Mapping Blasting Vibration Distribution in Coal Mining Using Kriging Interpolation

Nur Efendi [1], Eri Barlian [2], Indang Dewata [3], Mulya Gusman [4], Nurhasan Syah [5], Aprizon Putra [6] , Dino Gunawan Pryambodo [6]

[1] *Doctoral Program of Environmental Science, Universitas Negeri Padang, Hamka str, Padang, West Sumatra 25171, Indonesia*
[2] *Department of Coaching, Universitas Negeri Padang, Hamka str, Padang, West Sumatra 25171, Indonesia*
[3] *Department of Chemistry, Hamka str, Padang, West Sumatra 25171, Indonesia*
[4] *Department of Mining Engineering, Hamka str, Padang, West Sumatra 25171, Indonesia*
[5] *Department of Civil Engineering, Hamka str, Padang, West Sumatra 25171, Indonesia*
[6] *National Research and Innovation Agency, 47 Jakarta-Bogor str. Cibinong, West Java 16911, Indonesia*

***Abstract* – Coal mining has a significant impact on the environment and surrounding society. One of the main impacts of open-pit mining activities is vibrations generated from blasting, which have the potential to damage the ecosystem and building structures around the mine site. This research aims to analyze the distribution of blasting vibrations in the mining environment using the Kriging geostatistical method. The Kriging method was chosen to map the vibration distribution and produce zoning based on the level of vibration risk to the environment and surrounding society. The data used included vibration measurements from 25 blasting operations taken from 2717 drill points over one month. The results showed that the Kriging method successfully predicted vibration distribution well, producing a zoning map that divided the area into a safe zone, cautious zone, and hazard zone. The cautious zone is characterized by very high vibration intensity, which has the potential to damage building structures and endanger human health.**

These findings provide important insights for mine management in more effective risk mitigation and planning efforts to minimize the negative impacts of blasting vibrations on the environment and society.

***Keywords* – Blasting vibrations, spherical Kriging, geostatistical, sustainable environment, coal mining.**

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Corresponding author: Nurhasan Syah,
Department of Civil Engineering, Hamka str, Padang, West Sumatra 25171, Indonesia
Email: nurhasan@ft.unp.ac.id

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1. Introduction

Coal mining is one of the industrial sectors that significantly impacts the environment and society. According to the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia No 1827 K/30/MEM/2018, environmental management in mining activities involves various strategic steps, namely anticipation, recognition, measurement, assessment, prevention, management, and evaluation [1]. These steps aim to manage the environmental impacts that may arise from mining activities. In practice, the effects of coal mining activities can vary, direct and indirect, including environmental damage and significant social change.

The negative impacts of coal mining include air, water, and soil pollution, as well as changes in the social and cultural structure of the surrounding society. [2] add, that air pollution occurs due to dust and gas emissions from the mining process which can disrupt public health and the quality of the surrounding air. Furthermore, [2] explains, that water pollution can occur through the seepage of hazardous substances from piles of mining waste into water bodies, which can damage aquatic ecosystems and drinking water sources. Soil pollution occurs through the accumulation of mining waste which damages soil fertility and changes the natural landscape. In addition, according to [3], [4], [5], social and cultural changes can also occur along with changes in the economic structure and lifestyle of the society due to mining activities.

However, behind these negative impacts, coal mining activities also bring significant economic benefits. One of the main benefits is increasing employment and business opportunities for local society.

Mining activities often create new jobs and stimulate local economic growth through economic activities related to mining. In addition, coal mining can also increase export value, which contributes to state revenue and regional economic development. In the context of sustainability, managing the environmental and social impacts of coal mining is essential to achieve a balance between economic benefits and environmental protection. Research conducted by [6], [7] shows that a comprehensive and sustainable management approach can minimize negative impacts and ensure that the economic benefits of mining do not sacrifice environmental and societal health.

PT. Insani Baraperkasa (PT. IBP) is one of the companies involved in the coal mining industry in Indonesia. This company operates with a Coal Business Work Agreement Contract (CBWA) and manages an area of 24,477.60 ha [8], [9]. Meanwhile, the research location focuses on PT. Ansaf Inti Resources (PT. ANSAF), which is a subcontractor in the Separi Block, Berambai site. This mining area is located in Kertabuana Village, Tenggarong Seberang Sub-district, Kutai Kartanegara Regency, East Kalimantan Province, with an area of approximately 182 ha. The travel route from Samarinda to Bangun Rejo Village takes approximately 30 minutes using a two-wheeled vehicle or 20 minutes using a four-wheeled vehicle, continuing to the PT. ANSAF mining location which is approximately 10 km away, takes approximately 40 minutes in sunny weather and up to 60 minutes when it rains.

This research focuses on the analysis of the blasting vibrations on the environment around the mining area using an open-pit mining system. In open-pit mining activities, blasting is used to facilitate the process of extracting coal from the overburden. However, this blasting can cause vibrations that have the potential to damage the surrounding environment and surrounding building structures. Therefore, it is important to carry out effective vibration control to protect the environment and ensure the sustainability of mining operations. Blasting vibrations generated during the open pit mining process can have a significant impact on the environment and surrounding society. These impacts include disruption to the soil ecosystem, air pollution, and potential damage to building structures. Research by [10], [11] shows that high vibrations can damage ecosystems and building structures, which can threaten environmental sustainability and the quality of life of the surrounding society.

Therefore, prevention of air, water, and soil pollution, as well as effective management of mining waste are very important in reducing the negative impacts of mining activities. In addition, controlling the effects of blasting vibrations is also an important part of environmental impact management. The Indonesian National Standard (SNI) 7571 (2010) stipulates that the standard level of blasting vibrations in open-pit mining activities must comply with certain standards to protect buildings and the surrounding environment. Unmanaged blasting ground vibrations can cause human disturbance, discomfort, and damage to surrounding building structures. Therefore, it is important to conduct an accurate analysis of the blasting vibrations to minimize public complaints regarding damage to building structures and ensure sustainable environmental protection [12], [13].

Kriging is an interpolation method that allows the prediction of unobserved values based on existing data, taking into account spatial variability and correlation between data points. This approach provides a more accurate picture of the safe distance for humans and building structures, as well as the level of public complaints, by the provisions of Article 16 of the Environmental Law No 32/2009. Integrating this geostatistical method is expected to improve understanding of the blasting vibrations and support more effective risk planning and mitigation. This will allow the economic benefits of mining activities to be achieved without sacrificing environmental quality and the welfare of the surrounding society.

This research aims to analyze the distribution of blasting vibrations in the mining environment using the Kriging geostatistical method. This method will identify safe, less safe, and unsafe vibration zones for the environment and society, as well as determine the safe distance and area of vibration influence, according to the provisions of the Environmental Law No 32/2009 concerning Environmental Protection and Management. This zoning map is expected to provide guidance for mine managers in managing the impact of blasting vibration effectively, as well as ensuring that mining operations can be carried out with minimal environmental impact. In addition, this research presents methodological innovations through the use of geostatistical methods, especially Kriging, to produce a zoning map of blasting vibration distribution. Overall, this research is important to improve environmental management strategies in the coal mining industry. By applying a comprehensive and innovative methodology, it is expected that effective solutions can be found to minimize the negative impacts of blasting vibrations and improve the quality of life of society and environmental sustainability.

2. Methods

This research was conducted at PT. ANSAF, a sub-contractor of the Separi Block of PT. IBP, located at the Berambai site covering an area of ±182 ha. The research area spans Kertabuana, Buana Jaya, and Mulawarman Villages in Tenggarong Seberang Sub-District, Kutai Kartanegara Regency, East Kalimantan Province. To access the mining site, the journey begins in Samarinda City, continuing to Bangun Rejo, approximately 25 km away, which takes about 30 minutes by motorcycle or 20 minutes by car. From there, the remaining 10 km to the PT. ANSAF mining location takes around 40 minutes under clear weather conditions and up to 60 minutes during rain. The distance from Bangun Rejo to the mining location of PT ANSAF is approximately ±10 km, requiring about 40 minutes of travel using a mine employee bus or Light Vehicle (LV) under sunny weather conditions and up to 60 minutes during rainy weather. The geographic coordinates of the research location will be used to ensure the accuracy of mapping and analysis of the distribution of blasting vibrations and to support planning and risk mitigation in the mining area, as can be seen in Figure 1.

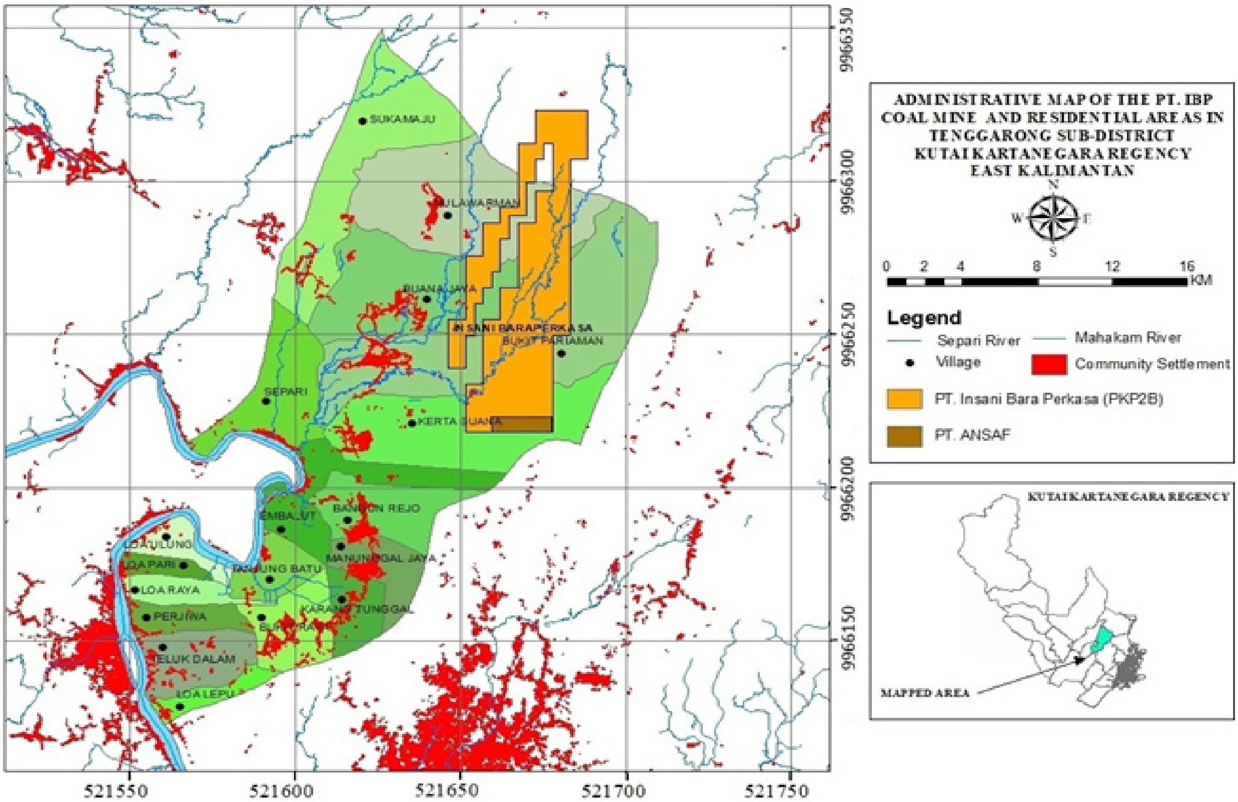

Figure 1. Map of research location

2.1. Application of Blasting Techniques and Drilling Patterns in Coal Mining

The ideal blasting operation for mining activities must meet the criteria of efficiency, low cost, and safety. To achieve these goals, several important aspects of blasting must be considered. Ideally, blasting operations should reduce material loss and break up blasting results uniformly. In addition, it is important to ensure that blasting operations do not disturb the surrounding environment. This includes controlling low vibration levels, avoiding fly rock, and minimizing noise. In the context of coal mining at PT. ANSAF, as explained by [14] in his paper, blasting is needed in several locations to strip the coal cover, assuming that around 70% of the overburden requires dismantling through drilling and blasting.

For mining activities, a 4-inch diameter shot hole is planned to be drilled using a FURUKAWA PCR 200 drill. The drilling pattern to be used is an alternating pattern, with simultaneous blasting in one row and successive between rows [15]. The distance from the blasting location to the nearest residential area is approximately 3,000 meters [16]. Based on the previous mining plan, the blasting direction is planned to be changed from South to North to suit the operational needs and local geological conditions (Figure 1). Illustrations related to drilling and blasting patterns can be seen in Figure 2.

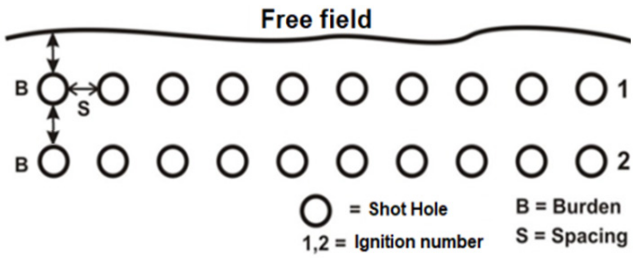

Figure 2. Drilling and blasting patterns

In the process of dismantling the coal overburden, the design of the blasting technique to be applied is based on the theory of R.L. Ash [17]. The blasting geometry is carefully designed to ensure the effectiveness and efficiency of the process. The main explosive used is ANFO, which is known for its high detonation velocity, which is 11,100 FPS (feet per second), and its specific gravity reaches 0.8 [18]. ANFO was chosen because of its ability to produce sufficient explosive energy, which is needed to effectively break the coal overburden. As part of the blasting system, a 400-gram booster is used as a primer to increase the explosive force and ensure that the main explosive can function optimally. For initial ignition, a Non-Electric Detonator (NONEL) is used, which allows for better control and reduces the risks associated with the use of electric detonators.

The blasting process is designed to accelerate production by dismantling the coal overburden consisting of various types of geological materials, such as siltstone, sandstone, and claystone. A well-planned blasting technique is expected to optimize the dismantling of the overburden and accelerate access to the coal to be mined, where the designed embankment slope will follow a certain geometry as shown in Figure 3. The single height of the slope will reach 6 meters with a single slope of 30°. While the overall height of the slope will reach 12 meters, with an overall slope of 25°. The width of the berm, or flat area at the bottom of the slope, is planned to be 42 meters. This geometric arrangement is expected to ensure the effectiveness of blasting in dismantling the overburden and optimizing the coal mining process.

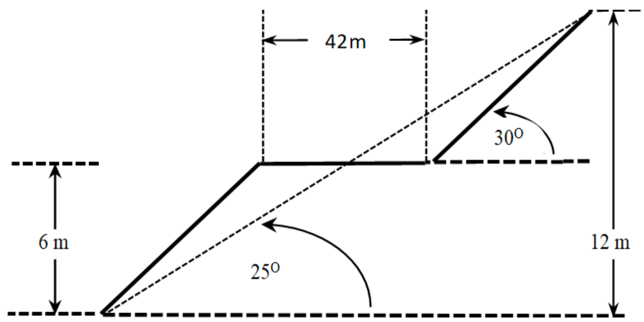

Figure 3. Geometry of drilling and blasting

2.2. Geostatistics and Kriging

Geostatistics, or spatial statistics, is an analytical method that measures the distribution of phenomena by considering spatial aspects. Unlike non-spatial statistics, which do not account for geographic relationships [19], geostatistics quantifies the correlation between values separated by distance and predicts values at unmeasured locations. A core element of geostatistics is the variogram or semi variogram, which measures spatial correlation between data points. Experimental variograms, calculated from observed data, help determine spatial characteristics and measure the average difference between data points separated by various distances. Ideal variograms include three key components, namely the range, sill, and nugget effect. The range represents the distance at which the variogram stabilizes, or reaches the sill value, while the sill is the plateau or stable value that the variogram approaches [20]. The nugget effect reflects small variations at very close distances [21]. In this research, experimental variograms were constructed in multiple directions with a lag distance of 100 meters to obtain a representative analysis of the spatial correlation. The spherical variogram model was selected for this analysis based on its close match with the experimental variogram, which effectively captured the spatial relationships in the data [22].

The Stanford Geostatistical Modeling Software (SGeMS) an open-source tool was used for geostatistical modeling. SGeMS allows for the estimation, simulation, and interpolation of spatial data with an intuitive interface that facilitates robust analysis. Using this software, the research applied Kriging spherical, a statistical estimation technique that functions as a Best Linear Unbiased Estimator (BLUE). This method provides local estimates without bias by considering the spatial variability of the available data. Ordinary Kriging (OK), one of the most common forms of Kriging, was used to estimate values of PPV based on available data points [23], [24]. The estimated value of the block variable is calculated using the Kriging equation, which ensures that the resulting estimate is unbiased and reliable. The weight (λ) is a crucial factor determined by the Kriging equation that relates the measurement data surrounding the estimated location. This weight dictates the contribution of data from various locations to the final estimate. Additionally, the Kriging variance is computed to assess the uncertainty in the estimates. This variance provides information about the potential variation in predictions, enabling an assessment of the estimates' accuracy and reliability. In this context, several parameters are used in the equation [25], [26]:

Z^* is the estimated value of the content to be estimated.
Z_i is the weighted content value according to the specified λ weight.
$\gamma(v,v)$ is the average value of $\gamma(h)$ if one end of the vector h shows domain $v(x)$ and the other end also shows the domain $v(x)$.
$\gamma(v,V)$ is the average value of $\gamma(h)$ if one end of the vector h shows domain $V(x)$ and the other end also shows the domain $v(x)$.
$\gamma(V,V)$ is the average value of $\gamma(h)$ if both ends of the vector h shows domain $V(x)$.

The use of OK in this research aims to produce a high-accuracy blasting vibration distribution zoning map. Applying this method is expected to determine the safe and unsafe zones around the blasting location, as well as identify safe distances for building structures and the surrounding community. The integration of this Kriging technique in vibration distribution analysis provides benefits in more effective risk planning and mitigation and ensures that the environmental and social impacts of mining activities can be properly controlled. Meanwhile, to visualize the distribution of PPV across the research site, a color-coded map was generated, which divides the PPV values into three main categories based on their intensity. This categorization provides an intuitive interpretation of the PPV data, making it easier to identify regions of concern, therefore, more details can be seen in Table 1.

Table 1. Color categories and required actions based on PPV distribution

Color	Category	Description
Red	High risk zone	Very high vibration intensity that can potentially damage structures and endanger human health.
Yellow	Medium risk zone	Significant vibrations that could cause mild to medium damage.
Green	Safe zone	Vibration intensity is within safe limits for structures and human health.

The use of these colors in the map allows for a quick visual assessment of the areas most affected by blasting vibrations. As supported by [27], such color-coded visualizations help decision-makers prioritize areas that require immediate intervention and ongoing monitoring. The integration of spatial data with Kriging results and color-coded maps provides a powerful tool for Spatial Decision Support Systems (SDSS), guiding mining operations toward more informed and effective environmental management.

This method of mapping PPV distribution aligns with Kriging spherical principles, where the spatial variability captured through the variogram is applied to estimate unmeasured areas, allowing for an accurate representation of ground vibrations.

The categorization of the map into red, yellow, and green zones provides an actionable framework for assessing and mitigating the environmental impact of mining activities.

3. Results

This section presents the findings from the spatial analysis of blasting vibrations using Kriging techniques. The results provide a detailed understanding of vibration distribution patterns, spatial characteristics, and risk areas in the mining environment.

3.1. Spatial Data Analysis for Kriging in Blasting Vibrations

The results of this research provide details regarding the data used for Kriging analysis. This data includes information about the source of blasting vibrations, the method used to collect the data, and the spatial characteristics of the data, which can include settings in three-dimensional (3-D) or two-dimensional (2-D). Kriging analysis in this research utilizes spatial or geographic data related to the phenomenon being studied, in this case, blasting vibrations in coal mines. The analysis process involves several key components such as:

1. Observation or measurement data obtained directly from the field, including vibration levels measured at various locations around the blasting area;
2. Each measurement data is equipped with geographic coordinates that indicate the exact position of each measurement point in a geographic context;
3. Additional information about the data that may include the time of measurement, environmental conditions, and other factors that may affect the measurement results;
4. Covariates that may affect the vibration distribution, such as rock type, layer depth, and mining activities occurring in the vicinity of the measurement area;
5. Variogram data used to assess how the variability of the measurement data changes with distance. Variograms are an important tool in Kriging to model the spatial structure of the data; and
6. Boundary or constraint data include information about geographic boundaries or other constraints that may affect the vibration distribution, such as mining area boundaries or safety zones.

The results of this Kriging analysis not only provide an overview of the blasting vibration distribution pattern but also indicate areas that are potentially high risk and require further mitigation to minimize negative impacts on the environment and the safety of the surrounding community.

In this research, Optimal Stochastic Index (ISO) mapping of Peak Particle Velocity (PPV) was conducted [28] using data from 2,717 borehole points over one month. Observations were made 25 times blasting at predetermined locations. This method describes the spatial distribution pattern of blasting vibration intensity in a 2-D.

This approach not only visualizes the propagation of vibration effects across the monitored area but also identifies specific zones that require immediate attention for risk reduction. The mapping results serve as a valuable tool for stakeholders in the mining and construction industries, enabling informed decision-making to mitigate environmental damage and enhance safety protocols. By integrating advanced spatial analysis techniques with a data-driven approach, this research contributes significantly to the broader understanding of blasting dynamics and their implications for sustainable practices in resource extraction and infrastructure development.

The ISO PPV results from the map (Figure 4), show the variation in blasting vibration intensity in the research site. Data from each blasting observation is used to calculate the measurement points spread around the borehole location. This process involves variogram analysis to determine the spatial model of the observed vibration and then applying the Kriging technique to estimate the PPV values between the observation points. The results of this mapping provide an overview of the spatial distribution of blasting vibration intensity in the research area, which can be used to evaluate potential risks to infrastructure and the surrounding environment. This information is important for sustainable coal mine management and mitigation of the negative impacts of blasting activities. More details can be seen on the map in Figure 4 and Figure 5 at the location (in 2-D and 3-D). More details can be seen on the map in Figure 3 at the location (in 2-D).

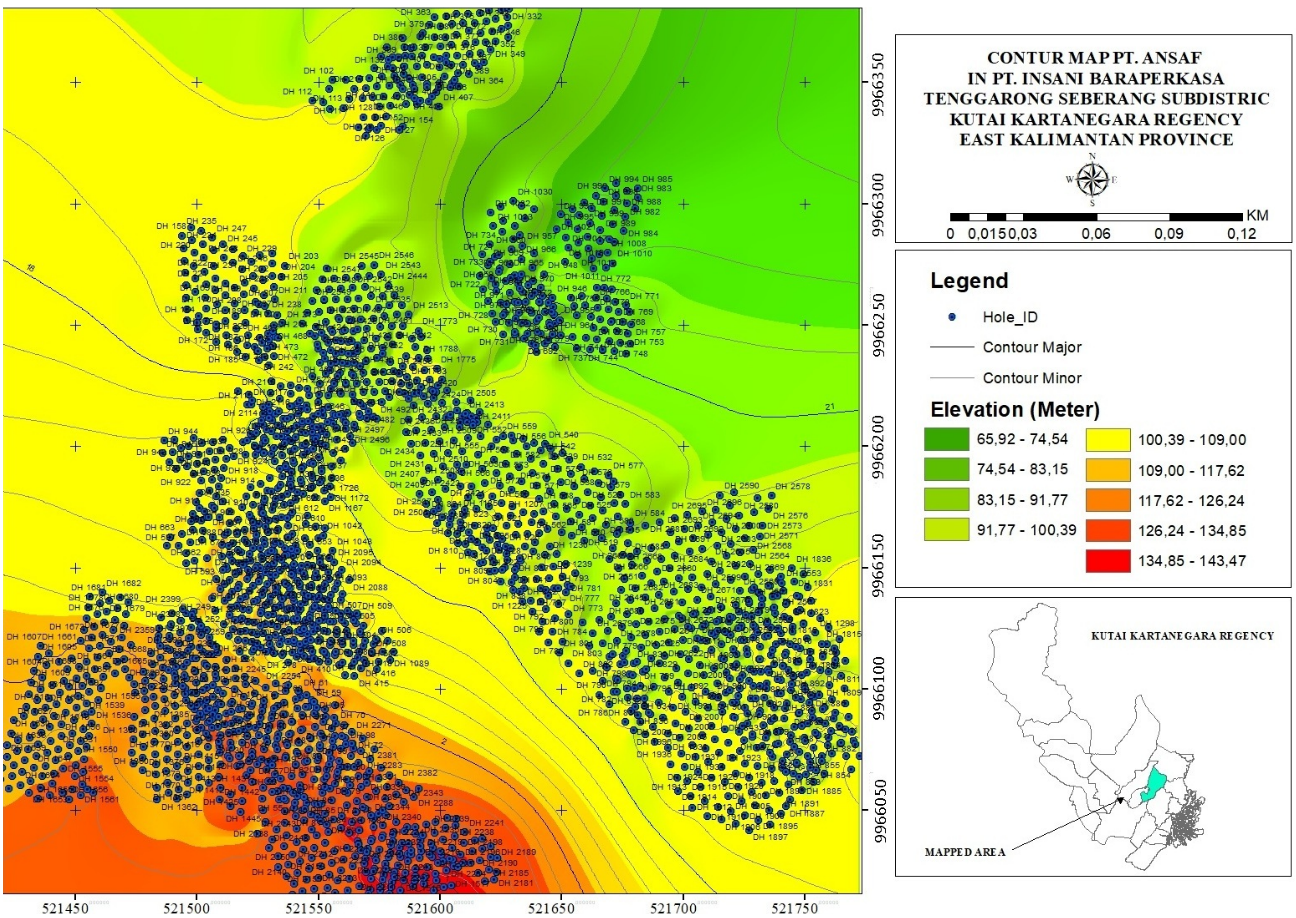

Figure 4. 2-D map view for a total of 2,717 drill holes in 1 month, in 25 blasting observations

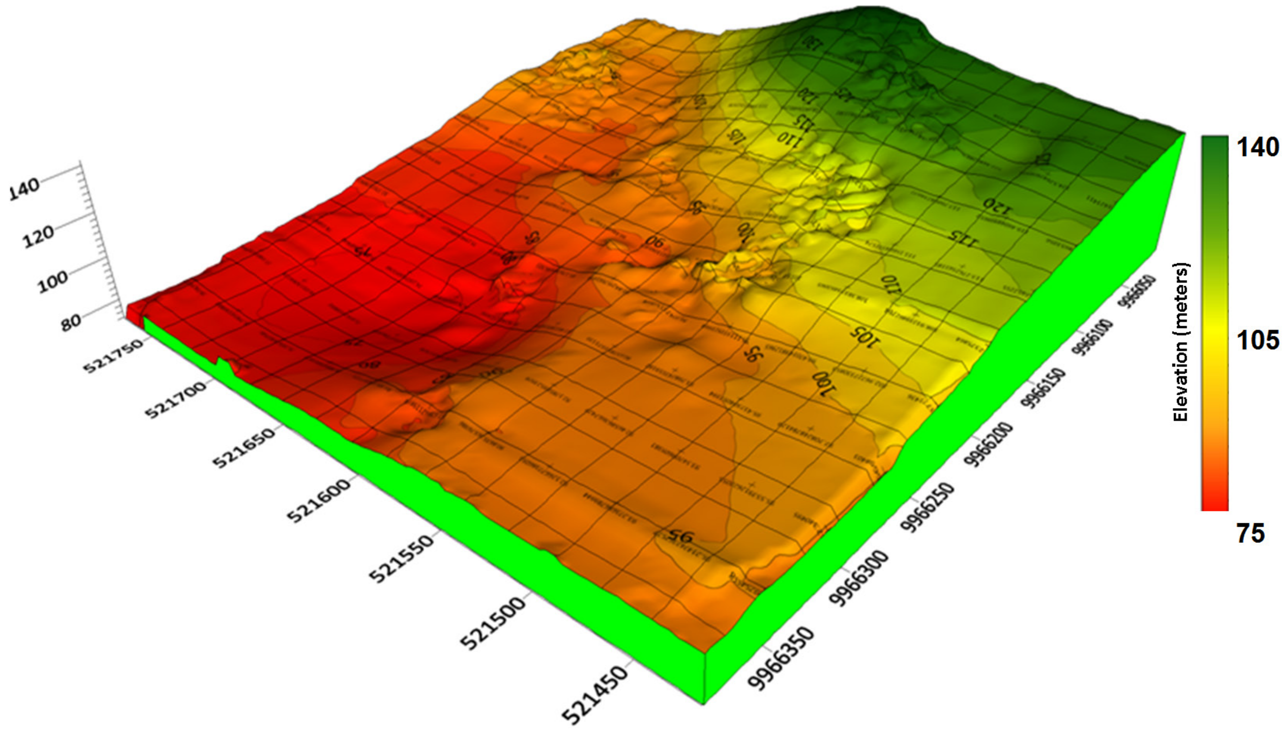

Figure 5. 3-D visualization for contour lines

In Figure 5 above is a 3-D visualization of the elevation data of the research area where the lowest elevation is depicted in red and the highest in green with a 50x50 grid which means the distance between 1 point and another is 50 meters. The highest elevation of the research area is 140 meters with an interval between elevations of 20 meters. The source of blasting vibration data is obtained from a geotechnical monitoring system installed around the coal mine area. This system is part of a wider mine monitoring system, designed to provide accurate real-time data. This data is essential for monitoring the potential impact of blasting vibration on the surrounding environment and existing infrastructure. By utilizing data from this monitoring, analytical techniques such as Kriging or other spatial methods can be used to evaluate the spatial distribution patterns of vibration.

The results of this spatial analysis not only provide insights into the distribution and intensity of vibrations but are also crucial for optimizing mining operations and minimizing environmental and structural risks. These insights enable the identification of high-risk zones, facilitating the implementation of targeted mitigation measures to reduce vibration impact on critical infrastructure and ecological systems. Moreover, this approach supports the development of predictive models to enhance safety protocols and improve the overall sustainability of mining activities.

Blasting vibration data collection in coal mines usually involves the use of various geotechnical sensors and instruments placed around the blasting area. These sensors record vibration data continuously, providing detailed information on the intensity and frequency of vibrations generated by blasting activities. The data collected helps in a more in-depth analysis of how the vibrations affect the surrounding area of the mine, both in terms of the environment and infrastructure. These spatial characteristics are also very important in the analysis and interpretation of the data, as they allow researchers to identify patterns and trends in the data that may indicate areas of risk. A deep understanding of the spatial characteristics of blasting vibrations allows researchers and mine managers to formulate more appropriate interventions to reduce negative impacts on the environment and local society. As an example of data visualization, Figure 6 shows a 3-D visualization of the results of PPV data Kriging with units of mm/s using the OK method. This visualization illustrates how blasting vibrations are distributed in space, with the distance between the x and y axes being 50 meters, and the variation in data elevation from the highest 4 to the lowest 1. This visualization is important because it provides a clear visual representation of the intensity and distribution of vibrations, facilitating an understanding of the areas most affected by blasting and allowing for more accurate and efficient mitigation planning. The elevations in this visualization are taken based on PPV data, which indicates the severity of vibrations at certain points in the mining area. More details can be seen in Figure 6.

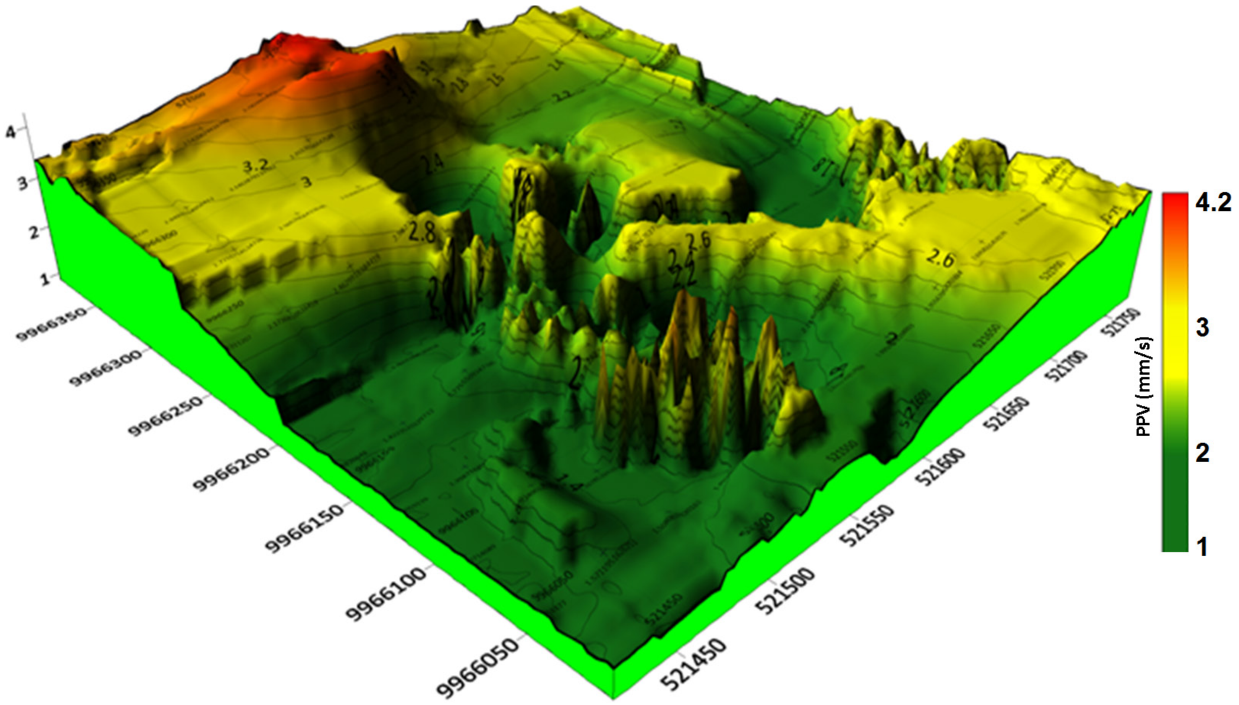

Figure 6. 3-D visualization of the Kriging results of PPV data with mm/s units using the OK method.

3.2. Variogram Results

This section describes the analysis results showing several variogram curves, which are used to research the spatial pattern of blasting vibrations. The resulting variogram is an essential statistical tool in the Kriging process, which functions to estimate unknown PPV values between existing observation points. PPV data collected from various borehole points were analyzed to understand the spatial relationship between PPV values at various distances. Using statistical techniques, the variogram was estimated to measure the degree of spatial dependence between PPV values at different distances. The results of this analysis were then used to build a variogram model that describes the spatial structure of PPV in the research location. More details can be seen in Figure 7.

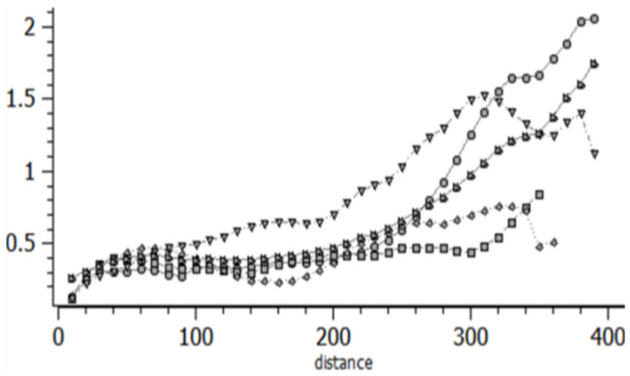

Figure 7. Model of PPV variogram

The results in Figure 6 above show four curves, each representing the measurement results from different groups or conditions, which are described in more detail as follows.

1. The circle curve shows a significant increase with increasing distance. Initially, the variable value is stable at around 0.5 at distances from 0 to 150. After 150, there is a sharp increase to a value of around 2 at a distance of 400. This indicates that this group experiences the most significant change in the measured variable compared to the other groups, indicating a strong spatial correlation at longer distances.
2. The inverted triangle curve shows a more moderate increase in value compared to the circle curve. From a distance of 0 to 200, the variable value increases gradually from around 0.5 to 1, then there is a more rapid increase, reaching around 1.5 at a distance of 400. This indicates a fairly strong spatial correlation but slower than the circle curve.
3. The square curve shows a more stable pattern with a slow increase in value from around 0.5 at distance 0 to around 1 at distance 400. This curve shows that this group has the slowest and most stable rate of increase, indicating low spatial variability.
4. The curve with the diamond symbol shows a gradual increase similar to the box curve, with the variable value increasing from about 0.5 to about 1 at a distance of 400. This indicates that this group has a similar rate of change to the group represented by the box curve, with a tendency for weak spatial correlation.

Overall, the results indicate a variation in the rate of increase in PPV variability with increasing distance, with the group represented by the circular curve showing the most significant change. This insight is invaluable for optimizing the Kriging method to predict PPV values at other locations within the coal mine. This results in decision-making not only in mitigating the impact of blasting vibrations but also in planning and managing mining operations more effectively. A thorough understanding of the PPV variogram model enables this research to better apply Kriging techniques, thereby improving predictions of PPV in different areas of the coal mine. This approach provides deeper insights into the environmental and infrastructural impacts of blasting vibrations and supports more informed decisions in overall operational planning and management.

In this research, variograms were employed to analyze the spatial patterns of PPV resulting from blasting vibrations in coal mines. These variograms were calculated using various azimuth and DIP orientations to create a model applicable to risk prediction and management within the mining areas [29].

Initially, PPV data were collected from observation points surrounding the blasting site, and the variograms were analyzed considering 1) azimuth orientation of 45 degrees and a DIP of 0 degrees. This approach captures the spatial correlation of PPV at a 45-degree angle from the north without significant elevation change. The analysis produced a variogram model that effectively describes the spatial structure of PPV at the research site, providing a valuable tool for predicting PPV intensity at other locations and aiding in risk management and decision-making in mining operations. Next, the PPV data were analyzed with 2) azimuth orientation of 90 degrees, corresponding to the northeast direction from the reference point, with a DIP of 0 degrees. The resulting variogram model illustrates the spatial variation of PPV in the northeast direction, offering a robust foundation for Kriging techniques, which allows for more accurate PPV predictions in other areas of the mine, thereby assisting in more effective risk management and operational decisions. More details can be seen in Figure 8 below.

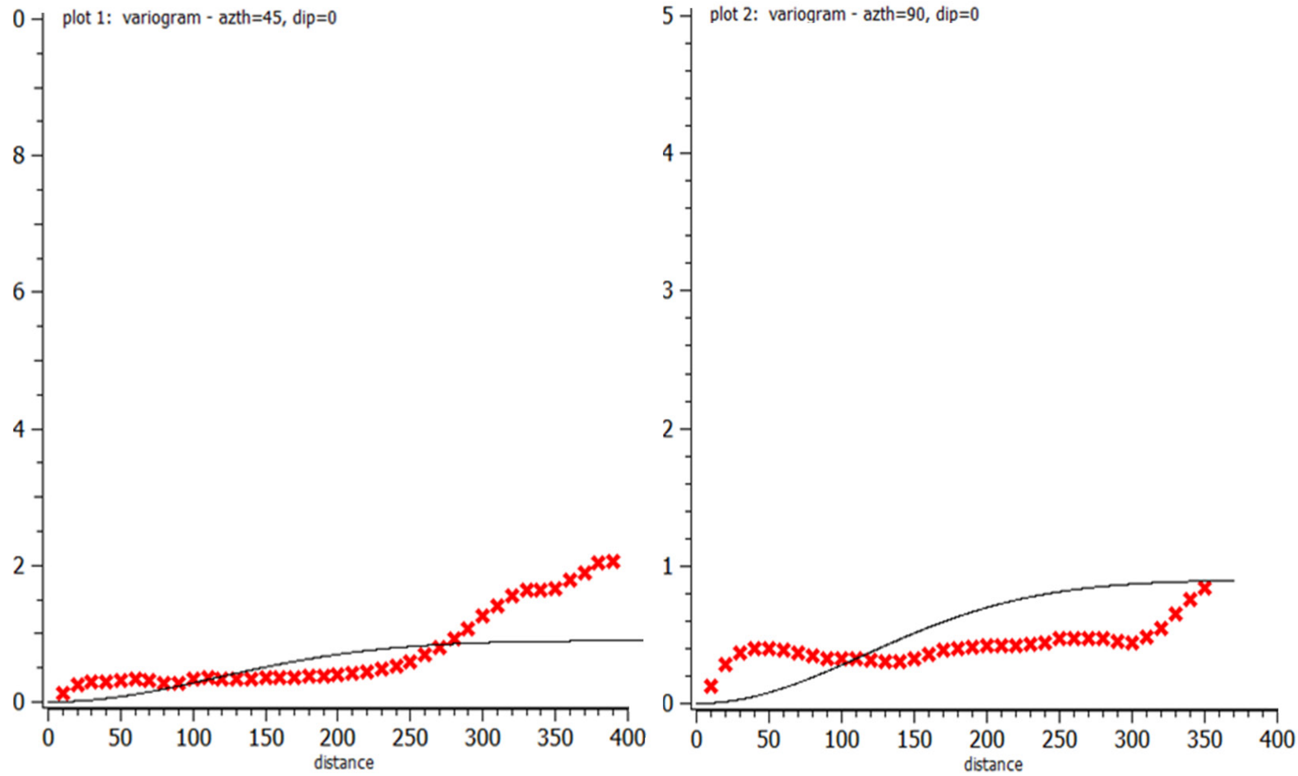

Figure 8. 1) Plot 1 for PPV variogram model, Azimuth 45, DIP 0; and 2) Plot 2 for PPV variogram model, azimuth 90, DIP 0

The following analysis was conducted considering an azimuth orientation of 135 degrees pointing southeast from the reference point, with a DIP of 0 degrees.

The results of this variogram analysis produce a model that supports the prediction of PPV intensity at other locations using the Kriging technique, which is very important for risk management and more accurate decision-making in coal mining operations.

The variogram value is relatively stable up to about 300 meters, with small fluctuations at the initial distance. After 300 meters, there is a slight increase in the variogram value but remains at a low level up to a distance of 400 meters. This shows that the PPV variability in the southeast direction is relatively low, with a strong spatial correlation in this distance range, indicating that PPV changes in this direction are consistent and reliable in spatial prediction. Next, the PPV data was analyzed with an azimuth orientation of 180 degrees, pointing south from the reference point with a DIP of 0 degrees. The resulting variogram model provides an overview of the spatial variation of PPV in the south direction, which is important for predicting PPV intensity at other locations in the coal mine with the Kriging technique showing a stable variogram pattern with a slight increase at a distance approaching 350 meters.

The variogram value remains low throughout the distance, indicating that the PPV variability in the south direction also tends to be low. This indicates a good spatial correlation in the south direction, which is important for maintaining the accuracy of PPV prediction in this area. More details can be seen in Figure 9.

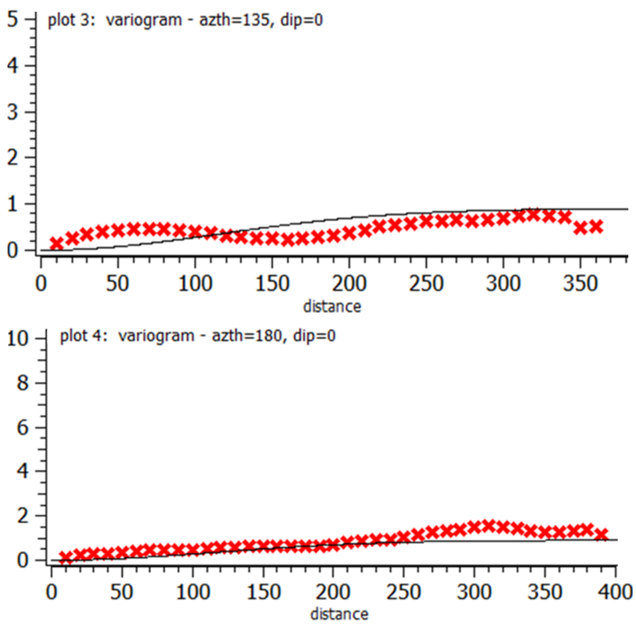

Figure 9. Plot 3 for PPV variogram model, azimuth 135, DIP 0; and Plot 4 for PPV variogram model, azimuth 180, DIP 0

The omni-directional variogram model, which describes the spatial dependence between PPV values from all directions around the blasting site in a coal mine, is shown in plots 5 and 6 (Figure 10). On the plots, the horizontal axis shows the distance between observation points, while the vertical axis shows the variogram value or semivariance, which measures the degree of spatial dependence of PPV at various distances.

The plots indicate that at short distances (0-100 meters), the variogram value is relatively low and stable, indicating a strong spatial correlation between PPV values at short distances. However, as the distance increases (more than 200 meters), the variogram value begins to increase, as seen from the increase in the semivariance value until it approaches 400 meters. This indicates that the spatial correlation between PPV values begins to weaken at longer distances, resulting in higher PPV variability.

The omni-directional variogram model generated from these two plots provides a comprehensive picture of the spatial pattern of PPV throughout the research site without being tied to a particular orientation. The results of this analysis are very important in the use of Kriging techniques or other spatial interpolation methods to predict the intensity of PPV at various locations in a coal mine. Thus, these two variogram plots show the variation of the spatial pattern of PPV with distance, which provides a solid basis for the prediction and management of the impact of blasting vibration in the mining area. More details can be seen in Figure 10.

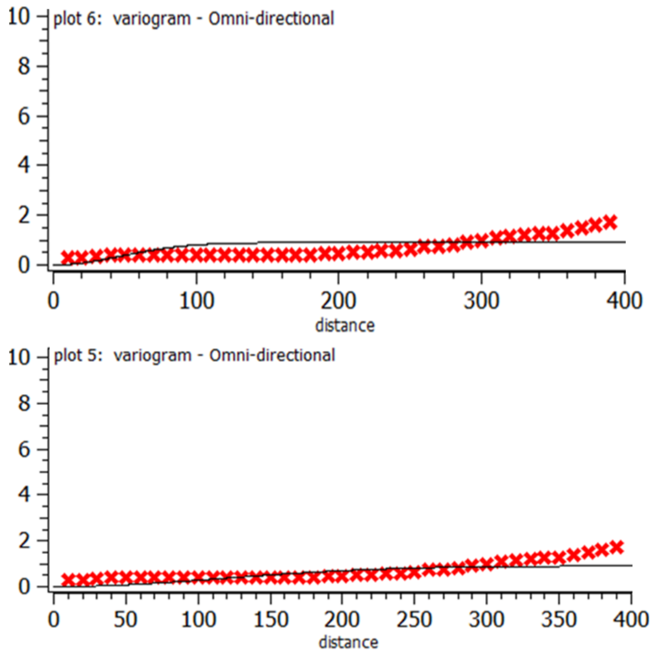

Figure 10. 1) Plot 5 and plot 6 for the variogram model, omni-directional

Spherical Kriging is one of the spatial interpolation methods that is very effective for predicting values at unmeasured locations, based on measurement data obtained from observation points spread across an area. This method belongs to the Kriging family that uses a variogram model with a spatial structure called "spherical" [30], [31], [32]. This model allows to capture of complex spatial patterns, especially in cases where data variability is influenced by the distance between observation points.

In the context of this research, PPV data were collected from various points around the blasting site in a coal mine. The variogram was then analyzed by considering several orientations, including 45-degree azimuth with 0-degree DIP, 90-degree azimuth, 135-degree azimuth, and 180-degree azimuth, as well as an omni-directional variogram model that analyzes the spatial pattern of PPV without considering a particular orientation. Each of these variogram models provides insight into the spatial structure of blasting vibrations in different directions, which is essential for producing accurate prediction models.

The spherical Kriging process is then applied by utilizing the obtained variogram models to perform spatial interpolation.

This process involves determining the optimal weights for neighboring observation points based on the spatial structure revealed by the variogram. The result is a 3-D model that predicts the PPV intensity across the coal mine area, even in locations that are not directly measured. This 3-D spherical Kriging model provides a comprehensive picture of the spatial distribution of blasting vibrations, which is very useful in risk management, environmental impact mitigation and optimization of mining operations. This resulting model is a very important tool in strategic decision-making related to mine operations, as it provides detailed and structured information on the potential impacts of blasting in various areas of the mine. More details can be seen in Figure 11.

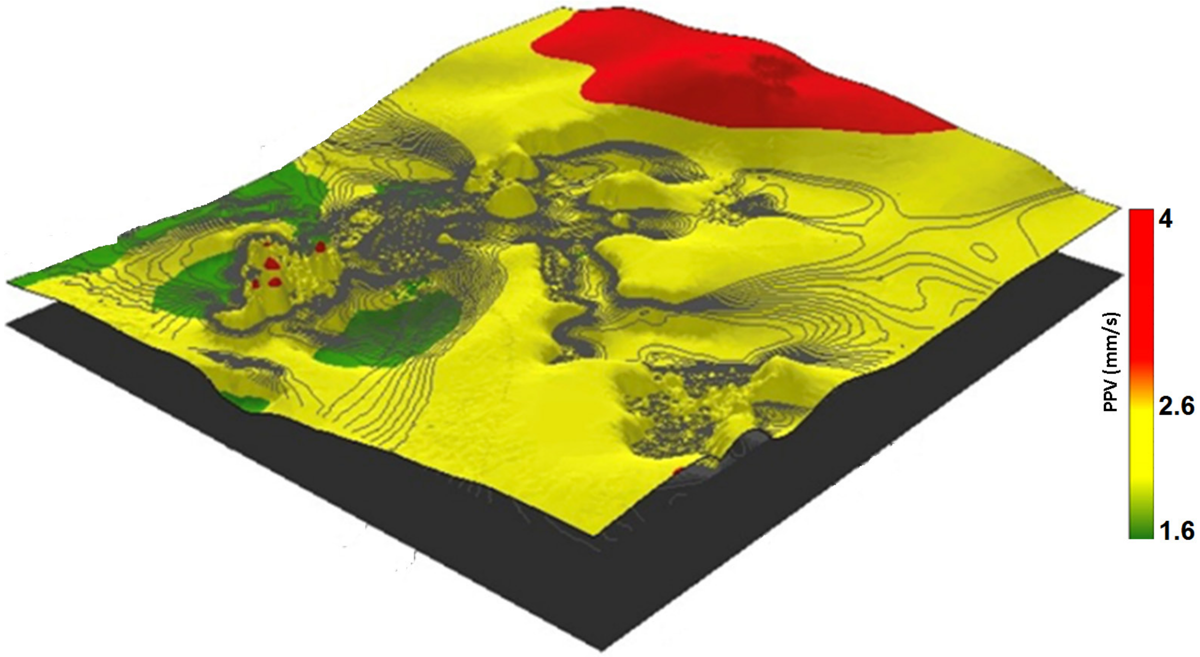

Figure 11. 3-D visualization of spherical Kriging for spatial distribution of PPV in coal mining areas

Validation and interpretation are two crucial steps in data analysis and research results, especially in spatial analysis such as Kriging or mapping of geographic variables. After the Kriging model has been successfully built, the next stage which is no less important is the validation process. This validation aims to ensure that the prediction results generated from the model have adequate accuracy and reliability. In addition, interpretation of the results also needs to be done to identify emerging spatial patterns, such as the distribution of blasting vibrations, and to reveal areas that may be vulnerable to the impact of these vibrations.

Validation is an important step taken to test the accuracy and reliability of the model resulting from data analysis. In the context of Kriging or spatial mapping, validation involves several important procedures that evaluate the model's performance in predicting values at unmeasured locations.

There are several methods commonly used in this validation: 1) Cross-validation is one of the most frequently used methods to evaluate the performance of the Kriging model. In this method, the data is divided into two subsets, namely the training subset and the testing subset. The Kriging model is then trained using the training subset, while the testing subset is used to test the model's ability to predict values at locations that are not directly measured. This method helps measure how well the model can predict spatial values objectively and reduces the possibility of overfitting; 2) Validation using independent data involves testing the Kriging model on data that was not used during the model-building process.

By using data that is completely separate from the training data, researchers can test the extent to which the model can generalize and produce accurate predictions on new data.

This is important to ensure that the model not only works well on familiar datasets, but also completely new data; and 3) Error analysis involves comparing the predicted values generated by the model with the actual observed data. Error metrics such as Root Mean Square Error (RMSE) or Mean Absolute Error (MAE) are often used to quantify how far the model's predictions are from reality. By analyzing these errors, researchers can identify weaknesses in the model and make necessary improvements to improve accuracy.

3.3. Interpretation of Kriging Results

In addition to validation, interpretation of Kriging results is also an important step in the spatial data analysis process. This interpretation aims to understand and interpret the meaning of the spatial patterns produced by the model, as well as to relate the analysis results to relevant practical implications. Several aspects need to be included: 1) Kriging results are often presented in the form of spatial maps that show the distribution of variation of the observed phenomena, such as blasting vibrations. Through the interpretation of these spatial patterns, researchers can identify areas with high or low intensity, and reveal spatial change patterns from the data. Understanding these patterns provides deeper insight into the spatial dynamics in the research site; 2) During the interpretation process, it is important to understand the factors that contribute to the observed spatial patterns.

For example, studies related to blasting vibrations, geological variability, topography, or human activity may be the main cause of the patterns seen on the spatial map; and 3) Once the spatial patterns and causal factors are identified, the results of the analysis need to be linked to practical applications in the field. For example, Kriging results indicate areas with high blasting vibration intensity can be used to develop more effective risk mitigation strategies, such as safer blasting site planning or strengthening infrastructure in areas vulnerable to blasting impacts. Thus, the results of this interpretation can provide real benefits for natural resource management, environmental risk mitigation, and spatial planning.

Through proper validation and careful interpretation, research can produce a deeper understanding of the spatial phenomenon being studied. Validation ensures that the model used is reliable and accurate, while interpretation provides the insights needed to translate the analysis results into real and relevant actions. The combination of these two steps allows for better decision-making and the development of more effective strategies in areas such as natural resource management, environmental risk mitigation, and sustainable development planning. The visual representation of spatial analysis using the spherical Kriging method to map the distribution of PPV blasting vibration intensity in the coal mining area can be seen in Figure 12 and 13.

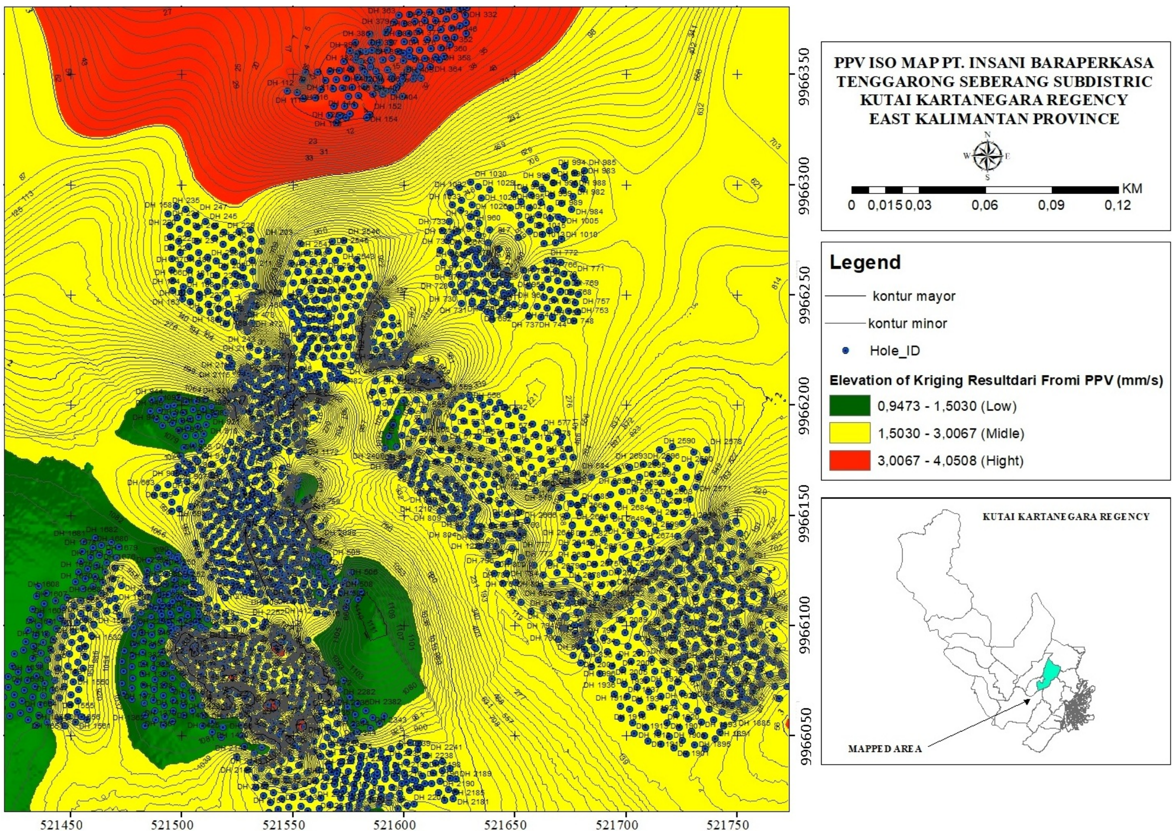

Figure 12. 2-D map view PPV isolation for PT.IBP

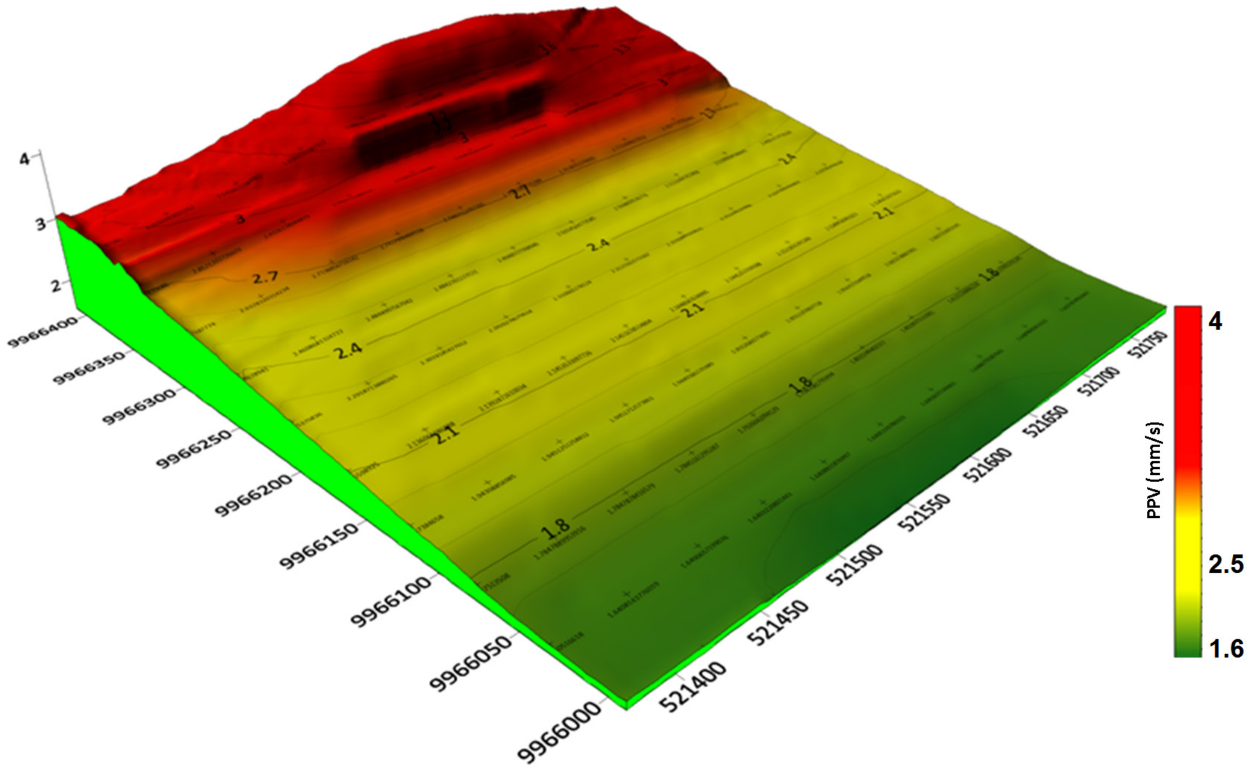

Figure 13. 3-D visualization interpolation results using the spherical Kriging method

The results of this analysis aim to identify and map the level of danger caused by blasting vibrations, as well as provide insights needed in mine management and environmental impact mitigation. The description of Figure 12 and Figure 13 is as follows.

1. The second Figure 12 is a PPV isolation map that maps the PT. IBP, Tenggarong Seberang Sub-district, Kutai Kartanegara Regency, East Kalimantan Province. This map provides a detailed view of major and minor contours, borehole locations, and PPV elevation levels based on spherical Kriging results. Green on the map indicates low intensity (safe zone), yellow indicates medium intensity (cautious zone), and red indicates high intensity (hazard zone). The map is also equipped with a legend that explains the PPV range in mm/s, providing clear information on the distribution of vibration intensity in the mine area, as well as the specific locations that are most affected by the blasting impact.
2. The Figure 13 shows a 3-D visualization of the interpolation results using the spherical Kriging method. This visualization illustrates the spatial distribution of blasting vibration intensity in the mine area, with colors representing various levels of vibration intensity. Green indicates a lower PPV value, while red indicates a higher PPV value. The red area depicts the area that receives the most significant vibration impact, making it a "hazard zone". In this visualization, contours, and grids depict the spatial variation of PPV based on the Kriging results, allowing visualization of the distribution of vibration energy along the mine area and helping to identify the areas most affected by blasting.

Overall, these two figures show the results of spatial analysis of PPV using the spherical Kriging method, which aims to map and understand the distribution of blasting vibration intensity at the mine site. The results of the Kriging correction for the PPV value provide a visualization of the distribution of vibration intensity with a well-defined hazard category. According to research by [33], Kriging is the most accurate geostatistical technique for estimating values at unmeasured locations based on the spatial pattern of existing points. This approach allows researchers to make more reliable predictions about geophysical phenomena such as blasting vibration, which have a significant impact on the surrounding environment and structures.

The results of the Kriging correction for the PPV value with the hazard category indicated by color are also supported by research conducted by [34]. They added that the division of hazard levels on this map allows mine managers to determine the most effective mitigation actions based on the measured vibration intensity in a particular area.

The red color, which indicates the highest PPV elevation, illustrates the danger zone, where the vibration intensity reaches a level that has the potential to damage structures and is dangerous to humans. Therefore, strict precautions are required in these areas. Yellow indicates a cautious zone that may require additional supervision to ensure operational safety, while green indicates a safe zone where the vibration intensity is within safe limits for human health.

Overall, the Kriging-corrected map provides a clear visual representation of the distribution of blasting vibration intensity, which is essential for risk management in mining. According to [35], [36], [37] such spatial information is not only useful in risk mitigation but also supports better decision-making in mine planning and environmental protection. With a deeper understanding of the spatial distribution of blasting vibration, mine managers can optimize mining operations more safely and sustainably.

4. Conclusion

This research successfully analyzed the distribution of blasting vibrations in mining areas using the spherical Kriging method, which is one of the most accurate geostatistical methods for predicting values at unmeasured locations based on spatial patterns of existing observation points. The analysis results show that vibrations generated from blasting activities in mining areas have a significant impact on the surrounding environment. This impact not only has the potential to damage building structures in areas most affected by vibrations, but can also affect the quality of life of people living around the mining site, both directly and indirectly. The distribution of vibration intensity varies, and by using the Kriging method, zones with different levels of risk can be clearly identified. High-risk zones are characterized by vibration intensities that can cause severe damage to infrastructure and are hazardous to human health. Medium-risk zones indicate the potential for lighter to medium damage, while low-risk zones include areas that are relatively safe from vibration impacts. This information is very important in helping mine managers plan and manage environmental impacts more effectively, as well as implementing more appropriate risk mitigation strategies. Vibration distribution mapping using Kriging predictive models also provides a more detailed and accurate picture of the areas most susceptible to blasting vibrations, allowing for safer and more sustainable mining operations planning. With this spatial information, mining operations can be optimized without compromising environmental quality and the well-being of communities around the mining area.

In addition, this approach supports better environmental risk mitigation efforts, while ensuring that the negative impacts of blasting activities can be minimized.

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References

[1]. Ardanu, T. M. (2021). *Coal Mining Reclamation Improvement in East Kalimantan Indonesia*. [Master's thesis, University of Twente].

[2]. Efendi, N., Barlian, E., Dewata, I., Syah, N., & Gusman, M. (2024). Ambient dust levels in the paths that are passed and not passed by barges on the Mahakan river–East Kalimantan. *AIP Conference Proceedings*. 3001, 1. Doi: 10.1063/5.0184148

[3]. Barlian, E., Dewata, I., Gusman, M., & Efendi, N. (2024). Effectiveness of Acid Mine Water Testing Using Sparing at PT. Bara Alam Utama. *JurnalPenelitian Pendidikan IPA*, 10(1), 100-107. Doi: 10.29303/jppipa.v10i1.5803

[4]. Hermon, D., Barlian, E., Umar, I., & Efendi, N. (2023). Post-Coal Mining Reclamation Land Sustainability Study in Tebo Regency. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 10330-10337.

[5]. Tost, M., et al. (2018). The state of environmental sustainability considerations in mining. *Journal of cleaner production*, *182*, 969-977. Doi: 10.1016/j.jclepro.2018.02.051

[6]. Mundaca, G. (2024). Economic valuation of environmental and health impacts from mining: the case of Peru. *Environment, Development and Sustainability*, *26*(1), 2415-2441. Doi: 10.1007/s10668-022-02826-1

[7]. Prasodjo, E., et al. (2015). Economic valuation of coal mining activity in Samarinda city, east Kalimantan, Indonesia. *Int J Appl Eng Res*, *10*, 26347-62.

[8]. Absori, A., et al. (2021). Environmental health-based post-coal mine policy in east borneo. *Open Access Macedonian Journal of Medical Sciences*, *9*(E), 740-744. Doi: 10.3889/oamjms.2021.6431

[9]. Efendi, N., Frinaldi, A., Lanin, D., Umar, G., & Gusman, M. (2023). Pertambangan Emas Tanpa Izin (Peti): Dampak Lingkungan, Sosial Dan Ekonomi Serta Peranan Hukum Lingkungan. *Jurnal Ilmiah Multidisiplin Nusantara (JIMNU)*, *1*(3), 123-128. Doi: 10.59435/jimnu.v1i3.57

[10]. Gusman, M., Afaz, T., & Efendi, N. (2021). Mining Investment Feasibility based on Economic and Environmental Aspects. *Indian Journal of Economics and Business.*, *20*, 1073-1082.

[11]. Mohsin, M., Zhu, Q., Naseem, S., Sarfraz, M., & Ivascu, L. (2021). Mining industry impact on environmental sustainability, economic growth, social interaction, and public health: an application of semi-quantitative mathematical approach. *Processes*, *9*(6), 972. Doi: 10.3390/pr9060972

[12]. Younger, P. L. (2004). Environmental impacts of coal mining and associated wastes: a geochemical perspective. *Geological Society, London, Special Publications*, *236*(1), 169-209. Doi: 10.1144/GSL.SP.2004.236.01.12

[13]. Pal Roy, P. (2021). Emerging trends in drilling and blasting technology: concerns and commitments. *Arabian Journal of Geosciences*, *14*(7), 652. Doi: 10.1007/s12517-021-06949-z

[14]. Lubis, J. F., Toha, T., & Ngudiantoro, N. (2017). Analysis of the Blasting Effect on the Environment around Blasting Areas at Pt. Semen Baturaja Persero, Tbk. *Indonesian Journal of Environmental Management and Sustainability*, *1*(1), 15-18. Doi: 10.26554/ijems.2017.1.1.15-18

[15]. Hifzirridho, H., Isjudarto, A., & Prastowo, R. (2021). Technical Study of Reducing Ground Vibration Levels on Overburden Blasting Activities in East Pit PT. Bungo Bara Utama Jobsite Kuansing Inti Makmur, Bungo District, Jambi Province. *Proceedings of the 2nd International Conference on Industrial and Technology and Information Design.*

[16]. Pujiyana, A. *Optimasi kinerja alat bor dalam memenuhi target produksi 92 m3/jam batu andesit PT. Gunung Bumi Perkasa, Kabupaten Sukabumi, Jawa Barat*. [Bachelor's thesis, Fakultas Sains dan Teknologi UIN Syarif Hidayatullah Jakarta].

[17]. Clarkson, M. A. (2022). *Fully Automated Drill and Blast for Mining*. [Doctoral dissertation, University of Southern Queensland].

[18]. Fourney, W. L. (2016). Mechanisms of rock fragmentation by blasting. *Comprehensive Rock Engineering*, 39-68.

[19]. Dotto, M. S., & Pourrahimian, Y. (2024). The influence of explosive and rock Mass properties on blast damage in a single-hole blasting. *Mining*, *4*(1), 168-188. Doi: 10.3390/mining4010011

[20]. Getis, A. (1999). Spatial statistics. *Geographical information systems*, *1*, 239-251.

[21]. Bohling, G. (2005). Introduction to geostatistics and variogram analysis. *Kansas geological survey*, *1*(10), 1-20.

[22]. Putra, A., Hermon, D., Prarikeslan, W., Syarief, A., Ridwan, N. N. H., Arifin, T., ... & Dermawan, A. (2025). Assessment of seawater quality and environmental sustainability for shipwreck diving tourism: a case study of mv Boelongan Nederland in Mandeh Bay, Indonesia. *Geography, Environment, Sustainability*, *17*(4), 171-182.

[23]. Li, Z., et al. (2018). An automatic variogram modeling method with high reliability fitness and estimates. *Computers & Geosciences*, *120*, 48-59. Doi: 10.1016/j.cageo.2018.07.011

[24]. Diamantopoulou, E., et al. (2024). Geostatistical Analysis of Groundwater Data in a Mining Area in Greece. *Hydrology*, *11*(7), 102. Doi: 10.3390/hydrology11070102

[25]. Dewata, I., & Putra, A. (2021). Kriging-GIS model for the spatial distribution of seawater heavy metals. *Periodicals of Engineering and Natural Sciences (PEN)*, *9*(2), 629-637.

[26]. Oliver, M. A., & Webster, R. (2014). A tutorial guide to geostatistics: Computing and modelling variograms and kriging. *Catena*, *113*, 56-69. Doi: 10.1016/j.catena.2013.09.006

[27]. Kleijnen, J. P. C. (2017). Kriging: Methods and Applications. *CentER Discussion Paper.*

[28]. Lizarazo-Marriaga, J., Vargas, C. A., & Tiria, L. (2018). A new approach to predict local site effects related to blast-induced ground vibrations. *Journal of Geophysics and Engineering*, *15*(5), 1843-1850.

[29]. Hogenboom, A. C., van Leerdam, J. A., & de Voogt, P. (2009). Measurement & Monitoring: 30th Quarterly Literature Update & Grant Survey. *Journal of Chromatography: A*, *1216*(3), 510-519.

[30]. Ding, Q., Wang, Y., & Zhuang, D. (2018). Comparison of the common spatial interpolation methods used to analyze potentially toxic elements surrounding mining regions. *Journal of environmental management*, *212*, 23-31. Doi: 10.1016/j.jenvman.2018.01.074

[31]. Lamamra, A., Neguritsa, D. L., & Mazari, M. (2019). Geostatistical modeling by the Ordinary Kriging in the estimation of mineral resources on the Kieselguhr mine, Algeria. In *IOP Conference Series: Earth and Environmental Science, 362*(1), 012051. Doi: 10.1088/1755-1315/362/1/012051

[32]. Hermon, D., Erianjoni, E., Dewata, I., Putra, A., & Oktorie, O. (2019). Liquefaction vulnerability analysis as a coastal spatial planning concept in Pariaman City-Indonesia. *International Journal of Recent Technology and Engineering (IJRTE)*, *8*(2), 4181-4186. Doi: 10.35940/ijrte.B3265.078219

[33]. Tarumasely, N. H., Wardana, N. K., & Prastowo, R. (2024). Analysis of Ground Vibration Levels Due to the Blasting Process at PT. Bumi Suksesindo. *JURNAL GEOCELEBES*, 51-61.

[34]. Davis, J. C. (2002). *Statistics and Data Analysis in Geology* (3rd ed.). John Wiley & Sons.

[35]. Wagianto., Syah, N., Dewata, I., Umar, I., & Putra, A. (2024). The population explosion: Indonesian's dilemma amid limited resources. *AIP Conference Proceedings, 3001,* 080013. Doi: 10.1063/5.0184169

[36]. Nazki, A., et al. (2024). Biotechnology Utilization for Enhancement the Environmental Carrying Capacity of Former Ex-Coal Mining Land. *EnvironmentAsia*, *17*(1). Doi: 10.14456/ea.2024.7

[37]. Aryantie, M. H., Hidayat, M. Y., Widodo, T., Putra, A., & Dewata, I. (2023). Environmental Perspectives to the Rejection of Javanese Karst Mining in Systematic Literature Reviews. *International Journal of Sustainable Development & Planning*, *18*(12). Doi: 10.18280/ijsdp.181207