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GROUND RESPONSE TO PROPAGATING AIRBLAST

C Madshus & A M Kaynia

Norwegian Geotechnical Institute (NGI), Oslo, Norway

1. INTRODUCTION

This article presents some of the observations and analyses made on the airblast-induced ground vibrations during blast tests at two different sites in Norway in 1994. The tests were part of the R&D project entitled "Blast Propagation through Forest" largely sponsored by the the Norwegian Defense Construction Services (NDCS). The main objectives of the project has been to study how blast waves are attenuated and modified, depending on the meteorological conditions, as they propagate over various terrain surfaces and ground types. The article attempts to highlight the mechanism of energy transfer from the air to the ground and the resulting attenuation in the airblast energy. Recordings from the two sites are used to highlight the main features of air-ground response coupling.

2. GROUND VIBRATION FROM AIRBLAST

The magnitude and characteristics of ground motions induced by airblasts are strongly influenced by the ratio between the velocity of surface waves in the ground and the speed of sound in air. At large distances from the blast point, the air pressure front may propagate nearly horizontally over the ground surface and thus acts as a moving load. In the realm of moving source mechanics, it has become customary to refer to the load speed as *subseismic*, *superseismic* and *transeismic*, depending on whether the load speed, C, is less than the shear wave velocity of the ground, V_S, greater than its compressional wave velocity, V_P, or is intermediate between these two velocities. Moreover, Mach Numbers $M_S=C/V_S$ and $M_P=C/V_P$ are defined to identify the load speed category.

Numerical and analytical studies on the ground response to moving loads (e.g., [1], [2] and [3]) have shown that as M increases, the ground displacements and stresses also increase until at $C=V_R$ (where V_R is the

Rayleigh wave velocity of the ground) a "resonance" condition occurs. As the Mach number increases further and enters the transeismic case, a plane shock wave, characterized with a jump in the displacement and an impulse in the stress components, is generated which propagates with the load. This wave and its front have been termed *Mach wave* and *Mach line*, respectively, and the angle of the wave front, $\theta = tan^{-1}(M_s^2-1)^{1/2}$, has been called the *Mach angle*. For higher load speeds, the superseismic regime is entered, and a second Mach wave, associated with the compressional wave velocity is generated. A comprehensive review of the features of waves generated by 2-D and 3-D moving loads has been reported in [4].

If, during the passage of a blast wave, air pressure, *p*, and vertical ground velocity, *v*, are simultaneously recorded at a measurement station, one could calculate the energy transfer, per unit surface area, from the air to the ground as:

$$w = \int_0^T p(t)v(t)dt \qquad (1)$$

where *T* is the duration of the airblast. One may then expect that for $C=V_R$, where large ground velocities are predicted by the theory, a significant energy transfer may also take place from the air to the ground. This not only has impact on the design of residential buildings and sensitive facilities, but also implies a reduction in the air pressure, in a way not properly accounted for in present calculation methods of airblast propagation. The two Norwegian sites, Haslemoen and Finnskogen, designated by NDCS for airblast tests and measurements, have provided a unique opportunity to observe the above theoretical considerations. As will be described, the soil conditions at the two sites are such that the blast waves are in transeismic regime at one site and in superseismic regime at the other. A brief account of some of the preliminary findings from these tests, which have bearing on the subject of air-ground response coupling, will be given in the following

3. DESCRIPTION OF TEST SITES

Haslemoen was the site of the airblast operations in June 1994. The blasts were carried out over a 1.5 km long stretch in an area covered by spruce forests. Five microphones at elevations 30, 16, 8, 4 and 2m above ground, and three seismometers installed in the ground at a depth of 0.75m, were used to measure the air pressures and ground velocities from 1 and 8 kg charges. The charges were detonated at various distances (ranging from 200m to 1400m) from the recording station, operated jointly by NGI and the University of Salford. The soil profile at the site consists of a fairly uniform, 60m deep layer of sandy silt overlying a rigid bedrock. The moist density of the soil was measured at 1450 kg/m^3 and the Poisson's ratio was estimated at 0.3. Seismic surveys with the Spectral Analysis of Surface Waves method (SASW) [5] indicated a shear wave velocity of about 130 m/s at 1.5m depth which increases to 150 m/s at 5m depth. (Ref. [6] gives a detailed account of the site and the test program.)

The second airblast tests were carried out at Finnskogen, in September 1994, in an about 20X20 km area covered by pine and spruce forests. Charges of weights 1, 8 and 64 kg were detonated at various distances (2 to 17km) from the recording station. Four microphones at heights 8, 4, 2, and 1m above ground registered air pressures and three geophones and three seismometers recorded the ground motions. To evaluate the air-ground coupling more accurately, air pressure was also measured just over the ground surface where horizontal and vertical seismometers were installed at 0.7m depth. The soil at this site consists of a deep layer of glaciofluvial sand with a mass density of 1800 kg/m^3 and Poisson's ratio of about 0.3. SASW measurements indicated a shear wave velocity of 140 m/s at 1m below ground surface, increasing to about 850 m/s at 20m depth. (Ref. [7] gives a detailed description of the site and the test program.)

4. OBSERVATIONS AND ANALYSES

Fig. 1 shows the time histories of the air pressure at 2m above ground and the vertical ground velocity for a 1kg charge detonated at a distance of 765m during Haslemoen test series [6]. Because in this site, the air pressure wave propagates with the superseismic speed (*C=340* m/s> V_s) the ground vibrations are set up only after the air pressure wave arrives. The vibrations then last for some time until the trailing ground waves (which were generated earlier by the moving air wave) pass through. The figure shows that the first cycles of ground motion are the direct result of air pressure loading on the surface while the ensuing motions are dominated by the trailing Rayleigh waves.

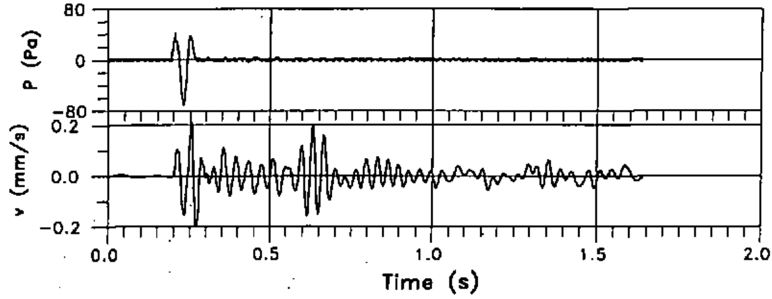

Fig. 1 - Typical Recorded Pressure and Ground Velocity at Haslemoen.

This feature somewhat changes for the transeismic speed, as shown in Fig. 2 which displays a typical recording made during Finnskogen test series [7]. The figure shows the time histories of air pressure at 1m above ground and the associated ground velocity for an 8kg charge detonated at 2 km from the recording station. The soil conditions at this site are such that high-frequency Rayleigh waves in the ground travel slower than the air pressure waves, while low-frequency waves travel faster than the air waves. At some frequencies, however, the two speeds will be identical and thus Rayleigh waves move with the air pressure wave. This can be verified by an examination of the first few cycles of ground vibrations in Fig. 2.

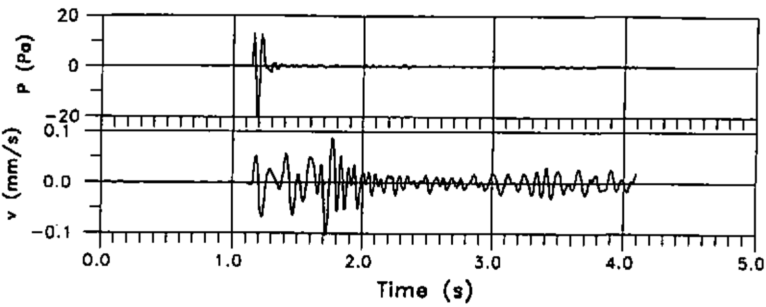

Fig. 2- Typical Recorded Pressure and Ground Velocity at Finnskogen

For sites with subseismic conditions, a completely different wave form is observed. Fig. 3 shows recordings of air pressure and ground motion at Lista Air Force Base [8], with a subseismic load condition. In such sites, the direct air-induced ground vibrations (point c in Fig. 3) are preceded by ground vibrations from outrunning compressional waves (a) and surface waves (b).

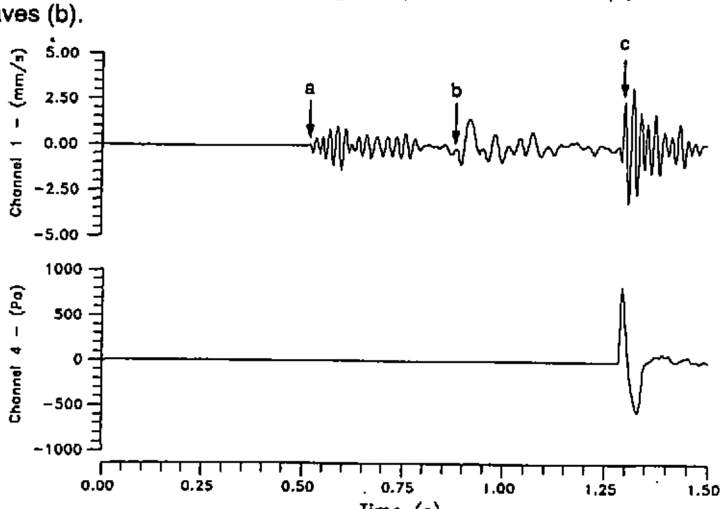

Fig. 3- Typical Recorded Pressure and Ground Velocity at Lista Air Force Base

5. AIR-GROUND RESPONSE COUPLING

To evaluate the coupling between the air pressure wave and ground response rigorously, one needs a numerical tool in which the ground and the air are modeled as layered viscoelastic and acoustic media, respectively, and the appropriate boundary and compatibility conditions are satisfied. Independent of such rigorous solutions, however, a general assessment of the coupling can be obtained by comparing the ratio of the maximum air pressure to the associated maximum ground velocity from actual measurements. This ratio may be referred to as the *apparent impedance* of the ground. Fig. 4 shows values of this parameter, plotted versus distance from the blast, for the Haslemoen and Finnskogen tests. For Haslemoen, which is categorized as superseismic condition, the apparent impedance varies from $3x10^5$ to $5x10^5$ Pa/m/s with an average value of about $4x10^5$ Pa/m/s. For Finnskogen, where transeismic conditions prevail, a larger scatter in the impedances is observed, with values ranging from $0.2x10^5$ to $4.5x10^5$ Pa/m/s. The data points in Fig.4 show a trend in the apparent impedance to decrease with distance which warrants an explanation. The frequencies representing the peak response depend on such factors as charge weight, distance and meteorological conditions, among others. For Haslemoen, the frequency is not expected to have substantial effect on ground response. At Finnskogen, high frequency waves which are affected mainly by near-surface soil properties, will behave superseismic and thus result in about the same response as at Haslemoen. However, for lower frequencies, which are more dominant at larger distances, the ground wave-velocity is close to the speed of airblast waves, and thus the "resonance" conditions and the corresponding low apparent impedance is expected. This in turn gives rise to more scatter in the results, as seen in Fig. 4.

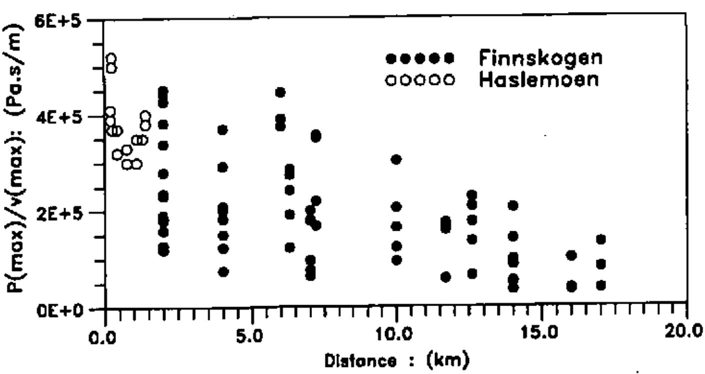

Fig. 4- Ratio of Maximum Air Pressure and Maximum Ground Velocity

To quantify the amount of energy transfer from the air to the ground at the site, the integral in Eq. (1) has been performed numerically on pairs of recorded vertical ground velocity and air pressure just above the ground [9]. Fig. 5 displays the energy transfer per unit area plotted versus time for the signals shown in Fig. 2. Another way of visualizing the same energy transfer is to draw the variation of the vertical ground displacement versus the air pressure, as in Fig. 6, and calculate the area enclosed by the resulting hysteresis loop. Compared with the energy density in the air pressure wave (which is estimated at $3x10^{-2}$ Nm/m^2 at the station where the above signals where recorded) this "leaking" of energy into the ground may constitue an important loss mechanism for the near-ground air pressure wave. This is particalurly remarkable when the Rayleigh-wave velocity of the ground is close to the sound speed, and warrants further research.

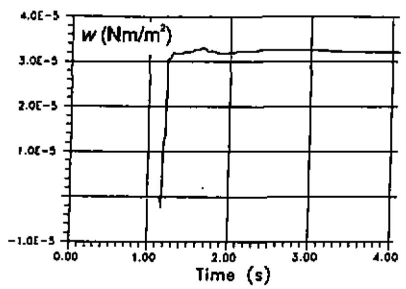

Fig. 5- Time History of Energy Density *w* for Signals in Fig. 2.

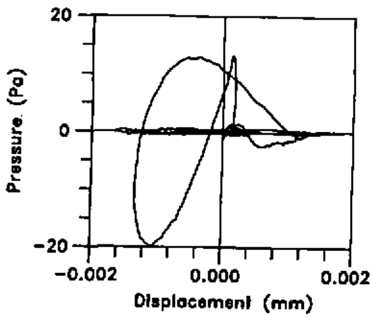

Fig. 6- Displacement vs pressure for Signals in Fig. 2

6. REFERENCES

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