Origin of the vibrations induced by tunnels' excavation

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ABSTRACT: In rock excavation (especially with explosives, but also in mechanical excavation), the vibrations of the medium where the excavation develops (rock mass) and those of the surrounding air (sound) are of great importance. After a synthetic description of the most common expressions of the "site laws" (charge - distance - vibration intensity correlations), attention is paid to the different types of technical problems where such correlations can be employed, on the basis of experimental cases and of literature data. Examples are presented consisting of suitable modifications of the excavation procedure to reduce the problem of vibrations. These modifications may concern, even jointly, the reduction of the pull, the increase of the drilling density (with corresponding reduction of the charges of the single holes), the increase of the delay numbers, the modification of the excavation system or, also, the isolation of the volume to be excavated with mechanical pre-cuts. The conclusions provide a straightforward approach to the assessment of charge per delay limits and recommendations are provided.

1 INTRODUCTION

The term "Site laws" is applied as a useful tool in blast work design, when damage to nearby buildings is feared (Wang et al. 2022). It represents a compromise between the correct representation of a phenomenon and the simplicity of its representation, strongly biased towards simplicity. Its usefulness cannot be denied when used correctly, i.e. to define safe charge limits or to calibrate the delay sequence.; However, some warning should be given against arbitrary use (i.e. to infer some features of a blast from the comparison of the observed effect to the predicted effect).

"Site laws" are expressions linking 3 variables: instantaneous charge (Q), distance taken as reference from the blast (R) and vibration disturbance intensity (peak particle velocity, PPV). The definition of these three parameters is simple even if special cases (not so rare in some construction sites) can complicate the problem:

- Q is the mass of explosive detonated with caps having the same delay number; attempts to replace the mass with the energy did not provide advantages as far as the accuracy of predictions is concerned: indeed, 1 kg of TNT (870 kJ) does not produce, the distance being equal, less vibratory disturbance than 1 kg of ANFO (1010 kJ). Also the definition of "instantaneous explosion" gave rise to discussions (still unsettled) on the minimal separation interval (nil, 4 ms, 8 ms, ...) to avoid cooperation;
- R is the distance from the center mass of the charge (or charges) to the recording station. Some uncertainty (and discussion) arises when several charges are detonated with the same delay number at different points of the same round, or when a very long charge is detonated: the integration of the effects of several "elementary" charges on the disturbance attended at the recording station is mathematically feasible, but debatable on the theoretical basis, and not

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apt to provide a simple rule (in jargon, it is common to say that “formulas longer than one inch are of no use in mining”);

– PPV (commonly reported as v) is accepted as an indicator of the intensity of the disturbance: discussions on the advantages of other indicators (acceleration, displacement, combined indicators) have been settled by the fact that the more common recording instruments are PPV recorders, and most regulations refer to PPV limit values. However, which component (vertical, radial, transverse) or resultant (synchronous, asynchronous) value should be considered is still debated.

If the definitions are almost univocal, a different situation concerns the mathematical formulations expressly used to connect Q, R, and PPV. In the following, the main mathematical forms proposed and adopted (or accepted) for the “site laws” are listed:

1. USBM (1959)	$ppv = \mathrm{K} \cdot R^{-n} \cdot Q^{\frac{1}{2}n}$	5. Davies at al. (1964)	$ppv = \mathrm{K} \cdot R^{-c} \cdot Q^{n}$
2. Ambraseys-Hendron (1968)	$ppv = \mathrm{K} \cdot R^{-n} \cdot Q^{\frac{1}{3}n}$	6. Ghosh-Daemen (1983)	$ppv = \mathrm{K} \cdot R^{-n} \cdot Q^{\frac{1}{2}n} \cdot e^{-cR}$
3. Langefors-Kihlström (1967)	$ppv = \mathrm{K} \cdot R^{-\frac{3}{4}n} \cdot Q^{\frac{1}{2}n}$	7. Ghosh-Daemen (1983)	$ppv = \mathrm{K} \cdot R^{-n} \cdot Q^{\frac{1}{3}n} \cdot e^{-cR}$
4. I. S. I. (1973)	$ppv = \mathrm{K} \cdot R^{n} \cdot Q^{-\frac{2}{3}n}$	8. CMRI (Pal Roy et al. 1993)	$ppv = m + \mathrm{K} \cdot R^{-1} \cdot Q^{\frac{1}{2}}$

It is often forgotten that “site laws” are born as “interpolation or extrapolation rules” rather than as explanations in the mathematical language of a physical phenomenon: dimensional consistency is simply ignored in the construction of the “site laws”. To be noticed, dimensionally consistent “site laws” can be built: for example, Zhou & Jin (2002) proposed:

$$\mathrm{ppv} = \mathrm{K} \cdot \left(\frac{\mathrm{R}}{\sqrt[3]{\mathrm{E}/\mathrm{K}'}} \right)^{-n} \tag{1}$$

where E is the energy released by the event, and K’ is a “site constant” having the dimensions of pressure, accounting for the strength of the ground (the load-bearing capacity of the ground). But this expression, as well as others that were omitted and as the more complex listed in Table 1 (those having more than two “site constants” to be obtained from statistical analysis of recorded blasts, or taking a binomial form) are scarcely used.

The simple fact that different formulas are employed and considered equally valid (no unmistakable proof has been given of the special merits of one of them) warns against the pretended accuracy of the predictions. Anyway, leaving out the simple coefficient as n, A, and α, it is important to highlight that all equations are based on two important parameters, K and B, called “site coefficients”.

Ideally, K and B should define the “site” (the effect of the unit charge when detonated in the site): for a given site, they should have accredited validity, but there are often discrepancies that should be attributed to the structure of the analyzed data populations and to the interpolation methods; obviously, the more the range of test blasts spreads above and below the unit charge, the more sensitive is the result. The last remark should be reported pertaining to the “site laws”: it is often forgotten that these equations are born as “interpolation or extrapolation rules” rather than as explanations in the mathematical language of a physical phenomenon: dimensional consistency is simply ignored in the construction of the “site laws”.

A commonplace observation, when working the recorded PPV, R, and Q values from a test campaign to obtain the coefficient K and the exponent (or exponents) of the law, is the extreme dispersion of the experimental points. It has been experimentally observed that the modality of performing site tests can strongly affect the distribution of the obtained outcomes.

For example, considering 20 experimental points obtained by a single blast but recording vibrations at different distances, the distribution of outcomes able to compute K and B is characterized by a lower dispersion compared to an alternative distribution obtained by the same number of points, in the same site, but based on 20 different blasts (Cardu & Oreste 2006).

In any case, at the maximum speed value (peak particle velocity) the role of the main indicator of the harmfulness of the vibration is recognized by many standards (Deutsche Institut für Normung 1999, British Standard 7385-2 1993, British Standard 5228-4 1992, Swiss Standard VSS-SN640-312a 1992, UNI 9916:2004, NTC 2018).

2 DRILL & BLAST IN TUNNELLING

The application of the Drill & Blast in tunneling is characterized by a serious problem, in terms of vibration. The general theme of the control of vibrations from explosives is long-standing, and a way of dealing with it has been consolidated based on the enormous "experience" collected on the most common works (exploitation of quarries, excavation work), certainly precious also for the case of tunnels, but from which it is difficult to draw uncritically. Blasting is generally inevitable for hard rock excavation activities not only in mining and quarrying, but also in tunnels, subways, highways, and dam construction. As these infrastructure activities are often close to (even mostly within) residential areas, environmental problems, unfortunately, occur by the ground vibrations and air blast induced by blasting (Shin et al. 2011). Tunnel construction with blasting in urban areas creates annoying ground vibrations and may inflict structural damage when excess amounts of explosives are used. It should be reported that about 20–30% of the energy due to blasting is utilized to fragment the rock (Kuzu 2008, Ozer 2008).

In the following, the problem of the control "at the source" of the vibrations in the specific case of the excavation of tunnels and of the forecast of their propagation at a distance is faced, with some examples of solutions.

2.1 *The problem of vibrations induced by blasting in tunneling, compared to other types of works*

In the most common rock excavation works (exploitation of quarries, excavation of roads or railway trenches, etc.) groups of parallel holes having the same geometry are repeatedly used, arranged according to a regular mesh (blasting pattern). An example is given in Figure 1.

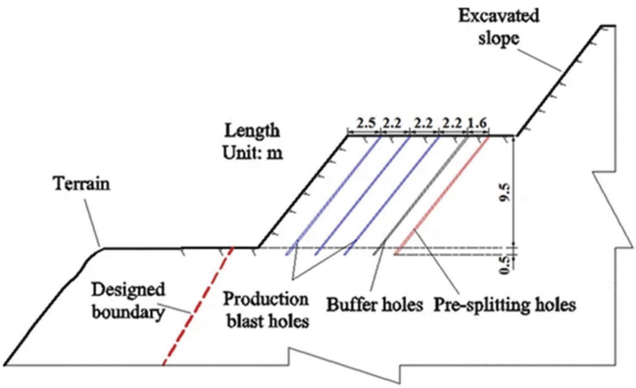

Figure 1. Example of excavation of a large-scale rock slope (Yan et al. 2016).

In these simple conditions, the control of vibrations, i.e. the operational prescription intended to prevent the intensity of vibrations exceed the imposed limit values by standards, is obtained with a simple procedure, and just as simply expressed: the vibratory effects, at different distances, of blast "tests", carried out with known charges, are measured, so that the "site law" and the distance - frequency correlation is obtained from the data collected. The site law usually adopted is of the type USBM:

$$v = K\left(\frac{R}{\sqrt{Q}}\right)^{a} \tag{2}$$

where: v = peak particle velocity (mm/s); Q = charge per delay (kg); R = distance (m); K, α = experimental constants, to be determined.

In the case of tunnels, the process is conceptually the same, but with many complications: first of all, the blasts are composed of groups of holes that have different functions: to create a first opening in the face, to widen it until it reaches a section just below the desired one, to refine its outline. These groups of blast holes are not only loaded in a different way but also cause, for the same charge and distance, a disturbance of a different entity (i.e. different site laws should be provided for holes with different functions). Moreover, while in the open pit excavations the protected target is rarely very close to the blasts, in the excavation of tunnels this eventuality is not rare: in addition to the buildings on the surface (Figure 2), other underground works that are very close are often to be considered (metric distances, or even zero: the excavation of a tunnel may border on the lining of another, as in the example of Figure 3), and sometimes the same supporting works of the tunnel being excavated. At very small distances from the charge, the usual definition of R (distance between the center of gravity of the charge and the object to be protected) and the implicit assimilation of the charge of the blast hole, which is an elongated cylinder, to a point where the charge itself is concentrated, makes no sense. In fact, it is certainly different to be 1 m away from a concentrated charge of 5 kg of dynamite, or 1 m away from the midpoint of a thin cylinder of dynamite with a total mass of 5 kg and 5 m long. In these cases, the site law can still be used, but with an appropriate correction. Furthermore, in the usual open pit blasting operations, the distance between the charges of the different holes, besides being almost constant, is quite large (metric). In such conditions, the charges surely explode under the action of the trigger, according to the scheduled times. Furthermore, a difference in vibratory disturbance can occur at a point on the surface, although the charges, the blasting plan, and the distance are the same, depending on whether the excavation face is approaching or moving away from the point itself.

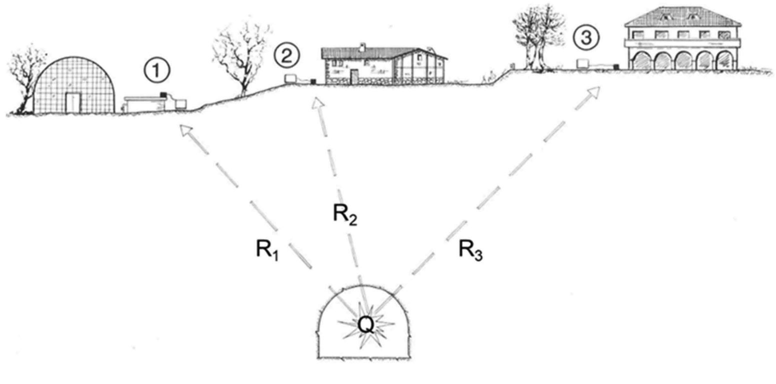

Figure 2. Example relating to the excavation of a tunnel at distances R_1, R_2, R_3 from different classes of structures: 1 = industrial buildings; 2 = residential buildings; 3 = monuments and/or delicate buildings.

This effect has been observed, but it does not seem to obey precise rules, and is sensitive to small distances (decametric or not) between the excavation face and the object under control. Finally, unless the excavation involves very small works, there is a much greater probability of passing through a large variety of rocks, with different characteristics of transmission of vibrations. The negative conclusion is that the control of vibrations in tunnel excavation requires a much less "automatic" approach than in ordinary open pit excavations and requires a heavier recourse to monitoring the effects on the sensitive objects to make possible timely corrections.

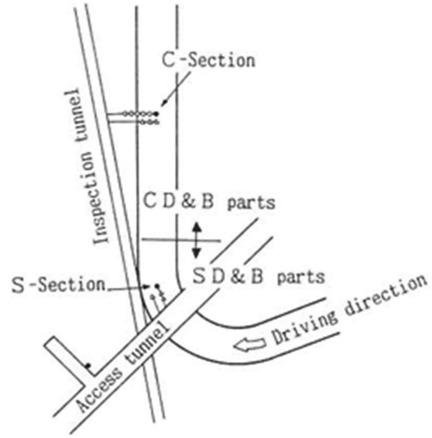

Figure 3. Example of a particularly difficult case of vibration damage control (tunnels underneath the town and very close to each other, in Tokyo). In the SD&B section, mechanical cutting of the profile and the subsequent blasting of the isolated volume with explosives (slot drilling and blasting) were used. In the CD&B section, an ordinary controlled blasting system with reduced charges was adopted (Hagimori et al. 1993).

2.2 *Types of blasts and their influence on the intensity of the disturbance produced*

In the excavation of tunnels, the holes of the group that creates the first opening are necessarily very close to each other: the distance can be decimetric or even less. In such conditions, the possibility of flash over (Figure 4) is not to be discarded: a charge can explode not by the action of its trigger, but by the impulse transmitted through the rock by a nearby charge (the transmission of the shock over decimeter distances requires only a few μs). Therefore, in addition to drilling precision, attention must also be paid to the type of explosive, which must not be too sensitive, and there is also a limit to the possibility of reducing single charges by reducing the blasting pattern. Almost always, the most consistent part of the vibratory disturbance is given by the cut-holes, which can be arranged according to an enormous variety of patterns; anyway, as a first approximation, the decomposition of the round can be ascribed to 3 groups of blast holes, listed in order of decreasing intensity, other conditions being the same, of the disturbance produced:

- cut holes: they have the task of preparing favorable conditions for those that will explode later, creating or extending “free walls” where these initially lack or are insufficient;
- production holes: they must break down most of the volume, taking advantage of the favorable conditions created by the previous group;
- contour holes: they have the purpose of outlining the contour of the wanted cavity, and therefore they essentially must detach what remains after the production blast holes have performed most of the work.

Contour holes usually explode in large groups and therefore, although individually lightly loaded, can result in a high charge per delay. Even in this case, however, they rarely represent a problem, being generally loaded with decoupled charges, e.g. a diameter smaller than that of the hole, and this reduces the vibratory effect produced (Figure 5); moreover, they operate with reduced burden, large free surface and on rock already damaged by the detonation of the remaining part of the blast.

It is at this point appropriate to consider the issue of the timing which, as can be guessed, has a fundamental role in the control of vibrations. Currently, there are 3 timing systems: electronic, with detonators incorporating an electronic timer, programmable with an accuracy of 1 ms; electric and Nonel (detonic tubes, shock tubes), both using pyrotechnic devices to obtain the wanted timing. Obviously, both, but above all the first, can have small deviations from the nominal value and, therefore, detonators of the same nominal delay would not explode at the same instant. The imprecision can be 5-10% of the nominal time, depending on the brand and batch of the detonators, and, therefore, gives rise to the non-coincidence of the design delay charge with that actually observed, especially for the blast holes that detonate last. In fact, assuming, for example, an inaccuracy of 10%, the detonators that nominally should explode 30 ms after the impulse, will explode in a time interval between 27 and 33 ms and, if several charges are triggered by these detonators, they will certainly cooperate for the purpose of vibratory disturbance. Differently, the detonators which nominally should explode 1000 ms after the impulse, will explode in a time interval between 900 and 1100 ms, and more charges triggered by them will very rarely cooperate.

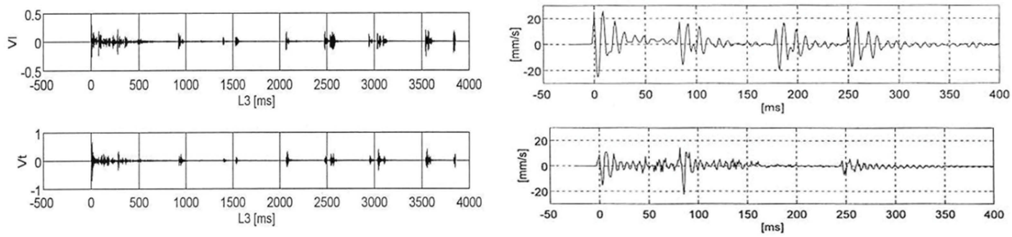

Figure 4. Left: example of a vibrogram of a blast in a small cross-section tunnel (the longitudinal component of the velocity above, the vertical component below), recorded about 30 m from the face. Notice the distinct peaks produced by each blast hole of each group, due to the dispersion of the pyrotechnic delays used. The total duration is 4 s. Right, top: vibrogram, recorded 30 m from the face, of the detonation of the first 4 cut-holes (same blast). Note the significantly higher speed of the 1st hole, although the charge was the same for all of them (2.5 kg of dynamite); perfectly smooth operation. Below: vibrogram, recorded during the advancement in the same tunnel, relating to the 4 cut-holes: the lack of the signal of the 3rd hole and the anomalous amplitude of the signal of the 2nd hole is evident: in fact, the 3rd hole exploded, due to flash over, together with the 2nd (Mancini & Cardu 2001).

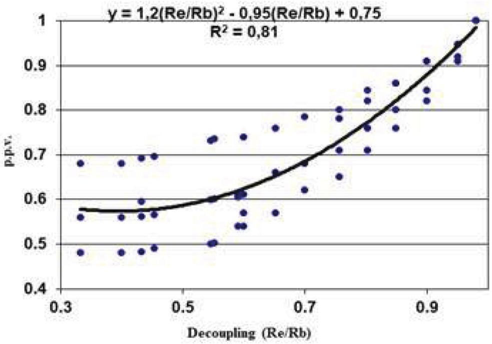

Figure 5. Correlation, with equal charge and distance, between the peak particle velocity p.p.v. and the charge decoupling, which is expressed as the ratio between the radius of the charge (Re) and the radius of the hole (Rb). The peak particle velocity is set = 1 per degree of decoupling of approximately 1 (Singh & Lamond 1995).

3 NORMS AND LIMITS

For many types of objects (houses, monuments, public buildings, industrial plants, etc.) the different countries have established rules that limit the intensity of the vibratory disturbance to which they can be subjected because of excavation works that take place nearby. However, there are also objects ignored by the regulations, for which limits must also be established and respected (for example rock walls, supporting works of a parallel tunnel or of the same tunnel being excavated, etc.). The limits set by the regulations are extremely cautious: they are essentially intended to exclude with a good safety margin, not the structural damage, but rather the so-called cosmetic damage. All the standards provide specific regulations for the disturbance produced by blasts, different from that adopted for other sources of vibration (such as vibrations produced by many operating machines or produced by traffic). Reference is made, for simplicity, to the model of the sinusoidal vibratory motion, which can be defined by only two of the four parameters (maximum elongation, maximum speed, maximum acceleration, frequency) with which it is usually described: for example, knowing the maximum speed and frequency, the maximum acceleration and maximum elongation can be deduced, etc. (Mancini & Cardu 2001); consequently, the standards take into consideration two parameters, generally, the maximum speed and the frequency: for the maximum speed limits are set as a function of the frequency. Of course, the limits are different depending on the degree of sensitivity of the object to be protected. The German standard DIN 4150 (Figure 6) and the Swiss standard SN 640312a are the most frequently used in Italy. Both refer to the particle velocity as the main parameter characterizing the vibration for the purposes of its potential harmfulness and establish different limits depending on the frequency and other factors: the nature of the object to be protected in both and, in the Swiss one, the nature of the operation that produces vibrations, that is, if it involves few or many exposures of the object to the disturbance.

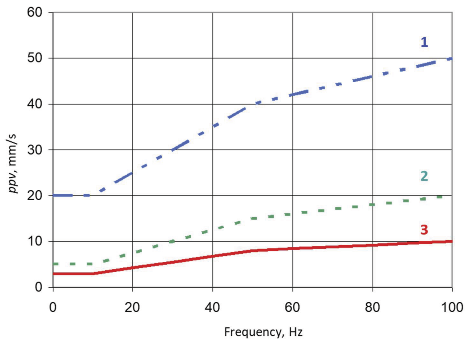

Figure 6. Graphic representation of the German standard DIN 4150, where the frequency and PPV limits to be respected for the different sensitivity classes of structures are noticeable.

With the relatively low delay charges used in tunnel excavation, the chances of reaching dangerous levels are very low, even for cortical tunnels or at a short distance from other excavations, except in exceptional cases such as the one shown in Figure 3. One of the most frequent cases that can be encountered is the problem of vibrations of existing service tunnels induced by blast-excavation of adjacent tunnels (Liang et al. 2013). It is generally acknowledged that low-frequency vibration has a greater possibility to cause structural damage than high-frequency vibration at the same PPV, as the structures have relatively low natural frequency (Yang et al. 2018). A delicate structure can be protected from the effect of vibrations with interventions on the structure itself or around it, isolating it, or reducing the cause of the disturbance at the source, by means of appropriate modifications to the excavation process. These modifications may concern, even jointly, the reduction of the pull (an example is given in Figure 7), the increase in the drilling density (with the corresponding reduction of the charges of the single holes), the increase in the number of intervals between the explosions, the abandonment of the full section system or, also, the isolation of the volume to be blasted with mechanical pre-cuts (this practice is indeed rare). In any case, a considerable slowdown in the excavation is to be expected. The simple reduction of the pull, while preserving the other characteristics of the blasting pattern and, therefore, the proportional reduction of the charge per hole, charge per delay, and total charge, is a common practice when the excavation face approaches a built-up area that it must underpass.

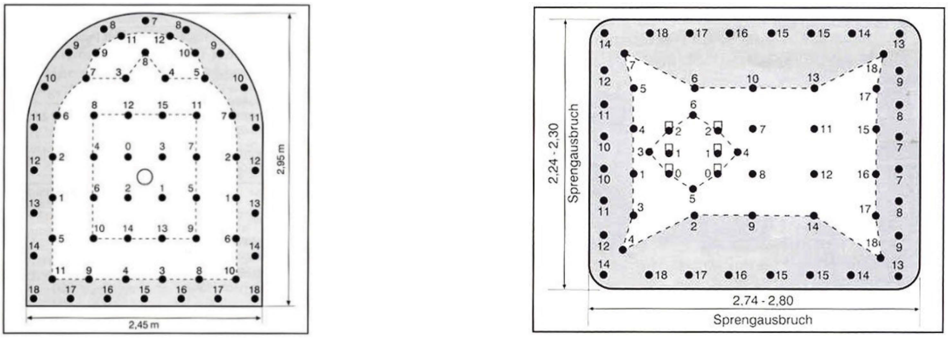

Figure 7. Excavation of the pedestrian access tunnels and lift shafts under Neuschwanstein Castle, Germany (Wild & Geuer 1999). To contain the vibrations, blasting patterns with very low pulls (1 m) and very high drilling density (9.1 holes/m^2) were adopted, to limit the max charge per delay to within 400 g; the cut was made with parallel holes. The blasts were triggered in three stages, to have a sufficient number of intervals, and, for this purpose, electric micro-delay detonators were used. Normally the limits were respected, with some modest exceeding: the maximum recorded value corresponded to 14 mm/s, with a frequency of 77 Hz.

4 CONCLUSION

The blasting excavations in highly urbanized areas are going to be continuous for a certain time and consequently, always more attention will be paid to the environmental issues, such as vibrations (Ozer 2008). Consequently, a tunnel project should include also the site law. Empirical relations with reasonable correlation coefficients must be established and suggested according to the site geology and rock mass characteristics. It must be reminded that a site law, in practical use, is an equation that is solved for Q for given R values, to warrant that limit PPV will not be exceeded at the foundations of the buildings. The limit of PPV, in his turn, should come from another predictive equation linking PPV (on the foundation) to stresses acceptable (in the most sensitive parts of the building), and acceptable stresses from another predictive equation, pertaining to the "strength of materials": a long chain. Any uncertainty in the predictions is accounted for by a "safety coefficient", and the result of the product of many safety coefficients could be an unnecessarily severe restriction of Q. The first "safety coefficient" in the chain takes a form different from the others: the K values, obtained from the data (blast tests, or preferably recorded production blasts) because of the best fit interpolation, are increased to obtain a "law" encompassing all the dispersed experimental points. It is correct and unavoidable: dispersion is a feature characterizing the "site" and the type of work here performed. However, it must be pointed out that these formulas, established just for the prediction of particle velocity, would give erratic results because of other effects. To support the reliability of the formulas, more events should be monitored, and regression analysis should be updated by more measured results depending on advances of the time.

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