



The blast-induced noise and ground vibration structural and human response: A case for the South African mud house homes

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Dates:

Received: 5 Oct. 2022

Revised: 24 Feb. 2025

Accepted: 4 Dec. 2025

Published: December 2025

How to cite:

Gumede, X. 2025. The blast-induced noise and ground vibration structural and human response: A case for the South African mud house homes. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 125, no. 12, pp. 737–748

DOI ID:

<https://doi.org/10.17159/2411-9717/2354/2025>

Abstract

Mud houses are common structures in most South African rural homes closer to the mining operations. Fulltime dwellers in these properties are often the elderly. The mine codes of practice and the South African legislative instruments attempt to define the damage criteria to limit the effect of the blast-induced noise and ground vibrations to different structures. All these assessment criteria are based on the peak particle velocity and noise generated during blasting. The South African safe limit criterion that was adopted was initially derived from the international standards, which were then used as a local guideline. This paper evaluates the currently adopted safe limit criteria used in South Africa for a mud house, currently rated at 6 mm per second and 120 decibels to 134 decibels, for blast-induced seismicity and noise, respectively. Further, a study was performed on a residential house near a coal mine (5.26 km) based in Mpumalanga following numerous complaints by the owner, launched at the mine and to the Department of Minerals and Petroleum Resources. The aim of the study was to measure the magnitude of blast-induced triggers experienced at the aggrieved homestead and to establish if there is a likelihood that an irritation or damage may be caused by these triggers. The seismometer was installed at about 2 m from the mudhouse, from 1 July 2022 to 31 of July 2022. Five blast-induced triggers were recorded during the period showing an average of 0.09 mm/s and 121 decibels for blast-induced seismicity and noise, respectively. The results obtained indicated a maximum seismicity of 0.15 mm/s. This seismicity was below the perceptible vibrations obtained from daily home activities such as walking, jumping, and door slamming, which produce 0.8 mm/s, 7.1 mm/s, and 12.7 mm/s, respectively. Seismicity was therefore not likely to have caused any annoyance and or damage. For noise, the results indicated a maximum of 123 decibels and an average of 121 decibels from five events recorded. A literature review suggests that slight damage may occur when airblast frequencies match the natural frequencies of structures at 120 decibels. Based on these results, it can be concluded, therefore, that the noise, rather than seismicity, is more likely to be the cause of damage to the structure assessed. For improvement, a new approach is proposed based on relating the safe limits to the structural and human response.

Keywords

mud houses, South African rural homes, safe limit criteria, structural response, blast induced annoyance and damage

Introduction

Blasting is a common rock breaking technique used in mining. It provides the primary energy required to break the rock into fragmentation sizes as may be required by the subsequent downstream mining value chain processes¹. During blasting, a large quantity of energy is released. The corresponding pressure and temperature produced during blasting is approximately 50 GPa at about 230°C, respectively (Prashanth, Nimaje, 2018). Only 20%–30% of the explosive energy² is used to break the rock. The rest of the energy is dissipated through ground vibration, fly rocks, back breaks, and air overpressure (Prashanth, Nimaje, 2018). A wave train is generated when explosive charges are detonated in a solid medium such as a rock. These waves generate different particle movements and travel at different wave velocities. The resulting ground-borne vibrations may have an effect on residential buildings. The effect may range from negligible effects to severe threshold human and structural impact. Different

¹The downstream processes include loading of the muck-pile, hauling and primary–tertiary beneficiation.

²Useful energy is the energy used to break and move the rock according to the blast design distance and muck-pile profile or shape (International Society of Explosives Engineering, 2021).

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structures and people respond differently to the blast-induced noise and ground vibration. The magnitude of the impact is therefore dependent on the structural or human response. The blast-induced noise and ground vibration is the principal public mining nuisance. It may scare people and livestock and damage or even collapse structures near the blasting source (Yan et al., 2016).

The blast-induced noise and ground vibration are a major source of complaints from the communities staying closer to the mines. The common complaints are as a result of structural damages believed to be caused by the blasting activities from the mine. Between the mines and complainants, it is a common cause that blasting generates ground vibration and noise. The noise and ground vibration may have a damaging effect on both structures and humans. Many countries established their own national standards to guard against the blast-induced noise and ground vibration impact. The countries that do not have their own standards usually adopt the set limits from countries that have. South Africa is one of the countries that, during the time of this study, did not have its own standards for blast-induced noise and ground vibration. South Africa has adopted the widely used United States Bureau of Mines Standard (USBM-RI 8507) to control the blast-induced noise and the ground vibration impact from mines on the communities and structures in close proximity to the mining operations. While different international standards cover the structural impact of blasting, there is still no internationally accepted blasting vibration assessment criteria on humans and specific structures of a unique design. The underplaying of the human impact factors in the then set limited criteria suggested that the houses near the mines were treated as structures and not as homes where humans stay. The criteria were focused on guarding against structural damages and omit the psychological, emotional, and physical impacts that the people who stay in these homes are likely to suffer.

The blast-induced noise- and ground vibration-related complaints trigger civil disputes between inhabitants and mining companies. The disputes between the inhabitants and the mining companies pose a direct threat to the South African economy. For this reason, this study suggests that blasting must be strictly controlled in environmentally sensitive areas. Engineering controls based on well-established scientific knowledge must be applied. Administrative controls must be used to further address technical issues and other challenges that may be encountered.

Objectives of the study

The objectives of this study were:

- To evaluate the currently adopted safe limit criteria used in South Africa for a mud house.
- To measure the magnitude of the blast-induced noise and seismicity at the mudhouse homestead.
- To assess the likely cause for damage and or annoyance.
- Make appropriate recommendation.

International standards on blast-induced noise and ground vibration

A large number of studies in the area of blast-induced noise and seismicity have been conducted since the early 1920s. The studies aimed to investigate the impact of the blast-induced noise and ground vibration on structures and their response (Sayed-Ahmed, Naji, 2006). Various standards and codes of practice were established as a result of the studies. These standards proposed different safe limits for the blast-induced noise and seismic impact on structures and humans. The main international standards used

are the United States Bureau of Mines Standard (USBM), the United States Office of Surface Mining (OSM), the British Standard, and German and Swiss Standards (Yan et al., 2016). China National Standard (GB6722-2014, 2014), India CMRS (Dhar et al., 1993) and Australian Standards (CA 23,1967) are not widely used but are internationally recognised.

The United States Bureau of Mines standard, commonly known as USBM-RI 8507, is a widely adopted criterion (Dowding et al., 2018). It is a standard criterion for safe limits against structural and threshold damage of buildings due to ground vibrations generated by blasting. After implementing this criterion, it was important to assess the structural and human responses. This initial state of the USBM criterion could not prevent the frequent complaints from residents complaining about blast-induced seismicity impact. An alternative USBM frequency-based safe limit was proposed, which took into account the effect of the dominant vibration frequency to assess the effect of ground vibration on structures (Siskind et al., 1980). The USBM-RI 8507 criterion was modified in 1992 by the US Office of Surface Mining (OSM) to reflect updated methodologies and findings in the assessment of geological and geotechnical conditions relevant to mining operations. Also, the modification was based on the scaled distance formula³, which considers the number of explosives per delay and the distance between the structure and the blast. The scaled distance method is considered as the conservative peak particle velocity (PPV) prediction method (Sayed-Ahmed, Naji, 2006). Britain uses the British Standard BS 7385 criterion for safe limit against blast-induced ground vibrations. This standard is comparable to the OSM criterion. The BS 7385 criterion separates buildings according to their sizes. This is done by adopting two lines for the safe limit, which are for large and small buildings (Sayed-Ahmed, Naji, 2006). Another commonly used standard is the German and Swiss Standards Criterion the DIN 4150. The two criteria are significantly conservative compared to the American and British criteria (Sayed-Ahmed, Naji, 2006). It is generally argued that the DIN 4150 criterion is not damage-based but rather intended to minimise the perceptions and complaints of house residents who live adjacent to blasting sites (Sayed-Ahmed, Naji, 2006).

The four main blast-induced monitoring standards were developed by four countries, namely the United States of America (USBM and OSM), Britain (BS 7385), Germany, and Switzerland (DIN 4150). The USBM and the OSM came about from a technical exercise, i.e., a 10-year research programme. It was aimed at establishing the safe limits for mainly structures, with the expectation that, once the safe limits had been established, the human complaints would be resolved. This goal was not achieved as the complaints from people residing closer to the mines continued (Yan et al., 2017). The British proposed the idea that the size of the house matters. The BS 7385 introduced a two-lines method for the smaller and larger buildings. This was not based on in-depth research such as that of the USBM. The American and British standards may be seen as a technical approach in solving the blast-induced noise and seismicity impact on structures and

³PPV, is the forecast peak particle velocity defined by the equation $a \left(\frac{R}{\sqrt{W}} \right)^{-b}$. The factor $\frac{R}{\sqrt{W}}$. The factor R/\sqrt{W} defines the scaled distance. R is the distance from the blast to the structure. W is the mass of charge per delay in kg. The constants a and b are site-specific constants that are a function of the transmission properties of the rock mass. The standard values for a and b are 0.800 and 1.600 for predictive assessment prior to the establishment of actual values.

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humans. The Germans and Swiss seem to have followed a tactical approach as opposed to a technical approach, in that they applied an engineering judgement on an already established technical content. Their approach can be equated to a stakeholder management administrative tool that seeks to manage the conflict between the mine and residents.

South African standards and guidelines on blast-induced noise and ground vibration

South Africa did not have a standard for the blast-induced noise and ground vibration (DMRE, 2020). This regulatory void prompted the Mining Regulations Advisory Committee (MRAC) to establish a task team to facilitate the development of the guidance note on a minimum standard regarding ground vibration, noise, airblast, and flyrock (Department of Mineral Resources Mine Health and Safety Inspectorate, 2020). This guideline was developed to provide a framework to manage the risk of ground vibration, noise, air blast, and flyrock. No in-depth local research was done, such as in the case of the USBM, but instead, the guidance note was designed around best practices, principles, and standards. It was developed for the mining industry to align with international best practices and current South African mining laws.

The Mine Health and Safety Act (MHSA) of 1996 (Department of Mineral Resources, 2020) makes provisions in the interest of safety for the people not working at the mine who may be affected by the activities at the mine. Section 5(2) of the MHSA provides that, as far as reasonably practical, every employer must identify relevant hazards and assess the risk to which persons who are not employees may be exposed. It further requires the employer to ensure that persons who are not employees, but who may be affected by the activities at the mine, are not exposed to any hazard to their health and safety. According to the MHSA Regulation 4.16(2), blasting within 500 m of surface structures must be protected. The Department of Mineral and Petroleum Resources (DMPR) directive released on 27 February 2020 requires that all opencast mines in Mpumalanga, operating within close proximity to the communities (within 500 m–2000 m), must ensure the protection of their structures, specifically from blast-induced hazards. The Government Gazette issued on 2 August 2024 directed that all opencast mines operating within a 2,000 m proximity to the communities develop and implement a mandatory code of practice (MCOP) according to the guidelines provided by the DMPR for the minimum standards on ground vibrations, noise, air-blast and flyrock near surface structures and communities to be protected, effective from 1 November 2024. The MCOP developed in accordance with the DMPR guidelines is used as a self-regulatory instrument by the mines and the DMPR to enforce compliance and protection of the structures and communities. Furthermore, the South African standard for ground-borne vibration measurements exists as part of the South African National Standard (SANS) 4866:2011). The South African Bureau of Standards adopted standard ISO4866 of the International Organisation for Standardisation (ISO). This standard provides guidelines for measuring vibrations and evaluating their effects on fixed structures but does not provide safe vibration limits on structures.

Prior to the implementation of the MCOP, the USBM standard R18507 was the adopted standard in South African. It was generally used as a guideline to assess whether ground vibrations exceed safe limits. According to the Mine Health and Safety Inspectorate (2020), the South African mining communities were generally unhappy with the standards used. The damage and/or deterioration

of their buildings were continuing, allegedly, as a result of the blasting activities from the mine. The MHSI (2020) further stated that the communities reported that they generally do not receive warnings of blasting activities. They experience anxiety and fear due to sudden blasting without prior notice. The procedures for lodging complaints were not clear to the community members, and they had little hope of recourse should they not receive a satisfactory response from the mine. Community surveys show that there are high levels of distrust between the communities and the mines (MHSI, 2020).

It was concluded that, before those of 1 of November 2024b, there were no statutory limits laid down in South African law concerning the blast-induced noise and seismicity safe limits for structures and humans. The onus was placed on the mine owner to ensure that the blasting operations do not cause damage to private property. The mine owner, in turn, relies on advice from experts such as engineers employed by the major suppliers of explosives or independent consultants (MHSI, 2020). The recent (1 November 2024) MCOP guidelines has provided guidance on the overall management of blast-induced noise, airblast, ground vibration and flyrock. Even with this intervention, it seems like there are still gaps within the system that have not been well addressed.

The prediction algorithms and structural response

Ground vibrations are the inevitable results of confined explosions. The rock close to the borehole is crushed or fractured (typically in the zone within 30-times that of the hole diameter) (Altunışık et al., 2021). A proportion of the energy is radiated as elastic energy in the form of compressional (P) and shear (S) waves (International Society of Explosives Engineering, 2021). Any vibrational energy that travels beyond the zone of rock breakage is wasted, only causing annoyance and damage (Mpofu et al., 2021). The class of seismic waves that distort the earth's surface most severely are known as surface waves. Surface waves have both vertical and horizontal compressional components of shear. Their effect on buildings depends on the wavelength of the waves, the footprint, and the height of the buildings (Adepitan et al., 2018). The seismic wavelength, in turn, depends on the charge mass, the seismic velocity of the rock, and soil that comprises the near-surface layer of the earth, which is usually the uppermost 10 m–30 m (Behzadafshar et al., 2018). Surface wave velocities (c) for near-surface materials typically range from 200 m/s (alluvium) to 2,000 m/s (slightly weathered granite). The particle velocity (V) is entirely different from wave velocity (c). The frequencies (f) produced by a typical blast in an open cast mine range from 5 Hz–200 Hz (Behzadafshar et al., 2018). The wavelength (C) = c/f thus ranges from 1 m to 400 m. The potential to cause damage to buildings is greatest when the wavelength is of the same order as the footprint of the building (Yan et al., 2021). The potential to cause damage to buildings is most closely correlated with the peak particle velocity (PPV). The damage is not only to structures, as this study also seeks to focus on the human element. Dowding et al. (2018) state that humans can detect ground motions with PPV as low as 0.8 mm/s. Buildings may experience cosmetic damage at PPV of 10 mm/s at frequencies of 10 Hz. Severe structural damage may occur when PPV exceeds 200 mm/s (Adepitan et al., 2021).

Particle velocity (V) depends on the amount of energy released by the explosive and the distance from the blast. The intensity of PPV is influenced by several parameters, namely, physical properties of rock mass, explosive characteristics, and blast design parameters like spacing, burden, number of holes, hole diameter,

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hole depth, distance from blast source, maximum explosive charge per delay, delay time, and stemming (International Society of Explosives Engineering, 2021). In light of the aforementioned, blast-induced ground vibration evaluation and prediction are important for the prevention of substantial damage to surrounding structures and dwellings. Several researchers have suggested various methods and empirical predictors to control the harm of ground vibration levels during blasting. All the empirical predictors are based on the maximum charge per delay and the distance from the blasting source to the structure (Adepitan et al., 2021). The vibration safety criterion should be established first to evaluate the blast-induced dynamic response effect and prevent the structures from being damaged. A scientific survey on representative houses and cracks should be conducted before and after blasting. This must be accompanied by understanding the demographics and other conditions of those who live in those properties. The study that seeks to establish the structural and human conditions of the surrounding mine communities is referred to as a pre-blast structural and census survey.

The prediction and response of the structure to blast-induced seismicity is done through an established mathematical logic. Under the action of stress wave, the tensile stress is generally responsible for cracking or damaging of structures, and particle velocities and frequencies are typically monitored during blasting (Dowding et al., 2028). Therefore, calculations based on plane wave conditions may provide a simple relation between measured particle velocities, frequencies, and expected response of the structures (Yan et al., 2016). Equation 1 expresses the one-dimensional stress wave theory:

$$\delta = \rho C_R V \quad [1]$$

where σ represents stress, Pa; ρ is the average density of stress wave spreading field, kg/m^3 ; C_R is the average surface wave velocity, m/s, and V is the absolute value of the PPV at a certain distance away from blast source, which is dependent on the surface seismic wave propagation, m/s. Once the dynamic tensile strength of the protected structure (δ_t) is given, Equation 1 can be rewritten as follows:

$$V = \frac{\delta_t}{\rho C_R} \quad [2]$$

The relationships among the propagating velocity of P wave (C_P) and S wave (C_S), dynamic elastic modulus of medium (E), and dynamical Poisson's ratio of medium (μ) are as follows:

$$C_P = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad [3]$$

$$C_S = \sqrt{\frac{E}{2\rho(1+\mu)}} \quad [4]$$

$$C_P = \sqrt{\frac{E(1-\mu) \cdot 2}{2 \cdot \rho(1+\mu)(1-2\mu)}} \quad [5]$$

Substituting Equation 4 into Equation 5 obtains Equation 6:

$$C_S = C_P \sqrt{\frac{1-2\mu}{2(1-\mu)}} \quad [6]$$

Surface waves are called Rayleigh waves. They travel along the surface of a solid medium, unlike body waves (P-waves and S-waves), which travel through the interior. The velocity of the R wave (C_R) is independent of frequency and is related to the elastic

constants of the medium. It can be approximately calculated with Equation 7:

$$C_R \approx 0.9C_S \quad [7]$$

Houses with weaker foundations or even soil foundations have weak shock resistance capability (Yan et al., 2016). The value $\mu = 0.23$, the average density of stress wave transmitting field ρ is 2500 kg/m^3 , and the velocity of P wave (C_P) is about 3000 m/s – 3500 m/s (Xu, 2012). The dynamic tensile strength of foundations can be thought of about $1/10$ – $1/20$ of seriously weathered rock mass (namely $\delta_t = 0.05 - 0.1 \text{ MPa}$) (Yan et al., 2016). This mathematical logic presents important information that could assist in guiding the establishment of the South African mud house blast-induced seismicity safe limits as proposed in this study. Isolated practical experiments conducted internationally and locally could be used to form a practical base that would be weighed against the theoretical base.

Human response to blast-induced noise and seismicity

According to Yan et al. (2016) humans can perceive ground vibration at levels as low as 0.8 mm/s . This is lower than the vibration level, damaging even the most fragile structures. It is important to understand human perception and the ability to feel seismicity. Yan et al. (2017) elaborated on the different levels of seismicity that humans perceive. Yan et al. (2017) indicated that daily life in a family home will produce perceptible vibrations. Such activities include walking, jumping, and door slamming, which produce 0.8 mm/s , 7.1 mm/s and 12.7 mm/s , respectively. Based on this information, it is clear that the main reason for vibration complaints is usually not based on structural damage but rather a psychological effect, which may result from fear of damage and/or nuisance. In line with this view, good public relations and education will help reduce anxiety and complaints (Yan et al., 2017).

The human body is a more complicated and sensitive system than concrete structures. Every part of the human body may respond to vibrations with different frequencies. Thus, the vibration frequency is vital in evaluating adverse effects on humans. It has been observed that the frequency of most concerns regarding environmental vibration is about 1.0 Hz – 50 Hz , which covers the resonating frequencies of most human body parts. It also indicates that the vibration with low frequency (1.0 Hz – 10.0 Hz) primarily impacts all kinds of viscera, while the middle frequency (10 Hz – 50 Hz) vibration mainly influences muscular tissue and sensory organs (such as the head and the eyeballs). High-frequency ($> 50 \text{ Hz}$) vibration mainly acts on the human body's central nervous system and nerve endings (Yan et al., 2017).

Community and individual psychological responses to seismicity involve some subjective attitudes about the kind of environment that is considered acceptable (Yan et al., 2016). Some individuals consider any noticeable responses unacceptable, whether perceived directly or indirectly through the secondary 'sounds' of structure responses or even sometimes mistakenly perceived. A case study from an Indiana (USA) coal mine site, which was being performed by the OSM, USBM, and five other federal and state offices (Siskind et al., 1993), revealed that 36 per cent of complaints, supposedly about the 'strong blasts', did not correlate in time with blasts at this mine or any mines within the region. Researchers concluded that there will always be complaints about these, and other similar experiences, at other blasting sites. Table 1 shows the safety thresholds for seismicity at specific frequency ranges for humans.

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Table 1
Safety thresholds of continuous vibration (less than 1 minute) on humans

Frequency range (Hz)	1.0 to 4.0	4.0 to 10.0	10.0 to 20.0	20.0 to 30.0	30.0 to 60.0	Average PPV (mm/s)
Perceptible (PPV (mm/s))	0.25 - 0.03	0.03 - 0.08	0.08	0.08 - 0.11	0.11 - 0.16	0.12
Uncomfortable (annoyance) (PPV (mm/s))	6.37 - 1.59	1.59 - 2.39	2.39 - 3.98	3.98 - 6.37	6.37 - 7.96	4.77
Tolerance threshold (PPV (mm/s))	63.7 - 15.9	15.9 - 23.9	23.9 - 19.9	19.9 - 27.9	27.9 - 39.8	31.9
Physiological damage (PPV (mm/s))	127.3 - 95.5	95.5 - 50.9	50.9 - 78.0	78.0 - 119.4	119.4 - 159.2	105

Table 2
Estimated cracking-threshold PPV for local residences in the construction site of the Baihetan Project

No	Residence type	Estimated tensile strength of foundation (MPa)	Average medium density of construction site (kg/m ³)	Average P wave velocity from the blast (m/s)	Estimated cracking PPV (mm/s)
1	Mud-brick house	0,05	2500	3200	11,7
2	Rough-brick house	0,08	2500	3200	18,8
3	Cosmetic - brick house	0,1	2500	3200	23,5

Internationally-based mudhouse experiment

An experiment at the Baihetan Project in China included a mud brick house, a rough brick house, and a cosmetic brick house. The result indicates that local residences near the construction site do not crack until PPVs exceed 11.7 mm/s–23.5 mm/s, which is identified with Dowding and Siebert's theoretical estimation (2000). The results further confirmed that the predictive assessment of blast-induced cracking threshold of the poor foundation local residences can be estimated according to Equations 1 to 6. The estimated cracking threshold results for the Baihetan Project are given in Table 2.

As a guiding principle, the vibration safety criteria of different countries are always conservative controls because the socially acceptable probability of occurrence of cracking must be taken into consideration. Furthermore, human annoyance has become essential in the blasting industry, especially for repeated blasting operations. According to Yan et al. (2016) the human body can detect PPV at the level of 0.8 mm/s with clearly perceptible levels at 10.0 mm/s. The PPVs needed to cause cosmetic building damage to ordinary structures vary among the different standards worldwide but is typically in the range of 5 mm/s–50.0 mm/s, based on ISO10137 1992, BS7385 1993, and DIN 4150 1999 (Yan et al., 2016). Chiappetta (2000) suggested that the strictest standards must be set to reduce cosmetic damage and decrease the annoyance levels of people to avoid civil disputes between inhabitants and construction companies. Table 3 shows the PPVs at low, medium, and high frequency for various international standards.

Airblast and noise

Airblast and noise are one of the primary sources of complaints (Chiappetta, 2000). The airblast (or overpressure) is the change in pressure and is expressed in decibels (dB). Airblast in the context of opencast mining, is generally the superposition of a number of air pressure pulses produced by the blast-induced explosion (MHSI, 2020). The pressure pulse may be above or below the ambient atmospheric pressure (MHSI, 2020). The wave travels at the local speed of sound. Noise is merely the audible part of the airblast greater than 20 Hz (Dowding et al., 2018). At large distances from a blast, much of the energy may travel at sub-audible frequencies, which cause windows and doors to rattle, which may alarm people. For a South African mudhouse roofed with congregated iron sheets

and stabilised with loose weights, the rattling on the roof may be exacerbated, triggering higher annoyance than expected. Dowding et al. (2018) indicated that the main airblast and noise hazards arise from the energy carried at frequencies lower than the human hearing range. This suggests that rattling, which is felt and heard, may be a result of the undetected sound waves. According to Yan et al. (2017), the rattling of windows and ornaments is likely to occur when airblast frequencies match the natural frequencies of structures. This is possible at 120 dB. The effect of the undetected sound waves may be mistakenly thought to have been caused by seismicity. The airblast is reflected at hard interfaces such as topography and buildings (Espley-Jones, Goetzsche, 2020). The airblast gets refracted when the speed of sound changes due to variations in temperature, humidity, wind speed, and wind direction (Dowding et al., 2018).

Many studies of the human response to air pressure pulses use long durations of steady-state audible noise sources. This is not representative of mining airblasts, which are impulsive (a short duration), have a large infrasonic component (frequency too low to be heard), and are strongly influenced by weather conditions. Thus, human sensitivity is extremely difficult to define because of the vast variable audibility of any particular event (Yan et al., 2017).

The threshold of human hearing at 1 kHz is a sound pressure level of about 20 μ Pa, or 0 dBL (Dowding et al., 2018). This is similar to the noise made by a mosquito at a range of 3 m. The ANSI-1969/ISO-1963 standard uses 6.5 dB SPL (sound pressure level) at 1 kHz as the threshold, with a 10 dB correction applied for older people (16.5 dB) (Dowding, 1985). Normal conversation is 60 dBL–80 dBL, and average street traffic is about 85 dBL (Dowding, 1985). To give a local example of a loud noise, a South African vuvuzela⁴ at a range of 1 m produces a sound pressure level of 120 dB (Swanepoel et al., 2010). Prolonged exposure to sound pressure levels above 85 dB can cause hearing damage. If the predominant frequency of the event is low (25 Hz), a pressure pulse of 115 dB might be unnoticeable to most people. If the predominant frequency is well into the range of human hearing (20 Hz to 20 kHz for young people), a pulse of the same amplitude might be annoying (Swanepoel et al., 2010).

⁴Vuvuzela is a long horn blown by fans at soccer matches in South African stadiums

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Table 3

International blast-induced ground vibration standards for selected country

No	Protected structure	PPV at low frequency		PPV at medium frequency		PPV at high frequency		Standard / guideline
		PPV (mm/s)	Frequency (Hz)	PPV (mm/s)	Frequency (Hz)	PPV (mm/s)	Frequency (Hz)	
1	Loess cave dwellings, adobe buildings	$1.5 \leq \text{PPV} \leq 4.5$	$\text{DF} < 10$	$4.5 < \text{PPV} \leq 9$	$10 \leq \text{DF} < 50$	$9 < \text{PPV} \leq 15$	$50 \leq \text{DF} < 100$	China National Standard (GB6722-2014, 2014)
	Brick houses, large non-seismic block buildings	$15 \leq \text{PPV} \leq 20$	$\text{DF} < 10$	$20 < \text{PPV} \leq 25$	$10 \leq \text{DF} < 50$	$25 < \text{PPV} \leq 30$	$50 \leq \text{DF} < 100$	
2	Modern homes, dry wall interiors	18.8	$\text{DF} < 40$	-	-	50	$\text{DF} \geq 40$	USBM Standard (Siskind et al., 1980)
	Older homes	12.5	$\text{DF} < 40$	-	-	50	$\text{DF} \geq 40$	
3	Civil buildings not belonging to proprietor	$\text{PPV} \leq 5$	$\text{DF} < 8$	$5 < \text{PPV} \leq 10$	$8 \leq \text{DF} < 25$	$10 < \text{PPV} \leq 15$	$\text{DF} \geq 25$	India CMRS, (Dhar et al., 1993)
	Proprietary civil buildings with limited-service life	$\text{PPV} \leq 10$	$\text{DF} < 8$	$10 < \text{PPV} \leq 15$	$8 \leq \text{DF} < 25$	$15 < \text{PPV} \leq 25$	$\text{DF} \geq 25$	
4	Houses, low-story residential buildings, general commercial buildings	$\text{PPV} \leq 19$	$\text{DF} \geq 15$	-	-	-	-	Australian Standards (CA 23,1967)
5	Industrial buildings	$\text{PPV} \leq 20$	$\text{DF} < 10$	$20 < \text{PPV} \leq 40$	$10 \leq \text{DF} < 50$	$40 < \text{PPV} \leq 50$	$50 < \text{DF} \leq 100$	Germany Norm (DIN 4150,1999)
	Residential buildings	$\text{PPV} \leq 5$	$\text{DF} < 10$	$5 < \text{PPV} \leq 15$	$10 \leq \text{DF} < 50$	$15 < \text{PPV} \leq 20$	$50 < \text{DF} \leq 100$	
	Relatively more sensitive buildings	$\text{PPV} \leq 3$	$\text{DF} < 10$	$3 < \text{PPV} \leq 8$	$10 \leq \text{DF} < 50$	$8 < \text{PPV} \leq 10$	$50 < \text{DF} \leq 100$	

The South African mudhouse case study

A study was conducted at an anonymous coal mine (Mine) following a complaint from the property owner. The Mine is an open cast thermal coal mine located approximately 30 km east of Middelburg in the Mpumalanga province of South Africa. The houses assessed was a homestead compound located at a horizontal distance of 5.26 km from the mine boundary. The Mine required that a structural integrity assessment and blast monitoring be conducted for the households that launched complaints about alleged blast-induced damages to their properties. The first phase of the study was to conduct a structural integrity assessment to establish the extent and nature of the damage and determine the likely cause of the cracks. The assessment of the property commenced on 13 May 2022 and was completed on 16 May 2022. The results from the structural assessment, census survey, predictive assessment calculation, and engagement with the house owners led to the following facts being drawn:

- All three units assessed were residential houses.
- The units had well defined vertical cracks.
- The units were made up of mud bricks and wood, coated with a thin layer of cement.
- Major cracks were on the load bearing lintels and vertical poles.

- Major failure occurred between the load bearing lintels and vertical poles.
- Weights placed on the roof introduce load and vibration on the structure.
- Trapped water moisture on the wall was evident.
- The houses were approximately 5.26 km from the mine boundary.
- The houses were more than 70 years old.
- The mine was using electronic delay detonators on single hole firing timing configurations.
- The predictive assessment indicated a seismicity of 0.4 mm/s, which was unlikely to cause damage based on the international and local standards.

A study was conducted following the cracks at the house, which follow a well-defined pattern. There were general vertical cracks. Figures 1 to 3 show the original pictures taken during the assessment, which show the vertical cracks and wooden lintels' point of failure. Figure 4 shows trapped moisture in the wall and the weights on top of the roof. These weights are meant to stabilise the roof during experiences of wind. However, they introduce more loads on the wall and vibration during windy days. In the same picture, the wet wall can be observed, which is due to moisture. This moisture causes the mud bricks and the wood to expand. When

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Figure 1—Vertical cracks with crack monitors installed



Figure 2—Vertical cracks at wood lintels running straight down to the floor



Figure 3—Vertical cracks between the vertical poles and major failure in between



Figure 4—Moisture on the wall and heavy loose material on the roof introducing load and vibration

it shrinks as it dries, it creates voids and cracks that continuously expand under the natural origins.

The main points of weakness where major cracks were found are at the wood-cement contacts on wooden lintels and wooden poles. The wooden lintels and wooden poles are meant to relieve the load-bearing wall of the stress, however, since the wood expands more when absorbing water and it shrinks back to its origin the crack remains and creates a plain of weakness.

In summary, the study revealed that the structural design of the mud houses consists of mud bricks, wooden poles, and congregated iron sheets. Loose boulders and weights are often placed on the roof to stabilise the congregated iron sheets. The study further revealed that the standard wooden pole-mudbrick interface forms a plane of weakness. The plane of weakness is due to the weak bond between wood and mud. The study further revealed that the cement coating of the mud brick house traps moisture, which causes cracks. Another finding was that the loose boulders that are often placed on the roof exacerbate the impact on the structure and annoyance to the people.

The recent MCOP recognises that there could be houses not built according to engineering standards with structural integrity that is highly compromised. In addressing this issue, the guidelines use the principle of ‘who came first’, which means that the mine must put measures in place to ensure that structures that existed prior to the commencement of blasting operations are protected against the risks emanating from blasting operations. It further proposes that, where new structures are built close to the mine boundary after mining operations have commenced, these structures must be of a design that enables the structures to withstand the prescribed safety limits without sustaining undue damage. The mudhouse assessed was 70 years old and ‘came first’. This suggests that, irrespective of its structural integrity, the mine must ensure that its activities do not act as a catalyst to its further deterioration or subsequent damage.

Blast design parameters and predictive assessment

The blast parameters were obtained from the mine. The maximum parameters were used to create a worst-case scenario. The blast design parameters were assessed against the typical surface mine design parameters defined in the industry as the rules of thumb (RoT). The rule of thumb is an empirical standard, a guideline or norm. It is a general or approximate principle, procedure or rule based on experience or practice. The rules of thumb’s primary roles are to provide the perspective required to ensure practical concepts and designs and to facilitate in finding pragmatic solutions for operating problems. Table 4 shows the actual Mine blast parameters. Table 5 shows the typical blast parameters based on the RoT compared to the actual blast parameters at the coal mine.

Parameter	Value
Bench length (m)	100
Bench width (m)	40
Hole diameter (mm)	251
Bench height (m)	33
Burden (m)	7,5
Spacing (m)	8,0
Stemming length (m)	4,5
Total number of holes	65
Total metres drilled (m)	2,145
Total cubes broken (m ³)	128,725
Linear charge mass (kg/m)	56,91
Total mass of explosives (kg)	105,390
Powder factor (kg/m ³)	0,82

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Table 5b
Rule of thumb (test) for the Mine blast design

Parameters	Actual used	Typical range	Actual
Stemming range	3	10 -30 Ø	20
Burden range	4,5	25 - 40 Ø	29,5
Burden to spacing ratio	1,12	1 - 1.5	1,12
Bench height range	21	50 -140 Ø	138
Hole diameter (mm)	152		
Powder factor (Kg/m ³)	0,56		

Predictive risk assessment for blast-induced ground vibration

This section is a quantitative approach to further assess the likelihood of high seismicity reaching the Mnguni site from the Mine blasting activities. Extensive research by the USBM since 1942 has shown that the variation of ground vibrations from surface mines depends on the distance and the quantity of explosives as defined by the following equation:

$$PPV = a \left(\frac{R}{\sqrt{W}} \right)^{-b} \quad [8]$$

Where:

PPV, is the forecast peak amplitude or peak particle velocity.
 R is the radial distance (along the surface) to the seismograph.
 W is the mass of charge per delay in kg.
 The factor $\frac{R}{\sqrt{W}}$ defines the scaled distance.

The constants a and b are site-specific constants that are a function of the transmission properties of the rock mass.

This study used standard constants a and b of 0.800 and 1.600 for a and b, respectively, to estimate the PPV's safety circles regarding the structure. The aforementioned equation generated predictive seismicity based on the Mine blast parameters as a worst-case scenario. The results in Table 6 show that the seismicity from the mine boundary to the homestead, based on the current system used, would be 0.4 mm/s. This is below the normal unit trigger level of 1.2 mm/s. The human detectable threshold is reached at 3,400 m from the blast. The absolute minimal seismicity is at 7,000 m from the blast.

Table 6
Peak particle velocity generated from 400 m to 7000 m

Risk	Single hole firing
Charge mass per hole (kg)	1625
Distance (m)	PPV (mm/s)
400	25,9
500	17,9
600	13,3
700	10,3
800	8,3
900	6,8
1000	5,7
2000	1,8
3000	0,9
3400	0.8
5260	0.4
7000	0,2

Table 7
Records for July 2022

Actual Blast record	Date	Planned Blast Time	Actual Blast Time	Seismo Event Time	Vertical (mm/s)	Vertical (Hz)	Radial (mm/s)	Radial (Hz)	Transverse (mm/s)	Transverse (Hz)	Vector sum (mm/s)	Acoustic (dB)
1	1-Jul-22											
	2-Jul-22			12:17	0,02	10	0,03	2	0,04	3	0,04	123
	3-Jul-22											
	4-Jul-22											
	5-Jul-22											
	6-Jul-22											
	7-Jul-22											
	8-Jul-22											
	9-Jul-22											
	10-Jul-22											
	11-Jul-22											
	12-Jul-22											
	13-Jul-22											
	14-Jul-22											
	15-Jul-22											
	16-Jul-22											
	17-Jul-22											
	18-Jul-22											
2	19-Jul-22			13:05	0,02	39	0,04	3	0,03	3	0,05	121
	20-Jul-22											
3	21-Jul-22			12:07	0,03	60	0,03	6	0,04	3	0,05	120
	22-Jul-22											
4	23-Jul-22			15:03	0,02	171	0,13	1	0,09	2	0,15	121
	24-Jul-22											
	25-Jul-22											
	26-Jul-22											
	27-Jul-22											
	28-Jul-22											
	29-Jul-22											
	30-Jul-22											
5	31-Jul-22			16:21	0,02	9	0,13	2	0,1	3	0,16	121

Actual results

Table 7 shows the actual results for July. The maximum seismicity recorded was 0.15 mm/s. This was below the humanly detectable levels. The maximum noise level detected was 121 dB. This was below the threshold of 128 dB (not more than 10% of the results should exceed this figure) indicated in the guideline used during the study. However, this is above the threshold of 120 dB (not more than 10% of the results should exceed this figure) provided by the current guidelines. The results suggest that the maximum seismicity of 0.15 mm/s is below the perceptible vibrations obtained from daily home activities such as walking, jumping, and door slamming, which produce 0.8 mm/s, 7.1 mm/s, and 12.7 mm/s, respectively. The blast-induced seismicity is therefore not likely to have caused any annoyance or damage.

The results indicated a maximum of 123 dB and an average of 121 dB from five (5) events recorded. According to Yan et al. (2017), the rattling of windows and ornaments is likely to occur when airblast frequencies match the natural frequencies of structures, which is likely to occur at 120 dB. Based on these results, it can therefore be concluded that the noise is more likely to be the cause of damage than seismicity.

Summary of the seismicity results

Figures 5 and 6 show the graphical representation of the seismicity and noise results, respectively.

South African adopted guidelines for the blast-induced noise and seismicity

The South African-adopted safe limits guidelines for noise and seismicity, are shown in Tables 8 and 9. The safe limits for noise are expressed in a robotic format where green means safe; yellow means caution; and red means that safe limits are exceeded.

The safe limits of the blast-induced seismicity for different structures are shown in Table 9. These guidelines are adopted from the USBM criteria. The mudhouse is rated at 6 mm/s. These limits are based on the ground peak particle velocity and frequency and do not consider the individual structural and human response.

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Table 8
South African guidelines for noise level safe limits in a robotic format

Noise level (dB)	Noise level pressure (kPa)	Perception / resulting consequence	Allowable frequency of exposure for structures
100	0,002	• Barely noticeable	• No limit
110	0,006	• Readily acceptable	• Reduce structural exposure
128	0,05	• Currently acceptable by South African authorities that damage will not occur	• Not more than 10% of measurements should exceed this value
134	0,1	• Currently acceptable by South African authorities that damage will not occur • Poorly mounted pictures will fall • Rattling of objects on shelves/display units potentially falling	• No measurement should exceed this value outside of the mining boundaries
135-169	0,1-6,3	• High likelihood to break windows	• No measurement should exceed this value
170	6,3	• Will break a well-mounted window	• No measurement should exceed this value

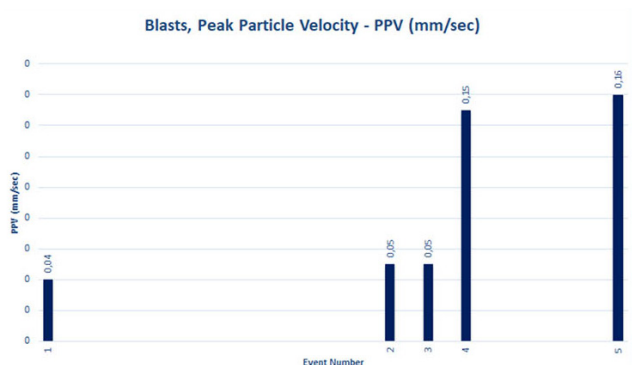


Figure 5—Boy Mnguni station PPV graph

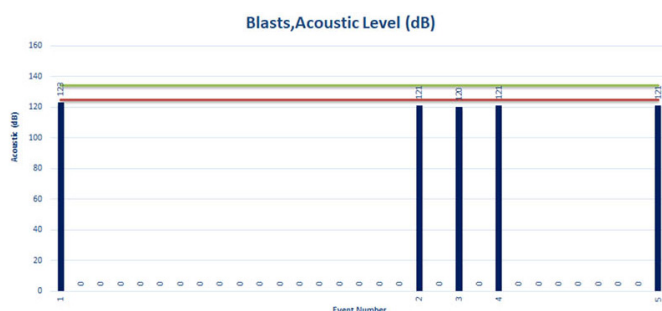


Figure 6—Blast-induced acoustic level Graph (dB)

Shortfalls in the structural response and set limits

The currently used safe-limit criteria for ground vibration, which are all based on the PPV and frequency of the ground vibrations, fail in many situations (ISEE, 2020). The safety limit criteria make no distinction for the structure's type, age, or stress history, all of which considerably affect the safety limits (Mahmoud, 2014). A significant drawback is also in the safe limit criteria itself. The currently adopted criteria were obtained by only correlating the structural damage to the intensity of the ground vibration. However, a safe limit criterion against ground-born vibrations due to blasting should be based on the structure vibration/response, not the ground vibration. The safe-level criterion should be applied to the PPV of the structural vibration due to blasting, not to the soil vibration. The vibration intensity depends on the soil-structure interaction that determines the structure responses to the ground excitation

Table 9
South African guidelines for the blast-induced seismicity safe limits

Structure type	Ground vibration safe limit (mm/s)
National roads / tar roads	150
Electrical lines (pylons)	75
Railway	150
Transformers	25
Waterwells	50
Gas pipelines	25
Telecoms towers	50
General house of proper construction	25 (USBM criteria)
Informal settlements	12.5 (USBM criteria)
Rural building - mud houses	6 (USBM criteria)

(Sayed-Ahmed, Naji, 2006). A ground vibration frequency of 40% (or more) greater than the fundamental frequency of the structure introduces a structure PPV that is less than the PPV of the ground vibration (Altunışık et al., 2021). On the other hand, a ground vibration with a frequency below the fundamental frequency of the structure causes the structure to vibrate at least as much as the ground.

If the ground vibration frequency is close to the structural natural frequency, a state of resonance may be generated, and the PPV of the structure will increase considerably beyond the PPV of the ground vibration. This phenomenon is disregarded in all the currently adopted safe limit criteria against ground-born vibrations due to subsurface blasting.

Low-rise buildings have a natural frequency of 4~12 Hz (Siskind, 1980). However, the structures and their parts (floor and walls) respond differently to ground vibration as they have different natural frequencies. The natural frequencies are 12 HZ~20 Hz for interior wall horizontal vibrations and 8 HZ~30 Hz for floor vertical vibrations (Siskind, 1980). Mid-wall vibrations cause residential buildings to rattle, making vibration more noticeable and aggravating human response to annoyance from ground vibration (Siskind, 1980). It is difficult, if not impossible, to follow a uniform vibration standard to reduce the human perception of vibration due to subsurface blasting (Baliktis, 2001). Scientists and engineers

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around the world have challenged the current safe limits, which are based on threshold/structure damage prevention. Svinkin (2004) proposed an application of an amplification factor ranging between 2 and 4.5 to the soil PPV in the frequencies range of 4 Hz to 30 Hz as a modification to these criteria to consider the structure's resonance effect. Dowding et al. (2018) also agreed with the notion of the limitations in the current safe limits. The challenges in the safe limit criteria for structures get even more exaggerated for the structurally even weaker South African mudhouse structure. There is a need to investigate the South African-based mudhouse safety limit to ensure maximum protection of the citizens. The combination of engineering and administrative means could help solve the current problem, which will likely cause tension between the miners and the mudhouse homeowners. The South African law puts the safety of citizens first regarding mining hazards. It does not prescribe the details on how. It places the responsibility on the mine to ensure that its activities will not put the lives of the citizens in danger. The new MCOP guidelines put emphasis on the effective communication between the mine and the communities as far as blast notifications are concerned. This helps to manage the psychological impact likely to be caused by sudden unexpected blast-induced noise and seismicity.

The South African legal provision for the safety of persons staying in close proximity to the mines

The results from this study help guide the future areas of development in terms of the policy and practice. The results suggest that the DMPPR-recommended safe limits should, for all purposes, be used as a guideline and use the risk assessment to establish the actual safe limits based on the prevailing conditions on the ground. A practical site-specific risk assessment (RA), code of practice (COP) and standard operating procedures (SOPs) will help to ensure that the mine permit holders operate in harmony with their neighbouring communities and in compliance with the law.

The South African Mine Health and Safety Act, (MHSA) of 1996 (Department of Mineral Resources, 2020), makes provisions in the interest of safety for the people not working at the mine who may be affected by the activities at the mine. Section 5(2) of the MHSA provides that, as far as reasonably practicable, every employer must identify relevant hazards and assess the risk to which persons who are not employees are exposed. It further requires the employer to ensure that persons who are not employees, but who may be affected by the activities at the mine, are not exposed to any hazard to their health and safety. According to the MHSA Regulation 4.16(2), surface structures within 500 m of blasting must be protected. The DRME directive released on 27 February 2020 requires that all opencast mines in Mpumalanga, operating within close proximity to the communities (within 500 m–2000 m) must ensure that structures be protected. The Government Gazette issued on 2 August 2024 mandated that all opencast mines operating within a 2,000 m proximity to the communities conduct a structural integrity survey of all the affected structures or buildings, effective from 1 November 2024. The mudhouse homestead investigated in this study was situated at a distance of 5,260 m from the mine. This distance falls outside of the distance for which the law demands the risk assessment to be done prior to blast. The homeowner complained that the blasting activities were damaging his properties. The mine argued that the houses are situated far away, hence no pre-blast structural assessment was done, and no risk assessment or consultation was done. The DMR on the other hand, as the regulator, took the host community complaints seriously, however, lacked the appropriate standards and law that could be used when issuing judgements. Due to these challenges,

the exploitation of natural resources in South African has led to a variety of problems within host communities. In recent times, South Africa has witnessed an emergence of a disturbing trend by host communities (Seth, 2021). Such a reaction from the South African communities is not different from other host communities worldwide. Most mining companies are now resorting to relocating communities to pave the way for open-cast mining activities (Seth, 2021).

Recommendations

A hazard identification and risk assessment (HIRA) approach is recommended to address the South African mudhouse challenges. The HIRA is a standard method used in the South African mining industry. This method involves the process of identifying the relevant hazards and controls being applied to all activities that will be performed. The hierarchy of controls must be introduced to enhance the effectiveness of the controls in addressing the identified risk. The effectiveness of the controls in terms of risk elimination, substitution, and isolation must be prioritised. Engineering and administrative controls are used as key risk mitigation measures. Zero tolerance in terms of mudhouse structural damage and human annoyance must be applied. The safety limits are to be guided by the human and structural response to blast-induced noise and seismicity. The actual structural elements and the condition of the people living in the properties must be factored.

Elimination of the risk at source

An ideal solution is to eliminate the hazard or risk whenever it is possible to do so. However, elimination can be difficult to achieve due to costs involved or impossible due to technical reasons. The necessity for blasting in highly environmentally sensitive areas must first be established. Overburden may sometimes be stripped using mechanical methods rather than blasting. However, in most cases, blasting will be the only viable mining method.

Substitution

This solution suggested is that all the mudhouses, within a distance from the mine where structural and human response indicate a significant risk, would be replaced with stronger structures. Replacement of the mudhouses may be impractical to implement from a cost point of view; this may throw marginal mines out of business.

Isolation

The creation of a pre-split line in the direction of the sensitive structures creates a barrier between the active mining blocks and the sensitive structures. This significantly reduces the seismicity. The actual site seismicity transmission properties can be established by placing seismicity monitors on either side of the pre-split to assess the efficiency of the pre-split as a seismicity proof. The noise isolation factor can be achieved through effecting stemming that reduces the wasted energy component during blasting.

Engineering controls

Both blast-induced noise and ground vibration are highly dependent on the number of explosives used per an 8 milliseconds delay. An amount of charge mass per delay that would reduce the safety circles must be opted. Electronic delay detonators allow for a single hole or explosive deck firing. This results in a highly reduced charge mass per delay compared to the pyrotechnic methods. The engineering controls should include the types of blasting products and blast design systems that generate minimal noise and seismicity. These controls must be considered, and the site-specific results should be recorded.

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Administrative controls

The administrative control should include the SOP with respect to blasting near mudhouses. A review, development and implementation of policy, and legislative measures to address the blasting impact on humans and structures around the mines are recommended. This is already being done, but it is further recommended that the administrative measures cover both technical and psychological aspects of the defined problem focused more on mudhouses as a weakest structure. Effective community engagement must be developed, implemented, and maintained.

Conclusion

The blast-induced seismic and noise impact on South African mudhouses has been explored in this paper. This paper critically evaluated the currently adopted safe limit criterion used in South Africa against the international standards such as those used in Australia, China, Switzerland, and the USA. The maximum seismicity of 0.15 mm/s obtained during the study was found to be below the perceptible vibrations generated during the daily home activities such as walking, jumping, and door slamming, which produce 0.8 mm/s, 7.1 mm/s, and 12.7 mm/s, respectively. This was used to eliminate seismicity as a likely cause for any annoyance and/or damage. The maximum noise of 123 dB and an average of 121 dB from five (5) events recorded suggested that the noise was a more likely cause of annoyance and/or damage.

The study identified the gaps in the current regulatory instruments. It established that the current safe limit criterion focus on the general structural damage with little regard to human impact and response. A new approach is proposed based on relating the safe limits to the structural and human response. The results from this study will help in the development of a policy for better regulating the environmental impact emanating from blasting activities from mines. A mudhouse is the weakest residential structure. Addressing the challenges faced by the mudhouse dwellers could help resolve other related challenges.

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