PLANNING AND EXECUTION OF ROCK BLASTING IN URBAN AREAS

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Abstract: Proper management of technical risks during blasting facilitates efficient project management and helps keeping costs and safety at an acceptable level. It is of crucial importance to incorporate the process of risk management in the design and execution of the project. Risk analyses of the environmental effect of blast-induced vibrations are, in many cases, based on crude concepts which do not take into consideration the fundamental nature of vibratory motion. Realistic modeling of wave propagation in soil and rock requires that correct dynamic parameters are considered and appropriate attenuation models are applied. It is possible to apply relatively simple vibration attenuation concepts for prediction of vibrations in soil and rock and their interaction with structures on or below the ground surface.
Keywords: rock blasting, risk management, risk analysis, vibration monitoring, vibration attenuation, scaling laws

1. INTRODUCTION

Large infrastructure projects are currently being planned and executed worldwide, many in heavily populated areas. During civil engineering works, such as blasting and excavation, noise and vibrations are generated which can affect residents and industrial activities in the vicinity. Inadequate project assumptions, lack of funds, incorrect priorities, ignorant project engineers or misjudgments of vibration problems can lead to damages, increased costs and unexpected delays. In order to limit potentially negative consequences of ground vibrations, more efficient management of construction risks is required. Unfortunately, knowledge of how to perform a proper risk analysis is often missing. Lacking understanding of risks associated with blasting projects may lead to over-conservative design assumptions, resulting in unnecessary costs. Alternatively, underestimating vibration risks can result in unexpected damages to buildings, complaints from the public, with delays and unforeseen costs and delays. By applying a structured risk management concept, the cost-effectiveness, especially of complex civil engineering projects, can be enhanced without generating uncontrollable risks.

Proper management of risks associated with blasting projects requires fundamental understanding of vibration propagation in soil and rock and their interaction with structures located on or below the ground surface. Rapid technical advances in rock excavation by blasting have taken place and powerful numerical methods are available for advanced modeling. Also, understanding of dynamic properties of soil and rock has evolved, especially in the area of earthquake engineering. Advanced, relatively inexpensive, vibration monitoring and data acquisition systems are available today, which provide valuable information about wave propagation in the ground and dynamic interaction of structures and foundations. Unfortunately, these advances are rarely applied on blasting projects in order to make more accurate vibration analyses and predictions of vibration risks. All too often, crude, empirical methods are applied, using out-of-date standards, not taking advantage of the theoretical advances in soil and rock dynamics.

2. RISK MANAGEMENT OF CIVIL ENGINEERING PROJECTS

Civil engineering projects may imply different risks which often can be related to specific

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activities in the project. For larger engineering projects, authorities, investors, project owners and the insurance industry have started to demand a structured management of technical risks. The aim is, through risk management, to bring about a constructive interaction between the affected parties (designer, contractor and the owner/user, but also residents and third parties). In this way, safer working environment and greater trust from the public can be created and risks can be lowered to a level which is technically acceptable and meet the requirement of the project regarding time, costs and environmental impact.

Design and implementation of large civil engineering works in populated areas can be a complex task, involving many parties. Risk management ought therefore to be included as an integrated part in the design and execution of a project – and not be treated as a desk product, often isolated from engineering practice. Correctly applied, risk management can be a powerful instrument in the decision process.

Planning and execution of projects is governed and/or affected by different, sometimes competing, requirements and regulations, such as cost, time schedule, project quality, safety, environmental impact etc. Civil engineering works can have negative effects during the construction period but may also affect the environment over longer periods (e.g. the operation period of infrastructure projects). By applying structured risk management, potentially undesirable effects and negative consequences can be identified and managed in a structured process, in order to keep consequences on an acceptable level. If risk management is applied at an early stage of a process there are greater possibilities to manage and control project risks, thereby optimizing project time schedules, quality demands, safety and costs. It can be of even greater importance in smaller projects, as damages and delays in these cases might have proportionally greater consequences.

The process of risk management ought to also be coordinated with other, related project activities, such as environmental impact assessment, safety considerations, quality control and quality management.

2.1. *Management of Technical Risks*

In civil engineering projects, usually only technical risks are considered. However, for larger projects, the effect of natural risks (such as precipitation, floods, frost and earthquakes) can also be of significance. The aim of a technical risk analysis is to identify all activities which can affect the project and its environment in a negative way. Often the expression *risk analysis* is used without understanding its signification or practical application. Technical design (i.e. analysis of vibration problems or selection of damage criteria) can be part of, but is not sufficient for a risk analyses. A risk analysis has a much broader aim than a technical design, as it is a part of an ongoing process of risk management, which needs to be adapted to project conditions and changes.

The starting point of a technical risk analysis is the identification of undesirable events which may occur as a result of different project activities. In engineering projects a statistical database is rarely available for the assessment of damage due to construction activities, such as blasting. Instead, risk assessments must usually be based on past experience and engineering judgment, taking into consideration project-specific conditions. In contrast to natural risks, undesirable events affecting an engineering project can usually be managed and controlled. Risk management of civil engineering projects consists of several stages shown in Figure 1 and is an interactive process, where changing conditions can require re-assessment of risks and risk reducing measures.

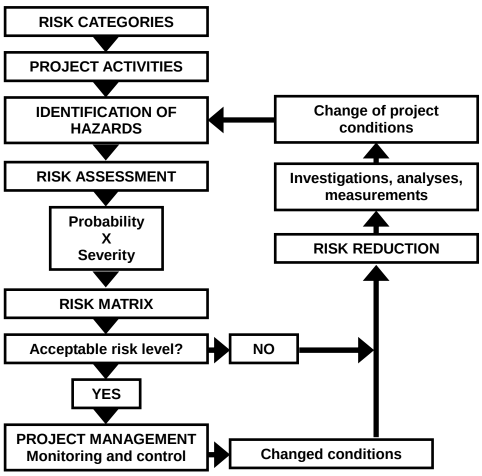

Figure 1. The different stages of risk management.

3. RISK ANALYSIS OF VIBRATION PROBLEMS

Assessment of risks related to vibration problems, such as blasting, is often handled in a crude manner. While optimization of blasting rounds and detonation methods has long been an eminent and prioritized research area (Langefors and Kihlström, 1978), prediction of wave propagation in geological materials and analysis of vibrations, on the other hand, is still based on crude concepts which are inaccurate and, in some cases, erroneous. To accurately assess risks related to blasting, fundamental aspects of vibrations in soil and rock need to be considered. Unfortunately, this fact is often overlooked.

3.1. Properties of Vibrations from Blasting

Vibrations can be described by different parameters. The most common parameter to measure is the particle velocity, v (mm/s), which should not be confused with the propagation velocity (speed) of waves. The time history of a vibration record is usually given in terms of particle velocity, but may also be described by acceleration, a (m/s^2), or displacement, u (m). The relation between these parameters depends on the frequency, f (Hz), which is equivalent with the number of vibration cycles per second. The frequency of a vibration signal provides valuable information, a fact which is not always appreciated. A typical signal from blasting, measured on the surface of a rock tunnel (granite) is shown in Figure 2. The duration of the blast round was around 6 s and the peak vibration velocity was around 70 mm/s.

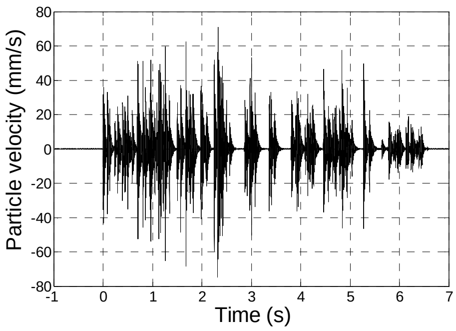

Figure 2. Time history of recorded particle velocity from a full-face tunnel blast.

Damage to a structure (due to fatigue), settlement or strength loss of soil can also depend on the number of vibration cycles. This effect can be taken into consideration by applying the concept of *equivalent vibration cycles* where the damage potential of one single peak is compared to several cycles of lower vibration amplitude – a concept which is common in earthquake engineering.

3.2. Wave Propagation in Soil and Rock

Close to the detonation point, where the rock mass is fractured, vibrations are very complex and difficult to describe. With increasing distance (distances greater than approximately one wavelength) propagation of waves can be analyzed using theory of elasticity. Part of the vibration energy is radiated radially from the source as elastic waves. In a continuous medium (no boundaries) two types of waves exist, P- and S-waves. The P-wave is a compression wave where the particles move in the same direction as the direction of wave propagation (Bodare, 2009). The S-wave is a shear wave where the particles move normal to the direction of propagation. Along a free surface (e.g. ground surface) there are surface waves propagating; Rayleigh waves (R-waves) and in layered media there are other surface waves, such as Love-waves (L-waves), see Figure 3. The information in Figure 3 is of practical significance when determining the measuring direction of a transducer as its direction relative to the motion of particles decides which wave type will be measured. The selection of measurement direction of a transducer assumes that the location of the point of detonation and the location of the transducer are known.

In order to be able to compare measurements at different locations, the same type of wave (P- or S-wave) must be recorded. As blast-induced vibrations generally are dominated by P-waves, it is necessary to mount the transducer in the direction of the propagating P-wave. The dominating frequency of P-waves is around twice that of S-waves. In addition, the amplitude of an S-wave is around half the amplitude of a P-wave for blast vibrations. The preferable option is to perform vibration measurements in three orthogonal directions and to calculate the radial component (vector). The importance of measuring direction is illustrated in Figure 4.

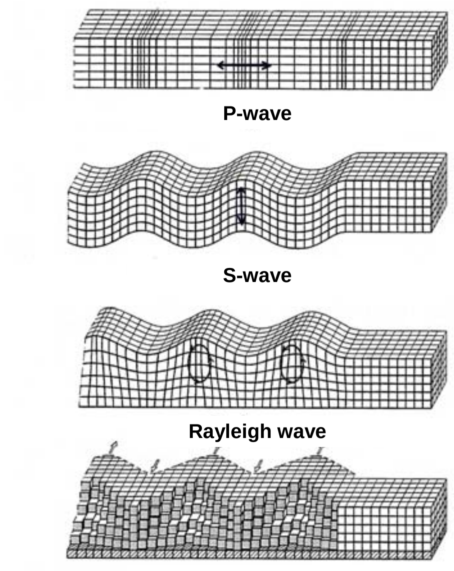

Figure 3. Particle motion for different types of elastic waves. Modified after Bolt (1976).

Figure 4 illustrates the propagation of a P-wave from location A and B, respectively. Blasting at location A will generate the highest vibration levels in the vertical tunnel wall in the horizontal direction while blasting in location B will give the largest vibrations in the tunnel roof. Positioning of vibration sensors and selection of measuring direction should be generally in the radial direction from the blast site. If vibrations are measured perpendicular to wave propagation, the S-wave would be recorded, with lower frequency and reduced vibration amplitude.

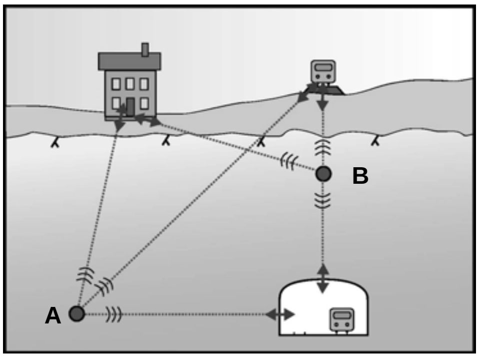

Figure 4. Wave propagation from two blast locations, A and B, to tunnels, buildings and structures on the ground surface.

The measured vibration amplitude depends on the direction of wave propagation, also in the case of buildings or structures on the ground surface. Different vibration signals will be recorded in the structures on the ground surface from blasts at location A and B, respectively. In the case of buildings above the vibration source, the P-wave reaches the foundation of the building from an almost vertical direction. For a more detailed discussion about vibration monitoring in tunnels, reference is made to a companion paper to this conference, Wersäll et al. (2009).

4. ATTENUATION OF VIBRATIONS IN SOIL AND ROCK

For a proper prediction of vibration amplitudes at different locations from a blasting source, it is important to apply correct vibration attenuation models. Naturally, extensive simplifications need to be made since the vibration pattern generated by blasting is quite complex, especially in the near field. However, it is possible to predict with sufficient accuracy the wave path and vibration damping, based on relatively simple attenuation laws. Empirical attenuation equations need to be treated with caution, especially if they are based on statistical treatment of measurement data without taking into consideration which wave type and direction of vibration component that was measured. Oversimplification of prediction models results in inaccurate predictions and misleading conclusions.

Vibration propagation can be analyzed using theory of elasticity (e.g. Bodare, 2009). If solely geometrical attenuation (i.e. damping with distance and no energy losses due to internal damping) is regarded, the vibration amplitude v_2 at distance r_2 can be calculated from Equation (1) when the vibration amplitude v_1 at distance r_1 is known,

$$v_2 = v_1 \cdot \left(\frac{r_1}{r_2} \right)^n \qquad (1)$$

where the exponent n is equal to 1 for body waves (P- and S-waves) and 0.5 for R-waves. Note that in the literature, a variety of different values for the exponent n is given, in contradiction to fundamental wave propagation laws.

It should be noted that the vibration amplitude in Eq. (1) represents the resulting component in the direction of propagation (for the P-wave). The energy of waves does not only decrease because of geometrical attenuation but also as a result of internal (material) damping, (energy dissipation). In order to take internal damping into consideration in the wave attenuation relationship of Eq. (1), a multiplicative exponential function is introduced which results in the following equation

$$v_2 = v_1 \cdot \left(\frac{r_1}{r_2}\right)^n \cdot e^{-\alpha \cdot (r_2 - r_1)} \tag{2}$$

where α is the absorption coefficient, defined as

$$\alpha = \frac{2\pi \cdot D \cdot f}{c} \tag{3}$$

The absorption coefficient, α describes the hysteretic (friction) damping capacity of the material and depends on damping ratio, *D*, frequency of vibration, *f*, and propagation velocity, *c*, of the wave considered (e.g. P-wave velocity for blasting in rock). At small strains the value of *D* is approximately one percent. Figure 5 illustrates the absorption coefficient as a function of wave velocity and frequency.

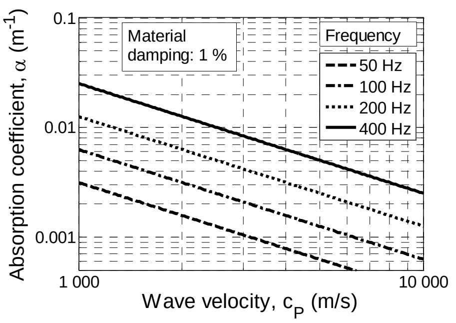

Figure 5. Dependence of absorption coefficient on wave velocity and vibration frequency.

The absorption coefficient decreases with decreasing frequency and increasing wave propagation velocity. In hard rock with a P-wave velocity of 5000 m/s and a vibration frequency of 300 Hz, for example, α is estimated to 0.0037 m^{-1} and for a frequency of 100 Hz, to 0.0013 m^{-1}. In a fractured rock mass, the wave propagation velocity is substantially lower and therefore the absorption coefficient increases. In loose rock with a P-wave velocity of 2000 m/s and for a frequency of 300 Hz, α increases to 0.0094 m^{-1} and if the vibration frequency is 100 Hz, α is 0.0031 m^{-1}. Figure 6 illustrates the relative vibration amplitude for body waves as a function of relative distance and absorption coefficient according to Equation (2) if r_1 (reference distance) is assumed to be 10 m. If, for example, α is 0.0100 and the peak particle velocity (PPV) at a distance of 10 m is 20 mm/s, the PPV at 60 m is 2 mm/s. It is important to realize that the slope of the curve depends of the wave type, i.e. the exponent *n* which for P-waves is equal to 1.0.

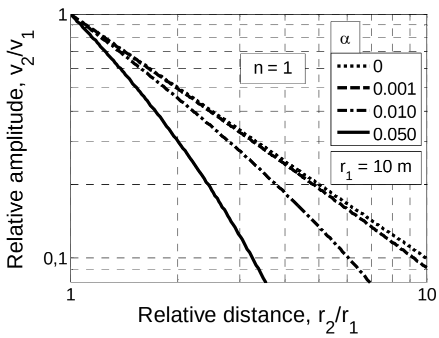

Figure 6. Attenuation of vibration amplitude as a function of distance between 10 m and 100 m and absorption coefficient.

From Equations (2) and (3) it is possible to assess the frequency dependent attenuation. In addition to hysteretic damping (i.e. the number of cycles), viscous damping can influence vibration attenuation. However, this effect is assumed to be less important for wave propagation in rock.

Within the field of rock blasting it is common practice to predict vibrations using empirically determined attenuation relationships based on regression analyses of vibration measurements. Such relationships are often denoted *scaling laws* since distance is scaled by detonation charge. One example commonly used is

$$v = K \cdot \left(\frac{R}{\sqrt{Q}}\right)^{-m} \tag{4}$$

where *v* is peak particle velocity, *R* is distance from blast site to transducer, *Q* is cooperative charge and *K* and *m* are empirically determined constants. The constant *m* is in many cases denoted *n* which should not be confused with the exponent *n* in Eqs. (1) and (2). Scaling laws can be useful in areas with similar geological conditions, if transducers record the same type of wave and measure in the same direction. However, measurements of different waves and at different locations are frequently mixed and regression analysis thus yields large scatter and inaccurate prediction.

5. CONCLUSIONS

In all civil engineering projects, risk management is of crucial importance for safe and economic planning and execution of rock blasting. Risk management, if organized in a structured manner, has positive effects on cost, time and safety of the entire project. It is also a necessity that risk assessment is based on correct assumptions, i.e. realistic prediction of wave propagation and correct measurement of relevant vibration parameters.

For risks related to vibratory problems, factors such as measuring direction and frequency range need to be considered. Relatively simple analytical concepts can be used to predict the propagation of vibrations in rock formations and soil layers. One of the most important factors is the direction of wave propagation and the orientation of vibration transducers, as these factors decide which wave type and thus vibration frequency and amplitude will be measured. Fundamental properties of dynamic waves must be considered when analyzing and predicting vibrations. It is possible to predict vibration attenuation, taking into account wave type, vibration frequency and material damping. However, at present, attenuation laws (scaling laws) are often based on statistical treatment of different types of vibration measurements. Oversimplification of vibration attenuation laws, especially when applied without considering fundamental laws of wave propagation, can lead to misjudgment of blast-induced vibrations.

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