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LOW FREQUENCY VIBRATION AND NOISE FROM MILITARY BLAST ACTIVITY: PREDICTION AND EVALUATION OF ANNOYANCE

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ABSTRACT

A method for the prediction of blast-induced air pressure, impulse noise and building vibration in communities around military blast sites is presented. The method is applied to calculate the impulse-noise and vibration exposure to the inhabitants over one year at an actual site. Criterion values for impulse-noise and recently developed criteria for vibration are presented. Noise and vibration exposure are discussed versus the criterion values.

1 - INTRODUCTION

Military blast activity leads to low frequency impulse noise and vibration which may annoy people living in the neighbourhood of the blast fields. This paper takes an example from an actual site, where charges ranging from fractions of kg to about 100 kg TNT-equivalent are regularly exploded for training and demolition purposes. The nearest neighbouring communities are from about 1500 to 3000 m away, and do mainly contain one- and one-and-a-half story single-family wooden houses. The ground in the area consists of sand and silt with some gravel. The blast site has a bed of silty, sandy gravel and the charges are exploded on the ground surface or slightly buried under a sand cover. In the direction towards the living communities the blast site is partly shielded by a shallow sandy slope. The rest of the propagation path from the blast site to the living quarters goes over flat terrain with low vegetation. In one direction it partly goes over sea.

Based on actual measurements at the site and on a recently finished research programme on blast noise and vibration propagation, a prediction tool has been developed and used together with protocols from the blast activity, and weather observations to estimate the statistical variation of impulse noise and vibration at two of the neighbouring communities covering one year of blast operation of the field. The noise and vibration estimates have been compared with commonly used criteria for impulse noise annoyance and new criteria for building vibration annoyance based on a recently performed sociological study. It is demonstrated that for the conditions around this blast field, and particularly due to the ground conditions, the vibration criteria may set more strict limitations on the blast activity than the impulse noise criteria.

2 - PREDICTION MODEL FOR VIBRATION AND NOISE

For rating the annoyance vibrations impose on humans in buildings, the vibration of the most unfavourable position on a floor in a living room need to be estimated [1], [2]. A charge which explodes on or in the ground may transmit vibration to a building floors along three different paths: (a) Directly, as seismic waves throughout the ground and through the foundation into the building. (b) Through air pressure which induce secondary ground vibration which again transmits to the building and (c) Through air pressure acting directly on the building. Which path dominates in the vibration transmission in an actual case will mainly depend on the factors: Burial of the charge, distance between charge and building, weather condition and topography, ground conditions and dynamic properties of the building.

Figure 1 plots traces of ground vibration and air pressure recorded at the actual site, 420 m from a slightly buried charge of 50 kg TNT. The ground vibration trace clearly shows the directly transmitted compressional wave, shear wave and Rayleigh wave. No response is recorded on the microphone until the air pressure wave arrives towards the end of the trace. At the same instance the seismometer shows the air-pressure-induced ground vibration response. At this location and for these ground conditions, the air-pressure-induced peak vibration is about four times higher than the directly transmitted vibration. Since, here, the Rayleigh wave velocity of the ground is higher than the sound speed in air, the Rayleigh wave arrives before the air pressure.

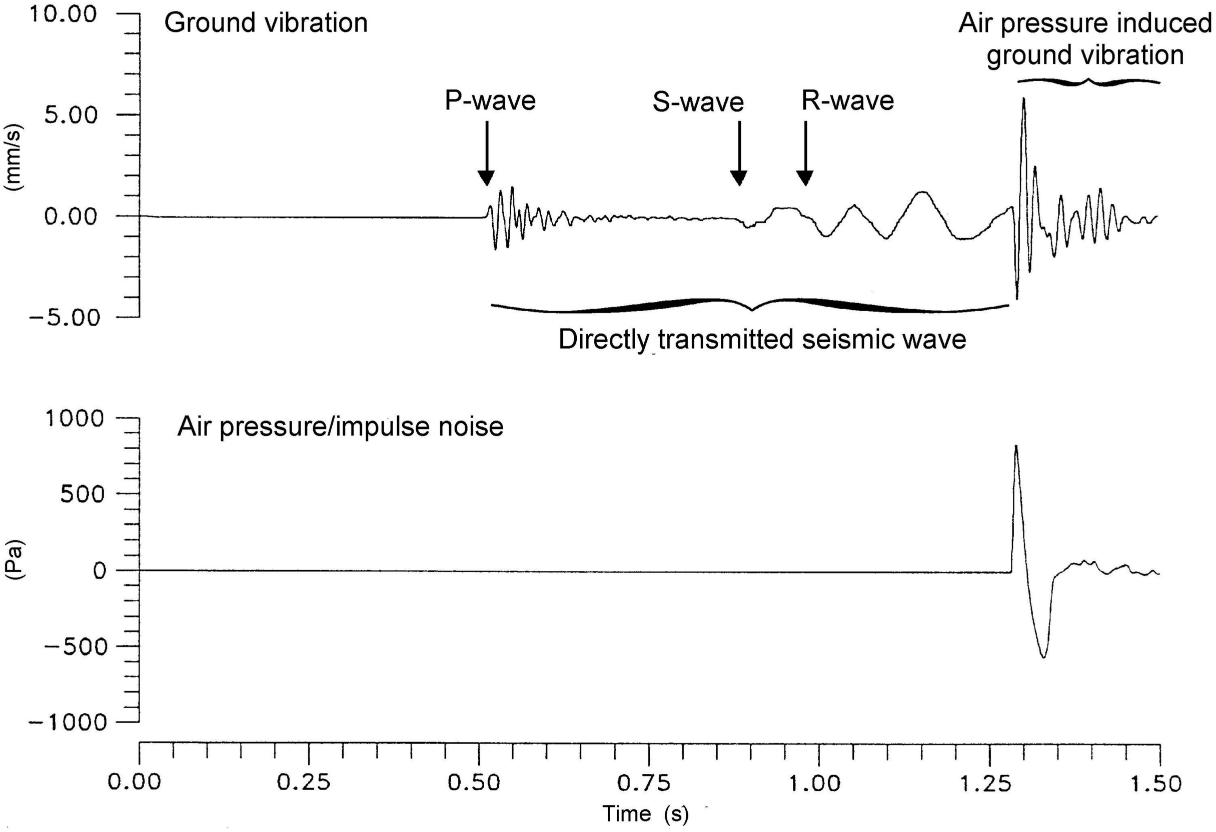

Figure 1: Recorded ground vibration and air pressure 420 m from a 50 kg charge.

Due to the hysteretic loss mechanisms in soils [3], seismic waves attenuate at a higher rate than air pressure waves, particularly in sandy soils. At longer distances, the air-pressure-induced ground vibration will therefore completely dominate. This was demonstrated through measurements in the neighbouring communities of the actual site, where the directly transmitted waves were not detectable compared to those induced by air pressure. The prediction of ground vibration on soil sites at long distances from surface or slightly buried blasts, therefore reduces to prediction of the air pressure and the air to ground vibration coupling.

Air-pressure to ground-vibration coupling has previously been studied e.g. in [4]. There the coupling is mainly devoted to the porosity of the ground and the 2nd compressional wave. The international research project "Norwegian Trials" [5] have recently made extensive studies of low frequency impulse sound propagation and air-to-ground coupling. Here also coupling through non-local interaction with the Rayleigh waves in the ground was focused [6], [7]. It was found that this coupling may be strong, and particularly when the Rayleigh wave velocity is close to the sound speed in air. It was also found that the coupling can often be expressed with sufficient accuracy over the actual frequency range through a site-dependent factor relating peak particle velocity in the ground to peak air pressure above the ground. Depending on the soil conditions this factor may vary substantially from site to site. The coupling factor was specifically measured at the actual site. It was found to be reasonably constant within each community and to vary between 3 mm/s/kPa and 20 mm/s/kPa among the communities. Factors as high as 200 mm/s/kPa have been measured other places.

The coupling between free-field ground vibration and vibration on the building floors was estimated from some measurements at the actual site, supplemented by data from a larger study on vibration from railway traffic, covering the same frequency range [8]. For the actual buildings there is typically a amplification factor of 2 from peak ground vibration to peak floor vibration.

The direct air pressure action in setting buildings into vibration was estimated from some few measurements at the actual site, supplemented by data from a Swedish investigation [9]. It was found that the air-pressure-induced ground vibration gave the highest floor vibrations for those communities with the highest air-to-ground coupling factors. For the community with the lowest coupling factor, the direct air pressure action gave the highest floor vibrations.

Estimation of peak air pressure from various charges was based on specifically measured air pressure propagation from the blast site to each neighbouring community. These measurements were performed under neutral weather conditions and formed the basic prediction model represented by a power relation between peak pressure and distance, scaled by the cube root of the equivalent charge weight. To account for the various weather conditions during each blast event throughout the year of investigation, the basic model was supplemented with corrections for wind speed and wind direction [10]. Temperature gradients and potential focusing was also accounted for by utilising information about clouds, air pressure, temperature and time of the day [11]. At the extreme the model introduces weather corrections to the peak pressure ranging from a factor of 0.7 for the most favourable weather to a factor of 4 for the most unfavourable weather, where focusing may occur.

When air pressure from blasts are used to calculate ground and building vibration, it is vitally important that the air pressure covers the frequency range at least down to 1 Hz, which is the lower limit when whole-body vibration effect on human is considered. Filtering of the air pressure, e.g. by C-weighting before calculating the vibration, will usually jeopardise the dominant part of the vibration.

3 - ACCEPTANCE CRITERIA FOR NOISE AND VIBRATION

The acceptance criteria for impulse noise referenced here are those presently used by the Norwegian Environmental Authorities for the establishment of new military training areas. For low frequency impulse noise, these criteria are based on an approach by Rylander [12], and posses the following specific criterion values: The number of single noise events with Lce > 90 dB-Cx are counted over one year. If this number is less than 100/year, the noise limit for single events is Lce=100 dB-Cx. If the count is 100/year or larger, the single noise limit is Lce=95 dB-Cx.

The Lce values in dB-Cx are estimated from the peak pressure; P_{peak}, in Pa, according to:

$$Lc = 20 \cdot \log\left(\mathrm{P_{peak}}\ /2 \cdot 10^{-5}\right) - 25$$

where the correction 25 dB is a commonly used number for low frequency impulse noise. A recently performed processing of measured data from the "Norwegian Trials", indicate that a somewhat lower number may be more appropriate for largest charges used in the actual case.

The criterion values applied for the building vibrations are based on a recently performed sociological study on the annoyance effect of traffic induced vibrations in homes [13]. Based on the interview of more than 1350 people living in hoses exposed to vibration up to 4 mm/s from road and rail traffic, combined with measurements and estimation of the vibrations exposure of each respondent, exposure-effect curves for this type of vibration have been established. Based on the results from the sociological study and the requirements of revised Norwegian Building codes, a new national standard NS 8176 [2] has been issued. The standard is based on the same "combined" frequency weighting function and 1s averaging as used in ISO 2631-3 [1]. The standard defines how the measurements are to be performed and how the results are to be treated statistically before compared to the criterion values. The criterion values refer to the most unfavourable point on the floor in a living room, are defined through four Vibration Classes, defined as follows:

- **Class A**: Corresponds to very good vibration conditions, where people will only perceive vibrations as an exception. Note: Persons in class A dwellings will normally not be expected to notice vibrations.
- **Class B**: Corresponds to relatively good vibration conditions. Note: Persons in class B dwellings can be expected to be disturbed by vibrations to some extent.
- **Class C**: Corresponds to the recommended limit value for vibrations in new residential buildings and in connection with the planning and building of new transport infrastructures. Note: About 15% of the affected persons in class C dwellings can be expected to be disturbed by vibrations, which is the limit of acceptable disturbance generally sat by the environmental authorities of Norway.

- **Class D**: Corresponds to vibration conditions that ought to be achieved in existing residential buildings, though class C should be aimed at based on a cost-benefit assessment. Note: About 25% of persons can be expected to be disturbed by vibrations in class D dwellings.

Table 1 gives the criterion values for the various classes in mm/s-w,rms, i.e. frequency weighted rms-value.

Vibration class	Class A	Class B	Class C	Class D
Vibration value, $v_{w,95}$ (mm/s)	0.1	0.15	0.3	0.6

Table 1: Criterion values for vibration in buildings according to NS 8141.

The vibration measure, $v_{w,95}$, is a statistical maximum value of weighted vibration, relevant for traffic vibrations. If applied to blast-induced vibration, the corresponding maximum value during each blast event will be the most relevant vibration measure. In the sociological study there is so far not found any significant correlation between annoyance and number of events and duration of this type of vibration. The standard is therefore based on single event values. Even though not developed for blast-induced vibration, the standard may also be applicable for that situation with some modification. At long distances the frequency of the blast-induced vibration is comparable to that of traffic vibration. However, the duration of each event and the number of events are significantly lower for blast than traffic. Even though no significant correlation with those parameters is found so far, there are reasons to assume that the criterion values may be increased slightly when applied to vibration from military blast activity.

4 - NOISE VERSUS VIBRATION AS DOMINANT ANNOYANCE FACTOR

Based on the above prediction models, protocols from the blast activity of the actual field over one year and corresponding weather recordings from a near by weather station, the impulse noise and floor vibration in some of the neighbouring communities have been calculated for each shot throughout one year. In total 314 blasts were performed over that year, with charges ranging from 0.1 kg TNT-equivalent to 88 kg, with an average charge weight of about 4 kg.

Figure 2 presents the results for the community with the highest air-to-ground coupling factor. The results are in the form of histograms defining the number of blast events leading to noise and vibration levels within defined bands.

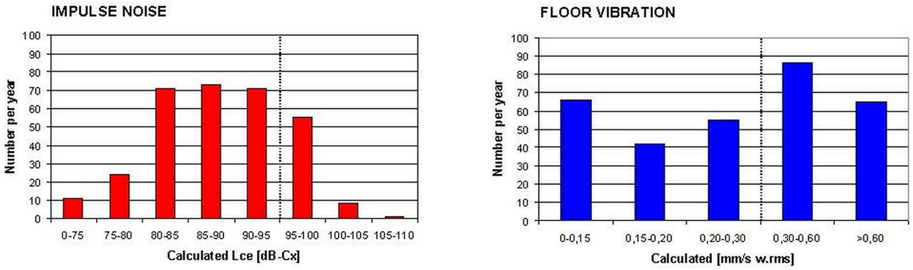

Figure 2: Histogram of calculated noise and vibration in one neighbouring community from one year of blast activity.

For impulse noise, the total number of events which gave Lce > 90 dB-Cx is >100. If applying the environmental regulations for establishment of new fields, the single event criterion value should be 95 dB-Cx. This value is indicated by the dotted line in the left hand plot in Figure 2. The number of blast events giving noise exceeding this limit is about 65, or 21% of all blasts. If, on the other hand, vibration Class C from NS 8176 was applied as a regulation, the criterion value for the corresponding building vibration should be 0.3 mm/s-w,rms. This value is shown by the dotted line in the right hand plot in Figure 2. This criterion values is exceeded in about 150, or 48% off all the blast events within the investigated year. For this site, the building vibration criterion from NS 8176, applied as for traffic vibration is thus posing a stricter limitation on the blast activity than the more commonly used impulse-noise single event criteria.

5 - CONCLUSION

Air pressure from military blast activity may set up substantial vibration in neighbouring houses. These vibrations can be calculated from the air pressure, provide the pressure covers the frequency range down to 1 Hz, and thus no weighting filter are applied to the recorded pressure. The use of vibration criteria may pose more strict regulations than more commonly used impulse noise criteria

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