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Field-based assessment of blast-induced vibration and slope stability in an andesite quarry

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Abstract

Purpose. In open-pit andesite quarrying, maintaining slope stability during blasting is a critical operational and safety concern. While previous research has focused primarily on peak particle velocity (PPV) and empirical vibration thresholds derived from coal or limestone mines, a gap remains in understanding the directional effects of blast-induced ground accelerations and their direct link to slope failure in fractured, hard rock environments.

Methods. This study integrates multi-directional, field-measured peak particle acceleration (PPA) data with detailed topographic and geometric slope analysis. By employing scaled distance (SD) attenuation models and pseudo-static stability modeling, it identifies critical thresholds for slope safety under real blasting conditions. The analysis differentiates between measurement points behind, in front of, and beside the slope, revealing the role of topographic effects in the propagation of vibration.

Findings. Results show two distinct patterns of PPV attenuation: locations behind the slope (LP1, LP2) experienced higher and more rapidly decaying PPVs due to topographic amplification, while front/side points (LP3, LP4) exhibited flatter attenuation trends. The transversal PPA component was consistently dominant, and modeling demonstrated that the factor of safety fell below the critical threshold when horizontal acceleration exceeded 0.17 g. This threshold serves as a practical upper limit for safe charge design in similar andesite settings.

Originality. The study presents the first comprehensive, field-based evaluation that links directional ground motion measurements, local slope geometry, and critical acceleration thresholds for slope failure in an andesite quarry, thereby moving beyond generalized empirical models and providing actionable, site-specific blast design guidance.

Practical implications. The findings support the adoption of site-calibrated vibration monitoring and directional analysis in blasting operations, enabling more precise control of charge limits and minimizing geotechnical risk – essential for maintaining safe and efficient extraction in quarries near sensitive infrastructure.

Keywords: *andesite quarry, blast-induced vibration, slope stability, scaled distance, directional ground*

1. Introduction

Open-pit mining operations in andesite quarries play a crucial role in supplying the essential construction materials necessary for infrastructure development in rapidly developping regions. The demand for constructing modern societies has necessitated the intensified extraction of high-quality crushed stone, such as andesite, from these quarries [1]. Andesite, valued for its compressive durability, is excavated through bench detonations that progressively expand the excavation perimeter. However, amplified production requirements have brought about more frequent explosive dismantlings, heightening concerns regarding their impact on slope security near operational routes and facilities. Slope failures in such settings potentially endanger workers and halt work, imposing financial burdens [2].

Blasting, while efficient for rock fragmentation, induces vibratory ground motions typically gauged as peak particle velocity (PPV) and peak particle acceleration (PPA). These vibration magnitudes depend on the explosive load's weight and location relative to the point of interest, often examined through scaled distance functions, SD = R/Q [3], [4].

Both PPV and PPA decrease as scaled distance increases, but larger explosive charges or closer proximities of blasting area are resulting in higher vibration levels and previous studies conducted by Kesimal et al. [5] and Liu et al. [6] emphasize that even slight hikes in PPA, particularly within the range of 0.1-0.2 g, can drastically undermine in the factor of safety (FoS) for the slopes. These vibrations can weaken slope material by amplifying shear stresses, especially in pre-fractured rock masses.

Despite extensive literature addressing blast-induced vibrations, research explicitly linking PPA to the factor of safety (FoS) for slope stability in andesite quarries remains notably limited. Previous studies have predominantly focused on PPV, frequently dependent on numerical simula-

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tions or generalized empirical methods derived primarily from coal or limestone quarry circumstances [7], [8]. Such broad approaches inadequately capture the dynamic responses of stiff, low-porosity rock types, such as andesite. Additionally, detailed analyses of directional PPA components (transverse, vertical, and longitudinal) are scarce, and the explicit identification of critical acceleration thresholds directly associated with slope instability is rarely addressed, resulting in sizable uncertainties in safe blast planning. Recent advances in statistical modeling, such as copula-based forecasting, have been proposed as a means of improving the reliability of slope failure prediction, thereby reducing false alarms and enhancing event detection in mining settings [9].

Crucially, the integration of scaled distance (SD) methods with pseudo-static slope stability analyses, achieved through direct field measurements [10] rather than purely numerical approaches, has not been comprehensively investigated or validated, especially in andesite quarry settings. This gap highlights a significant methodological contribution addressed by this study. Without specialized, field-based assessments, engineers face constraints in accurately determining safe explosive charge limits and effectively managing blast-induced risks in complex geotechnical settings.

This research gap underscores the need for empirical, site-specific studies to gain a deeper understanding of how blast vibrations impact slope stability in andesite quarries. In the absence of precise, field-calibrated models, mining operations risk substantial financial and safety consequences as production intensifies and approaches sensitive infrastructures.

To address these crucial shortcomings, this study presents contributions by explicitly integrating field-measured, multi-directional PPA data collected on-site, slope geometry ana-lyses, and the specific effects of blast orientation. Employing site-specific geomechanical parameters and pseudo-static modeling, this research identifies critical horizontal acceleration thresholds for slope failure. The significance of this study lies in providing the first comprehensive field-based evaluation that directly connects directional vibration analysis and slope geometry interactions to establish maximum permissible explosive charges, offering guidelines for safer blasting practices in andesite quarries. As mining operations continue expanding near vulnerable infrastructure, such integrated and calibrated approaches become indispensable for ensuring both safety and operational efficiency [11], [12].

2. Materials and methods

2.1. Study site

This study was conducted in an active andesite quarry located in Kulon Progo Regency, Yogyakarta Province, Indonesia. The mining area is situated between 240 and 315 meters above sea level. It features a rock slope composed of fractured andesite with no groundwater influence, as the water table lies beneath the pit floor. The overall slope height is approximately 75 meters with an overall slope angle of 55°, and a critical access road runs along the slope's toe, connecting the pit floor (mining area) to the processing plant. Maintaining the stability of this slope is therefore essential to ensure both operational continuity and safety, particularly during and after blasting activities.

2.2. Data collection

To evaluate the influence of blasting-induced ground vibrations on slope stability, a comprehensive dataset was collected from March to September 2024, consisting of 26 blast events. The data collection process involved four major components: discontinuity mapping, blasting geometry, blast vibration monitoring, and laboratory testing of rock properties. Discontinuity data were obtained using the scan-line method, with a focus on mapping the orientation of joint structures, including dip and dip direction [13]. Measurement lines ranged from 10 to 30 meters in length, using a geological compass, tape measures, and other field tools (portable GPS units, digital clinometers, geological hammers, and tablets for digital mapping). Blasting geometry data were collected for each blast event, including measurements of burden, spacing, hole depth, subdrill, and stemming length. These geometric parameters were used to calculate the explosive charge per delay and to estimate the scaled distance (SD), a key predictor of vibration intensity [14]. Blast-induced ground vibrations were recorded using Micromate seismographs equipped with geophones and microphones. Vibration data were visualized using Instantel Thor software. The monitoring network consisted of four stations strategically positioned around the slope: behind the slope (LP1 and LP2), in front of the slope (LP3), and beside the slope (LP4) (Fig. 1), all located within a 200-meter radius from the blast sources. Each blast event yielded peak particle velocity (PPV) data, which were subsequently used to estimate peak particle acceleration (PPA).

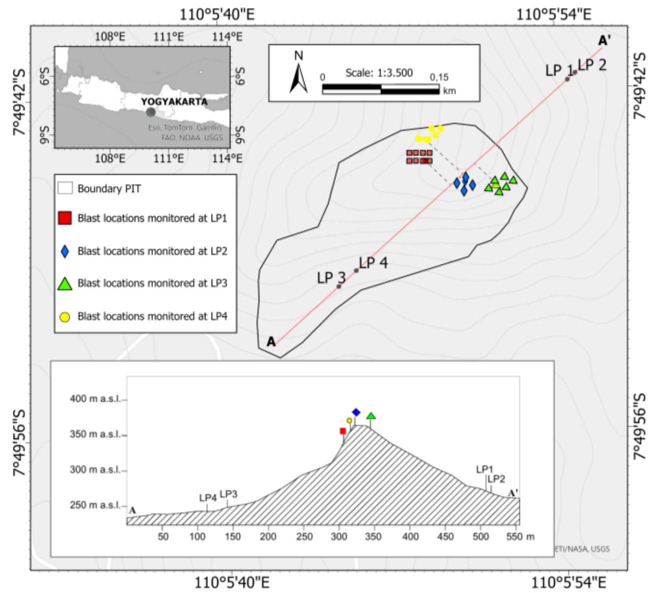

Figure 1. Blast event distribution and elevation profile at quarry site (A-A' Section)

Adjacent to slope stability issues, geomechanical properties such as physical and mechanical properties of rock are required and obtained through laboratory testing at the Rock Mechanics Laboratory, Department of Mining Engineering, Universitas Pembangunan Nasional Veteran Yogyakarta. Physical tests included measurements of natural density, dry density, saturated water content, degree of saturation, and porosity (Table 1). Mechanical tests involved uniaxial compressive strength (UCS), Young's modulus, and Poisson's ratio (Table 2).

Table 1. Summary of physical properties of andesite samples

Parameter	Median	Standard deviation
Natural density, g/cm^3	2.76	0.012
Dry density, g/cm^3	2.74	0.010
Saturated water content, %	0.56	0.15
Degree of saturation, %	94.74	18.18
Porosity, %	1.53	0.40

Table 2. Summary of the mechanical properties of andesite samples

Parameter	Median	Standard deviation
UCS, MPa	61.27	14.58
Young's modulus, MPa	2177.10	526.27
Poisson's ratio	0.30	0.03

2.3. Data processing

Data processing was carried out to interpret the implications of blasting on slope safety and to establish safe operational limits. Discontinuity data were processed using Rocscience Dips software to identify potential structurally controlled failure mechanisms (Fig. 2). The input data, including dip and dip direction, were plotted on stereonets to evaluate the likelihood of failures.

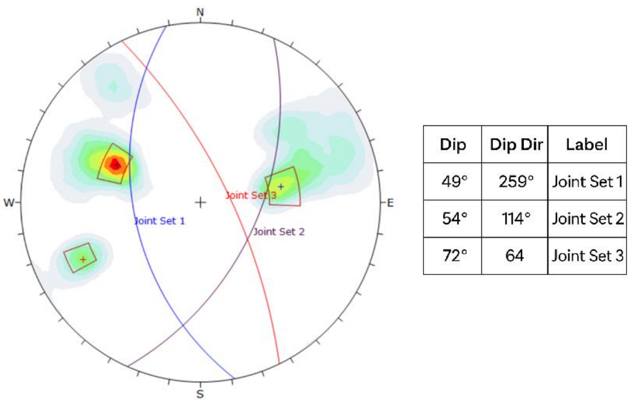

Figure 2. Stereonet projection of discontinuity sets in the rock mass

The stereonet analysis revealed three primary joint sets: Joint Set 1 (Dip/DipDir: 54°/75°), Joint Set 2 (70°/23°), and Joint Set 3 (48°/279°). Based on their orientations and the slope face azimuth, structurally controlled failures such as planar or wedge failure are likely under unfavorable conditions. These findings were either incorporated into the Slide2 analysis or, if not critical, treated as supporting assumptions for consideration of the failure mode.

Data processing was carried out to interpret the implications of blasting on slope safety and to establish safe operational limits. Discontinuity data were processed using Rocscience Dips software to identify potential structurally controlled failure mechanisms. The explosive charge per delay was computed from the measured blast geometry, and when combined with distance measurements, was used to calculate the scaled distance for vibration analysis. Recorded PPV values were then converted into PPA using empirical equations, providing a basis for pseudo-static slope stability modeling [15]. The FoS was simulated under varying levels of horizontal acceleration. Saturated density values from Table 1 and shear strength parameters derived from Table 2 were applied using Rocscience Slide and Rocdata software. The aim was to determine the critical PPA threshold at which the FoS drops to near-critical levels (FoS = 1.1), thereby identifying maximum allowable explosive charges for different standoff distances to ensure safe blasting operations.

3. Results and discussion

3.1. Blasting geometry and ground vibration data

A total of 26 blasting events were documented across 10 dates between March and September 2024 (Table 3). Throughout the geometry data, such as the burden (2 m), spacing (3 m), stemming (2.2 m), and subdrill (0.5 m) were held constant. However, variations in hole depth (4.1-6.4 m) and powder charge length (1.9-4.2 m) resulted in a wide range of charge weights per delay (Q), ranging from 27.93 kg to 95.76 kg. These differences significantly influenced vibration responses. The highest recorded PPV was 3.689 mm/s on March 8, 2024, at a distance of 179 m under a charge of 88.38 kg. In contrast, a much lower PPV of 0.326 mm/s was measured on March 22, 2024, at a similar distance (184 m) but with a smaller charge of 57.40 kg. This comparison illustrates that explosive charge weight exerts a more dominant influence on vibration intensity than distance alone.

This pattern was further evident even at greater distances. For instance, on May 6, 2024, three blasts were conducted at 200 m, producing relatively high PPVs ranging from 0.595 to 0.628 mm/s. Despite the increased distance, these events utilized high charge weights ranging from 79.80 to 95.76 kg.

3.2. Vibration reduction characterized by scale distance

The energy content of the explosive (Q) in an andesite quarry is a stronger determinant of PPV than distance, particularly when the scaled distance remains low (Table 3). This observation is in line with prior studies in open-cast coal mining, including [3], which reported similar trends in surface blasting scenarios where charge magnitude played a critical role in controlling vibration levels. Regression analysis, as depicted in Figure 3, confirms the general trend of increasing PPV with higher Q. However, a more detailed examination reveals two distinct regression patterns when the measurement locations group data. One trend line corresponds to LP1 and LP2, monitoring points situated behind the slope, while the other pertains to LP3 and LP4, located in front of and beside the slope, respectively. This division suggests that site-specific conditions, such as topographic shielding, wave reflection, and subsurface heterogeneity, have a significant influence on ground vibration propagation. Notably, for equivalent charge weights, PPVs recorded at LP1 and LP2 are consistently higher than those at LP3 and LP4. This discrepancy is attributed to constructive interference due to wave reflections or energy trapping behind the slope. In contrast, LP3 and LP4, being more exposed or laterally positioned relative to the blast source, exhibit reduced vibration levels, which is likely due to unobstructed wave dispersion or geometric spreading. These observations underscore the importance of considering spatial context in vibration analysis.

These findings align with and extend the work of Singh and Roy [3], who established empirical relationships between Q and PPV in hard rock surface mines, specifically in granite and sandstone settings in India. Their study sites, characterized by relatively open-pit geometries and less topographic complexity, produced a well-defined power-law correlation where PPV increased predictably with larger explosive charges. When plotted alongside the current dataset, their observations align closely with the regression trend of LP1 and LP2, suggesting that similar wave amplification mechanisms are at play in topographically shielded or concave slope settings.

Table 3. Blasting geometry and ground vibration measurements

Distance, m & point	Date	Data count	Hole depth, m	Powder charge, m	PPV, mm/s	Hole count	Charge (Q), kg
179 (LP1)	5-Mar-24	2	5.40 ± 0.71	3.20 ± 0.71	2.835	12	68.74
	8-Mar-24	2	5.40 ± 0.71	3.20 ± 0.71	3.346	15	83.47
	29-Mar-24	4	5.00 ± 0.12	2.80 ± 0.12	2.326	11	53.86
182 (LP2)	15-Mar-24	1	5.4	3.2	3.21	15	85
	25-Mar-24	3	5.20 ± 0.17	3.00 ± 0.17	1.923	7	55.86
184 (LP3)	22-Mar-24	2	5.05 ± 0.07	2.85 ± 0.07	0.376	12	61.5
	24-Apr-24	3	5.43 ± 0.29	3.23 ± 0.29	0.445	11	72.97
	18-Sep-24	2	5.25 ± 1.63	3.05 ± 1.63	0.946	12	61.6
200 (LP4)	2-May-24	2	5.30 ± 0.42	3.10 ± 0.42	0.538	12	65.17
	29-Apr-24	2	5.35 ± 0.35	3.15 ± 0.35	0.524	12	63.57
	6-May-24	3	4.93 ± 0.58	2.73 ± 0.58	0.608	13	87.78

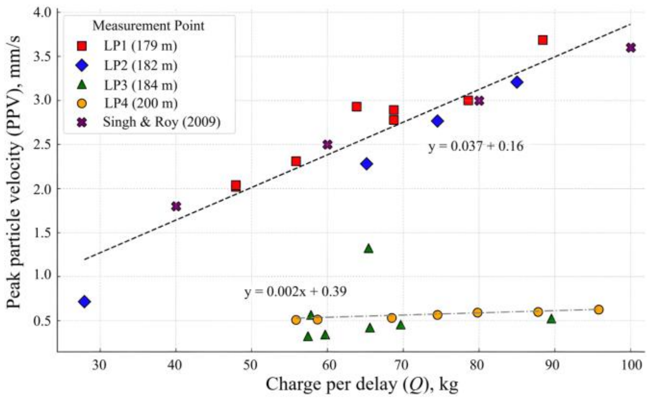

Figure 3. Comparison of charge per delay (Q) vs PPV

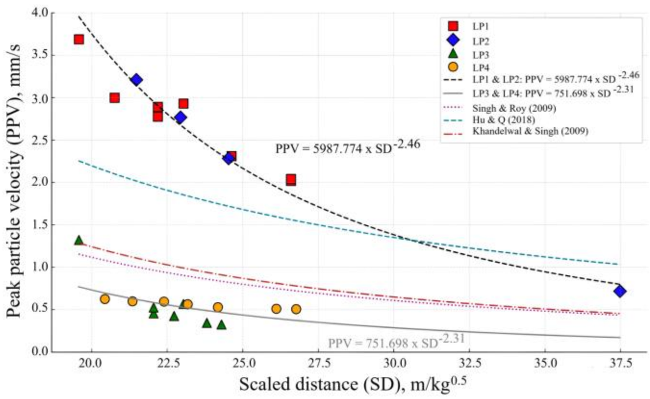

Figure 4. Comparison of scale distance (SD) vs PPV

In contrast, the flatter response observed in LP3 and LP4 indicates that the Singh and Roy [3] model may overpredict PPV in more open or laterally shielded terrains. Further supporting this perspective, Dzimunya et al. [16] introduced the Equivalent Path-Based (EPB) equation, which incorporates factors such as topography and rock mass properties into prediction models for PPV. Their approach acknowledges that traditional SD formulas may not adequately account for the complexities introduced by varying terrain and geological conditions. Similarly, Singh [17] emphasized the influence of geological factors, including rock type and structural features, on the reduction of blast-induced vibrations.

This research was conducted in an andesite quarry with fractured rock mass and relatively distinctive topographic variation; these considerations are realistic to the specific andesite quarry condition in general. The presence of concave slopes and benches contributes to complex wave behaviour such as reflection, focusing, or trapping, leading to the observed variations in PPV across different monitoring points. Figure 4 illustrates the relationship between SD and PPV, showing an inverse power-law trend as typically observed in blast-induced vibration studies. Notably, the data is divided into two distinct reduction patterns based on measurement location. The regression lines for LP1 and LP2 (behind the hill) follow the equations $PPV = 5987.774 \cdot SD^{-2.46}$, with $R^2 = 0.91$. Meanwhile, the regression for LP3 and LP4 (front and side of the hill) is $PPV = 751698 \cdot SD^{-2.31}$, with $R^2 = 0.40$. The steeper attenuation curve and higher coefficient of determination (R^2) in the LP1-LP2 dataset suggest that vibrations were more intense and decayed more rapidly with increasing SD. This may be attributed to topographic cratering effects, wave focusing, or less wave scattering in the rear-facing slope zone.

In contrast, the flatter and more dispersed LP3-LP4 regression indicates partial shielding, wave diffraction, or subsurface heterogeneity, which contribute to inconsistent attenuation patterns in the front or lateral slope directions.

To validate these observations, three reference models from previous studies were incorporated into the analysis. The model proposed by Singh and Roy [3], expressed as $PPV = 100 \cdot SD^{-1.55}$, was developed from surface coal mine blasting data. This equation represents a moderate reduction rate, falling between the two regression curves observed in the current study. It shows closer alignment with the LP3-LP4 data, which were recorded in front and beside the slope, suggesting similar surface blasting conditions in relatively unobstructed terrain. The model by Hu and Qu [18], $PPV = 80 \cdot SD^{-1.2}$, incorporates EPB adjustments and accounts for topographic and geological influences on vibration transmission. This equation also closely follows the reduction trend of the LP3-LP4 data, further supporting the role of terrain geometry and lithological complexity in moderating the decay of ground vibration. In contrast, the model developed by Khandelwal and Singh [19], $PPV = 150 \cdot SD^{-1.6}$, derived from investigations in magnesite mines, exhibits a steeper reduction curve. It aligns more closely with the regression of LP1-LP2 data, which were collected behind the hill, suggesting that steeper, fractured rock slopes may amplify blast-induced vibrations and cause more rapid decay due to wave convergence or topographic focusing. The discrepancy between the two fitted curves in this study confirms that SD, although a robust parameter, is not universally predictive across diverse terrain settings. Site-specific factors, particularly topographic shielding, slope orientation, and rock discontinuity patterns, play a crucial role in modulating vibration behavior.

Empirical field studies in andesite quarries show strong decay of PPV with distance. Nugroho & Purnama [20] measured bench blasts in an Indonesian andesite mine and derived a site-specific reduction law $PPV = 984 \cdot SD^{-1.66}$. Saptono and Lestari [21] report similar results at an Indonesian andesite quarry: a power-law fit yielded $PPV = 5.99 \cdot SD^{-2.5}$ (with $R^2 = 1.0$ for the 95% upper bound). In both cases, SD is the scaled distance in $\frac{m}{kg^{0.5}}$. Other studies on volcanic-like lithologies also agree on a rapid reduction level: for example, Özer et al. [22] found $PPV = 773 \cdot SD^{-1.68}$ ($R^2 = 0.79$) in a Turkish quarry. These empirical models (specific to site geology and blast setup) demonstrate that PPV drops roughly as $SD^{-1.5}$ to $SD^{-2.5}$ in complex rock settings.

To better understand the site-specific regression patterns observed in this study, a comparative review of prior empirical and numerical models is provided in Table 4. These references include vibration reduction equations from diverse geological settings, including surface coal mines [3], open pits with terrain corrections [18], and fractured magnesite slopes [19]. Table 4 also summarizes the effects of terrain and directional vibration characteristics, highlighting how topography, bench geometry, and wave reflection influence vibration decay. Notably, the steeper regression observed at LP1-LP2 aligns with studies reporting wave focusing behind slopes [23], [24], whereas the flatter trend at LP3-LP4 resembles patterns seen in laterally exposed or topographically complex sites. This research supports the conclusion that SD alone cannot universally predict PPV, and that terrain-specific calibration remains essential in quarry blast planning.

Table 4. PPV regression models, terrain effects, and directional vibration behaviour

Study	PPV equation	Terrain effect	Directional behavior
Current study (LP1-LP2)	$PPV = 5987.774 \cdot SD^{-2.46}$	Behind-slope focusing	High transversal PPA
Current study (LP3-LP4)	$PPV = 751.698 \cdot SD^{-2.31}$	Frontal/lateral dispersion	Lower transversal PPA
Singh & Roy [3]	$PPV = 100 \cdot SD^{-1.5}$	Surface mine, moderate attenuation	Not specified
Hu & Qu [18]	$PPV = 80 \cdot SD^{-1.2}$	Geology-adjusted path, open pit	Not specified
Khandelwal & Singh [19]	$PPV = 150 \cdot SD^{-1.6}$	Hard, fractured slope (magnesite)	Not specified
Song et al. [25]	Wave focusing near crest; P amplification	Convex crest amplifies waves	P-dominant but angle-sensitive
Fu, Ji, Pei, & Wei, [23]	Amplified PPV at bench crest	Bench geometry modifies vibration	Dependent on the slope face
Li et al. [24]	Reflection effects at convex corners	Wave convergence at the hill corner	Amplified at the top edge
Sun & Li [12]	Bench shape influences resonance	Slope geometry governs vibration	Bench resonance enhances motion
Abdelhafiez et al. [26]	Transversal motion dominant	Blast-face orientation amplifies SH motion	Transversal axis dominant

These and related studies provide site-calibrated reduction curves for volcanic/intermediate igneous rocks (andesite, basalt, etc.), which can be compared to more general models (USBM equations). In practice, each site's SD-PPV relationship must be measured or calibrated for more accurate vibration forecasting. Furthermore, the consistently higher PPVs observed at LP1 and LP2 for equivalent SD values imply greater vibration exposure in the rear slope zone. This may increase the sensitivity of these slope segments to dynamic destabilization. As a result, blast planning in proximity to sensitive or infrastructure-adjacent slopes should incorporate localized calibration of SD-PPV regression models, as well as directional propagation analysis, to minimize geotechnical risk.

3.3. Directional characteristics of the PPA component

Blast-induced vibrations propagate in three orthogonal directions (transversal, vertical, and longitudinal) and their relative magnitudes are influenced by source mechanism, geology, and terrain. Understanding these directional characteristics is critical for evaluating potential slope destabilization, particularly in bench blasting where slope faces are exposed. Figure 5 illustrates the comparative distribution of PPA components recorded during the study. Across 26 blast events, the transverse component generally exhibited the highest PPA values, followed by the longitudinal and then the vertical direction. For example, at LP2 (182 m), a typical blast recorded a transversal PPA of 0.0888 g, compared to 0.0835 g in the longitudinal direction and 0.0730 g in the vertical. However, when aggregating all data, the highest transversal PPA values (frequently exceeding 0.15 g) were consistently recorded at LP1 and LP2. This level of horizontal acceleration is recognized in the literature as approaching or surpassing the critical threshold associated with increased risk of slope instability [5], [27].

These results indicate a pronounced horizontal excitation toward the slope face at the behind-slope measurement locations, emphasizing the importance of site-specific vibration control in these zones. The box plot compares the distribution of PPA across transversal, vertical, and longitudinal components for four measurement points (LP1-LP4). Outliers (marked by diamond symbols) are observed predominantly at LP1 and LP2, especially in transversal and longitudinal directions, highlighting occasional high-amplitude ground motion behind the hill. LP3 and LP4, positioned at the front or side of the slope, show lower PPA values and fewer outliers, with LP4 exhibiting the least variability. Notably, no outliers were detected for LP4 in any PPA component, indicating stable, low-intensity vibration exposure at that location. The exact number of blast events recorded at each LP should be verified from the experimental dataset, but unless stated otherwise, the plot likely summarizes all available events per point.

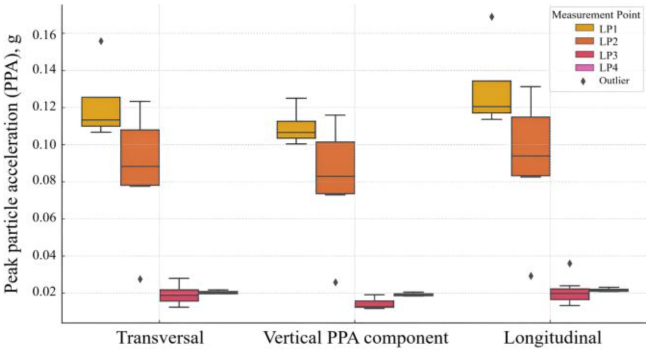

Figure 5. Comparison of scale distance (SD) vs PPV

This pattern is consistent with previous studies that highlight the prevalence of horizontal components in surface blasting. For instance, Liu et al. [28] found that near-field vibration energy in bench blasting tends to concentrate in the direction perpendicular to the blast face, enhancing transversal amplitudes. Similarly, Tang et al. [29] observed that structural anisotropy and bench geometry often channel energy into the slope-normal direction, intensifying the risk of lateral destabilization. The directional disparity is particularly relevant when translating PPA into pseudo-static acceleration input (α) for slope stability modeling. As most pseudo-static analyses employ a single horizontal acceleration vector, the transverse component becomes the most suitable proxy. In this study, the highest transversal PPA value reached 0.1560 g (recorded at LP1).

Blasting vibration studies have shown that convex slope features (protruding bench crests or hilltops) can significantly amplify blast-induced seismic waves. This amplification occurs because the outward-curved geometry of convex surfaces causes incoming wavefronts to bend inward as they propagate across the crest. As a result, the seismic energy is concentrated into a narrower zone, increasing vibration amplitude at or near the convex edge. Unlike flat or concave surfaces, where wave energy spreads out and attenuates, convex slopes act to focus and intensify ground motion.

This phenomenon is supported by both analytical and numerical models, as well as field measurements, which consistently report higher peak particle velocities (PPV) and accelerations (PPA) at convex slope features compared to sheltered or concave areas. Thus, convex terrain acts not only as a passive boundary but also as an active amplifier of ground vibration, thereby increasing the potential for vibration-induced slope instability in these zones. Song et al. [25] used discrete-element modelling of a blasting pulse in a steep granite slope and found that the slope strongly filters out high-frequency components (> 20 Hz). At the same time, low-frequency P-wave energy is amplified inside the slope, resulting in an elevation amplification effect. Likewise, Fu et al. [23] reported pronounced local amplification at free-face edges. Field monitoring and FEM analysis in a high bench showed that the outer bench edge and mid-bench points vibrated much more intensely than the inner or mid-slope points. In deep underground walls, Li et al. [24] observed a similar phenomenon, attributing a whiplash in the far-field motion to reflections from a convex corner (the curved rock anchor beam), which constructively superpose and boost the wave there.

These results imply that wave propagation over complex terrain is highly non-uniform. Convex crest geometry (a free face or bench toe jutting outward) concentrates seismic energy and raises PPVs behind it, while concave or recessed shapes tend to dissipate waves. In effect, wavefronts can be focused by ridge-shaped topography and reflected or mode-converted at sharp corners. In practical terms, this phenomenon results in amplified horizontal ground motions near slope crests and reduced motions at the slope toe. This pattern is consistent with the numerical simulations of Bouckovalas & Papadimitriou [30], who demonstrated significant amplification of horizontal vibrations at crest locations and attenuation at the toe. Overall, both laboratory and field studies in hard rock (granite, limestone, etc.) indicate that steep slopes impose an "arc-shaped" propagation path: seismic amplitudes decay more slowly along the slope interior but can peak near convex features. In short, hill slopes act as seismic modifiers – filtering frequencies and redirecting energy – so that terrain geometry critically controls where blast vibrations are amplified or damped. The complexity of bench geometry and blast orientation strongly influences the directionality of ground motion during quarry blasting. In irregular multi-bench terrain or layered rock, wave propagation paths become complex, breaking the usual symmetry of wave radiation. For instance, when a blast faces one side of an irregular pit, transmitted seismic waves can scatter, reflect, and recombine asymmetrically. This often leads to a pronounced prominence of the transverse (shear) component of particle motion. Seismically, ground motion from blasting is typically resolved into three orthogonal components: longitudinal (aligned with the blast direction), vertical (up-down), and transversal (perpendicular to both, typically aligned with the face). The transversal component is most sensitive to horizontal shear (SH) waves, often manifesting as Love-wave energy. Numerous studies, including those by Abdelhafiez et al. [26], highlight that seismographs positioned along the transverse axis capture the SH phase and often record the highest vibration amplitudes in quarry blasts, particularly when the bench layout and firing patterns favor horizontal shear excitation. Practically, a firing pattern parallel to a free face tends to excite stronger side-to-side (transversal) motion, while patterns directed perpendicular to faces drive more radial (longitudinal) or compressional waves.

Field observations support these ideas. Sun et al. [31] demonstrated on a slender bench slope that dynamic response is governed by both wave propagation and the slope's resonant vibration modes. Certain geometries can selectively amplify specific vibration modes, such as shear along benches. In bench blasts, the highest peak particle velocities (PPV) are often found aligned with the blast initiation direction, a result of constructive superposition of waves along that axis. Conversely, Song et al. [25] found that within steep slopes, P-wave (compressional) motions could dominate over S-waves, implying that the geometry may suppress shear motion under some circumstances. Thus, while the dominance of the transversal (SH) component is not universal, it emerges whenever the combined effects of terrain geometry and blast layout favor horizontal shear-wave generation and focusing.

3.4. Modeling-based guidelines for safe blasting

Figure 6 shows that as horizontal acceleration increases, the computed FoS declines, although the rate of decline becomes lower. In our pseudo-static models, FoS drops from ≈ 2.25 (static case) to ≈ 1.1 at a peak horizontal acceleration of 0.17 g (the maximum PPA measured). This finding is consistent with previous analyses: for example, Simangunsong et al. [27] found that in a coal-mine case, a pseudo-static FoS was only ≈ 1.04 at 0.12 g, whereas the dynamic (Newmark) FoS at 0.41 g remained higher (~ 1.35). This study similarly suggests that pseudo-static analysis may be conservative, but still provides a practical design limit. In short, blasts inducing horizontal accelerations above ~ 0.15-0.2 g will drive the FoS below ~ 1.1 in this study, indicating the stability limit. Furthermore, Figure 7 plots measured PPA against SD. As expected, PPA decays as the SD increases. A regression fit confirms a strong inverse power-law relationship, consistent with classical blast reduction models. We further color-coded points by charge per delay (Q): larger charges generally yield higher PPA at a given SD.

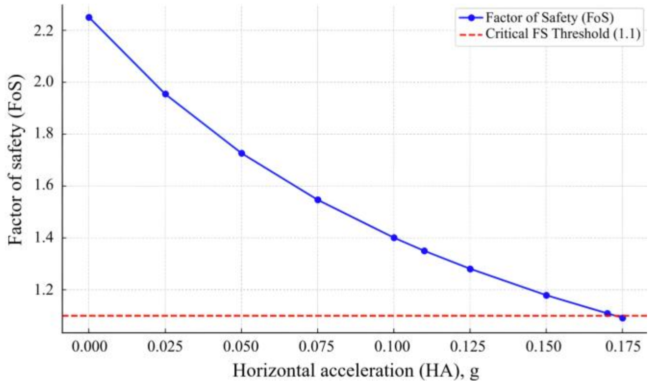

Figure 6. Factor of safety as a function of horizontal acceleration

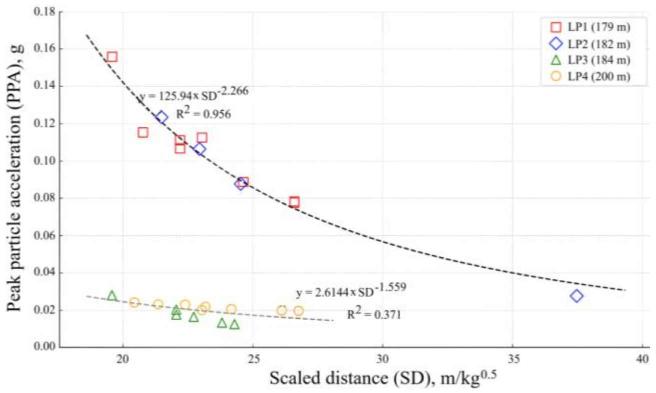

Figure 7. Correlation of peak particle acceleration (PPA) against scaled distance (SD)

Figure 8 shows the corresponding FoS versus PPA for each blast. The trend is monotonic: events with higher PPA correspond to lower FoS, as indicated by the downward slope of the scatter. In particular, our highest PPA (0.17 g, large Q, small SD) corresponds to FoS ≈ 1.1, whereas low-vibration blasts (PPA ≪ 0.1 g) maintain FoS > 1.5. Thus, the field data and models are consistent: controlling SD and Q (hence PPA) is directly linked to maintaining a safe FoS.

In practical terms, we can use the PPA-SD regression in Figure 8 to estimate safe distances for a given charge. Simangunsong et al. [27] recommend avoiding SD < 8 m/kg^0.5 to maintain stable slopes. In our data, the threshold PPA ≈ 0.12 g (their pseudo-static limit) is reached at about SD ≈ 8 for typical Q, supporting a similar guideline.

These results align with the broader literature on blasting and slope stability. Kong [32] notes that limiting PPV to on the order of 25-50 mm/s is often prescribed to protect rock and infrastructure. For blasting frequencies of tens of Hz, 50 mm/s corresponds roughly to 0.005-0.01 g. Although the primary focus of this study is on the PPA, it suggests that infrastructure criteria can be stricter than geotechnical limits. In practice, achieving these low PPV targets requires reducing charge weight per delay and increasing blast spacing. Indeed, Deressa et al. [8] found, through numerical modeling, that reducing bench height (and thus effectively Q per bench) and widening bench spacing significantly lowers PPV, yielding a higher dynamic FoS. For instance, increasing bench height from 5 to 12 m in their study reduced the static FoS by ~ 44% and the dynamic FoS by ~ 26%. In addition, shorter benches and wider spacing produced less ground vibration (bench-blast PPV dropping from 63.2 cm/s at 13 m to 23.99 cm/s at 18.5 m) and consequently improved slope stability.

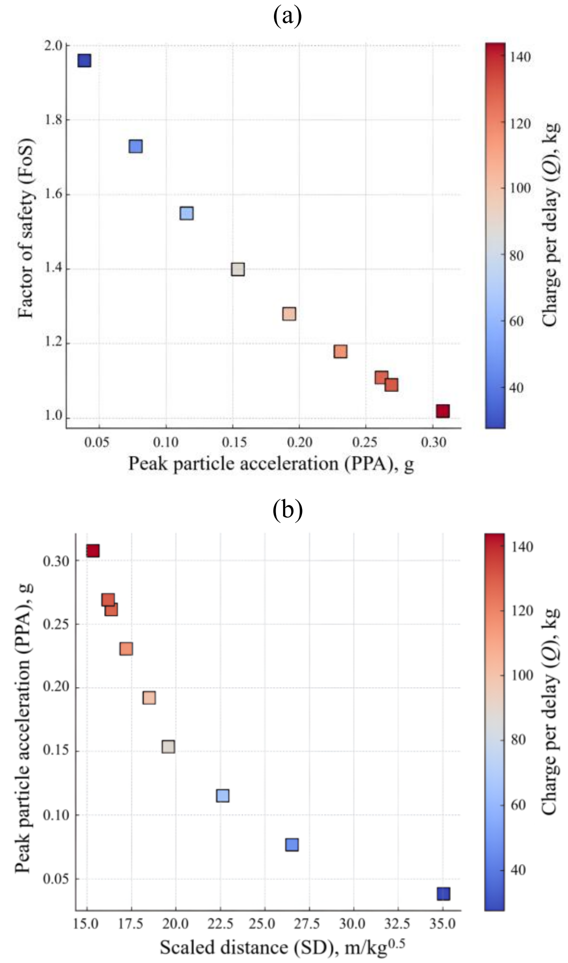

Figure 8. Interrelationship between blast parameters, vibration response, and slope stability

Geological factors must also be considered. Bazi et al. [33] employed finite-element models to demonstrate that blasts can induce highly non-uniform displacements in faulted slopes. In their study, points above a fault plane experienced the largest displacements, while points below the fault moved very little. They also found that groundwater pressure greatly amplifies blast-induced movements. These effects imply that even with the same PPA or SD, certain slopes (those with persistent faults or saturated layers) may respond more violently. Our field-based regression inherently averages over such site conditions; however, the literature suggests that extra caution is needed near faults or in groundwater zones.

4. Conclusions

This study delivers a comprehensive, field-based evaluation of blast-induced ground vibrations and their effects on slope stability in a fractured andesite quarry. By integrating detailed, site-specific measurements of PPA in multiple directions with analyses of slope geometry and blast orientation, the research reveals that topographic amplification and cratering effects can substantially intensify vibrations, particularly at points behind the slope.

Directional analysis confirmed the transverse component of PPA as consistently dominant, emphasizing the need for orientation-specific monitoring and modeling. Pseudo-static analyses using local geomechanical properties demonstrated that the slope factor of safety declines sharply as horizontal acceleration exceeds 0.17 g, identifying this threshold as critical for instability risk.

These results enable the establishment of maximum permissible explosive charges that maintain safety margins, with practical guidelines tailored to site geometry and operational distances. Ultimately, this work provides a validated context-sensitive framework for vibration prediction and safe blast design in andesite quarries, advancing beyond generalized models and supporting safer and more efficient mining practices near infrastructure.

Author contributions

Conceptualization: SS; Data curation: RFS, SRH; Formal analysis: VV, SS, OWL; Funding acquisition: SS, BD; Investigation: RFS, SS; Methodology: SS, VV; Project administration: AA; Resources: SS; Software: VV, RFS; Supervision: SS; Validation: BD, SRH; Visualization: VV, SS; Writing – original draft: VV, SRH; Writing – review & editing: AA, OWL, SS. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Польова оцінка вибухових вібрацій і стійкості укосів в андезитовому кар’єрі

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Мета. Кількісна оцінка впливу напрямних компонент вибухових прискорень на параметри вібрацій та стійкість укосів андезитового кар’єру на основі польових вимірювань пікових прискорень частинок, аналізу геометрії укосу та моделювання поширення вибухових хвиль.

Методика. Дослідження ґрунтується на багатовісних польових вимірюваннях пікових прискорень частинок (PPA), які поєднані з детальним аналізом рельєфу та геометрії укосу. Для оцінки ступеня впливу вибухових навантажень використано моделі ослаблення за масштабованою відстанню (SD) і псевдостатичне моделювання стійкості. Окремо проаналізовано точки вимірювання, розташовані позаду, перед та збоку від укосу, щоб визначити вплив топографії на поширення вібрацій.

Результати. Виявлено дві характерні моделі затухання пікової швидкості коливань частинок (PPV). Точки позаду укосу (LP1, LP2) демонстрували вищі значення і швидше зменшення PPV через топографічне підсилення. Встановлено, що точки перед та збоку (LP3, LP4) показали більш плавний характер зниження вібрацій. Доведено, що поперечна компонента PPA виявилась домінуючою, а результати моделювання засвідчили, що коефіцієнт стійкості укосу знижується до небезпечного рівня, коли горизонтальне прискорення перевищує 0.17 g. Це значення можна вважати безпечною верхньою межею для проєктування зарядів у подібних умовах.

Наукова новизна. Вперше виконано комплексне польове дослідження, яке напряму пов’язує просторову структуру вибухових коливань, локальні особливості укосу та критичні прискорення, здатні спричинити втрату стійкості. Дослідження виходить за межі узагальнених емпіричних підходів і пропонує практичні рекомендації, адаптовані до конкретного андезитового кар’єру.

Практична значимість. Отримані результати підтверджують ефективність локально каліброваного моніторингу та аналізу напрямних вібрацій під час планування вибухових робіт. Це дозволяє точніше визначати допустиму масу заряду та знижувати геотехнічні ризики, що особливо важливо для кар’єрів, розташованих поблизу технічної інфраструктури або населених пунктів.

Ключові слова: *андезитовий кар’єр, вибухові вібрації, стійкість укосу, масштабована відстань, напрямне прискорення*

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