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OPTIMISING TUNNEL BLASTING: PRACTICAL APPROACHES TO VIBRATION CONTROL AND SAFETY IN UNDERGROUND WORKS

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ABSTRACT: Blasting-induced vibrations represent a critical challenge in tunnel construction, where the confined environment and unique excavation conditions differentiate underground works from surface operations, such as open-pit mining. This paper focuses on vibration control and prediction, specifically in tunnelling, highlighting the distinct requirements and practical solutions for safe and efficient underground excavation.

Tunnel blasting is a highly cyclic process. Most of each work cycle is devoted to drilling, loading, and preparing the initiation system, while the detonation, which generates most of the vibrations, lasts only a few seconds. Each blast produces a sequence of extremely short impulses, separated by variable silent intervals, whereas drilling generates continuous, though considerably lower-intensity, vibrations. Rock fragmentation is achieved through impulsive pressures from explosive gases, with peak pressures typically ranging from 10^5 to 10^6 MPa over a few milliseconds. Each charge releases several megajoules of energy within microseconds, detaching and fragmenting rock volumes from hundreds of litres to several cubic metres. Depending on tunnel dimensions and excavation sequence, groups of 10–150 charges may be detonated in seconds. This emphasises the need for precise source-level vibration control and accurate prediction of vibration propagation to surrounding structures.

The paper provides an overview of tunnelling-specific blasting techniques and equipment and presents selected practical approaches that have proven effective in reducing vibrations. By concentrating exclusively on underground works, this study bridges the gap between general blasting experience and the specific demands of tunnel excavation, offering valuable guidance for engineers seeking safer, more controlled, and efficient construction practices.

1. INTRODUCTION

Vibrations generated by drill-and-blast tunnel excavation represent a key technical and environmental concern in underground construction. The detonation of explosives induces dynamic loads that propagate through the surrounding rock mass as elastic waves, resulting in ground vibrations that may affect nearby structures, underground utilities, and sensitive facilities. This topic has been extensively investigated over the years (Langefors & Kihlström 1978; Siskind et al. 1980; Persson et al.1994; Dowding 1996; Ozer 2008; Konicek et al. 2013; He et al. 2024), with systematic reviews highlighting research trends and key challenges in tunnel blasting studies, including vibration prediction, rock damage, and blast design optimization. In tunnelling practice, it is essential to distinguish ground vibrations from airborne effects, such as noise and air overpressure, since these phenomena originate from different physical mechanisms and are not directly correlated. Consequently, vibration and noise must be assessed independently when evaluating the environmental impact of blasting operations (ITAtech report n. 8 2016). Ground vibrations in drill-and-blast tunnelling are influenced by several factors, including charge per delay, blast geometry, initiation sequence, and rock mass properties. Monitoring is commonly performed using tri-axial sensors that measure particle motion along three orthogonal directions, from which particle velocity, acceleration, and displacement can be derived. Among the descriptors used to characterize vibration intensity, peak particle velocity (PPV) is widely adopted by international practice and standards as the primary parameter for assessing potential structural damage and disturbance (Guo et al. 2025). In accordance with DIN standards (DIN 4150-3 2016), PPV-based criteria provide a practical framework for controlling blasting impacts in tunnel excavation. Contemporary research continues to explore improved prediction methods for blast-induced vibrations (Ogunsola et al. 2025). Approaches based on field data, empirical equations, and machine learning models have been proposed to enhance PPV prediction and account for geological variability and site conditions. A thorough understanding of vibration generation, propagation, and measurement, in compliance with DIN standards, is therefore fundamental for safe, efficient, and environmentally responsible drill-and-blast tunnelling.

2. MEASUREMENT AND ASSESSMENT OF BLAST-INDUCED VIBRATIONS ACCORDING TO DIN AND ISO STANDARDS

The assessment of blast-induced vibrations in tunnel excavation relies on instrumental monitoring of ground motion, conducted in accordance with national and international standards. In Europe, vibration measurements are commonly performed following DIN 4150, while ISO 4866 (2010) provides complementary guidance on measurement procedures and evaluation criteria for buildings and structures (Khandelwal et al. 2007). Tri-axial sensors are installed on the ground surface or on structures of interest, allowing particle motion to be recorded along three orthogonal directions. Equipment specifications and installation procedures define sensor characteristics, coupling, orientation, and data acquisition requirements. Modern systems generally measure particle velocity or acceleration, from which displacement can be derived (Monjezi et al. 2016). Vibration intensity is primarily characterized by the peak particle velocity (PPV), defined as the maximum particle velocity recorded during a vibration event. PPV is widely adopted due to its clear physical meaning, robustness, and strong correlation with vibration-induced structural effects. DIN 4150-3 specifies PPV limit values for different structure categories and frequency ranges, accounting for frequency-dependent structural response, while ISO 4866 emphasizes measurement consistency and result interpretation. Consequently, frequency analysis is often required, particularly when vibration levels approach threshold values. In drill-and-blast tunnelling, monitoring locations are selected to represent the most vibration-sensitive receptors, such as nearby buildings, utilities, or existing tunnels. Vibration data are evaluated on an event-by-event basis and compared with applicable DIN and ISO criteria to verify compliance and support blast optimization. In addition, measured data are used to derive site-specific attenuation relationships linking PPV to distance and charge per delay (Nateghi 2011), which form the basis for vibration prediction, blast design optimization, and impact control.

3. TYPES OF VIBRATION DISTURBANCE INDUCED BY ROCK EXCAVATION

This section provides a general classification of vibration disturbances associated with different excavation techniques. A comparative summary of their main characteristics, relevant to DIN and ISO assessment, is provided in Table 1.

3.1 DRILL-AND-BLAST EXCAVATION

Drill-and-blast excavation is a cyclic process in which most of the working time is devoted to blast fume clearance, muck removal, drilling, charging, and preparing the initiation system. The event responsible for vibration disturbance, namely the detonation of explosive charges, lasts only a few seconds. From a vibration standpoint, blasting consists of a sequence of very short impulses characterized by high peak amplitudes, each with a duration of a few milliseconds, separated by delays typically ranging from a few tens to a few hundreds of milliseconds. In tunnel excavation, multiple charges are detonated in rapid succession, usually within a total duration of less than 10 seconds, depending on the blast design and initiation system. A typical vibration time recorded during a blast is schematically shown in Figure 1, highlighting the impulsive nature of the phenomenon and the separation between successive detonations. Rock fragmentation and detachment are achieved through the impulsive application of very high pressures generated by explosive gases. Each charge releases energy on the order of several megajoules within extremely short times, resulting in the excavation of rock volumes ranging from fractions of a cubic metre to several cubic metres per blast. Although drilling operations also generate vibrations, they are continuous and several orders of magnitude lower in intensity than those induced by explosive detonation.

Table 1. Comparison of Vibration Disturbances Induced by Different Tunnel Excavation Techniques

Excavation Method	Nature of Disturbance	Typical Energy per Event	Frequency Characteristics	Vibration Intensity	Relevance for DIN / ISO Assessment
Drill-and-blast	Impulsive, intermittent	Several MJ per charge	Broad band; high frequencies near source, lower frequencies dominant at distance	High	Critical method; PPV usually governs compliance with DIN 4150-3 limits
Hydraulic breaker	Impulsive, quasi-continuous	Few Kj per blow	Repeated impulses at low Hz; significant low-frequency content	Medium – low	Generally compliant at typical tunnel–structure distances; resonance effects possible
Road header/TBM	Continuous, pulsating	Continuous power (hundreds of kW)	Predominantly low-frequency, narrow-band	Low	Rarely critical; mainly relevant for sensitive structures or resonance conditions

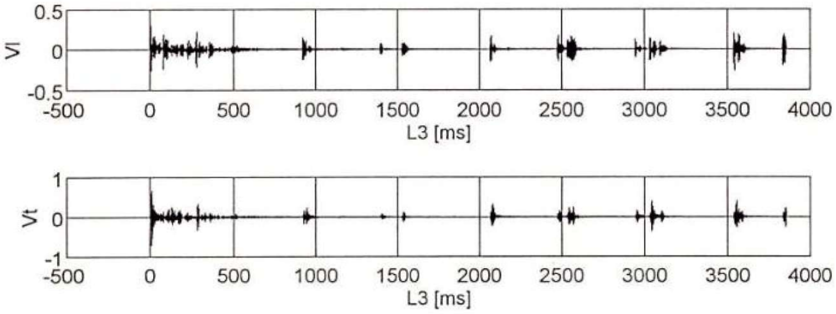

Figure 1. Example of a vibration record from a blast round during the excavation of a small-section tunnel (top: longitudinal velocity component; bottom: vertical velocity component), recorded at approximately 30 m from the tunnel face. Distinct peaks produced by each charge within the individual groups can be observed, due to the scatter in the pyrotechnic delays used. The total duration of the record is 4 s (Borla, 1996).

3.2 EXCAVATION WITH HYDRAULIC BREAKERS

Excavation using hydraulic breakers produces a continuous process, as rock detachment may overlap with muck removal. The resulting vibration disturbance is also continuous but generally of much lower intensity than that generated by blasting (Table 1). Rock fragments, typically of the order of a few liters in volume, are detached by repeated impacts of a steel tool driven by a percussive mass. The energy transferred to the rock at each blow is in the order of a few kJ, and multiple impacts are often required to achieve detachment. Impacts occur at frequencies of a few hertz, producing vibration records characterized by repeated high-frequency impulses separated by intervals on the order of 0.1 s, interspersed with longer pauses associated with machine repositioning. Despite the lower energy involved in each impact compared to blasting, the relatively low-frequency content of the excitation may, in some cases, favour resonance phenomena. In general, vibration levels induced by hydraulic breakers can be considered modest at the distances typically separating tunnels from vibration-sensitive structures, in agreement with the qualitative comparison reported in Table 1.

3.3 EXCAVATION WITH CONTINUOUS MECHANICAL MACHINES (ROADHEADERS, TBMS)

Continuous excavation machines remove rock by means of hard-metal or sintered carbide cutting tools that detach relatively small fragments, typically from a few to a few hundred cubic cm. Although the applied force is ideally continuous, it is in practice pulsating due to the repeated engagement of individual tools, resulting in a continuous but low-intensity vibration disturbance compared with blasting or percussive excavation. While many tools may be present, only a limited number cut simultaneously, and the total power transmitted to the rock mass is typically on the order of hundreds of kW. In some cases, vibrations transmitted to the rock mass may be dominated not by the cutting process itself but by machine-induced oscillations associated with the equipment's large mass and possible resonance phenomena. These vibrations are transmitted through the rock, which temporarily acts as the machine foundation. Overall, vibrations induced by continuous excavation machines are characterized by low amplitude and continuous duration, with interruptions occurring only during operational pauses such as repositioning or maintenance. In summary, the intensity of vibration disturbance during tunnel excavation is directly related to the size of rock elements detached during excavation and inversely to the specific energy required for excavation. Drill-and-blast excavation produces the highest vibration levels, followed by percussive mechanical methods, while continuous mechanical excavation generally results in the lowest vibration amplitudes. This qualitative relationship is schematically illustrated in Figure 2, while a comparative overview of vibration characteristics is provided in Table 1.

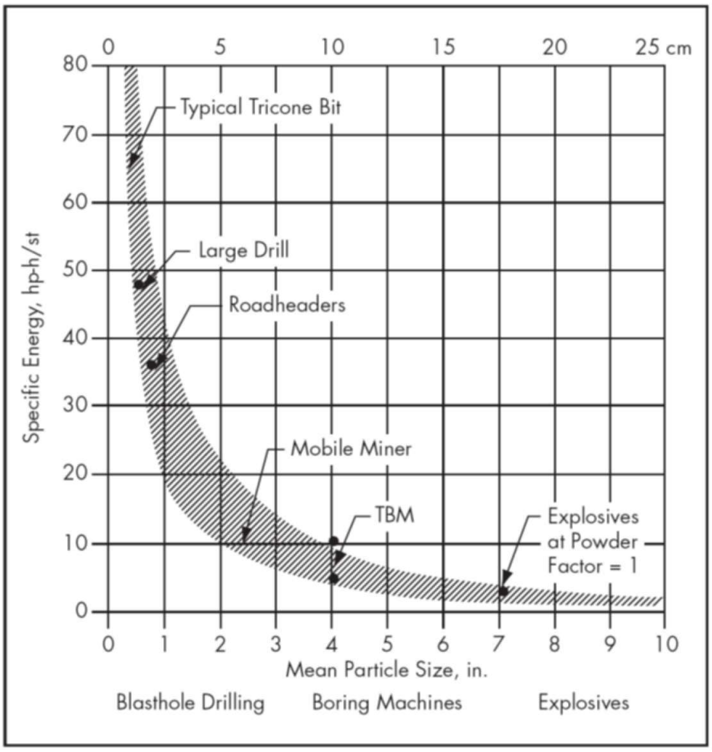

Figure 2. Correlation between the specific energy consumption in rock excavation (vertical axis) and the size of the produced fragments (horizontal axis). The left-hand side corresponds to the range of fine fragmentation (drilling), the central portion to medium fragmentation (mechanical excavation), and the right-hand side to coarse fragmentation (blasting) (Friant 1989).

4. SPECIFIC FEATURES OF BLAST-INDUCED VIBRATIONS IN TUNNELLING

Drill-and-blast excavation is addressed in greater detail in this paper because it is the excavation technique most closely associated with critical vibration-related issues. Although vibration control in blasting has a long history and is primarily based on extensive experience from surface works, such as quarries and surface excavations, these approaches cannot be transferred uncritically to tunnel excavation. For this reason, a concise overview of vibration control in tunnel blasting is provided, highlighting the specific features and constraints that distinguish tunnels from more conventional blasting applications. The remainder of this chapter focuses on vibration control at the source during tunnel excavation and on predicting vibration propagation at a distance, with reference to representative and effective solutions adopted in practice.

In typical surface blasting operations such as quarrying or road and railway cuttings, excavation is performed using regular blast patterns with parallel blastholes arranged in a uniform grid. Each hole is designed to fragment a defined rock volume, with charge weights proportioned accordingly. Blast initiation follows a simple, established sequence in which holes are fired progressively toward free surfaces, ensuring that each hole detonates with the designed burden. Under these controlled conditions, vibration control is relatively straightforward. Vibration limits at protected receptors are defined by standards, usually expressed as PPV, as a function of frequency. The standard control procedure involves conducting trial blasts with known charges, measuring vibrations at various distances, and deriving site-specific attenuation laws and distance–frequency relationships. Based on the minimum distance to the protected structure and its sensitivity class, the allowable PPV limit is identified for the expected frequency range, and the maximum permissible charge per delay (CPD-max) is determined. The CPD represents the maximum explosive mass effectively acting simultaneously in vibration generation; charges detonating within a short time window, typically less than about 8 ms, are considered cooperative. The resulting CPD-max is then used to design or verify blasting layouts by adjusting charge weights and delay timing.

While this methodology is well established for surface blasting, tunnel excavation introduces additional geometric and operational constraints that significantly affect vibration generation and propagation.

The site law is commonly expressed in the following form:

$$PPV = K\left(\frac{R}{\sqrt{Q}}\right)^{\alpha} \tag{1}$$

where:

PPV = particle velocity (mm/s);

Q = explosive charge (kg);

R = distance (m);

K, α = experimentally determined constants.

In minor blasting works, vibration control may rely on site laws derived from similar cases, without dedicated trial blasts. A similar approach can be applied in tunnel excavation, although it involves additional complexities:

A. Tunnel blast rounds consist of groups of charges with different functions (cut, production, contour), which are charged differently and may generate different vibration levels under the same charge and distance conditions, potentially requiring function-specific site laws.

B. Tunnel blasting is often carried out very close to protected receptors, including nearby underground structures such as adjacent tunnels or support systems. At such short distances, the point-source assumption and conventional distance definitions are no longer valid, and site laws must be applied with appropriate corrections to account for elongated charges.

C. Charges, particularly in the cut, are closely spaced, often at decimetric distances or less, increasing the risk of sympathetic detonation, and limiting charge reduction through tighter blast patterns due to constraints on drilling accuracy and explosive sensitivity.

D. Vibration levels at a given point may differ depending on whether the tunnel face is advancing toward or away from a receptor. This effect is mainly relevant at short distances and lacks consistent predictive rules.

E. Tunnel excavation is more likely than surface blasting to encounter highly variable geological conditions, leading to differing vibration transmission behaviour.

Overall, vibration control in tunnel excavation requires a more adaptive, less automated approach than surface blasting, with a strong reliance on continuous vibration monitoring to enable timely adjustment of blasting parameters.

5. BLAST TYPE AND THEIR INFLUENCE ON VIBRATION INTENSITY

Tunnel blasting terminology requires clarification due to the lack of full standardization in the literature. Tunnel excavation by explosives proceeds cyclically, through the fragmentation and removal of a cylindrical rock volume whose cross-section matches the tunnel profile and whose length equals the blast advance (round length). A blast round consists of a set of cooperating blastholes designed to fragment and displace this volume; its removal exposes a new tunnel face advanced by the round length. Blastholes are characterized by drilling diameter (typically 30–50 mm), length, charge weight (generally variable among holes), firing sequence, and firing time, defined as the delay relative to the first detonation. Multiple blastholes may share the same nominal firing time; although minor deviations may occur due to timing inaccuracies, the firing order must be maintained. The effective advance should ideally equal the drilled length, but in practice it reaches about 90% of that; the ratio of actual advance to drilled length defines the blast efficiency. A blast round is further described by the excavation section, advance length (typically 0.5–7 m), number of blastholes, firing sequence, drilling density, total charge, and specific explosive consumption. A key design parameter is the cut type, i.e. the technique used to create the initial cavity at the tunnel face that enables subsequent rock breakage. For this study, blastholes are grouped into three categories:

- Cut holes, typically 4–12 for parallel cuts (excluding uncharged dummy holes) or 6–16 for inclined cuts, which create the initial opening; they detonate individually or in small groups with very short delays (usually 20–60 ms);
- Production holes, whose number depends on the tunnel section (from a few units up to ~100), progressively enlarge the opening and account for most of the excavated volume; they detonate with longer delays than cut holes, typically in the range of 50–200 ms between successive groups;
- Contour holes, arranged along the excavation perimeter (usually 1–3 holes/m), lightly charged and fired last, generally in groups, to shape the final profile.

In most cases, cut holes are the main contributors to vibration disturbance. Despite the variety of layouts, cut types can be grouped into two main categories, listed below in order of decreasing vibration intensity under comparable conditions.

1. Parallel-hole cuts with empty relief holes (*Canadian cuts*) are mainly used in small-section tunnels. One or more charged holes detonate adjacent to empty holes that act as limited free surfaces, forming an initial cylindrical cavity later enlarged by parallel holes. Vibration levels are relatively high due to the restricted initial free surface, and high-resolution measurements at short distances may even distinguish the contribution of individual cut holes (Figure 3). However, vibrations remain lower than those from crater cuts because detonation is distributed over time, typically 100–500 ms when timing performs as designed.
2. Inclined cuts (V-, wedge-, and fan cuts) are widely used in medium to large tunnel sections. Holes are drilled with increasing inclination and fired sequentially to detach a rock wedge and enlarge the cavity. The larger initial free surface generally results in lower vibration levels than parallel-hole cuts.

Production holes are usually uniformly charged and designed to break similar rock volumes. Their contribution to vibration is typically well controlled through timing and is not a critical factor.

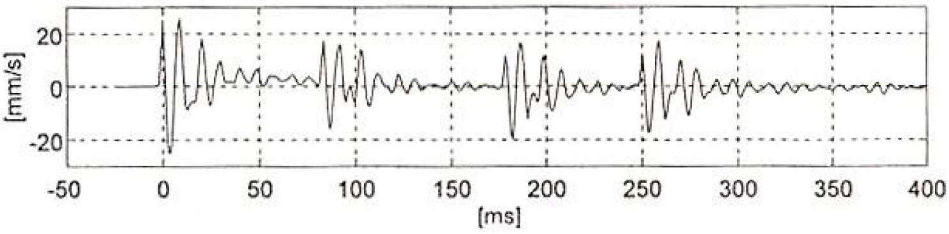

Figure 3. Vibrogram recorded at 30 m from the tunnel face showing the detonation of the four cut holes of a parallel-hole round in a small-section tunnel. The first charge produced a significantly higher particle velocity, even though all holes contained the same explosive charge (2.5 kg of dynamite), indicating proper functioning.

Contour holes, although lightly charged, may generate relatively high CPD values because they often detonate in groups. However, they rarely cause vibration problems, as decoupled charges are commonly employed, significantly reducing vibration effects for the same charge weight (Figure 4). Furthermore, they act on already fractured rock and benefit from large free surfaces.

Timing is a key factor in vibration control. Three systems are used: electronic detonators with millisecond precision, electrical delay detonators, and non-electric shock-tube systems (Nonel). The latter two rely on pyrotechnic delays and exhibit timing scatter of 5–10% of the nominal delay, depending on manufacturer and batch. This can cause discrepancies between designed and actual charge per delay, particularly for late-firing holes. With a 10% inaccuracy, detonators nominally set at 30 ms fire between 27–33 ms, allowing charge cooperation and increased vibration, whereas detonators set at 1000 ms fire within 900–1100 ms, making cooperation unlikely. If scatter does not cause overlaps between successive delays, it may paradoxically reduce vibration levels by lowering the effective charge per delay.

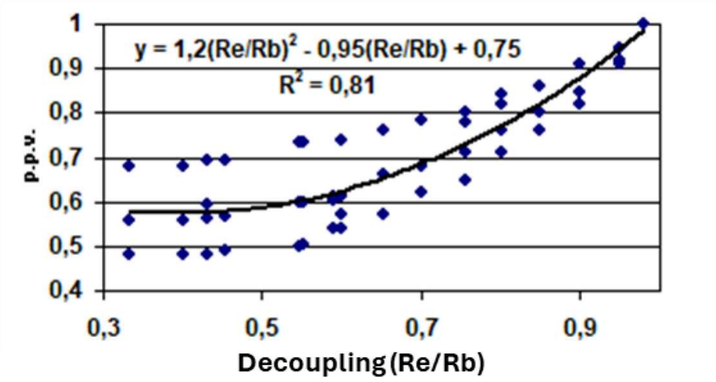

Figure 4. Correlation, for equal charge and distance, between the peak particle velocity (PPV) and the degree of charge decoupling (ratio between the charge radius and the borehole radius). The peak particle velocity is set equal to 1 for a degree of decoupling ≈ 1 (Singh & Lamond 1995).

A timing error with consistently negative effects is sympathetic detonation, where a charge is initiated by a nearby explosion Figure 5). This is relatively common in the cut holes of Canadian rounds due to closely spaced boreholes and drilling inaccuracies. In such cases, premature detonation increases CPD, resulting in higher vibration levels. This malfunction cannot be mitigated by more advanced detonators.

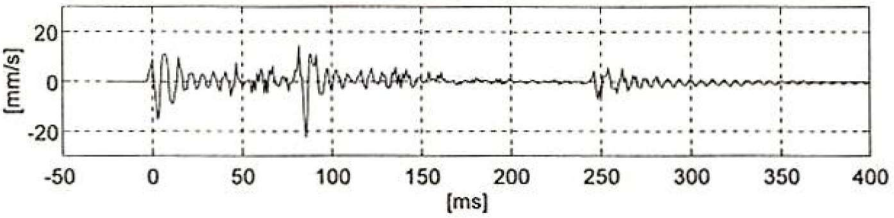

Figure 5. Vibrogram of the explosion of the four cut holes of a parallel-hole round (same tunnel as in Figure 3). The absence of the signal from the third hole and the abnormally high amplitude of the second-hole signal should be noted. The third hole detonated sympathetically (flashover) with the second, resulting in an effective increase in the charge per delay.

6. SITE LAWS AND NORMS

The concept of a site law has often been criticized because it is not a physical law but an empirical correlation, valid only for specific blasting operations and limited operating conditions at a given site. Nevertheless, relationships linking charge per delay, distance, and peak particle velocity (PPV) are essential tools for predicting vibration levels and assessing how changes in charge or distance affect compliance with allowable limits. Numerous site-law formulations have been proposed (USBM 1959; Ambraseys & Hendron 1968; Langefors & Kihlström 1978; Indian Standard Institution 1973; Davies et al. 1964; Ghosh & Daemen 1983; Singh et al. 1993). These can be grouped into two categories: formulations based on scaled distance and those using charge and distance as independent variables. Scaled distance is commonly defined as:

$$D_s = \frac{R}{Q^b} \qquad (2)$$

where $R$is distance, $Q$is charge per delay, and $b$is typically 0.5 (square-root scaling), although other exponents are sometimes used. Scaled-distance laws express PPV as a function of D_s, while alternative formulations express PPV directly as a function of $R$and Q. Scaled-distance laws are widely used because they involve few variables and are easily derived from field data, although more complex formulations may be theoretically more rigorous. All site laws become unreliable when extrapolated beyond their calibration range, and no site characteristic clearly favors one formulation; among them, the classical USBM law appears, on average, less unreliable. In tunnelling, long-distance extrapolation is rarely critical because the CPD is small and vibration levels at distances of about 100 m are generally acceptable. Greater uncertainty arises at short distances beyond the near-field zone (3–4 borehole diameters), where the point-charge assumption fails, particularly when the distance to the structure is comparable to the charge length; this limitation was addressed by Persson & Holmberg (1978) through charge integration along the explosive column. Most regulations limit blasting vibrations to prevent cosmetic damage and reduce disturbance. Standards distinguish blasting from continuous vibration sources and typically adopt PPV and frequency as damage indicators. In Italy, practice mainly refers to DIN 4150-3 and SN 640312. DIN 4150-3 defines frequency-dependent limits for industrial, residential, and sensitive structures, with maximum PPV values of 40, 15, and 8 mm/s at the top floor. The Swiss standard defines PPV as the vector sum of three components, classifies buildings into four sensitivity classes, and applies frequency- and repetition-dependent limits. For structures not covered by standards, limits are generally expressed in PPV, although acceleration may govern rock-block sliding (Cravero 1988). Indicative PPV limits for rock range from 200–2000 mm/s depending on quality (Page 1987). Given the small charges used in tunnelling, hazardous vibration levels are unlikely; former Swiss guidelines prescribed 30–40 mm/s for underground structures. Mature concrete behaves similarly to good-quality rock (Oriard 1980), while immature concrete requires lower PPV limits that increase with curing time (Abersten 1994).

7. CONTROL OF BLAST-INDUCED VIBRATIONS IN DAMAGE-SENSITIVE TUNNEL EXCAVATION

In vibration-sensitive tunnel blasting, particularly in urban environments near existing structures or immature concrete, design objectives may exceed regulatory compliance and aim at negligible damage. Vibration control should therefore be integrated into blast design rather than treated as a post-design check. Empirical prediction laws remain useful when calibrated with site-specific data and applied within their validity range; however, their limitations are most pronounced in the near field, where short distances invalidate point-source assumptions and require conservative interpretation. Under these conditions, physically based approaches that account for the distributed nature of explosive charges, such as charge integration methods proposed by Blair & Minchinton (2006), Gómez et al. (2020), and Gou et al. (2025), are more appropriate for short-distance assessment. The maximum instantaneous charge is the primary control on blast-induced vibrations; reducing the CPD and optimizing delay sequencing is generally more effective than refining prediction models. Delay design must limit constructive wave superposition while maintaining acceptable fragmentation, as shown by tunnelling practice and waveform analyses (Blair 2014, 2015; Yang et al. 2016; Sanchidrián et al. 2017; Lu et al. 2018; Zhang et al. 2020; Li et al. 2021). Perimeter control techniques further reduce vibration transmission by limiting overbreak and preserving rock mass stiffness near existing tunnels. Continuous vibration monitoring based on peak particle velocity and frequency supports verification of negligible-damage objectives and adaptive blast optimization through predefined thresholds and corrective actions (Table 2).

Table 2. Example of a vibration control framework for negligible-damage tunnelling.

Measured PPV (relative to target limit)	**Engineering interpretation**	**Typical action**
≤ 60%	Fully acceptable	No change to blast design
60–80%	Approaching the critical zone	Reduce the CPD; adjust delay timing
> 80%	Potentially unacceptable	Stop and redesign the blast; perform a pilot test

Such an approach allows proactive control of vibration levels and avoids operating close to threshold conditions, where prediction uncertainty and variability may compromise safety margins. Special attention is required when vibration-sensitive materials are present, such as immature concrete, whose resistance to vibration increases rapidly with curing time but remains significantly lower than that of mature concrete or competent rock. In these situations, conservative limits and additional safety margins should be applied, and blast designs should be adapted accordingly. Overall, negligible-damage tunnel excavation can be reliably achieved by combining conservative design choices, calibrated empirical prediction, physically informed interpretation of near-field effects, and systematic monitoring. When applied consistently, this approach allows the safe and efficient use of drilling and blasting even in highly constrained environments.

8. CONCLUSIONS

Blast-induced vibrations represent a critical control issue in tunnelling, especially in urban environments where sensitive structures may be located close to the blast source. Common predictive laws are empirical and adequate for preliminary assessments, but their main limitation lies in the near-field zone. Regulatory vibration limits are deliberately conservative and focus on preventing cosmetic damage and disturbance, with peak particle velocity being the most appropriate parameter for the frequency range typical of blasting. Differences among standards and the absence of explicit criteria for rock masses, underground excavations, and concrete elements require case-specific evaluation. Although low charge weights in tunnelling generally result in safe vibration levels, unfavourable geological conditions, geometric constraints, or immature concrete can significantly reduce tolerance. Effective vibration control, therefore, requires an integrated approach combining empirical prediction, conservative limits, physical understanding, and site-specific monitoring.

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SESSION 5

BIM, numerical modelling, research, development and sustainability

Session chairs: *Munfah Nasri, Monika Mitew-Czajewska, Eva Hrubešová, David Mašín*

Invited Lecture

UNDERGROUND SPACE DEVELOPMENT AS A CATALYST FOR URBAN GROWTH

N. A. Munfah

Oral Presentations

NEW TRENDS IN FACE SUPPORT METHODS FOR MECHANIZED TUNNELING

P. Hybský , V. Gall, A. Valdivia & P. Griesbach

REDUCTION OF ENVIRONMENTAL IMPACT OF A TBM PROJECT USING INNOVATIVE SOLUTIONS FOR SOIL CONDITIONING AND BACKFILLING GROUT

E. Barbero, E. Dal Negro & A. Picchio

AUTOMATED ANALYSIS OF SEGMENTAL RING OVALITY IN TBM TUNNELS

T. Langar, P. Matter & L. Hannan

RETHINKING TUNNEL CONSTRUCTION: DIGITALIZATION IN THE BIM PILOT PROJECT TUNNEL HOLSTEIN

J. Jäger, C. Kostner, P. Schallner, L. Staggl, S. Steiner

DESIGN AND CONSTRUCTION OF FIBER REINFORCED CONCRETE (FRC) TUNNEL PRECAST LINING WITH FIBER ENABLED CARBON FOORTPRINT REDUCTION

B. De Rivaz

INFLUENCE OF STRUCTURAL AND OPERATIONAL CONSTRAINTS ON THE EFFECTIVENESS OF BLOCK BACKFILLING: FINDINGS FROM WATERPROOFING OF A DEUTSCHE BAHN TUNNEL

C. Rhein, G. Vollmann & M. Thewes, Schälicke & C. Camós-Andreu, A. Decker, C. Christoph

NEXT GENERATION TUNNEL WATERPROOFING

Y. Boissonnas & S. Schreiner

STUDY OF POLYPROPYLENE FIBER-REINFORCED CONCRETE IN PRECAST TUNNEL LINING

J. Gomez, J. Duran & J. Cho

AUTOMATION OF SHOTCRETE APPLICATION

R. Antretter

UTILISATION OF GEOTHERMAL ENERGY FROM TUNNELS WITH A FOCUS ON THE NOVÉ DVORY METRO D STATION

L. Mařík, J. Hobza & P. Dědina

IMPLEMENTATION OF GEOLOGICAL MODELS AND GEOSCIENCE DATA INTO BIM PROJECTS
Z. Rudovský & J. Franěk

Posters

DATA DRIVEN GEOTECHNICAL DESIGN: TOWARD A DIGITAL GEOTECHNICAL BASELINE FOR HARD ROCK MECHANISED TUNNELLING

R. Angelov, H. Salzgeber, M. Ernst & M. Flora

SUSTAINABILITY ASSESSMENT OF POLYPROPYLENE FIBER AND HYBRID REINFORCEMENT SYSTEMS IN PRECAST TUNNEL LININGS

J. Duran

POSSIBILITIES OF USING NUMERICAL SIMULATIONS FOR THE DESIGN OF ENERGY GEOSTRUCTURES

E. Hrubešová & M. Mohyla

SECOND GENERATION OF EUROCODE 7 AND APPROACH TO PARTIAL FACTORS WHEN USING FEM

J. Pruška

CALCULATION OF CONCRETE TUNNEL LININGS, INTERACTION DIAGRAM, STRENGTH AND DEFORMATION MODULUS OF CONCRETE

J. Zlámal

FINITE ELEMENT INVESTIGATION OF THE SAFETY FACTOR OF TUNNEL PRIMARY LINING IN A DEEP TUNNEL UNDER SQUEEZING CONDITIONS

G. Antonucci & G. Scognamiglio

ELECTROCHEMICAL REDUCTION OF LOESS ADHESION ON SHIELD MACHINE CUTTING TOOLS

L. Wang & W.C. Cheng, E. Bilotta

THE SUSTAINABLE TUNNEL REINFORCED WITH GLASS FIBER REINFORCED PLASTIC (GFRP) BARS

A. Focaracci, L. Rosati

A HYBRID DATA-DRIVEN APPROACH FOR PREDICTING RETAINING WALL DEFORMATION

L. L. Mu & K. Yan

ANALYSIS OF SEGMENTAL TUNNEL LININGS AT EXTREME LEVELS OF OVALIZATION CAUSED BY SOIL EROSION

E. Sturt, G. Montalbini & H-I. Jung