

Impact of Crush Zone on PPV in Claystone and Limestone Blasting with a Quantitative Approach

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Article Information	ABSTRACT
Article History Received : January 23, 2026 Revised : February 07, 2026 Published : April 02, 2026	Blasting in open pit mines aims not only to achieve optimal rock fragmentation but also to control the impact of generated ground vibration. This study aims to analyze the influence of the crush zone on Peak Particle Velocity (PPV) in blasting activities involving claystone and limestone layers. Field data were collected from 25 blasting operations with varied parameters: number of blast holes 25–160, explosive charge per hole 50–111 kg, and measurement distance 504–537 m. The recorded actual PPV ranged from 1.221 to 3.404 mm/s. Statistical analysis was performed using power regression to model the relationship between Scaled Distance and PPV. The results show a strong inverse relationship between Scaled Distance and PPV, where higher blasting energy concentration forms a more intensive crush zone as the initial source of vibration. Blasting in limestone yields relatively higher PPV compared to claystone under similar Scaled Distance conditions, due to the elastic and more brittle properties of limestone. The model's prediction accuracy reached 91.5% on average. Practically, to maintain PPV at a safe level (<3.404 mm/s), it is recommended to keep the Scaled Distance ≥ 48.82 m/kg^{0.5} and limit the explosive charge per hole to the range of 50–90 kg, especially in limestone. This study confirms the key role of the crush zone and rock lithology in blasting vibration mechanisms, providing a basis for optimizing safe and sustainable blasting designs.
Keywords: <i>Blasting;</i> <i>Crush Zone;</i> <i>Peak Particle Velocity;</i> <i>Scaled Distance;</i> <i>Claystone;</i> <i>Limestone.</i>	

INTRODUCTION

Blasting remains the most widely applied method for rock mass excavation in mining and civil engineering projects. The effectiveness of blasting operations is evaluated not only based on fragmentation quality but also on the ability to control blast-induced ground vibrations, which pose significant risks to nearby structures, slopes, and the environment. Among various vibration indicators, Peak Particle Velocity (PPV) is widely recognized as the most representative parameter for assessing vibration-induced damage potential (Dowding, 1985; Kahriman et al., 2017).

Ground vibration is the dynamic response of a rock mass resulting from the rapid release of explosive energy. The magnitude of PPV is influenced by multiple factors, including explosive type and charge weight, blasting geometry, distance from the blast source, geological conditions, and rock mechanical properties (Hosseini et al., 2023). To evaluate and predict ground vibration levels, empirical approaches based on scaled distance are commonly used. However, such approaches often exhibit high variability in prediction accuracy, particularly in heterogeneous

geological settings, indicating the presence of underlying physical mechanisms that are not fully accounted for (Monjezi et al., 2016).

One key physical mechanism governing the initiation and propagation of blast-induced stress waves is the formation of the crush zone. The crush zone is defined as the region surrounding a blast hole where stresses generated by detonation pressure exceed the compressive strength of the rock, resulting in severe rock mass damage. According to Persson et al. (1994), the size and intensity of the crush zone are primarily controlled by detonation pressure, borehole diameter, and the mechanical properties of the rock. A higher concentration of explosive energy generally produces a more extensive and intense crush zone.

The crush zone plays a dual role in blasting dynamics. On one hand, it serves as the primary source of stress waves that generate ground vibrations. On the other hand, it acts as an energy dissipation medium, absorbing part of the explosive energy through intense rock crushing and plastic deformation before the stress waves propagate into the surrounding rock mass (Liu et al., 2019). Consequently, the characteristics of the crush zone significantly influence the initial amplitude and attenuation behavior of ground vibrations, which are ultimately reflected in PPV values.

Peak Particle Velocity serves as a critical parameter for assessing ground vibration levels induced by blasting activities, with charge weight representing one of the most significant factors influencing its magnitude (Dufo-López et al., 2024). While traditional empirical models predominantly rely on maximum charge per delay and monitoring distance to estimate PPV, recent research indicates that incorporating additional blast design parameters such as burden can enhance prediction accuracy across varying geological conditions (Murmu et al., 2018; Xue, 2019). However, the relationship between charge weight and PPV is not strictly linear, as higher explosive charges do not necessarily result in proportionally increased vibration intensities due to the complex interplay of wave damping and interference effects (Hosseini et al., 2023).

Recent research emphasizes the importance of understanding blast-induced vibrations due to their potential impacts on operational safety, environmental protection, and infrastructure integrity (Paurush & Rai, 2022). Excessive ground vibrations can cause structural damage, slope instability, and ecosystem disturbance, making vibration control a critical component of sustainable mining practices. This issue is particularly relevant in deep-hole bench blasting, commonly applied in large-scale open-pit mining. In such operations, suboptimal blast designs and complex geological conditions often result in uneven fragmentation, excessive fines generation, and elevated vibration levels (Gao et al., 2023).

Although many studies have investigated PPV prediction using empirical and statistical models, most focus primarily on the relationships between blasting parameters and scaled distance, without explicitly incorporating the role of the crush zone and its interaction with different rock lithologies (Monjezi et al., 2016). In reality, rock type plays a crucial role in determining how explosive energy is absorbed, dissipated, and transmitted. Claystone, which is relatively softer, more plastic, and porous, tends to absorb a portion of the blasting energy through plastic deformation, thereby reducing stress wave transmission. In contrast, limestone is generally stiffer and more brittle, allowing elastic energy to propagate more efficiently and potentially resulting in higher PPV values under similar blasting conditions (Zhang et al., 2021).

Therefore, this study aims to conduct a quantitative analysis of the impact of crush zone characteristics on PPV in blasting operations involving claystone and limestone formations. By integrating field data, rock mechanical properties, and blast design parameters, this research seeks to elucidate the role of the crush zone in controlling ground vibration behavior. The results are expected to contribute to a deeper scientific understanding of blasting vibration mechanisms and provide a practical basis for optimizing blast designs to achieve safer, more efficient, and environmentally responsible mining operations.

RESEARCH METHODS

The research methodology is designed to quantitatively analyze the influence of the crush zone on PPV values in blasting activities conducted in claystone and limestone layers. A quantitative approach is employed as it enables objective and measurable evaluation of relationships among variables based on field data.

Measurements were carried out using a Micromate Instantel (portable seismograph/vibrometer) capable of recording ground vibrations along three axes (vertical, longitudinal, and transverse). The instrument records data with a high sampling frequency designed to capture the vibration frequency range caused by blasting (generally 2–200 Hz). The sensor (geophone) was directly planted on a solid and flat ground surface at the measurement site. The measurement location was determined based on the company's Road Blocker Map, with a minimum safe distance of 500 meters from the blasting center (referring to company safety procedures and SNI standards). The sensor orientation was adjusted so that the longitudinal component was aligned with the direction of wave propagation from the blasting site. The main parameter recorded was the Peak Particle Velocity (PPV) in mm/s, particularly the vertical component (Peak Vertical Velocity), which served as the primary reference according to standards.

Data were obtained from 25 blasting operations carried out in two main lithologies, namely claystone and limestone. The parameters analyzed include the number of blast holes, explosive charge per hole (charge weight), vibration measurement distance, scaled distance, and actual PPV values. A summary of the main blasting parameters is presented in Table 1.

Table 1. Summary of Blasting Parameters

Parameter	Minimum	Maksimum
Number of holes (N)	25	160
Charge weight (kg/hole)	50	111
Measurement distance (m)	504	537
Scaled distance (m/kg ^{0.5})	48,82	72,69
Actual PPV (mm/s)	1,221	3,404

This research methodology is carefully designed to quantitatively analyze the influence of the crush zone on Peak Particle Velocity (PPV) in blasting activities involving claystone and limestone layers. A quantitative research approach was chosen due to the nature of the problem, which requires precise measurement and statistical analysis of the resulting data. As explained by Creswell and Creswell (2018), quantitative research is particularly appropriate when researchers aim to test theories or hypotheses, measure the prevalence of phenomena, or determine relationships among variables.

The selection of this quantitative method is based on the need to obtain objective numerical data regarding blasting parameters and the resulting ground vibration impacts. To achieve the research objectives, a causal-comparative research design will be applied. This design enables comparisons between groups exposed to the crush zone and those with little or no exposure, with the aim of identifying potential causal relationships between the presence of the crush zone and the measured PPV values.

In this study, power regression was employed as the primary statistical method to model the relationship between Scaled Distance and Peak Particle Velocity (PPV). Model validation was conducted through the coefficient of determination (R^2), comparison of actual prediction values, and evaluation of compliance with SNI standards.

The main hypothesis to be tested is that the presence of a significant crush zone will correlate with an increase in PPV, which may imply a higher risk of structural damage in the surrounding area. This study will follow the principles outlined by Sugiyono (2019) regarding quantitative research, which emphasize accurate measurement and generalization of results.

The research activities were carried out based on the following stages:

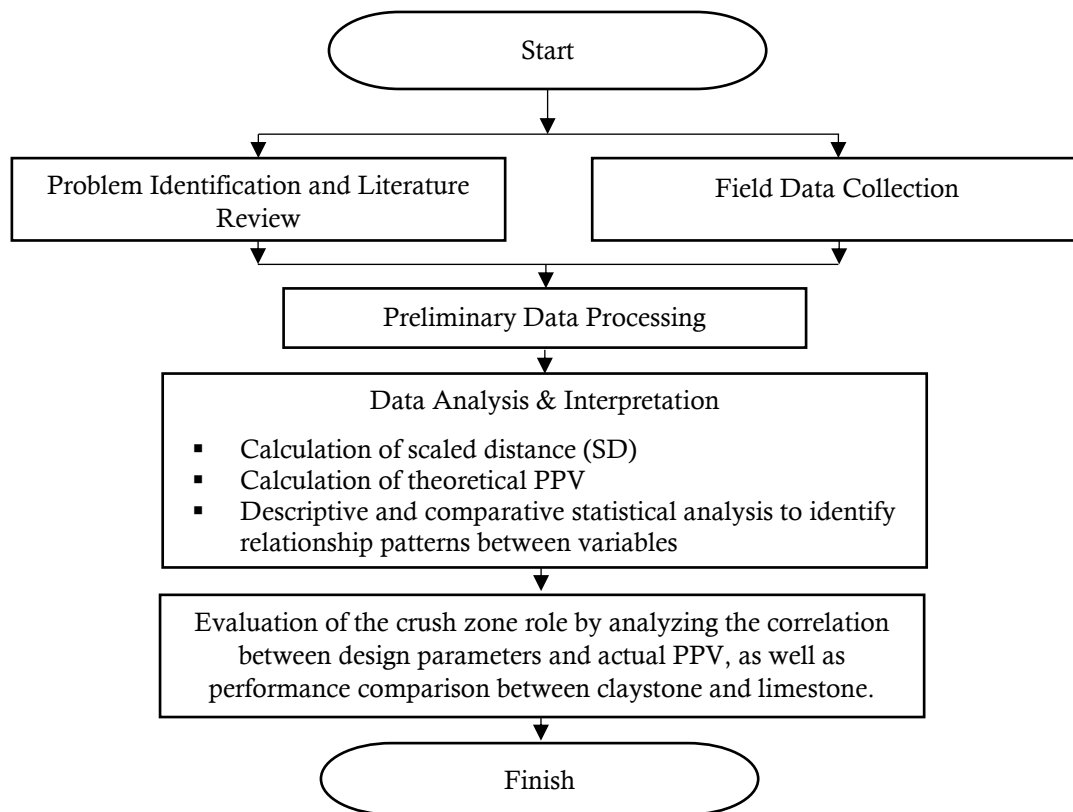


Figure 1. Research Flowchart

The research flowchart illustrates the systematically structured stages designed to analyze the influence of the crush zone on Peak Particle Velocity (PPV) in blasting activities. The study begins with problem identification and a literature review to formulate the conceptual framework and research variables, followed by field data collection, including blasting geometry parameters, explosive charge, vibration measurement distance, rock types (claystone and limestone), and actual PPV values. The collected data are then processed through the calculation of scaled distance and theoretical PPV as the basis for quantitative analysis. The analysis stage includes evaluating the relationship between scaled distance and PPV, the relationship between charge weight and PPV, and analyzing the influence of rock type on vibration characteristics. The results are subsequently interpreted through an evaluation of the role of the crush zone by linking numerical findings to the physical mechanisms of energy release and propagation during blasting. Finally, conclusions are drawn to summarize the research outcomes and their implications for controlling blast-induced ground vibration.

RESULTS AND DISCUSSION

Relationship Between Scaled Distance and PPV

This study represents an empirical validation and practical application of theoretical concepts proposed in previous research, experimentally demonstrating the inverse relationship between scaled distance and PPV as well as the influence of explosive charge weight and rock type, by employing crush zone characteristics to explain the mechanisms underlying the observed data. These findings directly support and confirm that the crush zone is the initial source of vibration waves and that rock lithology (such as limestone and claystone) determines energy allocation.

The analysis results indicate a clear inverse relationship between scaled distance and Peak Particle Velocity (PPV). At smaller scaled distance values, PPV tends to increase significantly. This

pattern is consistent with the basic concept of blasting energy propagation, where a decrease in scaled distance reflects an increase in energy concentration per unit distance from the blast source.

Physically, this condition is closely related to the formation of the crush zone around the blast hole. At low scaled distances, detonation pressure and explosive gas energy are more concentrated, resulting in a more intensive crush zone. This zone becomes the primary source of initial stress waves with high amplitude before undergoing attenuation within the rock mass. This phenomenon reinforces the finding that crush zone characteristics directly contribute to the magnitude of measured PPV, particularly at relatively short observation distances.

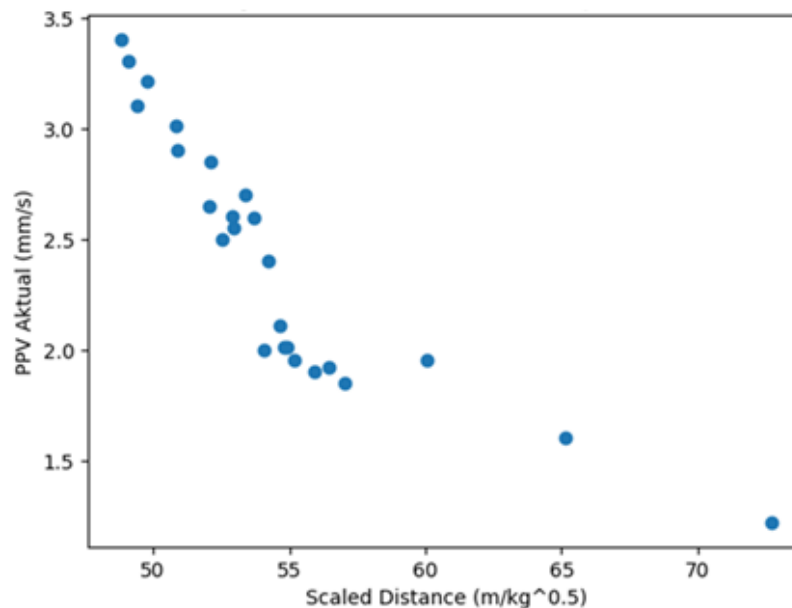


Figure 2. Relationship Between Scaled Distance and Actual PPV

Figure 2 illustrates the relationship between scaled distance and actual PPV. An inverse relationship is evident, where smaller scaled distances correspond to higher PPV values. This indicates that greater blasting energy concentration produces a more intensive crush zone and increases the amplitude of initial vibrations.

Influence of Charge Weight on PPV

The analysis of the relationship between charge weight per hole and PPV values shows a tendency for PPV to increase with higher explosive charges. Increasing charge weight raises the total energy released during detonation, which directly amplifies peak pressure on the blast hole walls. This is also consistent with previous studies, where the amount of explosive material influences ground vibration levels by considering the overlapping effects of wave interference.

This high pressure expands and strengthens the crush zone, thereby increasing the elastic energy transmitted into the surrounding rock mass. Consequently, the generated vibration waves have greater amplitude, reflected in higher PPV values. These findings suggest that charge concentration is a key parameter in controlling blast-induced vibration, as it directly influences crush zone formation as the initial source of vibration waves.

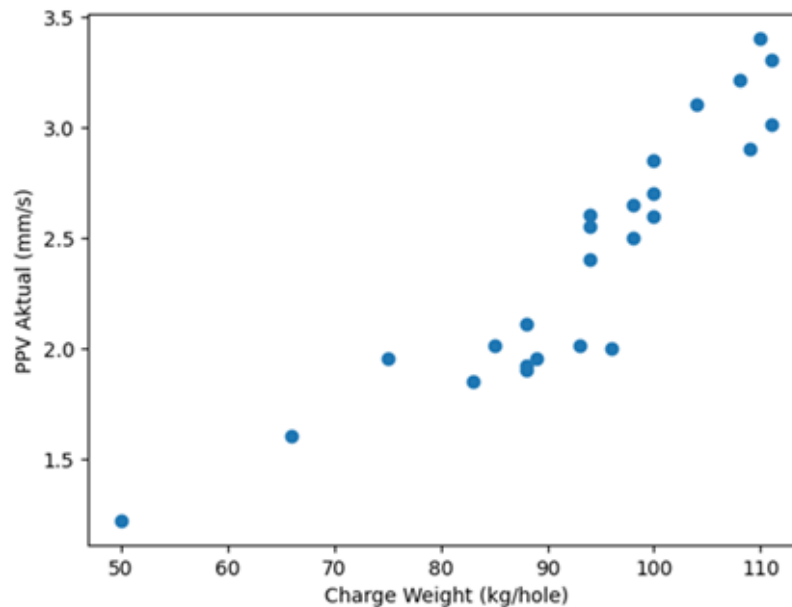


Figure 3. Relationship Between Charge Weight and Actual PPV

Figure 3 shows the relationship between charge weight and actual PPV. Increasing explosive charge per hole leads to higher PPV values. This condition demonstrates that charge concentration directly contributes to crush zone formation as the primary source of vibration waves.

Influence of Rock Type

A comparison of PPV values based on rock type shows that blasting in limestone layers produces relatively higher PPV values compared to claystone under comparable scaled distance conditions. This difference can be explained by the mechanical properties of the two rock types. This is also consistent with previous studies, which indicate that rock type influences the absorption of blasting energy.

Limestone has higher elastic modulus and compressive strength, as well as brittle behavior, allowing blasting elastic energy to be transmitted more effectively as vibration waves. In addition, the crush zone formed in limestone tends to be geometrically more limited but with a higher energy concentration, resulting in greater initial wave amplitude.

Conversely, claystone, which is more plastic and porous, tends to absorb part of the blasting energy through plastic deformation and microfractures within the crush zone. This process dissipates part of the energy before it propagates as vibration waves, leading to lower measured PPV values.

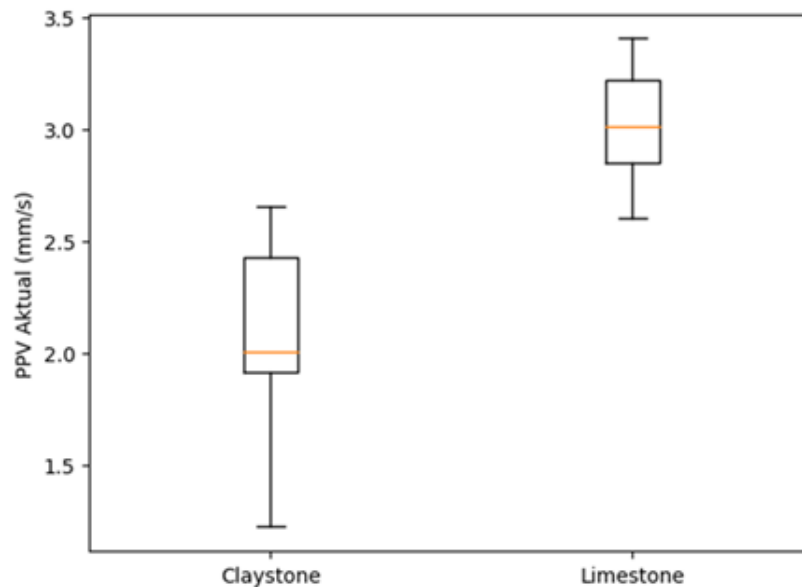


Figure 4. Comparison of PPV Based on Rock Type

Figure 4 illustrates the comparison of PPV based on rock type. PPV in limestone is relatively higher than in claystone. This is due to the stiffer mechanical properties of limestone, which allow elastic energy to be transmitted more effectively, whereas in claystone, part of the energy is absorbed through plastic deformation within the crush zone.

Evaluation of Prediction Accuracy and Its Implications for Understanding the Crush Zone

The accuracy of PPV prediction (comparison between theoretical and actual PPV) averaged 91.5%, ranging from 81.63% to 98.87%. The overall high accuracy indicates that the scaled distance model can represent the energy propagation mechanism well. However, variations in accuracy, especially in cases with larger deviations, indicate additional factors such as site-specific crush zone characteristics, rock heterogeneity, or details of the blasting pattern (delay timing) not fully captured by the simple model. This strengthens the argument that a quantitative understanding of the crush zone can improve predictive vibration modeling.

CONCLUSION

Based on the results of the study on the influence of the crush zone on Peak Particle Velocity (PPV) in blasting of claystone and limestone, it can be concluded that the crush zone acts as the initial source of vibration. High concentrations of explosive energy, indicated by a small scaled distance and large charge weight lead to increased PPV, with limestone producing higher vibrations than claystone due to its elastic properties. Practically, to maintain vibrations at a safe level ($PPV < 3.404$ mm/s), it is recommended to keep the scaled distance ≥ 48.82 m/kg^{0.5} and limit the charge weight per hole to the range of 50–90 kg, particularly in limestone. In claystone, the charge weight range can be more flexible, up to 111 kg, provided strict monitoring is applied. Furthermore, blast design should take into account the characteristics of the crush zone and lithology to optimize operations that are both safe and sustainable.

ACKNOWLEDGEMENTS

This award is presented to PT. Riung Mitra Lestari Jobsite Multi Tambangjaya Utama, Gunung Bintang Awai District, South Barito Regency, Central Kalimantan Province, for facilitating the location of this research, and to the Department/Study Program of Mining Engineering, University of Palangka Raya, for their substantial assistance in its execution.

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