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A next-generation blast design via seismic intelligence

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Abstract

Blast-induced ground vibration remains one of the most important environmental and geotechnical constraints in open-pit mining. This paper presents a compact Seismic Intelligence framework that integrates pilot-hole seismic monitoring, inverse source-waveform estimation, Q-factor-based attenuation and adaptive electronic-delay optimization. The method uses measured three-component vibration records to reconstruct a representative source signal, propagate it through a frequency-dependent attenuation model and simulate multi-hole wave superposition. A GO-AI optimization routine then adjusts delay intervals under practical constraints, including minimum delay separation, neighbour-based firing and maximum blast duration. Field-scale validation on a blast with more than 300 blastholes showed strong agreement between simulated and measured response, with R^2 approximately 0.94 and practical prediction error below 12%. The optimized delay sequence reduced constructive wave interference, lowered PPV and shifted part of the spectral content toward higher frequencies. The framework also supports hybrid zone-based control, allowing vibration reduction in sensitive sectors while maintaining sufficient seismic energy in waste zones for fragmentation. The results indicate that waveform-based adaptive blast design can improve prediction reliability, environmental compliance and operational control compared with conventional empirical scaled-distance approaches.

Keywords

Seismic Intelligence, Blast optimization, PPV, Delay design, Q-factor.

1 Introduction

Ground vibration induced by production blasting is generally evaluated through peak particle velocity (PPV), frequency content and the response of nearby structures or slopes. Conventional scaled-distance methods remain attractive for preliminary design because they require only charge weight and distance, but they cannot explicitly represent waveform shape, frequency-dependent attenuation or phase interaction between many blastholes (Siskind et al. 1980; Dowding 1996). These limitations become critical in large open-pit blasts where hundreds of holes interact through electronic delay timing and where local geology controls wave transmission.

A modern blast design method should therefore combine field measurements with a physics-informed simulation of wave propagation. The Seismic Intelligence concept developed in this study uses a pilot-hole vibration record as the site-specific source signature and then optimizes the full-blast delay sequence. The aim is to control not only the maximum PPV, but also the temporal and spectral structure of the resulting wavefield. This makes it possible to reduce damaging low-frequency constructive interference while maintaining effective energy release for fragmentation.

2 Methodology

2.1 Workflow

The workflow is summarized in Fig. 1. A pilot hole is first detonated under controlled conditions and recorded at up to five monitoring stations. These measurements are used for source-waveform reconstruction and calibration of attenuation parameters. The calibrated model is then used to simulate the multi-hole response of the full blast, after which the GO-AI optimizer searches for a delay pattern that satisfies operational constraints and reduces the selected vibration objective.

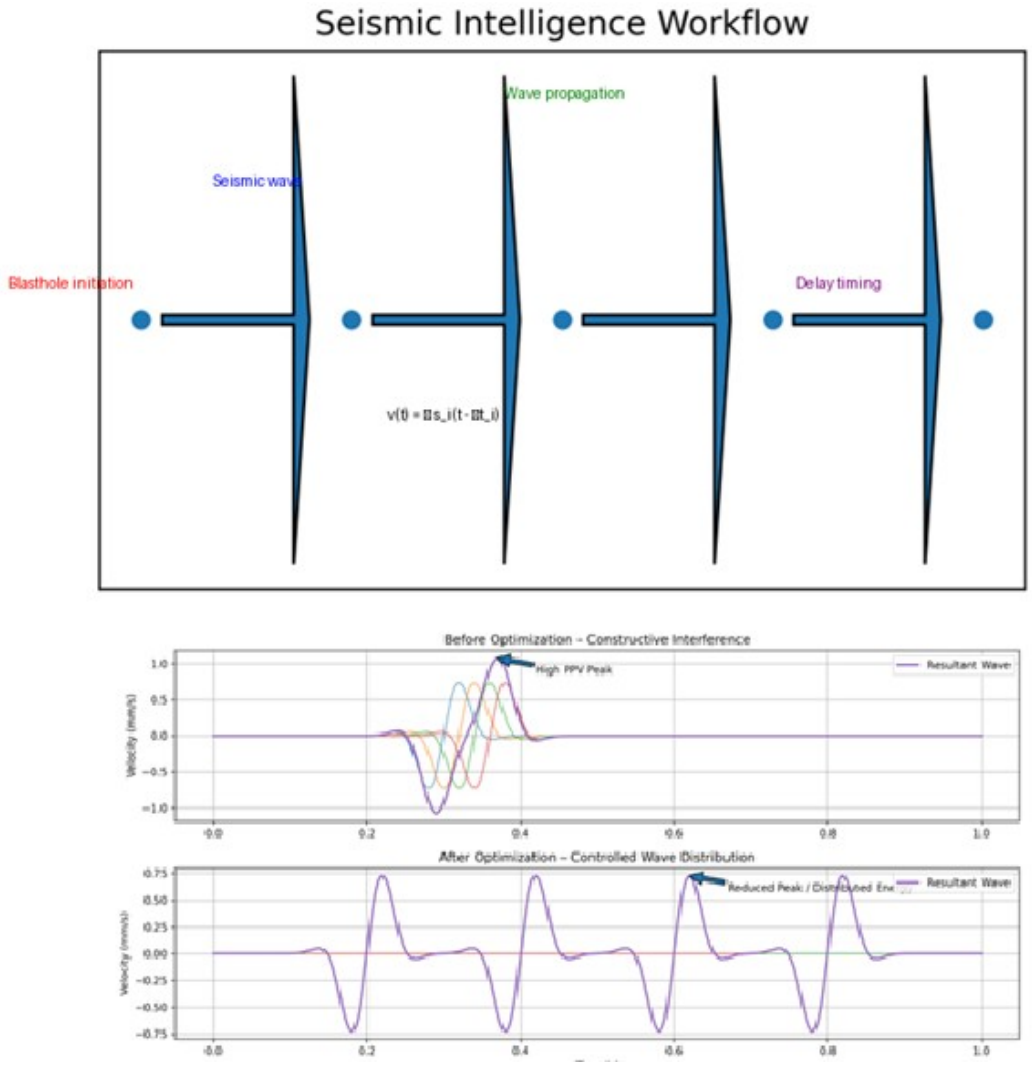


Fig. 1 Seismic Intelligence workflow for pilot-hole measurement, source inversion, attenuation modelling and adaptive delay optimization.

2.2 Signal inversion and attenuation

For the j-th monitoring point, the measured velocity history is written as a source signal multiplied by a propagation function:

$$v_j(t) = G(d_j)s(t) \quad (1)$$

where $v_j(t)$ is the recorded vibration signal, $G(d_j)$ is the propagation function and $s(t)$ is the source signal. The representative source signal is reconstructed by normalizing the measured signals with respect to distance-dependent attenuation:

$$s(t) = (1/N)\ \Sigma_j[v_j(t) / G(d_j)] \quad (2)$$

The attenuation model uses a Q-factor formulation to represent energy dissipation during wave propagation (Kumar et al. 2022; Wang et al. 2023):

$$A(r) = A_0 \exp(-\alpha r), \quad \alpha = \pi f/(Qv) \quad (3)$$

where A(r) is amplitude at distance r, A0 is the reference amplitude, f is frequency, v is wave velocity and Q is the quality factor. This formulation is useful because it accounts for the stronger attenuation of higher-frequency components in fractured rock masses.

2.3 Multi-hole simulation and delay optimization

The vibration response of a group blast is computed by superposing the delayed contribution of individual blastholes:

$$v(t) = \Sigma_i\ s_i(t-\Delta t_i)G(d_i) \quad (4)$$

where $s_i(t)$ is the scaled hole signal, Δt_i is the electronic delay and $G(d_i)$ is the propagation term between the i-th hole and the monitoring point. The optimization problem is expressed as:

$$J = w_1 PPV + w_2(1/E_s) \quad (5)$$

where J is the cost function, E_s is seismic energy, and w_1 and w_2 are weighting factors. The constraints include a minimum delay separation of 8 ms, neighbour-based firing, avoidance of repeated consecutive delay values and a user-defined or default maximum blast duration. For hybrid blasting, the global objective is extended by assigning different weights to vibration-sensitive ore or slope sectors and energy-oriented waste sectors.

3 Results and discussion

3.1 Field-scale validation

The method was evaluated using a large open-pit surface blast containing more than 300 blastholes. Pilot-hole records from multiple monitoring locations were used to calibrate the source signal and attenuation behaviour. The reconstructed waveform preserved the first major peak, dominant frequency and general signal envelope of the measured records. The practical reconstruction error was below 10%, which is sufficient for subsequent waveform-based simulation.

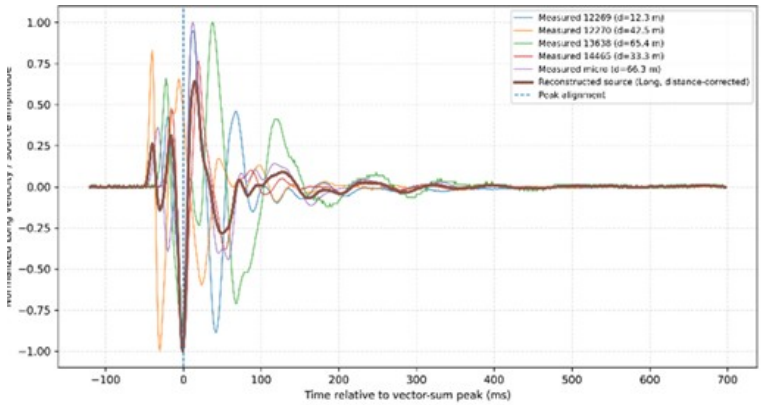


Fig. 2 Example comparison between measured pilot-hole records and the reconstructed source waveform.

The simulated and measured PPV values were then compared across the monitoring points. The agreement was strong, with R^2 approximately 0.94 and most errors within the 10–12% engineering band. This indicates that the combined inversion, attenuation and superposition model captured both the general amplitude decay and the main phase structure of the blast-induced wavefield.

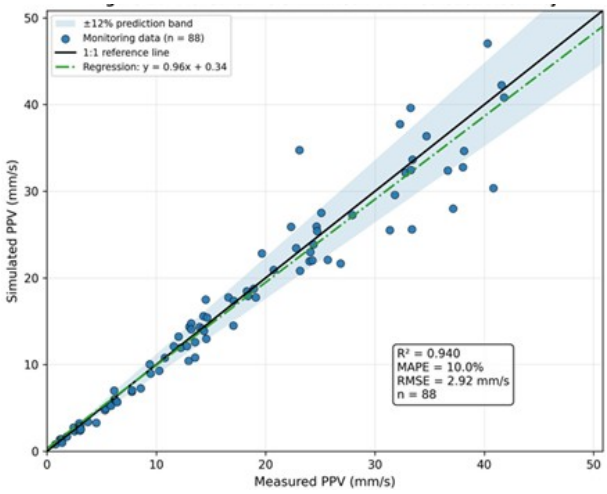


Fig. 3 Simulated versus measured PPV values with a one-to-one reference trend.

Table 1. Summary of model performance and engineering meaning.

Indicator	Result	Engineering meaning
Source reconstruction error	<10%	Pilot record suitable for simulation
PPV prediction	$R^2 \approx 0.94$	Strong measured-simulated agreement
Practical PPV error	<12%	Acceptable controlled-blasting accuracy
Delay optimization	PPV reduction up to about 40%	Reduced constructive interference
Frequency response	Higher-frequency shift	Lower resonance and faster attenuation

3.2 Delay and frequency effects

Before optimization, closely spaced delay intervals caused constructive overlap and relatively high-amplitude peaks. After optimization, the waveforms were redistributed in time, reducing peak amplitude and producing a smoother vibration envelope (Fig. 4). This demonstrates that electronic delay timing is not only a sequencing tool, but also a direct control variable for wave interference.

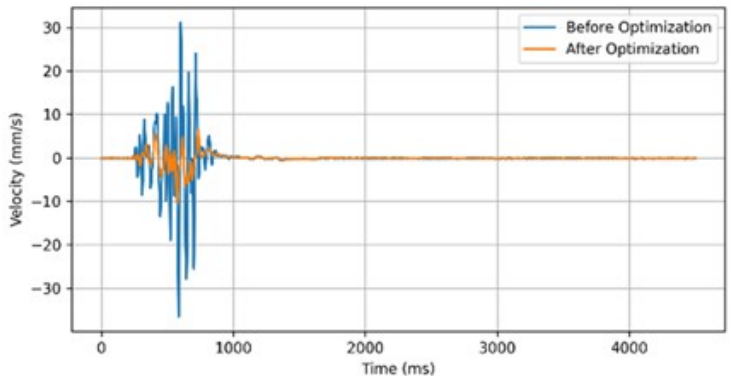


Fig. 4 Comparison of resultant vibration before and after adaptive delay optimization.

Frequency analysis showed a reduction in low-frequency components and a shift of energy toward higher-frequency bands. This is beneficial because low-frequency vibration is more likely to interact with structural resonance, whereas higher-frequency components generally attenuate faster with distance. The frequency-domain result therefore supports the use of waveform-based delay design rather than PPV-only empirical control.

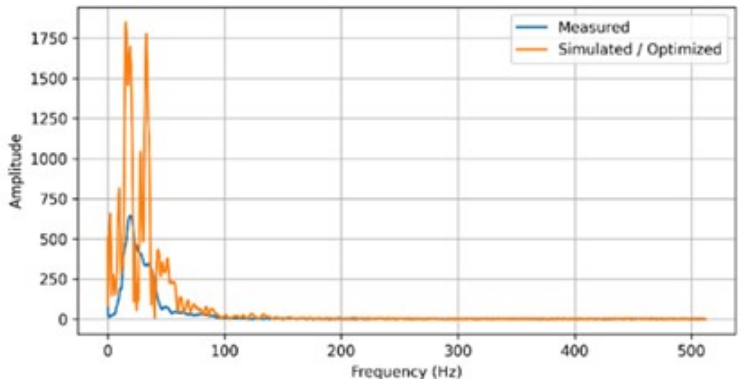


Fig. 5 Frequency-domain comparison showing reduced low-frequency content after optimization.

3.3 Hybrid zone-based control

A practical advantage of the framework is its ability to assign different objectives to different blast zones. In ore or slope-sensitive areas, the optimizer prioritizes lower PPV. In waste sectors, the objective may allow higher seismic energy to support fragmentation. The spatial PPV distribution in Fig. 6 illustrates how a single blast can be managed using different local objectives while preserving a continuous firing pattern.

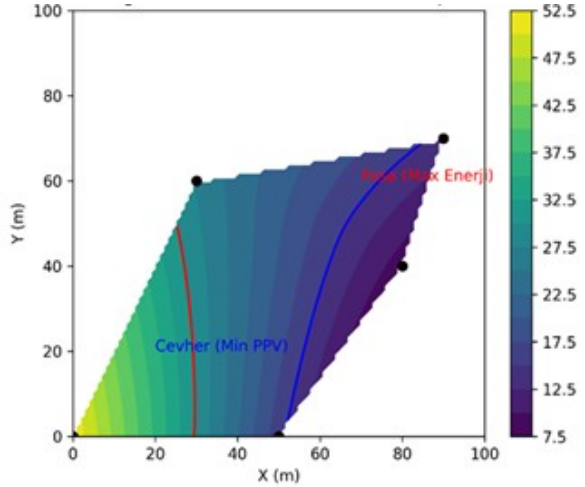


Fig. 6 Spatial PPV distribution used for hybrid zone-based vibration and energy management.

3.4 Residual error and implementation aspects

Residual error analysis was used as a final check on predictive stability. The residuals were concentrated around small values without extreme outliers, indicating that the calibrated model remained stable across different monitoring positions and distances. This is important for practical blast design because a model that performs well only at one station may still be unsafe for regulatory control. The residual pattern shown in Fig. 7 therefore supports the use of the proposed framework as an adaptive design and quality-control tool rather than a single-use prediction equation.

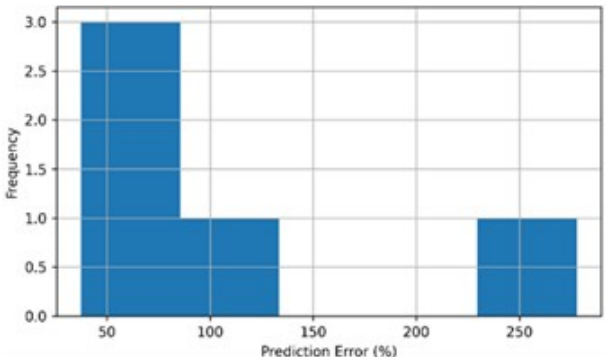


Fig. 7 Residual error distribution used to evaluate stability of the measured-simulated PPV comparison.

For field implementation, the procedure can be embedded into a standard blasting workflow. After the first pilot measurement, the system estimates the source signal and attenuation parameters, calculates trial delay patterns, and produces PPV and frequency checks for the selected monitoring points. After the production blast, measured waveforms are compared with predictions and the error is used to update the next design. This feedback structure is particularly useful in open-pit mines where benches, free faces and geological conditions change continuously.

4 Conclusions

This paper presented a compact Seismic Intelligence framework for controlled blast design in open-pit mining. The method moves beyond empirical scaled-distance prediction by integrating pilot-hole measurements, inverse source reconstruction, Q-factor attenuation, multi-hole superposition and adaptive delay optimization. The following conclusions can be drawn:

– Pilot-hole inversion captured the dominant source waveform with practical error below 10%.

– The Q-factor model provides a physically consistent way to represent frequency-dependent attenuation.

– Multi-hole simulation reproduced field PPV values with R^2 approximately 0.94 and error below 12%.

– Optimized electronic delays reduced constructive interference and shifted vibration energy toward safer higher-frequency ranges.

– Hybrid zone control enables vibration minimization in sensitive sectors while preserving fragmentation energy in waste zones.

Overall, the framework provides a data-driven and physics-informed route for more reliable blast design, environmental compliance and operational control. Future work should focus on real-time monitoring integration, automatic feedback calibration and broader validation under different geological conditions.

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