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Stemming Length, Rock Strength, and Blast Impacts: Linking Ground Vibration and Air Overpressure to Community Perceptions at a Ghanaian Manganese Mine

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Abstract

Regulatory limits for blast-induced ground vibration and air overpressure aim to prevent structural damage, yet host communities often report substantial disturbance at operations whose recorded values are mostly within those limits. This case study examined that coexistence at the Nsuta manganese mine, Ghana, using records of 117 production blasts (January to March 2026) and a survey of 120 residents of Akyem and Tarkwa Banso. All recorded air overpressure (AOp) values were below the 117 dB(L) limit, and seven peak particle velocity (PPV) values (5.98%) exceeded 2.0 mm/s. Achieved stemming length and uniaxial compressive strength (UCS) had the strongest associations with AOp ($r = -0.50$ and -0.49) and PPV ($r = -0.42$), but were almost perfectly correlated ($r = 0.98$), so their effects could not be separated. Achieved stemming averaged 2.60 m against a 4 m design, although charge per hole was more consistent with the design length. Among residents, 71.7% rated the overall impact of blasting as at least moderate, and only 30.8% and 20.8% were satisfied with blast notification and complaint handling. Differences between the two communities were small and not significant. Assuming the observed rate of about 475 blasts per year, residents near the monitoring point would experience at least 239 perceptible blasts (PPV > 0.3 mm/s) and about 28 blasts exceeding the 2.0 mm/s limit annually. Per-blast compliance with LI 2177 therefore fails to represent cumulative community exposure; the study proposes a screening checklist for blast monitoring archives and recommends improved record-keeping, community-based monitoring and engagement to reconcile regulatory compliance with residents' experience.

Keywords

Blast-Induced Ground Vibration, Air Overpressure, Stemming, Uniaxial Compressive Strength, Community Perception, Blast Monitoring Data Quality, Open-Pit Mining

1. Introduction

Drilling and blasting remains the dominant method of rock breakage in surface mining, quarrying and civil construction because it offers a low unit cost of fragmentation and can be applied across a wide range of rock mass conditions (Brantson et al., 2024; Darkwah & Ativor, 2026). Its efficiency, however, is limited by how explosive energy is partitioned. Only a small fraction of the chemical energy released on detonation, commonly estimated at 20% to 30%, does useful work in fracturing and displacing the rock mass. The remainder is lost as heat, seismic waves transmitted through the ground, pressure waves transmitted through the atmosphere, and kinetic energy imparted to uncontrolled projectiles (Hustrulid, 1999). These losses appear in the environment as ground vibration, air overpressure, flyrock, dust and toxic fumes. They form the principal interface between a blasting operation and the communities around it (Bhatawdekar et al., 2021).

The magnitude of each effect depends on controllable design variables and on site conditions that cannot be controlled. Ground vibration, usually expressed as peak particle velocity (PPV) together with its dominant frequency, scales with the maximum charge detonated per delay and attenuates with distance. This relationship is commonly expressed through the scaled distance concept (Siskind et al., 1980). Air overpressure is governed by charge confinement, stemming length and material, burden relief, face orientation and the release of gases through geological discontinuities. Atmospheric conditions such as wind direction and temperature inversion can increase it substantially at receptors located some distance from the blast. Flyrock is driven mainly by inadequate burden, insufficient or poor-quality stemming, and weak zones within the rock mass, and it can travel well beyond the designated danger zone (Monjezi et al., 2010). Detonation also releases nitrogen oxides and carbon monoxide, particularly where the explosive is poorly formulated, water-affected or incompletely detonated. Combined with blast-generated dust, these emissions degrade air quality and pose recognised risks to human health and ecosystems (Manisalidis et al., 2020). The interaction of these mechanisms means that a blast compliant with one parameter may still produce unacceptable outcomes in another.

Residents near blasting operations may report building damage, disturbance, health concerns and livelihood disruption (Amegbey et al., 2012; Emmanuel et al., 2018). Such reports require assessment because exposure, construction conditions, and other environmental sources can contribute to the same outcomes. Human perception and annoyance can occur below structural damage criteria, so measured

compliance does not necessarily imply absence of disturbance. Conversely, a report of cracking does not establish blast causation. The United States Bureau of Mines criteria (Siskind et al., 1980) account for structural response and vibration frequency. Applying such criteria to local sandcrete block, mud-brick and other non-engineered dwellings requires attention to construction condition and foundation characteristics. This study did not test cumulative structural deterioration or the applicability of international damage criteria to the local housing stock.

The persistence of these problems reflects several interacting factors. These include geological variability that is not represented in standardised blast designs, deviations between designed and implemented blast parameters caused by human error, inadequate pre-blast planning, and monitoring programmes that are too sparse in space and time to describe actual exposure (Bajpayee et al., 2004; Bhatawdekar et al., 2021). Advances in electronic initiation, vibration and airblast monitoring, and predictive modelling have improved control at well-resourced operations. Nevertheless, blast design inputs, measured environmental responses and community experience are rarely examined together at a specific site. Without that link, mitigation measures tend to be generic and reactive, not tailored to the geology, geometry and receptor configuration of the operation. Narrowing the gap between intended and actual outcomes requires site-specific evidence, systematic data collection, and mitigation strategies that cover the full range of drill and blast impacts (Afum & Amegbey, 2015).

Previous work has approached these effects from three directions that seldom meet. Engineering studies have established damage thresholds for structures and models for predicting PPV and air overpressure; Singh and Roy (2010), for example, observed the first cosmetic cracks in brick-mud-cement houses only at PPV of about 52 to 56 mm/s. Studies of human response show that vibration is perceived and becomes a source of complaint at much lower levels. Guidance in BS 5228-2 treats 0.3 mm/s as just perceptible in residential environments and 1.0 mm/s as likely to cause complaint unless residents have been warned and given an explanation (BSI, 2014), and annoyance depends on the source of vibration as well as on the measured exposure (Waddington et al., 2014). Social research on mining has shown that community acceptance depends strongly on trust, procedural fairness and the quality of communication (Lawson & Bentil, 2014; Moffat & Zhang, 2014). Few studies combine a mine's compliance records with a survey of exposed residents at the same site and over the same period. In addition, the growing body of machine learning work in mining (Ativor et al., 2025; Ativor et al., 2024; Ziggah et al., 2023), including the prediction of blast-induced effects (Temeng et al., 2020; Ativor et al., 2026), relies on archived operational data whose quality is seldom examined before use, although dataset quality and coverage largely determine the reliability of the resulting models (Dumakor-Dupey et al., 2021).

The Nsuta manganese mine, operated by Ghana Manganese Company Limited (GMC) in the Tarkwa-Nsuaem Municipality of the Western Region, provides a rel-

evant setting for such an investigation. The mine exploits manganese oxide and carbonate ores hosted within Birimian metavolcanic and metasedimentary sequences through open-pit methods, and drill and blast is used to liberate both ore and waste. The lithological contrast between the ore horizons and the enclosing phyllites and associated units, together with weathering profiles and structural discontinuities, produces variable rock mass conditions that affect energy transmission and blast outcomes. The active pit lies close to the host communities of Nsuta Zongo, Akyem and Tarkwa Banso, whose residents have raised repeated complaints about the effects of blasting on their buildings, health and livelihoods. Earlier work at the mine addressed blast impact prediction (Afum & Amegbey, 2015), but measured blast performance has not been examined alongside community perception at the site. The site thus combines geological variability, close proximity of vulnerable structures and an established record of community grievance. These are the conditions under which generic blast management practices are most likely to fail.

This study describes recorded blast effects and community perceptions at the Nsuta mine. It documents the reported operating geometry, compares recorded PPV and AOp values with the limits in Regulation 199 of the Minerals and Mining (Explosives) Regulations, 2012 (Republic of Ghana, 2012), and explores bivariate associations with the available blast variables. It then describes reported impacts and satisfaction among surveyed residents of Akyem and Tarkwa Banso. The two datasets are compared at the interpretation stage to identify monitoring, operational and engagement priorities. The study is exploratory: it does not estimate household-specific exposure, identify independent causal effects or validate a predictive model.

The study makes three contributions. First, it brings together compliance records and resident perceptions from two host communities of a Ghanaian manganese mine over the same quarter. Second, it screens the mine's monitoring archive before interpretation and presents the checks as a checklist for assessing other blast monitoring records, including datasets used to train predictive models. Third, it demonstrates that per-blast compliance with LI 2177 does not fully capture either community's experience and identifies how compliance reporting and community engagement could better reflect residents' concerns.

2. Study Area

The Nsuta mine is located south-east of Tarkwa in the Tarkwa-Nsuaem Municipality of the Western Region of Ghana (**Figure 1**). The company is the sole producer and exporter of manganese in Ghana. It is privately owned, with Consolidated Minerals Africa Limited holding a 90% interest and the Government of Ghana a 10% free-carried interest. The company's manganese concession covers 170 km^2 in and around Nsuta, and less than 3% of this area has been mined so far. The mine has three pits (Pits A, B, and C), and mining is currently confined to Pit C. The nearest host communities, Nsuta Zongo, Akyem and Tarkwa Banso, lie close

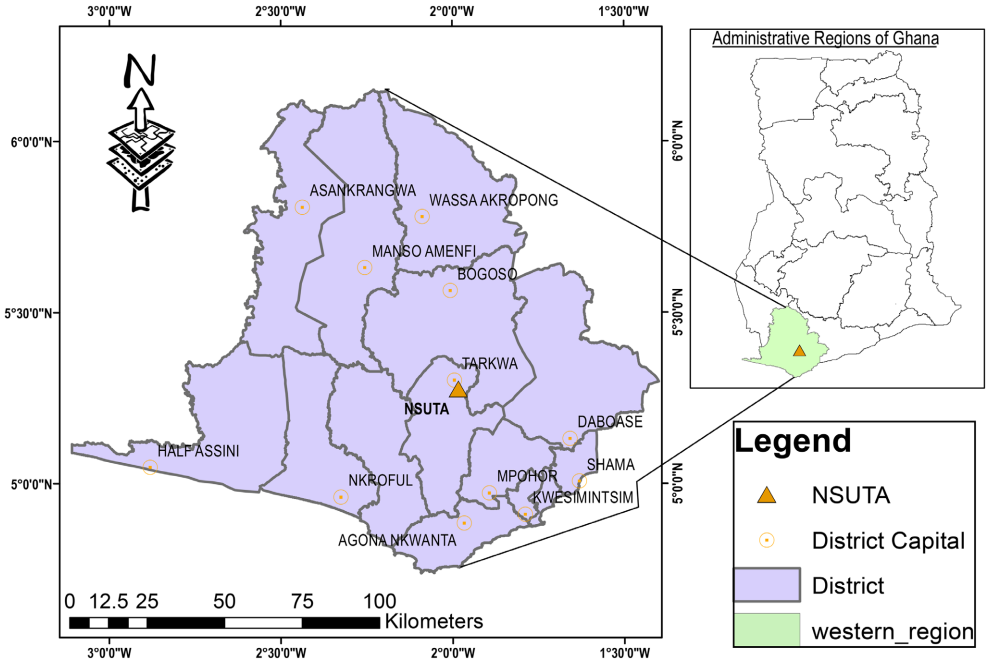


Figure 1. Location of the Nsuta manganese mine in the Tarkwa-Nsuaem Municipality, Western Region, Ghana.

to the active pit. Ore and waste are hauled with 100 t and 150 t Komatsu and CAT haul trucks. Ore is delivered to a run-of-mine (ROM) pad beside the primary crusher at the pit exit, and waste rock is sent to the waste dump.

3. Materials and Methods

3.1. Data Description

The study used two datasets: an instrumented blast monitoring record from the mine and a structured community perception survey.

3.1.1. Blast Monitoring Data

The blast monitoring data came from the mine's blast logs and seismograph records for production blasts fired in Pit C between January and March 2026. The raw records had been compiled monthly and concatenated into one spreadsheet. This left incomplete entries and repeated header rows, which were removed before analysis. The final dataset contained 117 valid production blasts: 43 in January, 34 in February and 40 in March 2026. This matches the number of blasts logged by the mine for the quarter. The dataset is held at blast level: each of the 117 records contains one value of each design, geotechnical and response variable for one blast.

Ground vibration and air overpressure were recorded by the mine's environmental monitoring team with a GeoSonics SSU 3000EZ Plus portable seismograph, at one monitoring point per blast near a structure in the direction of the host communities. The unit records three orthogonal components of particle velocity (longitudinal, transverse and vertical) from an external triaxial geophone, and air

overpressure from a linear 2 Hz high-pass microphone. In its standard configuration, the seismic range extends to 130 mm/s with a resolution of 0.06 mm/s, and the linear acoustic range is 78 to 142 dB(L); lower, higher-resolution ranges are available for both channels, and both channels have a frequency response of 2 to 250 Hz (−3 dB). Stated accuracy within one year of a multi-frequency factory calibration is 5% for the seismic channels and ±10% or 1 dB for the acoustic channel, and the unit has internal dynamic (seismic) and electronic (acoustic) calibration checks (GeoSonics Vibra-Tech, 2026).

The unit was used within 12 months of its factory calibration, in line with ISEE guidance (ISEE, 2017); the calibration certificate is held by the mine's environmental department. The triaxial geophone was oriented so that its three axes matched the source-receiver geometry of each blast. The longitudinal (L) axis, marked by the arrow on top of the geophone, was aligned horizontally along the line from the monitoring point to the centre of the blast, so that the L channel records the radial component of motion. The transverse (T) axis lay horizontally at right angles to that line, and the vertical (V) axis was perpendicular to the levelled base. Because blast locations changed within Pit C, the bearing from the monitoring point to each blast centre was taken from the blast plan and checked with a compass, and the geophone was re-aligned to it before each blast. It was then levelled with its bubble level, since a tilted geophone mixes the components and fails the calibration test. The geophone was placed between the blast and the structure, at least 1.2 m from the foundation, as the manufacturer recommends. ISEE guidance requires burial or rigid fixing when particle acceleration exceeds 0.2 g (ISEE, 2015). At the highest recorded PPV (2.56 mm/s), acceleration stays below 0.2 g for frequencies up to about 120 Hz, well above those expected at 621 m to 1 900 m, so spiking into firm, undisturbed ground gives adequate coupling. The microphone was mounted on its stand about 1 m above ground, fitted with its windscreen and given an unobstructed line to the blast. Before each blast, the unit's calibration test was run, and recording proceeded only when the sound channel and all three seismic channels passed. Recording was triggered by either channel, with a seismic trigger of 0.25 mm/s and an acoustic trigger of 100 dB(L). Blasts with PPV below the seismic trigger were therefore captured through the acoustic channel, and all such records have AOp of about 100 dB(L) or more (Section 4.4.3), while the seismic channel captured blasts with lower AOp. The record length was 10 s, which sets a sampling rate of 500 samples/s per channel and covers the arrival of both ground and air waves at these distances.

For each event, the seismograph reports the peak particle velocity and its frequency on each of the three channels, together with a resultant peak particle velocity (RPPV). The mine's records give one PPV value per blast without stating whether it is the largest component peak or the resultant. Because the resultant is equal to or greater than the largest component, the number of values above 2.0 mm/s depends on which was transcribed, and the seven values above 2.0 mm/s are reported as recorded exceedances of the limit. The records also include PPV

values below 0.06 mm/s (minimum 0.02 mm/s) and AOp values below 78 dB(L) (minimum 76.00 dB(L)). Such values are possible only with one of the lower, higher-resolution ranges, which indicates that the unit was not used in its standard configuration. Whatever the range used, these values lie close to the detection floor and are treated as low-level readings rather than precise measurements. Channel frequencies and individual event reports are held by the mine but were not included in the dataset compiled for this study.

The retained variables were total explosive quantity (kg), number of blast holes, explosive charge per hole (kg), distance to the monitoring point (m), design stemming (m), recorded final stemming (m), UCS (MPa), AOp (dB(L)) and PPV (mm/s). The design stemming was 4 m. Recorded values were compared with the limits of 2.0 mm/s for ground vibration and 117 dB(L) for air overpressure set by Regulation 199 of the Minerals and Mining (Explosives) Regulations, 2012 (Republic of Ghana, 2012). These comparisons apply to the monitored locations and do not establish conditions at every dwelling.

Final stemming was measured in the field after charging, as the length of the unfilled collar above the explosive column, and entered in the blast log as one value per blast. The log does not record how many holes were measured in each blast or how the measurements were combined, so within-blast variation is not represented. UCS was assigned to each blast as the value of the geotechnical domain in which the blast was located, taken from the mine's domain model; it is therefore a domain-level estimate of intact-rock strength, not a measurement at the blast. The test method and specimen count behind the domain values are not documented in the log. Throughout this paper, achieved stemming refers to this field-measured blast-level value. The stemming deficit is defined as 4 m minus that value. Because the deficit is an exact linear transformation of stemming, its correlation with another variable has the same magnitude and opposite sign; deficit plots do not provide independent statistical evidence.

The blasts were drilled with 115 mm vertical holes to an average depth of 10 m on 10 m benches. Burden and spacing ranged from 4 m × 4.5 m in hard rock to 5 m × 5.5 m in soft rock, in a staggered pattern. Holes were bottom-primed with a 250 g Pentolite booster and a 500 ms down-the-hole detonator, and the column was charged with Riomex 7000 emulsion. Initiation used 25 ms surface delays, with 17 ms, 42 ms and 67 ms connectors on the trunk lines. **Table 1** summarises the blast dataset.

3.1.2. Community Perception Data

The survey was conducted in March 2026 in Akyem and Tarkwa Banso, selected purposively as the two host communities nearest the active blasting areas. Nsuta Zongo was not surveyed. Tarkwa Banso includes a company resettlement of 308 houses built for residents relocated from the 500 m buffer around Pit C-North (Ghana Manganese Company, n.d.). The inhabited area of each community defined eligibility. Sixty adults were interviewed in each community, one per household: the household head or another resident aged at least 18 years. Dwellings were

Table 1. Descriptive statistics of the blast monitoring dataset (n = 117).

Parameter	Mean	Median	Std. Dev.	Minimum	Maximum	Range
Quantity of explosive per blast (kg)	6777.72	6354.00	4057.73	48.00	19,642.00	19,594.00
Number of blast holes	90.84	89.00	45.67	9.00	221.00	212.00
Explosive per blast hole (kg)	72.34	75.52	23.11	5.33	144.00	138.67
Distance from blasting point (m)	1292.62	1300.00	318.75	621.00	1900.00	1279.00
Air overpressure, AOp (dB(L))	100.17	103.00	10.06	76.00	115.00	39.00
Ground vibration, PPV (mm/s)	0.56	0.44	0.59	0.02	2.56	2.54
Final stemming length (m)	2.60	2.56	0.45	0.90	3.74	2.84
Stemming deficit (m)	1.40	1.44	0.45	0.26	3.10	2.84
Uniaxial compressive strength, UCS (MPa)	136.86	136.50	12.17	90.40	169.90	79.50

selected at random across each community. No household register was available, so selection probabilities and the response rate could not be calculated, and pooled percentages are unweighted. With 120 respondents, the maximum margin of error for a pooled proportion is about ±8.9 percentage points at 95% confidence, assuming simple random sampling.

The questionnaire was administered by the research team and supported by informal interviews. It had six sections. Section A recorded community, gender, age, education, occupation and length of residence. Section B covered awareness of blasting, frequency of exposure, sources of blast information and adequacy of notice, and asked respondents to rate the overall impact of blasting on their household (no impact, minor, moderate or severe). Section C asked respondents whether they had experienced seven effects: ground vibration, noise or air overpressure, dust, building cracks, disturbance of daily activities, fear or anxiety, and sleep disturbance. Section D asked respondents who reported an effect in Section C to rate its severity on a five-point scale (1 = very low, 5 = very high). Section E measured satisfaction with the mine's blast notification and complaint handling systems and its overall effort to reduce blasting effects. Section F contained open-ended questions on the main effects of blasting and on suggested mitigation measures. The respondent profile is presented in Section 4.5.1.

3.2. Research Framework

The study used a convergent design in which archived blast monitoring data and a structured community survey were analysed separately and compared at the interpretation stage (Creswell & Plano Clark, 2018). Both strands were principally quantitative. Informal interviews and open-ended responses provided context and were not coded formally. The monitoring record covers January to March 2026; the survey was administered in March. The framework comprised four stages:

- Document the operating geometry and identify gaps in the blast records.
- Describe PPV and AOp, compare recorded values with the regulatory limits

and examine associations with the blast variables.

- Describe the prevalence and severity of reported impacts and residents' assessment of notification and complaint handling.
- Compare the two datasets to identify engineering, monitoring and engagement priorities.

3.3. Review of Drill and Blast Practice

The operational description used site records, design documents and consultation with the drill and blast team. It covered geometry, explosives, initiation and reported monitoring practice. Available geometry was expressed as burden-to-diameter, spacing-to-burden, bench-height-to-burden and stemming-to-burden ratios, and compared with indicative rules of thumb (Hustrulid, 1999). These benchmarks are screening references, not statutory requirements or proof of an optimum design. Average hole depth and bench height were also compared, but actual subdrill was not measured hole by hole. The review was not a complete regulatory audit.

3.4. Analysis of Blast Monitoring Data

3.4.1. Descriptive Characterisation

The 117 production blasts were first described using the mean, median, standard deviation, minimum, maximum and range of each variable. Comparing the mean with the median showed whether a variable was skewed. Because the variables have different units and magnitudes, relative dispersion was compared using the coefficient of variation, which expresses the standard deviation as a percentage of the mean. This step established the operating envelope represented by the dataset and showed which response variable was more variable from blast to blast.

3.4.2. Stemming Performance

Recorded stemming deficit was examined as a descriptive indicator of departure from the stated design. Inadequate stemming can contribute to premature gas release, airblast and flyrock, while effects on vibration also depend on charge, timing and burden relief (Hustrulid, 1999). These mechanisms were considered as possible explanations rather than assumed findings. Because stemming was measured at blast level, interpretation applies to blasts rather than individual holes.

3.4.3. Comparison with Regulatory Limits

Recorded PPV and AOp values were compared with the limits of 2.0 mm/s and 117 dB(L). Counts and percentages above each limit were calculated by month and for the full quarter, and both responses were plotted by blast sequence. The proportion of blasts above each limit was given a Wilson 95% interval (Wilson, 1927); for AOp, with no values above the limit, an exact one-sided 95% upper bound was calculated. Monthly exceedance rates were compared with the Freeman-Halton extension of Fisher's exact test. To express the record as household exposure, the per-blast rates were converted into the probability of at least one exceedance in a

month and the expected number of exceedances per year, assuming that blasting continued at the observed rate of 117 blasts in 90 days and that blasts were independent. The number of blasts above 0.3 mm/s, the level at which vibration may be just perceptible in residential environments (BSI, 2014), was bounded from the median PPV.

3.4.4. Correlation Analysis

Pearson correlations measured linear associations among total explosive quantity, number of holes, monitoring distance, recorded stemming, UCS, AOp and PPV, with two-sided tests at the 0.05 level. With n = 117, $|r| \geq 0.18$ is significant at this level. Spearman rank correlations were computed as a check because PPV is right-skewed. Approximate 95% confidence intervals for the principal coefficients were calculated with the Fisher z transformation (Section 4.3). The four associations between the responses and stemming or UCS ($|r| \geq 0.42$) have $p < 0.001$ and remain significant after a Bonferroni correction for the 21 pairwise tests among the seven variables. The correlations describe associations, not independent causal effects.

3.4.5. Analysis of the Strongest Associations

AOp and PPV were plotted against UCS and stemming deficit, least-squares trends were fitted, and R^2 was reported as a measure of bivariate fit. Blasts were grouped at a recorded stemming of 3.0 m for descriptive comparison, and the seven PPV values above 2.0 mm/s were examined separately. Because UCS and stemming were almost collinear, their separate effects were not estimated, and the physical mechanisms discussed in Section 4.4 are treated as hypotheses.

3.4.6. Consistency Checks on the Blast Records

Three checks were made on the internal consistency of the blast records. First, the closeness of the UCS-stemming relationship was examined to judge whether the two variables behave as independent measurements. Second, the first-order partial correlation between AOp and PPV controlling for recorded stemming was calculated from the pairwise coefficients. Third, the charge expected per hole was calculated for a 115 mm, 10 m hole at an assumed bulk emulsion density of 1.15 g/cm^3 and compared with the recorded mean charge per hole. The recorded exceedances were also compared with PPV predicted for the mine in earlier work (Afum & Amegbey, 2015).

3.5. Analysis of Community Perception Data

Survey responses were summarised as counts and percentages of the 120 respondents. Severity was rated on a five-point scale by respondents who reported each effect, and mean severity was calculated over those respondents (Section 4.5.2). A prevalence-severity product, the proportion reporting an effect multiplied by its mean severity, was also calculated to rank effects by their combined breadth and intensity across the sample; it is a descriptive index, not a validated scale. Satisfaction responses were grouped into satisfied (very satisfied and satisfied), neutral

and dissatisfied (dissatisfied and very dissatisfied). Wilson 95% intervals were calculated for selected proportions (Section 4.5.4). Results were tabulated for the pooled sample and for each community. Proportions in Akyem and Tarkwa Banso were compared with Fisher's exact test; differences are reported with hybrid score 95% intervals (Newcombe, 1998) and phi coefficients, and the four-level overall impact rating was compared with the Mann-Whitney U test. With 60 respondents per community, a difference of about 22 to 25 percentage points is needed for 80% power at the 0.05 level, so non-significant differences are interpreted with their intervals rather than as evidence of no difference. Open-ended responses were used to inform interpretation and are not reported as a separate thematic analysis, and the item on the mine's overall mitigation effort is not analysed in this paper.

3.6. Integration of Datasets

Integration consisted of a qualitative comparison of monitoring summaries and survey findings. Records were not linked by blast, dwelling or respondent. A proportion of monitored blasts and a proportion of residents have different units, denominators and reference periods. Their numerical difference therefore describes the gap between compliance and reported experience but is not an effect estimate. The comparison examines the coexistence of mostly low recorded amplitudes and substantial reported disturbance. Possible explanations include perceptible exposure below damage criteria, unmeasured exposure at other dwellings, previous experience and dissatisfaction with communication. Their relative contributions were not estimated.

3.7. Data Processing

Data cleaning, statistical analysis and graphical presentation were carried out in Microsoft Excel and the Python programming language.

4. Results and Discussion

4.1. Characteristics of the Blast Dataset

The 117 production blasts span a wide operating range (Table 1). Total charge per blast varied from 48.00 kg to 19,642.00 kg, and the number of holes varied from 9 to 221, with a mean charge per hole of 72.34 kg. Monitoring distances ranged from 621.00 m to 1900.00 m (mean 1292.62 m), so the records describe far-field responses at the community edge rather than near-field responses at the pit.

The two environmental responses behaved very differently. AOp averaged 100.17 dB(L) with a standard deviation of 10.06 dB(L), and its values were concentrated in a band well below the 117 dB(L) limit. PPV averaged 0.56 mm/s with a median of 0.44 mm/s and had a coefficient of variation of about 105%. Most blasts produced low vibration: 99 of the 117 blasts recorded less than 1.0 mm/s, and 36 recorded less than 0.1 mm/s, close to the detection floor of the instrument. A small number, however, produced values several times the mean. The values above 2.0 mm/s therefore came from occasional high records, not from a high baseline level

of vibration.

Recorded blast-level stemming averaged 2.60 m, ranged from 0.90 m to 3.74 m and was below the 4 m design in all 117 records, a mean deficit of 1.40 m (35% of design). Field-measured stemming therefore fell systematically short of design, a shortfall examined further in Sections 4.3 and 4.4.4. The 4 m design is itself longer than the 3 m reported for the mine in earlier work (Afum & Amegbey, 2015). Recorded UCS ranged from 90.40 MPa to 169.90 MPa (mean 136.86 MPa).

Table 2 compares reported geometry with indicative design benchmarks. Spacing-to-burden ratios were 1.10 to 1.13, and design stemming-to-burden ratios were 0.80 to 1.00. Bench-height-to-burden ratios of 2.0 to 2.5 indicate relatively stiff burdens under the cited rule of thumb. The soft-rock burden was 43.5 hole diameters, above the tabulated indicative range. Average hole depth equalled the stated bench height, but this does not establish the subdrill of individual holes. Earlier work reported 11 m holes and 1 m subdrill (Afum & Amegbey, 2015). Applying the overall recorded mean stemming to the two nominal patterns gives ratios of 0.52 to 0.65; these are illustrative calculations, not rock-type-specific achieved means. Geometry, rock structure, loading and timing require joint assessment through monitored trials rather than prescription from these ratios alone.

Table 2. Blast design parameters compared with common surface blast design guidelines.

Parameter	Hard Rock	Soft Rock	Common Guideline	Assessment
Hole diameter, D (mm)	115	115	–	–
Burden × spacing, B × S (m)	4.0 × 4.5	5.0 × 5.5	–	–
Burden to diameter, B/D	34.8	43.5	About 25 to 40	Soft rock above range
Spacing to burden, S/B	1.13	1.10	1.0 to 1.5	Within range
Stiffness ratio, H/B (H = 10 m)	2.5	2.0	3 or more	Below; stiff burden
Design stemming to burden, T/B	1.00	0.80	About 0.7	At or above indicative value; optimum not established
Illustrative achieved stemming to burden	0.65	0.52	About 0.7	Below guideline
Subdrill (m)	Not measured	Not measured	About 0.3B (1.2 to 1.5)	Cannot assess from average depths
Illustrative powder factor (kg/m^3)	0.40	0.26	Site specific	Earlier work reported 0.50
Charge per delay (kg)	Not recorded	Not recorded	Required for scaled distance	Data gap

Benchmarks are indicative rules of thumb from Hustrulid (1999), not regulatory limits. Illustrative powder factor = overall mean charge per hole (72.34 kg)/(B × S × 10 m); it is not a measured mean for each rock type. Achieved-stemming ratios likewise use the overall mean.

4.2. Recorded Values Relative to Regulatory Limits

Table 3 summarises the PPV and AOp values above the limits by month, and Figure 2 shows both responses by blast sequence with the limits superimposed.

Table 3. Monthly distribution of blasts and recorded values above the regulatory limits.

Month	No. of Blasts	Recorded PPV Values > 2.0 mm/s	Recorded PPV Threshold Exceedance (%)	Recorded AOp Values > 117 dB(L)
January 2026	43	3	6.98	0
February 2026	34	3	8.82	0
March 2026	40	1	2.50	0
Total	117	7	5.98	0

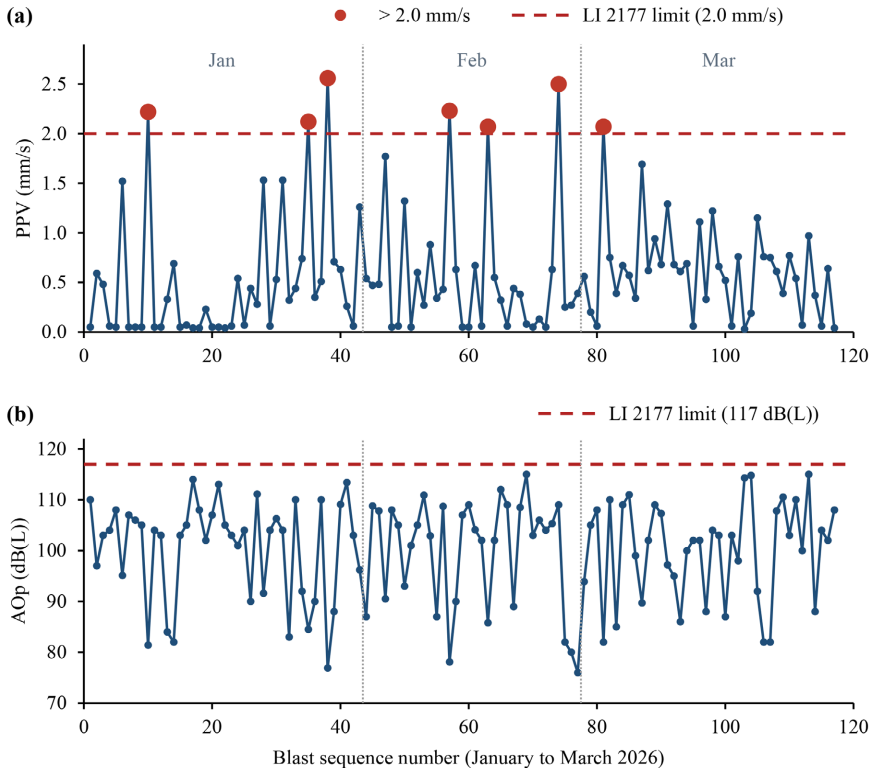


Figure 2. Recorded (a) PPV and (b) AOp for the 117 blasts monitored from January to March 2026, by blast sequence, with the LI 2177 limits shown as dashed lines.

All recorded AOp values were below 117 dB(L), the highest being 115 dB(L); with no values above the limit, the underlying rate is unlikely to exceed about 2.5% of blasts (exact one-sided 95% bound). Seven PPV values (5.98%; 95% CI: 2.9% to 11.8%) exceeded 2.0 mm/s, with a maximum of 2.56 mm/s. Ground vibration, not air overpressure, is therefore the parameter of concern at this operation, subject to confirmation of the PPV metric and review of the seven records.

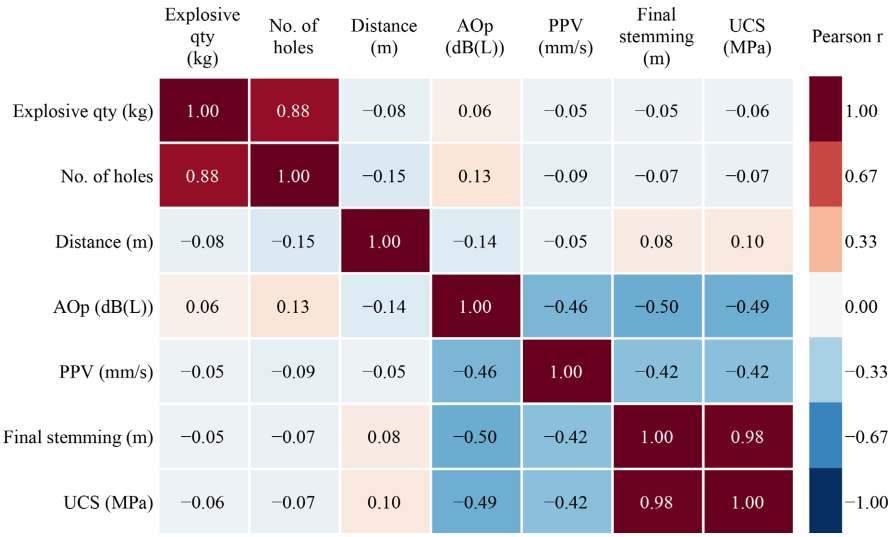
Values above 2.0 mm/s occurred in each month: three in January, three in February and one in March (6.98%, 8.82% and 2.50%). The monthly rates did not differ significantly (Freeman-Halton exact test, $p = 0.56$), and a single quarter is too short to establish a trend. Six of the seven were recorded at 1200 m to 1800 m and one at 626 m, and distance showed little association with PPV (Section 4.3).

Earlier work at the mine predicted PPV of 0.67 to 1.15 mm/s at 400 m for 100

kg per delay (Afum & Amegbey, 2015). Values above 2.0 mm/s at three to four times that distance would require larger charges per delay, local ground amplification, changes in geology or initiation since that study, or records in which the distance or the triggering event does not match the blast. The seismograph reports the frequency of each channel, but these values were not included in the compiled dataset, so frequency-dependent damage criteria (Siskind et al., 1980) could not be applied.

4.3. Correlation Structure of the Blast Parameters

Figure 3 presents the Pearson correlation matrix of the blast parameters and responses. Three features of the matrix are central to the interpretation of the results.



	Explosive qty (kg)	No. of holes	Distance (m)	AOp (dB(L))	PPV (mm/s)	Final stemming (m)	UCS (MPa)
Explosive qty (kg)	1.00	0.88	−0.08	0.06	−0.05	−0.05	−0.06
No. of holes	0.88	1.00	−0.15	0.13	−0.09	−0.07	−0.07
Distance (m)	−0.08	−0.15	1.00	−0.14	−0.05	0.08	0.10
AOp (dB(L))	0.06	0.13	−0.14	1.00	−0.46	−0.50	−0.49
PPV (mm/s)	−0.05	−0.09	−0.05	−0.46	1.00	−0.42	−0.42
Final stemming (m)	−0.05	−0.07	0.08	−0.50	−0.42	1.00	0.98
UCS (MPa)	−0.06	−0.07	0.10	−0.49	−0.42	0.98	1.00

Figure 3. Pearson correlation matrix of blast design parameters, rock strength and blast-induced responses (n = 117).

First, the variables usually expected to control blast-induced effects had almost no explanatory power. Total explosive quantity and number of holes were strongly correlated with each other (r = 0.88), as expected, but neither was meaningfully related to AOp or PPV ($|r| \leq 0.13$, $p > 0.15$). Distance showed only weak, non-significant associations with AOp (r = −0.14) and PPV (r = −0.05). This does not contradict scaled-distance theory, in which charge mass and distance govern vibration and airblast amplitude. Total charge per blast is a poor proxy for the maximum instantaneous charge per delay, which controls peak amplitude, and the monitoring distances fall within a relatively narrow far-field band. Charge per delay was not recorded, so the attenuation relationship could not be tested directly.

Second, final stemming length and UCS showed the strongest associations with both responses. Both were negatively correlated with AOp (r = −0.50 and −0.49) and with PPV (r = −0.42 for each), and all four associations were significant ($p < 0.001$). Because PPV is strongly right-skewed, Spearman rank correlations were

also computed as a check. They gave the same pattern, with coefficients of −0.46 and −0.45 for AOp and −0.47 and −0.48 for PPV, so the relationships are not driven by a few extreme values. Shorter stemming and weaker rock were both associated with higher AOp and higher PPV.

Achieved stemming and UCS were almost perfectly correlated (r = 0.98; 95% CI: 0.97 to 0.99), so their separate associations with the responses cannot be distinguished. Because UCS is a domain value and stemming was measured in the field, the relationship shows that blasts in weaker domains retained less stemming. The fit is unusually close. The least-squares line implied by this coefficient and the descriptive statistics of the dataset predicts stemming of 0.92 m at the lowest UCS (90.40 MPa) and 3.80 m at the highest (169.90 MPa), almost exactly the recorded extremes (0.90 m and 3.74 m). A correlation this strong between a field measurement and a domain-assigned value means that achieved stemming varied mainly between geotechnical domains, with little scatter between blasts within a domain. Two explanations are consistent with this. Collar material may be lost more readily during drilling and charging in weaker domains, or drilling, charging and stemming practice may differ systematically between domains. Both are domain effects, and the data cannot separate them. Stemming and UCS should therefore be read jointly as indicators of geotechnical domain rather than as independent blast-level variables. The relationship also shows that stemming was not increased to compensate for weaker ground. Table 4 presents the Pearson correlation coefficients between the study parameters and their approximate 95% confidence intervals.

Table 4. Principal Pearson correlations with approximate 95% confidence intervals.

Variable Pair	Reported r	Approximate 95% CI
Stemming and AOp	−0.50	−0.62 to −0.35
UCS and AOp	−0.49	−0.62 to −0.34
Stemming and PPV	−0.42	−0.56 to −0.26
UCS and PPV	−0.42	−0.56 to −0.26
Stemming and UCS	0.98	0.97 to 0.99
AOp and PPV	−0.46	−0.59 to −0.30

Intervals were calculated with the Fisher z transformation for n = 117 and assume independent observations.

4.4. Rock Strength, Stemming, and Blast-Induced Responses

4.4.1. Rock Strength

Recorded AOp and PPV decreased as recorded UCS increased (Figure 4). One possible explanation is loss of collar integrity in weaker material, which would shorten the effective stemming column and open paths for gas venting. Collar condition and gas venting were not observed, and UCS is a domain-level intact-rock value rather than a measure of rock mass structure at the blast, so this remains a hypoth-

esis. The seven PPV values above 2.0 mm/s occurred in domains with UCS of 123.60 to 131.60 MPa, below the dataset mean.

4.4.2. Stemming Deficit

AOp and PPV both increased with the recorded stemming deficit (Figure 5). The 19 blasts with recorded stemming of at least 3.0 m had a mean AOp of 86.16 dB(L) and a mean PPV of 0.43 mm/s, against 102.89 dB(L) and 0.59 mm/s for the 98 blasts with less than 3.0 m. Mean AOp was about 17 dB(L) lower in the group with longer recorded stemming. Because recorded stemming tracks UCS so closely, this group is also the group in stronger rock, and the difference cannot be attributed to stemming alone.

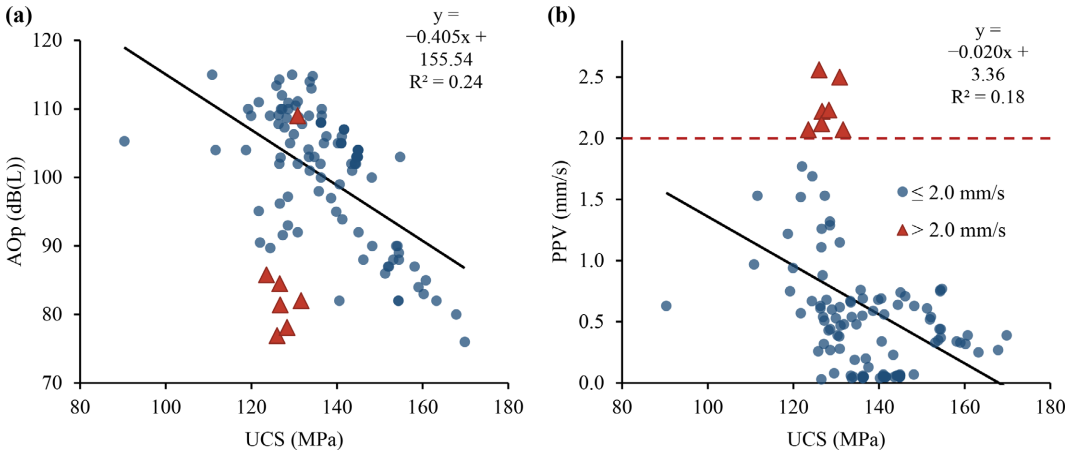


Figure 4. Recorded UCS against (a) AOp and (b) PPV. Triangles mark the seven PPV values above 2.0 mm/s.

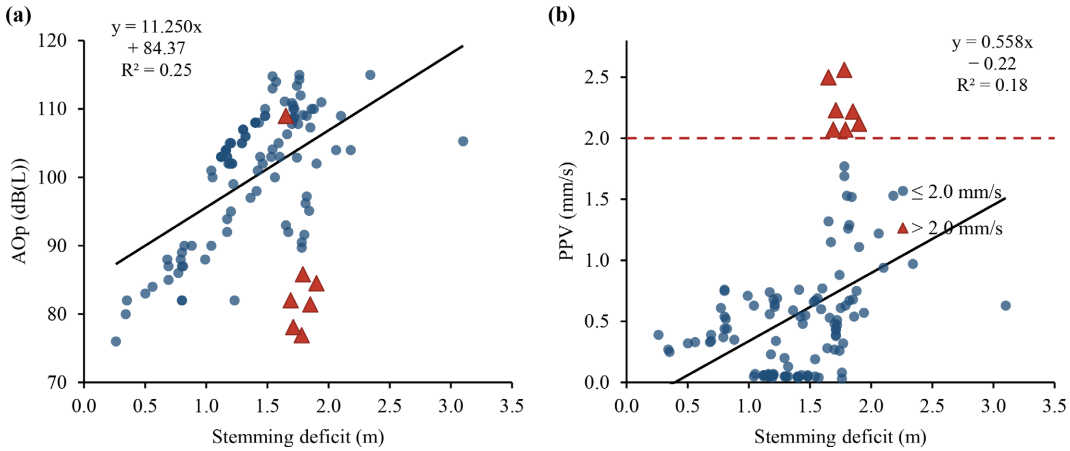


Figure 5. Recorded stemming deficit (4 m minus recorded stemming) against (a) AOp and (b) PPV. Triangles mark the seven PPV values above 2.0 mm/s.

All seven PPV values above 2.0 mm/s combined below-average recorded UCS with an above-average recorded stemming deficit: mean UCS of 127.7 MPa against 136.9 MPa overall, and mean deficit of 1.77 m against 1.40 m. Because the two variables are almost collinear, these are overlapping descriptions rather than independent risk factors, and with charge per delay unrecorded, they do not identify

what caused the high values.

4.4.3. Relationship between Air Overpressure and Ground Vibration

AOp and PPV were themselves negatively correlated (r = −0.46). This is notable because both responses also increased as blast-level stemming decreased. Figure 6 plots PPV against AOp, with each blast shaded by its achieved stemming length.

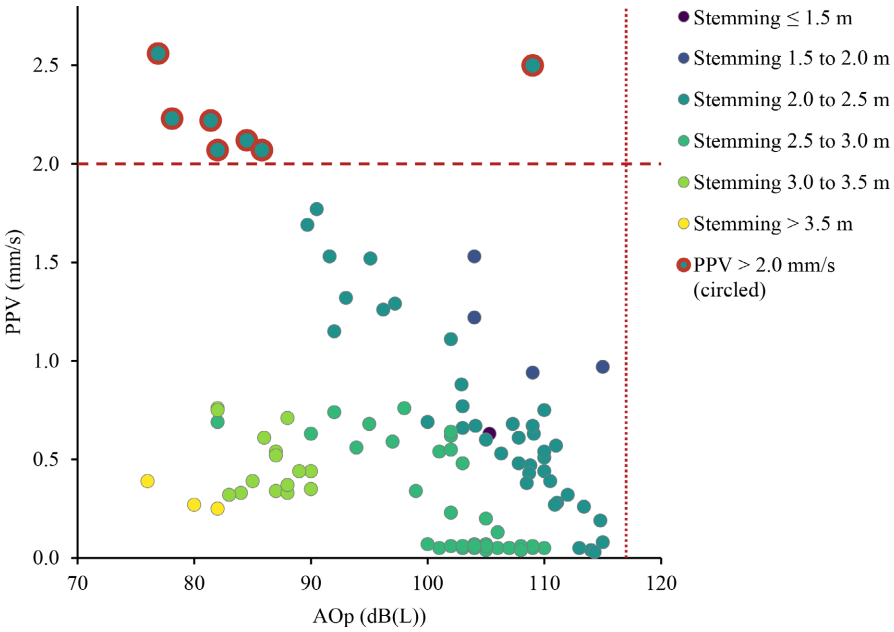


Figure 6. PPV against AOp for each blast, shaded by recorded stemming length. Circled points are the seven PPV values above 2.0 mm/s.

Blasts with the longest recorded stemming tended to have low AOp and low PPV. Among blasts with shorter stemming, six of the seven PPV values above 2.0 mm/s had AOp of only 76.90 to 85.80 dB(L), close to the 78 dB(L) lower limit of the microphone's standard range, while the 17 blasts with AOp of at least 110 dB(L) had a mean recorded stemming of 2.25 m and a mean PPV of 0.34 mm/s. Holding recorded stemming constant, the AOp-PPV partial correlation is about −0.85. A trade-off this strong at a single far-field point is difficult to explain by partitioning of energy between air and ground, which peak amplitudes do not measure. Differences in charge per delay, face orientation, weather, propagation path or monitoring location are more likely contributors, and AOp values near the measurement floor may understate airblast for some blasts. Testing these explanations requires hole-level records, initiation timing, meteorological data and waveforms recorded at more than one location.

4.4.4. Limits of the Statistical Evidence

Because UCS and final stemming length are almost collinear, their separate contributions cannot be isolated with this dataset. The single-variable trends explain only part of the variation in the responses (R^2 of 0.24 to 0.25 for AOp and 0.18 for PPV). Because charge per delay and the other controlling variables listed in Sec-

tion 4.8 were not recorded, the non-significant correlations for total charge and distance therefore do not show that confinement alone governs the responses. The relationships reported here are associations consistent with a confinement-related explanation; they do not establish it and are not a predictive model.

At an assumed density of 1.15 g/cm^3, a fully coupled 115 mm explosive column contains approximately 11.95 kg/m. In a nominal 10 m hole, 4 m stemming leaves 6 m of charge, or about 71.7 kg; 2.60 m stemming leaves 7.4 m, or about 88.4 kg. The reported mean charge per hole was 72.34 kg. These summary-based calculations flag a need for reconciliation, but they do not prove erroneous stemming: actual depth, density, loading, voids, decks and aggregation may differ. A charge of 5.33 kg can represent partial loading and is not physically impossible. A charge of 144 kg exceeds the approximately 119.5 kg capacity of a completely filled nominal 10 m hole under these assumptions and requires checking against actual geometry and density. Secondary blasts, deeper holes or data errors are possibilities, not established explanations. Matched hole-level depth, charge and stemming measurements are needed.

4.4.5. Screening Checklist for Blast Monitoring Archives

The checks applied in Sections 3.1.1, 4.2, 4.3 and 4.4 are summarised in Table 5

Table 5. Screening checklist for blast monitoring archives, with the findings at Nsuta.

Check	What It Tests	Finding in This Study	Action If the Check Fails
1. Instrument configuration	Model, range setting, resolution and calibration documented for every record	Model and calibration documented; range setting not recorded; values below the standard resolution and range present	Record the range setting; flag values near the detection floor
2. PPV metric	Whether the logged PPV is the largest component peak or the resultant	Not stated in the log	Retrieve from event reports and state the metric
3. Frequency	Dominant frequency available for each channel	Recorded by the instrument but absent from the compiled dataset	Retrieve from event reports; apply frequency-dependent criteria
4. Charge per delay	Maximum instantaneous charge recorded for each blast	Not recorded	Record it; required for scaled-distance analysis
5. Charge and geometry	Recorded charge per hole against the charge implied by diameter, depth, density and stemming	Mean charge (72.34 kg) fits the 4 m design, not the measured 2.60 m; extremes exceed hole capacity	Reconcile hole depth, stemming and charge hole by hole
6. Independence of predictors	Correlation between candidate predictors and how each was obtained	Stemming and UCS r = 0.98; UCS is a domain value	Treat as a domain indicator; do not enter both in one model
7. Plausibility of responses	Recorded values against site predictions and attenuation expectations	PPV above 2.0 mm/s at 1200 m to 1 800 m, beyond earlier site predictions	Review waveforms, event times and locations
8. Structure between responses	Partial correlation between responses after controlling for the main predictor	AOp-PPV partial r ≈ −0.85	Check monitoring location, geophone orientation and weather before pooling records

Checks 1 to 4 concern the completeness of the record, checks 5 and 6 its internal consistency, and checks 7 and 8 the plausibility of the responses.

as a screening checklist. Each check can be run on a mine's routine monitoring archive using summary statistics and the instrument documentation, before the data are used for compliance assessment, attenuation modelling or the training of predictive models. At Nsuta, every check identified at least one gap or inconsistency, and none of these would have been visible from the compliance rates alone. Machine learning studies of blast-induced effects frequently draw on archives of this kind (Dumakor-Dupey et al., 2021); screening them first reduces the risk that a model learns recording practice rather than blast behaviour.

4.5. Community Perception of Blasting Impacts

4.5.1. Respondent Profile and Exposure

Table 6 summarises the profile of the 120 respondents.

Table 6. Profile of survey respondents (n = 120).

Characteristic	Category	Respondents (%)
Gender	Male	59.2
	Female	40.8
Age (years)	18 to 30	26.7
	31 to 40	31.7
	41 to 50	23.3
	Above 50	18.3
Education	No formal education	15.0
	Basic	35.8
	Secondary	30.8
	Tertiary	18.3
Length of Residence	Less than 5 years	13.3
	5 to 10 years	24.2
	11 to 20 years	35.0
	More than 20 years	27.5

Men accounted for 59.2% of the surveyed sample. Respondents aged 18 to 40 years accounted for 58.4%, and 50.8% had no more than basic education. Most respondents (62.5%) had lived in their community for more than ten years, including 27.5% for more than twenty years.

Awareness of blasting was reported by 92.5% of respondents, and 65.8% described blast effects as frequent or very frequent (Figure 7(a)). The mine recorded 117 blasts over the 90-day quarter, approximately 1.3 blasts per calendar day. Not every blast is necessarily perceptible at every household. The 7.5% who were unaware of blasting indicate a gap in notification coverage that should be assessed directly. Figure 7(b) shows the overall perceived impact, which is examined in Section 4.5.4.

4.5.2. Prevalence and Severity of Reported Impacts

Ground vibration and noise were the most widely reported effects (86.7% and 83.3%) and had the highest mean severity among those affected (4.31 and 4.14) (Figure 8; Table 7). They also ranked first and second on the prevalence-severity

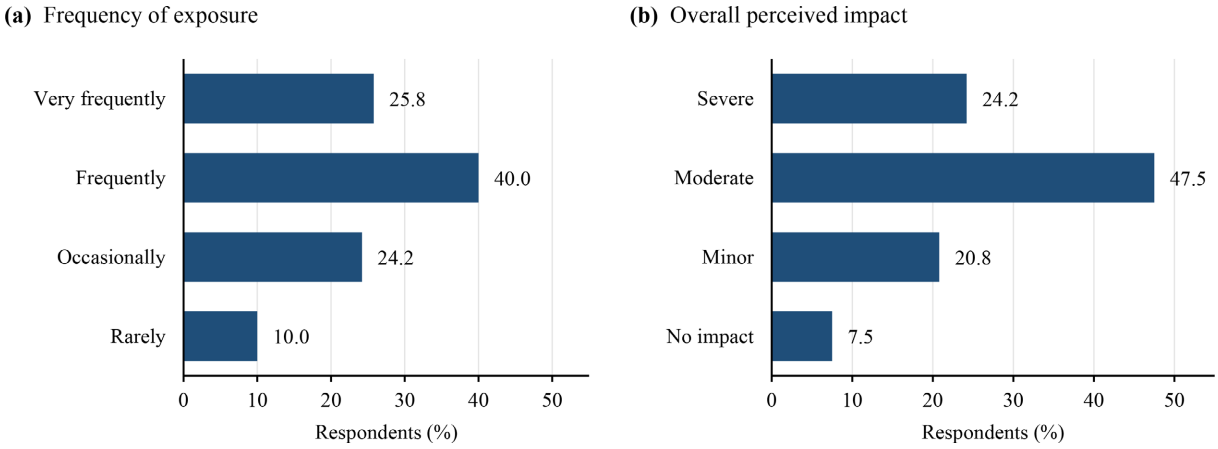


Figure 7. Community responses on (a) frequency of exposure to blast effects and (b) overall perceived impact of blasting.

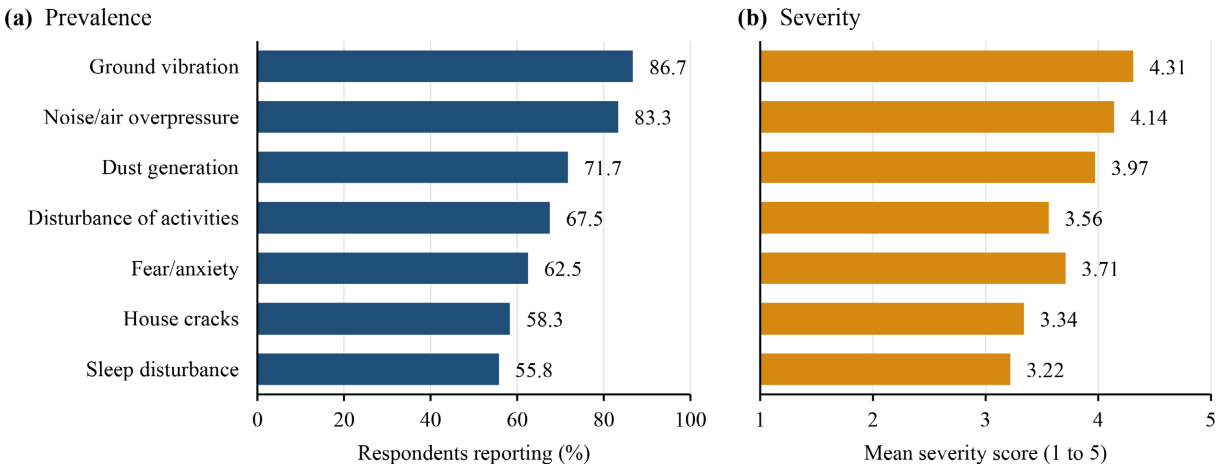


Figure 8. Blast effects reported by respondents: (a) prevalence and (b) mean severity score on a five-point scale.

Table 7. Reported prevalence and severity of effects and an exploratory prevalence-severity product.

Effect	Respondents Reporting, n (%)	Reported Mean Severity among Those Affected	Rank	Exploratory Prevalence-Severity Product	Rank
Ground vibration	104 (86.7)	4.31	1	3.74	1
Noise or air overpressure	100 (83.3)	4.14	2	3.45	2
Dust	86 (71.7)	3.97	3	2.85	3
Disturbance of daily activities	81 (67.5)	3.56	5	2.40	4
Fear or anxiety	75 (62.5)	3.71	4	2.32	5
House cracks	70 (58.3)	3.34	6	1.95	6
Sleep disturbance	67 (55.8)	3.22	7	1.80	7

Mean severity is on a five-point scale (1 = very low, 5 = very high) among respondents reporting each effect. Prevalence-severity product = (number reporting/120) × mean severity.

product. They correspond to the two monitored parameters, PPV and AOp, although reported noise may also include other mine sounds. Residents therefore reported substantial disturbance from the effects, whose recorded values were mostly below the limits. Dust was reported by 71.7% (mean severity 3.97); the survey did not distinguish blast dust from haulage, crushing or other sources.

The psychosocial effects are substantial. Fear or anxiety during blasting was reported by 62.5% of respondents, and those affected rated it more severe than disturbance of daily activities (3.71 against 3.56). Because disturbance of daily activities was more widespread (67.5%), the order of the two is reversed on the prevalence-severity product (2.40 against 2.32). Sleep disturbance was reported by 55.8% of respondents, with a mean severity of 3.22 among them. Residents experience blasting not only as a physical sensation but also as an anticipated event that causes stress. The predictability of blasts and the warning residents receive would be expected to influence this response, although the survey did not test that relationship directly.



Figure 9. Cracks on the exterior (left) and interior (right) walls of a dwelling at Tarkwa Banso, with close-up views, shown as an illustrative example.

House cracks were reported by 58.3% of respondents, with a conditional mean severity of 3.34. **Figure 9** illustrates cracks in one dwelling but does not establish their cause or representativeness. Settlement, moisture, thermal movement, materials, construction quality and age can also contribute to cracking. The study did not inspect building condition systematically or match dwelling exposure to reported damage. Pre- and post-blast condition surveys, structural assessment, exposure records and consideration of alternative causes would provide complementary evidence for evaluating individual claims.

4.5.3. Notification and Complaint Handling

Only 30.8% of respondents were satisfied with notification and 20.8% with complaint handling, while 54.2% and 60.0%, respectively, were dissatisfied (**Figure 10**). Dissatisfaction was higher for complaint handling than for notification. Per-

centages are based on all 120 respondents, including those who had not lodged a complaint. These findings identify engagement priorities, without proving which process contributed most to overall impact.

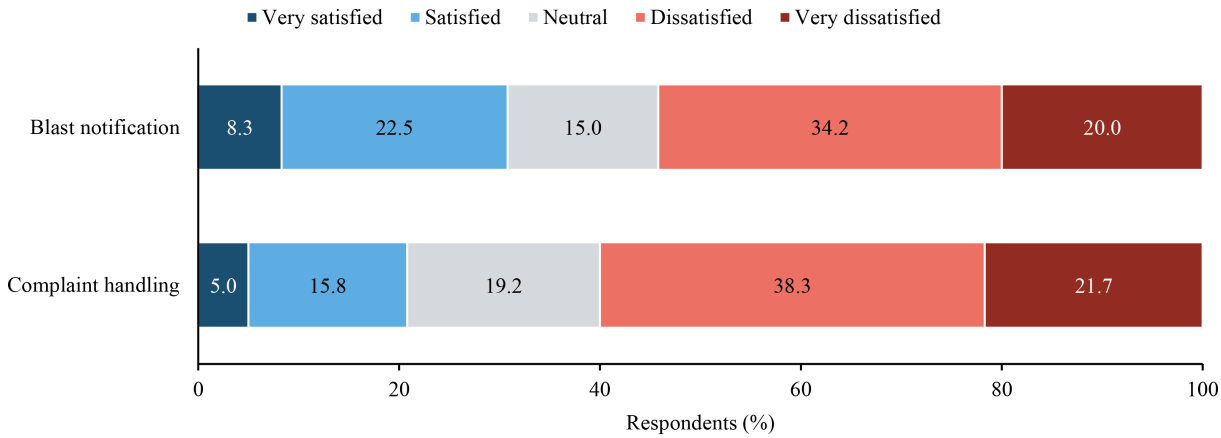


Figure 10. Respondent satisfaction with the mine's blast notification and complaint handling systems.

Notification and complaint handling offer practical opportunities for management action alongside technical monitoring. Accessible local-language announcements, suitable warning signals and clear explanations of blasting schedules should be developed with community input and evaluated for reach and understanding. Any fixed schedule should be consistent with operational safety and communicated when changes occur.

4.5.4. Overall Perceived Impact

In the pooled sample, 71.7% rated the overall impact of blasting as at least moderate (24.2% severe and 47.5% moderate), 20.8% as minor and 7.5% as having no impact (Table 8).

Table 8. Selected survey proportions and nominal 95% Wilson intervals.

Survey Response	Count/120	Sample (%)	Nominal 95% Interval (%)
At least moderate overall impact	86/120	71.7	63.0 to 79.0
Satisfied with notification	37/120	30.8	23.3 to 39.6
Satisfied with complaint handling	25/120	20.8	14.5 to 28.9
Dissatisfied with notification	65/120	54.2	45.3 to 62.8
Dissatisfied with complaint handling	72/120	60.0	51.1 to 68.3
Ground vibration reported	104/120	86.7	79.4 to 91.6
Noise reported	100/120	83.3	75.7 to 88.9

Counts correspond to the reported percentages at n = 120. Intervals were from simple random sampling and do not account for unknown selection probabilities or non-response.

Table 9 and Figure 11 compare the two communities. Tarkwa Banso recorded

higher proportions than Akyem on every indicator, by 6.7 to 10.0 percentage points. Ground vibration was reported by 90.0% in Tarkwa Banso against 83.3% in Akyem, noise by 86.7% against 80.0%, and at least moderate overall impact by 76.7% against 66.7%. None of the differences was statistically significant (Fisher's exact $p = 0.31$ to 0.54), and all effect sizes were small (phi ≤ 0.11). The four-level overall impact rating was also higher in Tarkwa Banso, with 28.3% rating it severe against 20.0% in Akyem and 5.0% reporting no impact against 10.0%, but this difference was not significant either (Mann-Whitney U = 1544, $p = 0.15$, r = 0.13).

Table 9. Reported effects and overall impact by community.

Indicator	Akyem (n = 60), n (%)	Tarkwa Banso (n = 60), n (%)	Total (n = 120), n (%)	Difference, Tarkwa Banso − Akyem (95% CI), Percentage Points	*p*	phi
Ground vibration	50 (83.3)	54 (90.0)	104 (86.7)	6.7 (−5.9 to 19.2)	0.42	0.10
Noise or air overpressure	48 (80.0)	52 (86.7)	100 (83.3)	6.7 (−6.9 to 20.1)	0.46	0.09
Dust	41 (68.3)	45 (75.0)	86 (71.7)	6.7 (−9.4 to 22.3)	0.54	0.07
Disturbance of daily activities	38 (63.3)	43 (71.7)	81 (67.5)	8.3 (−8.3 to 24.4)	0.44	0.09
Fear or anxiety	35 (58.3)	40 (66.7)	75 (62.5)	8.3 (−8.8 to 24.8)	0.45	0.09
House cracks	32 (53.3)	38 (63.3)	70 (58.3)	10.0 (−7.5 to 26.6)	0.35	0.10
Sleep disturbance	31 (51.7)	36 (60.0)	67 (55.8)	8.3 (−9.2 to 25.2)	0.46	0.08
Overall impact at least moderate	40 (66.7)	46 (76.7)	86 (71.7)	10.0 (−6.1 to 25.4)	0.31	0.11

p from two-sided Fisher's exact test. Differences are Tarkwa Banso minus Akyem with 95% confidence intervals; phi is the phi coefficient.

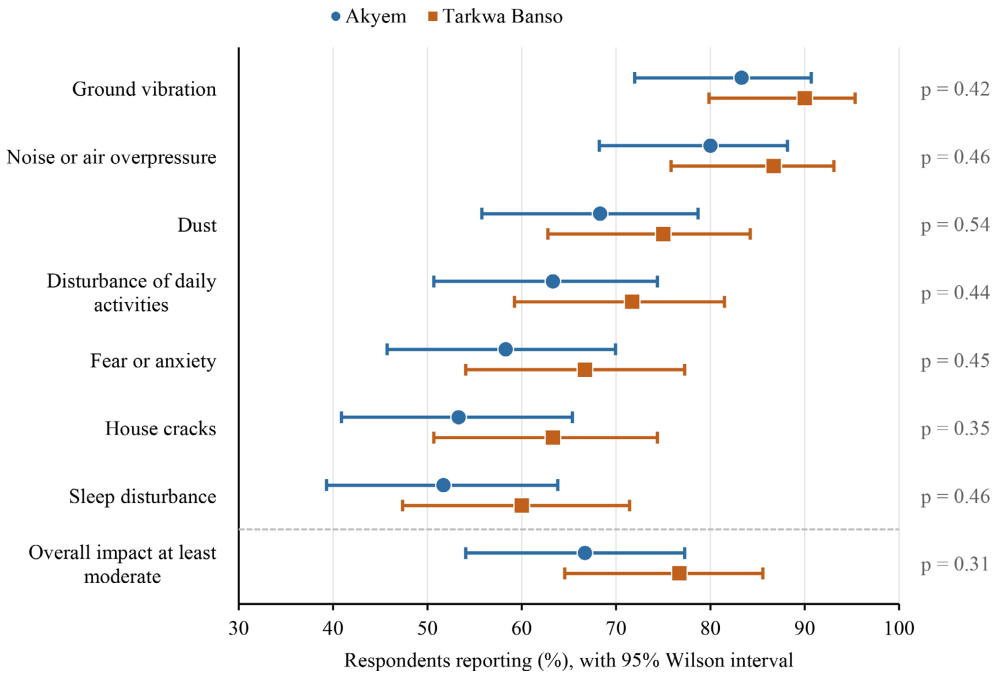


Figure 11. Proportions of respondents reporting each effect and at least moderate overall impact in Akyem and Tarkwa Banso, with 95% Wilson intervals and Fisher's exact *p*-values.

The 95% intervals for the differences extend from about −9 to +27 percentage points, so the data are consistent both with no difference and with a moderate excess of reported impact in Tarkwa Banso. The consistent direction is plausible, since part of Tarkwa Banso is a resettlement for residents moved from the buffer zone of Pit C-North, but household distance to the blasts was not measured, so the difference cannot be attributed to exposure. The two communities therefore reported broadly similar experiences, and mitigation and engagement should cover both, with Tarkwa Banso a reasonable first priority for dwelling condition surveys and additional monitoring points.

4.6. Comparing Recorded Blast Effects with Community Experience

Most recorded amplitudes were below the regulatory limits, yet 71.7% of residents rated the overall impact of blasting as at least moderate. The two figures measure different things, individual blasts at a monitoring point and residents' cumulative experience, so their difference is descriptive. It nonetheless shows that per-blast compliance does not capture how blasting is experienced in these communities.

These results are consistent with the literature on human response to vibration. Of the 117 blasts, 99 produced PPV below 1.0 mm/s, but more than half exceeded the 0.3 mm/s level that BS 5228-2 treats as just perceptible in residential environments (median 0.44 mm/s), and the same guidance expects levels around 1.0 mm/s to cause complaints unless residents are warned and given an explanation (BSI, 2014). At a rate of more than one blast a day, perceptible but compliant events are therefore likely to be noticed repeatedly. By contrast, the highest recorded PPV (2.56 mm/s) was about one-twentieth of the level at which Singh and Roy (2010) observed the first cosmetic cracks in brick-mud-cement houses. The cracking reported by 58.3% of respondents is therefore unlikely to result from single events of the recorded magnitude, although cumulative effects, other causes and higher exposure at unmonitored dwellings cannot be excluded. The widespread dissatisfaction with notification and complaint handling also matches evidence that community acceptance of mining depends on trust and procedural fairness as much as on physical impacts (Moffat & Zhang, 2014), and that Ghanaian communities become more critical of mining once operations begin and communication channels weaken (Lawson & Bentil, 2014).

Expressing the monitoring record as exposure for a household near the monitoring point makes this gap concrete (**Table 10**; **Figure 12**). At the observed rate of about 39 blasts a month, the probability that a month contains at least one PPV value above 2.0 mm/s is 0.91 (0.69 to 0.99 on the interval for the exceedance rate), and it was 0.88 to 0.93 for the three months monitored. A 94% compliance rate therefore still implies an exceedance in most months. If blasting continued at the quarter's rate of about 475 blasts a year, about 28 PPV exceedances (14 to 56) would be expected annually, while AOp exceedances would remain rare, with an upper bound of about 12. Over the same year, at least 239 blasts, or at least 0.66 a day,

Table 10. Exposure measures derived from the monitoring record.

Measure	Value	Basis
PPV values above 2.0 mm/s	7 of 117 (5.98%; 95% CI 2.9% to 11.8%)	Wilson interval
AOp values above 117 dB(L)	0 of 117 (upper 95% bound 2.5% of blasts)	Exact one-sided bound
Difference between monthly PPV exceedance rates	$p = 0.56$	Freeman-Halton exact test
Blasting rate	1.3 per day; about 39 per month; about 475 per year	117 blasts in 90 days
Probability of at least one PPV exceedance in a month	0.91 (0.69 to 0.99); 0.88 to 0.93 in the months monitored	Binomial model at the observed rate and its 95% interval
Expected PPV exceedances per year	About 28 (14 to 56)	Observed rate and its 95% interval
Expected AOp exceedances per year	0 (upper bound about 12)	Upper 95% bound
Blasts above 0.3 mm/s (just perceptible)	At least 59 of 117; at least 0.66 per day; at least 239 per year	Median PPV of 0.44 mm/s; BS 5228-2 guidance (BSI, 2014)

Values assume blasting continues at the observed rate and that blasts are independent; they describe exposure at the monitored location.

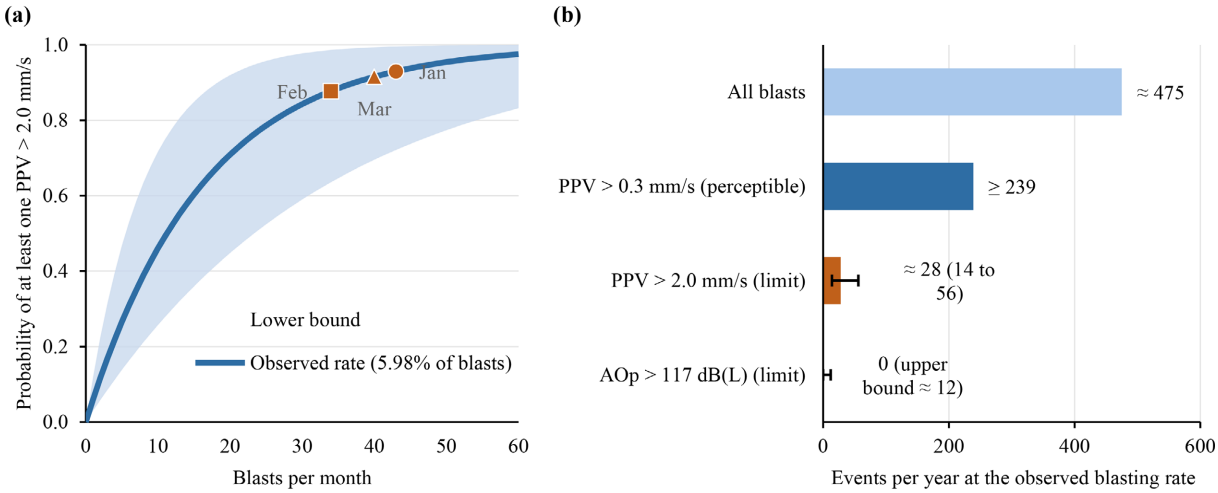


Figure 12. Monitoring record expressed as exposure: (a) probability of at least one PPV value above 2.0 mm/s in a month against the number of blasts per month, with the 95% interval of the exceedance rate and the three months monitored; (b) events per year at the observed blasting rate, with 95% intervals or bounds for the limit exceedances.

would exceed the 0.3 mm/s level at which vibration may be perceptible in residential environments, because more than half of the recorded values were above it. These figures are consistent with the 65.8% of respondents who reported frequent or very frequent exposure, and they explain why residents experience blasting as a near-daily event although few blasts exceed the regulatory limits. They assume a constant blasting rate, independent blasts and exposure similar to that at the monitoring point, and they should be read as orders of magnitude rather than predictions.

Several explanations warrant investigation. People may perceive events below structural damage criteria. Exposure can vary with household location, propaga-

tion path and event timing, and one monitoring point cannot represent every dwelling. The gap is not confined to one community: both Akyem and Tarkwa Banso reported substantial impact, with only small differences between them (Section 4.5.4). Residents may also draw on experience from before the monitoring period, and notification and complaint-handling experiences could influence responses.

The evidence therefore supports parallel priorities without ranking their causal importance. The seven high PPV records, the reconciliation of stemming with hole depth and charge, and the differences in practice between geotechnical domains require technical review. Survey dissatisfaction supports evaluating notification and grievance procedures. Linking georeferenced household responses to verified exposure measurements, building condition and complaint histories would allow more direct assessment of these candidate explanations.

The findings also bear on regulation. LI 2177 sets limits for individual blasts, and compliance is assessed blast by blast at monitored points. Three additions would make compliance reporting more informative to host communities: periodic reporting of the number of perceptible events at community locations alongside per-blast compliance, which at Nsuta would have shown at least 59 perceptible events in the quarter against seven exceedances; minimum standards for advance notification of blasting, which BS 5228-2 already treats as good practice (BSI, 2014); and defined response times for blast-related complaints, with records available to the regulator. These measures would leave the structural damage limits unchanged but would address the part of community experience that those limits do not cover.

4.7. Implications for Blast Management

The findings point to measures in four areas: the verification of blast records, blast design, monitoring and community engagement. Because the evidence is associational, the technical measures are best introduced as monitored trials, so that their effect on both ground vibration and air overpressure is measured rather than assumed.

The first priority is to improve the quality of the blast records on which design decisions rest. Achieved stemming and hole depth should be measured in every hole after charging and reconciled with the charge loaded, so that the shortfall against the 4 m design can be explained and the effects of stemming and rock strength separated. The blast log should also record the maximum charge per delay, delay timing, powder factor, actual burden and spacing, face orientation and weather at the time of firing, which together would allow a site-specific attenuation model to be developed. Domain-level UCS values should be supplemented with bench-level rock strength and rock mass observations at each blast, and the testing behind the domain values should be documented.

With these records in place, drilling, charging and stemming practice can be compared between geotechnical domains, and trials of stemming practice designed where the comparison reveals systematic differences. Stemming, burden relief and

delay timing should be evaluated together within these trials, without assuming that an improvement in one response will necessarily worsen the other, and any change should be assessed against the approved design and the measured outcome.

Monitoring should be strengthened in three respects. The waveforms, component channels, event times, locations and instrument records of the seven PPV values above 2.0 mm/s should be reviewed first, so that any redesign rests on verified exceedances. Additional monitoring points within Akyem and Tarkwa Banso would record exposure at more than one bearing and distance for each blast and provide a firmer basis for relating measured levels to residents' experience. Pre- and post-blast condition surveys of dwellings within the zone of influence, beginning with those nearest the active pit, would allow claims of structural damage to be assessed on evidence.

Community engagement requires equal attention, because dissatisfaction with notification and complaint handling was widespread in both communities. A logged complaint management system with a defined response time, a designated community liaison officer and feedback to each complainant would make the handling of grievances visible and accountable. Notification methods, such as sirens, oral announcements in the local language and a published blasting schedule, should be developed with residents and evaluated for their reach and understanding. Finally, georeferencing surveyed households and repeating the perception survey after the technical and communication measures are introduced would allow the separate effects of these measures on reported impact to be evaluated.

4.8. Limitations

The record covers one quarter and cannot show seasonal or long-term patterns. Maximum charge per delay, initiation timing, actual geometry, face orientation and weather were not recorded, so the scaled-distance relationship could not be evaluated. Stemming was measured at blast level without a documented sample size per blast, UCS is a domain value rather than a blast-level measurement, and the near-collinearity of the two prevents separate interpretation. Individual event reports, channel frequencies and the PPV metric used in the records were not part of the compiled dataset; the measurement range setting was not recorded, and some PPV and AOp values lie close to the detection floor. Measurements at one location per blast do not describe exposure at every dwelling, and peak amplitudes do not quantify radiated energy. The correlation intervals and the partial correlation were calculated from rounded coefficients, and the annual exposure estimates assume a constant blasting rate and independent blasts.

The cross-sectional survey is subject to recall, attribution, selection and non-response bias. No household register was available, so selection probabilities and the response rate could not be calculated, and equal allocation between communities was not population-weighted. Wilson intervals assume simple random sampling, and the prevalence-severity product is a descriptive index. Responses were

not linked to individual blasts or to exposure at each dwelling. The comparison between Akyem and Tarkwa Banso could detect only differences of about 22 to 25 percentage points, and because it used community-level counts, the separate contributions of exposure and satisfaction to perceived impact were not modelled at respondent level. Nsuta Zongo was not surveyed, dust sources were not distinguished, damage was not assessed structurally, and informal interview material was not coded formally.

5. Conclusion

This case study compared records of 117 production blasts with the reported experience of 120 residents near the Nsuta manganese mine. All recorded AOp values were below the 117 dB(L) limit, and seven PPV values (5.98%) exceeded 2.0 mm/s, making ground vibration the parameter of concern. Six of these were recorded at 1 200 m to 1 800 m, and they should be confirmed by waveform review and by establishing the PPV metric.

Recorded stemming and UCS had the strongest associations with both responses but were almost perfectly correlated, so their effects could not be separated. Recorded stemming averaged 2.60 m against a 4 m design, while charge per hole was consistent with the design length. Reconciling field-measured stemming with hole depth and charge is therefore the first technical priority. Achieved stemming was lowest in the weakest geotechnical domains, consistent with loss of collar confinement in weaker ground or with differences in practice between domains; this and energy partitioning remain hypotheses until hole-level records and bench-level rock strength are available. Total charge and distance showed no significant associations, but charge per delay was not recorded, and their physical importance was not tested.

Despite mostly low recorded amplitudes, 71.7% of residents rated the overall impact of blasting as at least moderate; ground vibration and noise were the most common and most severe effects, and satisfaction with notification (30.8%) and complaint handling (20.8%) was low. Tarkwa Banso reported higher proportions than Akyem on every indicator, by 6.7 to 10.0 percentage points, but none of these differences was significant, so the two communities reported broadly similar experiences. At the observed blasting rate, the record implies at least 239 perceptible blasts and about 28 PPV exceedances a year at the monitored location, with an exceedance in most months. Per-blast compliance therefore does not describe community experience at this mine. The relative contributions of physical exposure and communication could not be estimated because the datasets are not linked.

The screening checklist developed here identified at least one gap or inconsistency in every check applied to the mine's monitoring archive. Applying such checks before archives are used for compliance assessment or predictive modelling, and adding reporting of perceptible events, notification standards and complaint-response times to compliance under LI 2177, would make blast management more reliable and more responsive to host communities.

The practical priorities are to record charge per delay and the depth, stemming and charge of each hole, retrieve the channel frequencies and PPV metric from the seismograph event reports, add monitoring points within the communities, and improve notification and complaint handling with residents. Future work should link georeferenced household responses, dwelling condition and measured exposure, and evaluate technical and engagement measures through monitored follow-up.

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Ethics Statement

The survey was conducted in accordance with the research ethics requirements of the University of Mines and Technology, Tarkwa. Participation was voluntary; the purpose of the study was explained to each respondent, informed verbal consent was obtained before the interview, and no personal identifiers were recorded.

Data Availability

The blast monitoring data were provided by Ghana Manganese Company Limited and are available from the corresponding author on reasonable request, subject to the permission of the company. The anonymised survey data are available from the corresponding author on reasonable request.

Author Contributions

All authors contributed to the study conception and design, data collection, analysis and preparation of the manuscript, and read and approved the final version.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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