp. 598–605, 2021. http://dx.doi.org/10.19606/j.cnki.jmst.2021.05.009

[4] Y. L. Li, R. S. Yang, S. Z. Fang, H. Lin, S. J. Lu, Y. Zhu, and M. S. Wang, "Failure analysis and control measures of deep roadway with composite roof: A case study," *International Journal of Coal Science & Technology*, vol. 9, no. 1, p. 2, 2022. https://doi.org/ 10.1007/s40789-022-00469-1

[5] P. A. Adesida, "A rock engineering system approach to estimation of blast induced peak particle velocity," *International Journal of Mining and Geo-Engineering*, vol. 57, no. 1, pp. 101–109, 2023. DOI: 10.22059/IJMGE.2022.343687.594973

[6] R. K. Wharton, S. A. Formby, and R. Merrifield, "Airblast TNT equivalence for a range of commercial blasting explosives," *Journal of Hazardous Materials*, vol. 79, pp. 31–39, 2000. https://doi.org/10.1016/S0304-3894(00)00168-0

[7] C. J. Konya and E. J. Walter, *Surface blast design*. New Jersey: Prentice Hall, 1990.

[8] P. P. Roy, *Rock Blasting: Effects and Operations*. Rotterdam: A. A. Balkema Publishers, 2005.

[9] G. G. U. Aksoy and O. Aksoy, "Usage of seismic quality factor in prediction of blast induced vibrations," *MT Scientific*, no. 18, pp. 133–146, 2020.

[10] S. Ercins, "Vibration prediction with a method based on the absorption property of blast-induced seismic waves: A case study," *Open Geosciences*, vol. 16, no. 1, p. 20220633, 2024. DOI: 10.1515/geo-2022-0633

[11] X. Qiu, H. Qiu, W. Shen, X. Shi, X. Li, and W. Zhi, "Study on blast-induced vibration of single-hole cylindrical charge," *Journal of Vibration and Control*, vol. 31, no. 5-6, pp. 836–850, 2024. https://doi.org/10.1177/10775463241234122

[12] S. Zhao, L. Wang, and M. Cao, "Chaos game optimization-hybridized artificial neural network for predicting blast-induced ground vibration," *Applied Sciences*, vol. 14, no. 9, p. 3759, 2024. https://doi.org/10.3390/app14093759

[13] D. Nolan and D. Temple Lang, "Computing in the statistics curricula," *The American Statistician*, vol. 64, no. 2, pp. 97–107, 2010. https://doi.org/10.1198/tast.2010.09132

[14] G. Cobb, "Mere renovation is too little too late: We need to rethink our undergraduate curriculum from the ground up," *The American Statistician*, vol. 69, no. 4, pp. 266–282, 2015. https://doi.org/10.1080/00031305.2015.1093029

[15] M. C. Tucker, S. T. Shaw, J. Y. Son, and J. W. Stigler, "Teaching statistics and data analysis with R," *Journal of Statistics and Data Science Education*, vol. 31, no. 1, pp. 18–32, 2023. https://doi.org/10.1080/26939169.2022.2089410

[16] A. Ahmad, "Use of Minitab statistical analysis software in engineering technology," in *2019 ASEE Annual Conference & Exposition*, Tampa, FL, USA, 2019. DOI: 10.18260/1-2--33490

[17] D. J. Biau, B. M. Jolles, and R. Porcher, "P value and the theory of hypothesis testing: an explanation for new researchers," *Clinical Orthopaedics and Related Research*, vol. 468, no. 3, pp. 885–892, 2010. https://doi.org/10.1007/s11999-009-1164-4

[18] E. J. Mascha and T. R. Vetter, "Significance, errors, power, and sample size: The blocking and tackling of statistics," *Anesthesia & Analgesia*, vol. 126, no. 2, pp. 691–698, 2018. https://doi.org/10.1213/ANE.0000000000002741

[19] P. Cheng, Y. Li, C. Lu, S. Jiang, and H. Xu, "Study on blasting effect optimization to promote sustainable mining under frozen conditions," *Sustainability*, vol. 14, no. 24, p. 16479, 2022. https://doi.org/10.3390/su142416479

[20] Y. Fissha, "Mining for a sustainable world: the adoption of sustainable blasting techniques," *Aspects in Mining & Mineral Science*, vol. 10, 2023. DOI: 10.31031/amms.2023.10.000745

[21] B. Kılıç, *Analysis of drilling and blasting activities in an open pit mine with two different risk assessment method*, MSc Thesis, Department of Mining Engineering, Institute of Natural and Applied Sciences, University of Hacettepe, Ankara, Türkiye, 2023.

[22] M. Sazid, M. R. Saharan, and T. N. Singh, "Effective explosive energy utilization for engineering blasting–initial results of an inventive stemming plug, SPARSH," in *ISRM Congress*, 2011. ISRM. DOI:10.1201/b11646-237

[23] R. Li, S. Xu, Z. Li, F. T. Suorineni, and G. Zhu, "Development and testing of self-swelling cartridge for use as stemming material in open-pit blasting—a quarry case study," *International Journal of Rock Mechanics and Mining Sciences*, vol. 170, p. 105503, 2023. https://doi.org/10.1016/j.ijrmms.2023.105503

[24] T. Hüdaverdi and C. Kuzu, "Madencilik faaliyetlerinde patlatma kaynaklı çevresel etkilerin ölçülmesi ve analizi," 3. Madencilik ve Çevre Sempozyumu, 5–6 Mayıs, Ankara, 2005.

[25] S. O. Olofsson, *Applied explosives technology for construction and mining*, 2nd ed., Arla, Sweden: Applex Publisher, 1990.

[26] A. H. Bilgin, *Patlatma Mühendisliği Seminer Notları*, Orica-Nitro A.Ş., Nitromak A.Ş., Mkek Barut Fab. Müd., Soma, 2003.

[27] Salmi, E. F., and Sellers, E. J., A review of the methods to incorporate the geological and geotechnical characteristics of rock masses in blastability assessments for selective blast design, Engineering geology, 281, 105970, 2021.

[28] E. Hoek and J. W. Bray, *Rock Slope Engineering*, revised 3rd ed., London, UK: The Institution of Mining and Metallurgy, 1981.

[29] Ministry of Environment and Urbanization, *Patlatma Tasarımları ve Patlatma Kaynaklı Çevresel Etkiler Kılavuzu*, 2018. Available: https://webdosya.csb.gov.tr/db/ced/icerikler/patlatma-tasarimlari-ve-patlatma-kaynakli-cevresel-etkiler-kilavuzu-20180319120154.pdf (Accessed: Jun. 20, 2025).

[30] Duvall, W. I., and Fogelson, D. E., *Review of criteria for estimating damage to residences from blasting vibrations,* (Vol. 5968). US Department of the Interior, Bureau of Mines, 1962.

[31] D. E. Siskind, J. S. Virgil, S. S. Mark, and J. W. John, *Structure response and damage produced by ground vibration from surface mine blasting*, USBM RI 8485, New York, NY, USA: US Department of the Interior, Bureau of Mines, 1980.

[32] B. A. Mert, "Evaluation of environmental impact of blasting operations: An example of limestone quarry in Kuruyer-Hatay province," 6th International Scientific Research Congress, Şanlıurfa, Türkiye, Nov. 1–3, 2019.

[33] D. E. Siskind, *Vibrations from blasting*, Cleveland, OH, USA: International Society of Explosives Engineers, 2000.

[34] Bağdatlı, S., Analysis of environmental effects and vibration induced by cautious blasting during the excavation of approach tunnel of Libadiye station as part of the Uskudar- Umraniye- Cekmekoy subway tunnel project construction, Master's Thesis, Okan University, Institute of Science, İstanbul, Türkiye, 2013.

[35] D. P. Blair, "Charge weight scaling laws and the superposition of blast vibration waves," *Fragblast*, vol. 8, no. 4, pp. 221–239, 2004. https://doi.org/10.1080/13855140412331291610

[36] S. Arslankaya, "Comparison of performances of fuzzy logic and adaptive neuro-fuzzy inference system (ANFIS) for estimating employee labor loss," *Journal of Engineering Research*, vol. 11, no. 4, pp. 469–477, 2023. https://doi.org/10.1016/j.jer.2023.100107

[37] A. M. Adiandari, "Financial performance innovation since digital technology entered Indonesian MSMEs," *International Journal for Applied Information Management*, vol. 2, no. 1, pp. 50–58, 2022. https://doi.org/10.47738/ijaim.v2i1.29

[38] A. Wodecki, "The reserve price optimization for publishers on real-time bidding on-line marketplaces with time-series forecasting," *Foundations of Management*, vol. 12, no. 1, pp. 167–180, 2020. https://doi.org/10.2478/fman-2020-0013

[39] V. Yadav and S. Nath, "Forecasting of PM 10 using autoregressive models and exponential smoothing technique," *Asian Journal of Water Environment and Pollution*, vol. 14, no. 4, pp. 109–113, 2017. DOI: 10.3233/AJW-170041

[40] Groeneveld, R. A., and Meeden, G., *Measuring Skewness and Kurtosis,* Journal of the Royal Statistical Society: Series D (The Statistician), 33(4), 391-399, 1984.

[41] Moors, J. J., *The Meaning of Kurtosis: Darlington Reexamined,* The American Statistician, 40(4), 283-284, 1985.

[42] Hopkins, K. D., and Weeks, D. L., *Tests for Normality and Measures of Skewness and Kurtosis: Their Place in Research Reporting,* Educational and Psychological Measurement, 50, 717-729, 1990.

[43] DeCarlo, L. T., *On the Meaning and Use of Kurtosis*, Psychological Methods, 2: 292-307, 1997.

[44] Kline, R. B., *Principles and Practice of Structural Equation Modeling*, (Second Edition), NY: Guilford Publications, Inc, 2005.

[45] Fox, J., Applied Regression Analysis, Linear Models, and Related Methods, Thousand Oaks, CA: Sage, 1997.