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PEAK PRESSURE AND GROUND VIBRATION STUDY FOR WHITE'S COVE QUARRY BLASTING PLAN

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August 14, 2003

INTRODUCTION

Blasting for quarrying purposes is proposed to be conducted at White's Point, Digby Neck, Digby County, Nova Scotia by Nova Stone Exporters Inc. All blast locations are on land, and more than 70 m from the ordinary high tide line. A blasting plan has been submitted to DFO, and reviewers of this plan have expressed concern that peak pressure levels in the water column and ground vibration levels on the bottom, resulting from near-shore blasting, could approach maximum allowable thresholds for this environment. This short study provides a more detailed description of the shock wave propagation from the blast sites to the water column, including modelling of blast wave parameters. It suggests expected peak pressure and vibration levels in the near-shore region adjacent to the blast sites will adhere to the limits imposed by DFO guidelines outlined in "Guidelines for the Use of Explosives In or Near Canadian Fisheries Waters" (Wright and Hopky, 1988).

BLAST LOCATIONS

The initial blasts, referred to as Shot 1, will be performed on an outcrop situated on the inland side of White's Cove Road, approximately 20m inside the western boundary of the quarry property. This outcrop is identified in map DWG2 of the previously submitted White's Point Quarry Blasting Plan. The ground elevation at the shot site is approximately 15-18 m above the ordinary high water line. The outcrop is exposed massive basalt bedrock that underlies the entire quarry, and this bedrock extends underwater in the nearby offshore areas.

Shot 1 includes 56 separate four-inch diameter holes laid out in a 9-foot by 9-foot grid pattern parallel to the shoreline, and with relatively uniform depths between 27 and 29 feet. Each hole will be loaded with approximately 45 kg ANFO explosive, at 4.6 lbs/foot. It is proposed that the shot be initiated from the seaward side of the grid. Detonation timing for all holes was specified in the original blasting plan. That plan showed the average delay between adjacent holes as approximately 25 ms. This average minimum delay has subsequently been reduced to approximately 8 ms to satisfy safety requirements. The grid detonates predominantly from east to west, so coherent shock pressure fronts would be directed inland rather than toward the shoreline. The hole separation is significantly less than the distance the shock waves travel during even the 8 ms delay, so perfectly coherent summing of shot energy from different holes will not occur in any direction. Pulse durations however are greater than the delays (approx. 10-20 ms) so partial overlap of the signals, from two or three holes, may occur. The resulting reinforcement due to signal overlap will tend to extend the duration of the pulse rather than increase the peak pressure because the pressure waves from subsequent holes will arrive when the wave from the previous hole has already decayed in amplitude.

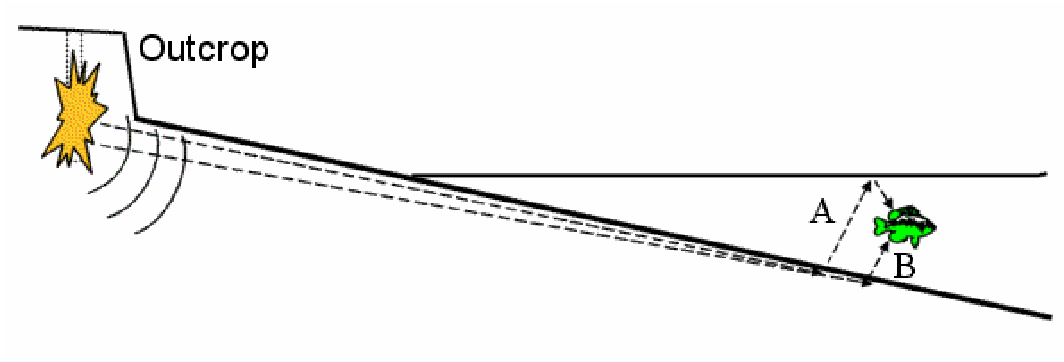

Figure 1: Diagram of pressure wave paths to receiving position in water column

Table 1: Minimum distances to important locations from Shot 1. Values based on White's Cove Quarry Blasting Plan – Addendum 1.

Location	Minimum Distance from Shot 1	Ground Elevation above Datum	Water Depth at Ordinary High Tide
Shot 1 (initiation point)	0 m	15 m	0 m
Ordinary high water Line	73 m	7.5 m	0 m
Water Line within 3-hours of Low Tide	118 m	Approx 5.5 m	2 m
Water Line at low tide	164 m	Approx 4 m	3.5 m

SHOCK PRESSURE WAVE

The pressure shock waves produced by ANFO detonations in the quarry will propagate from the blast sites to the shoreline (see Figure 1). Massive basalt formations comprise the bedrock throughout the entire quarry area. This rock has compressional wave speed approximately 5600 m/s and density approximately 3000 kg/m^3 (Bolinger, 1980). Massive basalts typically have low attenuation coefficients in the range 0.01 – 0.1 decibels per wavelength (Hamilton, 1980). The peak pressure of the outward propagating shock wave will be highest near the detonation site, but will decrease rapidly with distance from the detonation location due to spreading and attenuation losses. The pressure wave will continue to propagate in the basalt formation under the seafloor.

The blast effects model CONWEP (Hyde 1992) can be used to predict the shape of the shock wave pressure at distance from the detonation site. This model has been used to estimate the pressure wave for the present blast situation.

A CONWEP model run was performed for a single 45 kg ANFO charge detonated at 6.0 m. The basalt density and compression speed parameters, given previously, were input to this model. The resulting pressure time series were computed for the ranges indicated in Table 1. An additional run was performed at 500 m range to investigate the longer-range behavior. The resulting waveforms shown in Figure 3 represent the pressure within the basalt at the seafloor. The shape of the wave is observed to initially increase linearly from zero to maximum pressure over a short rise time. The pressure then decays exponentially back to zero. Both the rise time and time constant for decay increase with range from the source. Consequently the overall pulse length is greater at longer ranges.

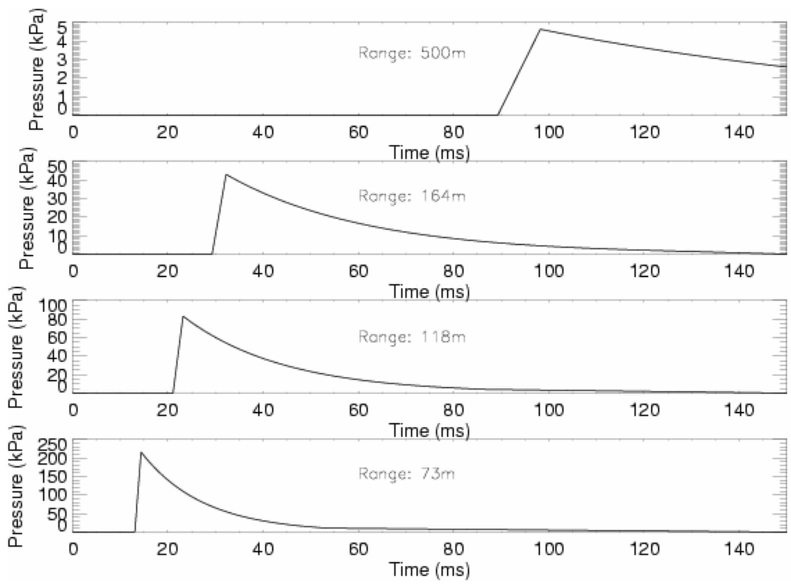

Figure 2: CONWEP-modelled shock pressure wave in basalt at various ranges.

The CONWEP model results are computed from empirical formulae based on measurements made from detonating bare demolition charges rather than from the less-compact cylindrical charge shape inherent to rock blasting. Consequently the CONWEP results may overestimate the peak pressure and may underestimate the rise times. Furthermore they do not account for the transmission through the seafloor, or for destructive interference by the water surface reflection. These effects, which will reduce the amplitude of the waterborne wave, are discussed in the following sections.

WATERBORNE PRESSURE WAVE

The pressure wave propagating in the seafloor will be partially transmitted into the water. The ratio of amplitude of the transmitted wave to that of the incident wave is referred to as the transmission coefficient *T*. It is dependent on the relative normal specific acoustic impedances of the basalt, Z_b and the water Z_w:

$$T = \frac{2Z_w / Z_b}{1 + Z_w / Z_b}, \text{ (e.g. Wright and Hopky, 1998).} \quad (1)$$

The impedances are functions of the densities, wave speeds, and the angle at which the wave is incident on the seafloor. For the present case, the incident wave in the basalt just grazes the seafloor interface. The transmitted wave propagates into the water at a relatively steeper angle: approximately 75° measured with respect to the seafloor. The specific normal impedances are given by the expression $Z = \rho c / \cos\theta$, where ρ is the density of the medium, *c* is the sound speed, and θ is the incidence angle measured from normal to the interface. For steep incident angles both the incident and transmitted waves have small incidence angles (θ *)*. In those cases the impedance is simply the product of density and sound speed. That situation is normally the case for underwater blasting projects and this is the reason that the impedance equations provided in DFO's blasting guidelines document are based on the small angle assumption. That assumption however is not valid for the geometry present at White's Point Quarry. The angle of incidence there is close to grazing (θ=90°); consequently the normal impedance of the basalt, Z_b will be very large. The transmission coefficient in this case approaches zero. This effect can be observed in the graph of Figure 2 (Oriard, 1985), which examined transmission loss through a similar rock-water interface. That figure however also shows that shear wave effects become important at shallow grazing angles. If we neglect shear waves then Equation 1 gives a transmission coefficient of just 0.03 for an incident wave at θ=80°. The inclusion of shear wave effects produces larger transmission coefficient: approximately 0.3. Interestingly, Oriard points out that in practice the transmitted levels are usually much lower, by a factor typically between 40 and 400, than predicted by this theory.

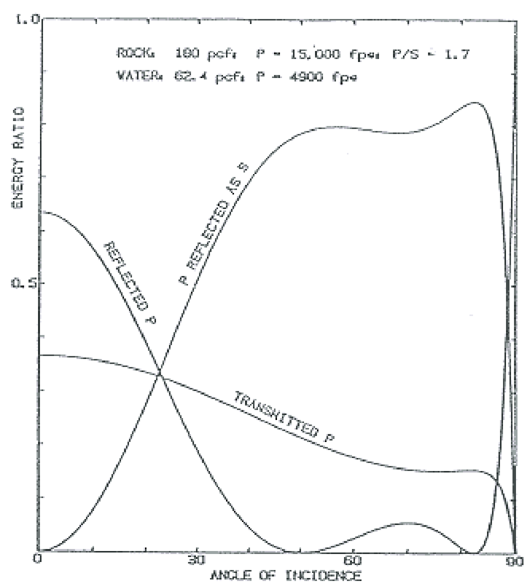

Figure 3: Relative transmitted energy ratios for sound energy incident from rock onto the seafloor, versus the incident angle at the boundary (Oriard, 1985). Energy ratios are approximately equal to the square of the transmission or reflection coefficients.

SURFACE REFLECTION

The angle of propagation for the transmitted wave in the water will be approximately 75° measured from the seafloor. This transmitted wave will reflect from the water surface, where it undergoes polarity reversal. This surface-reflected path is shown as path A in Figure 1. The reflected acoustic arrival interferes destructively with the upward traveling shock wave B. The resulting peak pressure will be lowered when the arrival time difference between the paths is less than the shock pulse rise time. The time difference can be expressed quite simply if it is assumed that the bottom is horizontal between the points at which the two rays leave the bottom; this is a good approximation for the quarry waterfront because the true slope at the site is only about 4 degrees. The time difference function in this case varies linearly with receiver depth:

$$\Delta t = 2Z_r \left[\frac{1}{c_w \sin\phi} - \frac{1}{c_b \tan\phi} \right], \tag{2}$$

where Z_r is the receiving (target) depth, c_w and c_b are the compressional wave speeds of the water and basalt, and ϕ is the angle of propagation in the water measured from the horizontal (note this is the complement of the incidence angle discussed in terms of impedance). Figure 4 shows time delays between surface reflection and direct path computed using Equation 2 for the present geometry.

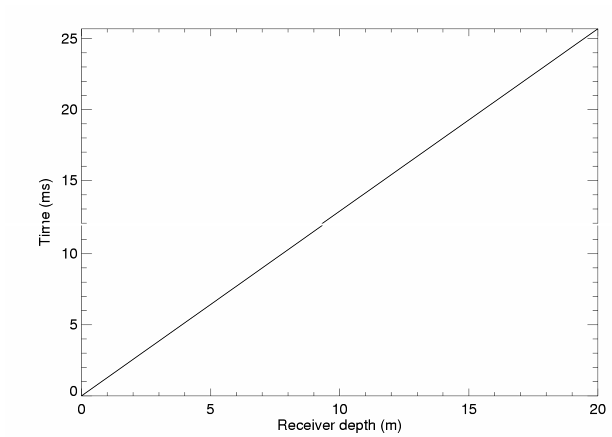

Figure 4: Delay between direct path and surface reflection as a function of receiver depth in the water.

We observe that the delay between direct path and surface reflection is expected to be approximately 1.2 ms for each meter of receiver depth. We have added the effects of a conservative transmission coefficient (0.3) and the destructive interference from surface reflection to the three closest-range waveforms from Figure 2. For each distance we have assumed the most conservative case where the receiving position is on the bottom at ordinary high tide (see depths in Table 1). Furthermore for the location at the ordinary high tide line, where water depth is zero, we have assumed a depth of 1m. These composite results are presented in Figure 5.

It is apparent that the pressures at even the closest location in the water are not expected to exceed 50 kPa. If the blasts are performed within 3 hours of low tide then the maximum pressures will likely remain less than approximately 25 kPa in the water. This is well below the 100kPa guideline recommended by Wright and Hopky (1998)

These pressures specified in the guidelines assume that the waveform will be that of a high explosive. It is the short rise time to a high peak pressure of shock pulses from high explosives that appears to be responsible for much of the damage to the marine animals during these detonations. A marine animal or human can easily withstand extreme changes in pressure and do so routinely. A human diver undergoes large pressure changes when rising from a depth of 100 feet to the surface. An instantaneous change in depth from 100 to 0 feet would cause explosive decompression and immediate death. The short rise time of a high explosive causes this kind of effect to occur near a blast. Other kinds of shock waves, such as those produced by airguns and low velocity explosives have slower rise times and cause much less damage. Because of this, it is not possible to use information of the effects of one kind of impulse (explosives) to estimate impacts of another such as airguns. As shown in Figure 2, in this situation rise time increases with increasing distance from the blast and so effects of peak pressure would be less than those predicted from a high explosive source. Behavioural responses are discussed below.

GROUND VIBRATION

The DFO guidelines document (Wright and Hopky, 1998) suggests a setback distance of 106.7 m to restrict peak ground velocities to less than 13 mm/s. This value is in fairly close agreement with the modelled peak velocity produced by CONWEP, shown in Table 2. That program gave 13 mm/s at 76 m corresponding with the ordinary high tide line. If blasting is restricted to within 3 hours of low tide then the water's edge will be at 118 m range from the blast and the guideline standoff range will be adhered to.

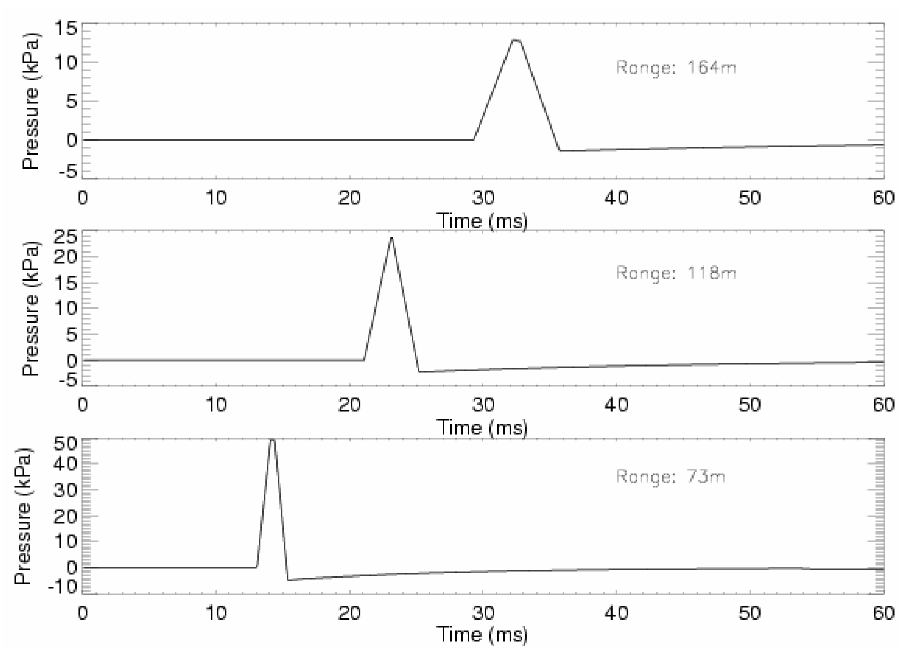

Figure 5: CONWEP-modelled pressure waveforms including pressure reductions produced by transmission from rock to water, and by destructive interference from the surface reflection. Receiver depths are at the respective bottom depths (see Table 1) at ordinary high tide.

Table 2: CONWEP modelled acceleration, velocity and displacement

Range	Peak acceleration	Peak velocity	Peak displacement
73 m	9.9 m/s^2	13 mm/s	0.53 mm
118 m	2.4 m/s^2	4.9 mm/s	0.33 mm
164 m	0.8 m/s^2	2.5 m/s	0.23 mm

LONG RANGE SOUND PROPAGATION

There is further concern that sound levels produced by these blasts will propagate to several kilometers range and possibly cause harassment to marine mammals. We note that the peak pressure at 500 m range will be approximately 5 kPa in the basalt. This corresponds with a peak level in the water of approximately 2 kPa, or equivalently 186 dB re 1μPa peak. Root-mean-square (RMS) levels are typically 5-10 dB less than the peak level as a result of signal spreading in time due to multipath propagation. DFO has recently accepted safety standoff thresholds of 180 dB RMS for toothed whales, and 190 dB for Pinnipeds in the vicinity of airgun systems used for seismic exploration. These thresholds represent received levels at which marine mammals could sustain temporary threshold shift (TTS). Temporary threshold shift is a temporary and recoverable increase in hearing threshold, similar to what a human would expense at a loud rock concert. The distance at which TTS could occur is commonly used as a distance for a safety radius around a noise source. The pulse rise times for airgun signals and the blast pressure wave at this range will be similar for these two types of noise source Consequently the same 180 dB RMS threshold should be appropriate here. The previously-proposed 500 m distance from the charge for a safety radius appears to be appropriate for toothed whales in this case. The safety range for Pinnipeds presumably could be approximately 1/3 this range, approximately 170 m, if inverse distance (1/r) acoustic spreading transmission loss is assumed. During seismic operations, airguns are shot every 20 seconds for hours on end. In this case, the entire event will be over in less than 0.5 seconds. In the United States, the National Marine Fisheries Service, which is responsible for implementation of the Marine Mammal Protection act has ruled that a single short noise pulse, such as that caused by an underwater explosion does not constitute disturbance (*U.S. Federal Register* 61 (#234, 4 Dec. 1996), page 64,337).

There has been a great deal of interest on the effects of seismic shooting on fish behaviour (see Davis and al. 1998 for a review). Seismic shots are fired every 20 seconds for hours and days on end. In this case, the entire event will be over in 0.5 seconds. A sound of short duration at 170 to 180 dB might cause a brief startle or alarm response in fish (Chapman and Hawkins 1969; Blaxter et al. 1981; Schwarz and Greer 1984; Pearson et al. 1992). The behavioural response should be transitory and have no significant impact on fish health or movements.

SUMMARY

This brief report analyzed the characteristics of the pressure and noise wave fields in the water column, and ground vibration levels on the seafloor and seashore. Peak sound pressure levels in the water column at the seashore are expected to be less than 50 kPa at ordinary high tide, and less than 25 kPa if blasting is performed within 3 hours of low tide. Peak pressure falls off rapidly with increasing distance from the blast. These levels are below those recommended in DFO guidelines.

Ground vibration levels were predicted using the CONWEP computer model. Peak ground velocity was predicted to be approximately 13 mm/s at the ordinary high tide mark at 76 m range. This location defines the upper limit of the intertidal zone. The predicted velocity is slightly less than the value presented in DFO's guidelines document, which suggests 13 mm/s should occur at 100.5 m for a 45 kg charge. This difference may result from the fact that the CONWEP model assumed ANFO explosive while the DFO distance may have assumed TNT-equivalent; ANFO has lower yield per equivalent weight than TNT. Corrections for differing types of explosive are not specified in the guidelines document. Vibration levels in the water would be well below those contained in DFO guidelines.

Long Range noise levels are predicted to be approximately 186 dB re 1μPa peak and 176-181 dB re 1μPa RMS at 500 m distance from the charge. DFO has recently used a threshold of 180 dB RMS for the safety range for toothed whale stand-offs from seismic airgun surveys. The proposed 500 m safety range therefore appears appropriate for protecting marine mammals from temporary threshold shift, which is the lowest form of physical injury. Disturbance effects on fish and marine mammals from a single event lasting less than 0.5 seconds should be negligible.

Concern has been raised that there would be an array effect resulting from the detonation of multiple charges in a short period of time. Coherent pressure summation effects from the proposed minimum 8 ms delays will extend the effective duration of, but will not significantly increase the resulting peak pressures of the generated pressure waves. The pressure pulses from different holes will not arrive simultaneously at any position because the hole separations are smaller than the distance the shock wave travels during the 8 ms delay. Weak constructive interference of the pressure waves from different holes may occur in the inland direction because of partial overlap of the individual hole signals. The potential constructive interference in the seaward direction is countered by the increase in effective delay in that direction due to the subsequently greater path lengths for later-detonating holes. The water surface reflection also significantly shortens the effective pulse duration, see Figure 5, thereby effectively eliminating the overlap that would otherwise occur. Thus, array effects would be negligible.

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