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Estimation of Partial Decoupling of Cavity Events

H. Douglas Garbin

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Estimation of Partial Decoupling of Cavity Events

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ABSTRACT (U)

One proven method of evading the detection of a nuclear test is to decouple the explosion with a large air-filled cavity. Past tests have shown it is possible to substantially reduce the seismic energy emanating from a nuclear explosion by as much as two orders of magnitude. The problem is not whether it can be done; the problem is the expense involved in mining a large cavity to fully decouple any reasonable size test. It has been suggested that partial decoupling may exist so some fraction of decoupling may be attained between factors of 1 to 100. MISTY ECHO and MINERAL QUARRY are two nuclear tests which were instrumented to look at this concept. MISTY ECHO was a nuclear explosion conducted in an 11 m hemispherical cavity such that the walls were over driven and reacted in a non-linear manner. MINERAL QUARRY was a nearby tamped event that is used as a reference to compare with MISTY ECHO. The scaled cavity radius of MISTY ECHO was greater than 2 m $/kt^{1/3}$. Both of these tests had free-field accelerometers located within 400 m of their respective sources. Analysis of surface ground motion is inconclusive on the question of partial decoupling. This is due to the difference in medium properties that the ray paths take to the surface. The free-field configuration alleviates this concern. The analysis consists of cube-root scaling MINERAL QUARRY's signal to MISTY ECHO's yield and calculating the ratio of the Fourier amplitudes of both the acceleration and the reduced displacement potentials. The results do not indicate the presence of partial decoupling. In fact, there is a coupling enhancement factor of 2.

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Introduction:

It is well known that when a nuclear test is conducted in a sufficiently large cavity, the resulting seismic signal is sharply reduced when compared to a normal tamped event. Cavity explosions are of interest in the seismic verification community because of this possibility of reducing the seismic energy generated which can lower signal amplitudes and make detection difficult. Reduced amplitudes would also lower seismic yield estimates that have implications in a Threshold Test Ban Treaty (TTBT). In the past several years, there have been a number of nuclear tests at NTS (Nevada Test Site) inside hemispherical cavities. Two of these tests were MILL YARD and MISTY ECHO that had instrumentation at the surface and in the free-field. These two tests differ in one important aspect; MILL YARD was completely decoupled[1,2] i.e. the cavity wall behaved in an elastic manner. Estimates show that MILL YARD's ground motion was reduced by a factor of at least 70. In contrast, MISTY ECHO was detonated in a hemispherical cavity with the same dimensions as MILL YARD but with a much larger device yield. This caused the walls to behave inelastically and the explosion was not decoupled.

The question of whether partial decoupling exists has not yet been resolved. Rodean's calculations[3] suggest a slight signal enhancement may occur in an overdriven cavity above an equivalent tamped explosion. His decoupling curve also shows a sharp increase in coupling near 10 m/kt$^{1/3}$ cavity radius. Thus, it appears that an explosion is either completely decoupled or completely coupled depending on the size of the cavity. It is suggested[3] that with the possibility of signal enhancement, if a foreign country wished to violate a TTBT and avoid detection, they would be forced to design a nuclear test capable of total decoupling the signal. However, full cavity decoupling is not an attractive method of evading a TTBT at large yields because of the volume required. If it is assumed that the scaled coupling radius (radius at which explosion becomes fully coupled) is 10 m/kt$^{1/3}$, the scaled coupling radius will require a spherical cavity with a radius of 53 m to completely decouple a 150 kt explosion. This would demand a very expensive mining operation if not carried out in salt. Even a 10 kt shot would require a 22 m cavity radius.

Recently, a paper by King et. al.[4] suggests that partial decoupling may be a viable option. They use computer hydro-code calculations of an over driven cavity to estimate the ground shock speed and thus calculate yield in a manner similar to CORRTEX methods. Their results imply a continuous decrease in coupling for a cavity in tuff. The calculations were carried out to a scale radius of 3.4 m/kt$^{1/3}$ which gave a 40% decrease in coupling. Thus, if full decoupling is not necessary, but a reduction of the seismic output is desired, cavity explosions become a feasible option. An estimate on the cavity size can be made by a straight line extrapolation of King et. al. curve. This is represented approximately by equation (1):

$$W/W_0 = 1 - R/10 \quad (1)$$

where W_0 = the actual yield
W = the seismically measured yield
R = the scaled cavity radius (m/kt$^{1/3}$).

The above relation is just a straight-line estimate of their coupling plot. It indicates that a scaled cavity radius of 5 m/kt$^{1/3}$ would suffice in reducing the seismic estimate by half. Under these conditions, a 150 kt explosion in a cavity with a 27 m radius would appear to have a yield of 75 kt. This is still a rather large volume to mine. For a 200 kt test to behave as if it were at the present 150 kt treaty limit, a cavity of only 14.6 m is required. Of course if the test limit is reduced to a lower level, the corresponding volumes are also reduced. Only an 11 m cavity is required to reduce a 10 kt explosion to a seismic yield of 5 kt. Figure 1 is a plot of the cavity radius as a function of yield if one wanted all explosions above 150 kt to appear to be at the present limit. Because of the possibility of partial decoupling, a closer look at the data in overdriven cavities is warranted.

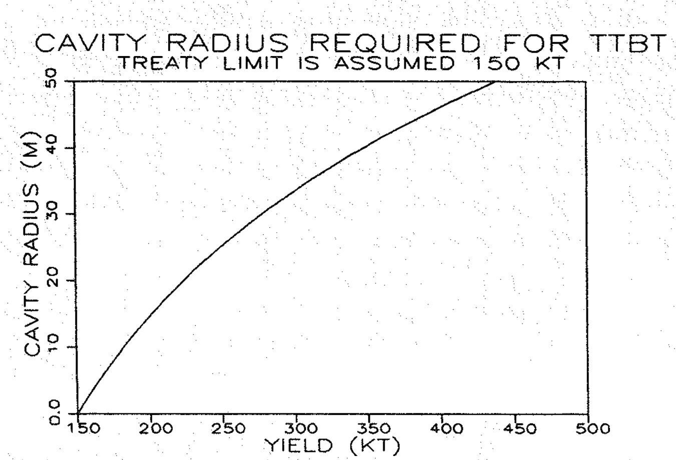

Figure 1: Required cavity radius for presumed nuclear yield to be within TTBT 150 kt limit.

Previous Data:

Although the calculations that produced the above estimates assume the existence of partial decoupling, data have not confirmed this result at seismic ranges. In previous experiments at NTS, decoupling was measured using surface accelerometers for both the reference and cavity explosions. The analysis of this data indicated that MILL YARD was completely decoupled and the overdriven cavity of MISTY ECHO produced no measurable decoupling. Both events used DIAMOND BEECH as the reference explosion. DIAMOND BEECH has several significant advantages as a reference explosion for its use with MILL YARD. First, it was detonated only a couple of hours after MILL YARD and the same surface gauges were used to measure the ground motion of both explosions. This utilization of the same gauges insured that the signals of both explosions traveled through similar structure, and propagation path differences are minimized. In contrast, MISTY ECHO is located about 1 km from DIAMOND BEECH and measured ground motion at different gauge locations. This spatial separation can accentuate signal differences not associated with the source.

The surface analysis has several assumptions to facilitate the calculations. This includes assuming the medium is a homogeneous half space and the propagation paths includes no layered structure for either the reference and cavity explosions. Although this assumption is appropriate for complete decoupling due to the large differences that arise in the signal amplitudes of the scaled reference and cavity data, it is expected that partial decoupling will produce differences that are more subtle. Thus, any variations from factors other than the source can give erroneous conclusions. If the path of the cavity and reference events are substantially different, then variations can occur in the signal that are a result of the path properties, not the source properties. In the surface analysis, the path is homogenized even though it is known that there is extensive layering from the working point to the surface in both cavity and reference events. Part of this can be justified in the low frequency limit because the long wave lengths would average or smear out the structure. The higher frequencies would sample the structure in more detail with the possibility of scattering and diffracting the signals differently in each path. Although these variations could possibly be removed using Haskell-Thomsen or other techniques, there still are uncertainties in the medium properties. A more direct method is to measure the signal in the free-field. If the source and receiver lie in the same layer, the analysis is greatly simplified by eliminating the necessity of performing exotic calculations. In fact, the medium is treated as a infinite homogeneous space.

Data has been obtained in both the free-field and free surface from several prior cavity events instrumentated with accelerometers. These include not only MISTY ECHO and MILL YARD, but also MISSION GHOST. MISTY ECHO was a nuclear explosion detonated in an 11 m hemispherical cavity. Ground motion was measured with several accelerometers located in the tunnel complex at ranges between 170 and 400 m. The decoupling calculations that were made used surface acceleration data collected at sites extending from ranges of 900 m out to 2100 m. Although the surface accelerometers indicated no gross decoupling[3], the scatter in the data does not eliminate the possibility of partial decoupling.

MISSION GHOST was also a cavity event, but it was much smaller in yield and radius (3.8 m) than MISTY ECHO. However, the scaled cavity radius of this event and MISTY ECHO were comparable. The surface gauges of this event were all in the spall region and this precluded any spectral analysis of the data. No decoupling estimates were made since spectral analysis is an important component in the calculation. The free-field signals were extremely noisy, and this report does not make any attempt to analyze the data.

MILL YARD was a fully decoupled nuclear explosion in an 11 m cavity[2]. Its scaled cavity radius was much larger than any of the previously mentioned events. The explosion was instrumentated with both surface and free-field accelerometers. Surface gauges were located at GZ and extended out to 2000 m. These were used in the decoupling calculations. The free-field gauges were within 24 m of the WP. The recorded free-field signals were due to the high frequency air shock pulse striking the surface of the cavity.

The main purpose of my MINERAL QUARRY experiment is to obtain free-field ground motion data to compare with free-field MISTY ECHO ground motion and determine if partial decoupling is present. In addition, estimates of the seismic attenuation (Q-factor) will be made. Specifically, attenuation estimates are made for a constant Q model.

EXPERIMENT DESCRIPTION

There were only two sites instrumentated in this experiment. These were located at ranges near enough to be considered in the free-field and far enough for the medium to respond linearly. The experiment consisted of two triaxial acceleration packages. Each were placed in 10 m deep bore holes located in the right rib of the bypass drift (Figure 2). They were at ranges of 700 ft. (215 m) and 1000 ft. (306 m) from the working point. The packages were aligned in a manner to produce radial, vertical and tangential signals with respect to the working point (WP). The accelerometers are designed to work in environments as high as 200 g which is well above the expected amplitudes.

The free-field gauges in MISTY ECHO were located at similar ranges. Figure 2 also shows the positions of three sites at ranges of 170, 350 and 363 m. The gauge located at 170 m may lie in the non-elastic regime. I am assuming a non-linear behavior for stresses above 0.25 kb and the 170 m station has a stress estimated at about .5 kb. The other two are situated on the opposite sides of a fault which is thought to have moved vertically. The radial signals did not exhibit differences in ground motion that the vertical components displayed.

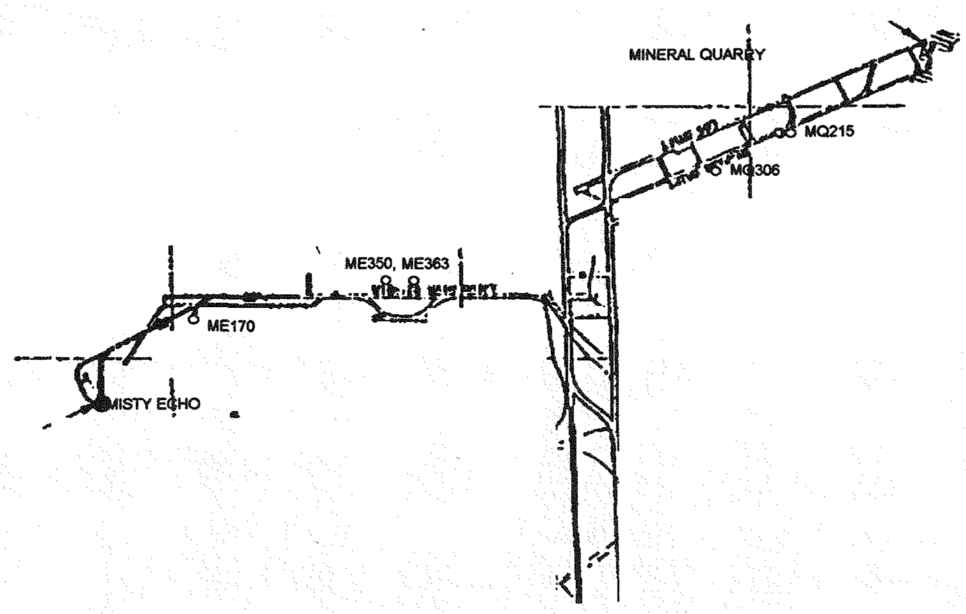

Figure 2: Tunnel gauge configuration of MISTY ECHO and MINERAL QUARRY

RESULTS

Three component acceleration data were obtained from two locations on the MINERAL QUARRY event. Plots of the six channels are shown in Figures 3,4 and 5. A total of about 0.8 seconds were recorded but only 0.4 seconds are shown on the plots. The radial components (Figure 3) give the largest amplitudes. The peak acceleration at 215 m is about 36 g and 15 g at 306 m. The data have very good signal to noise levels. Spectral calculations indicate the frequency content is good out to about 250 hz. Above that frequency, the signal amplitude resolution is too insensitive. This is a result of the gain being set high to insure the signal recording would not clip. The dynamic range of the system is not large with respect to the signals that are present.

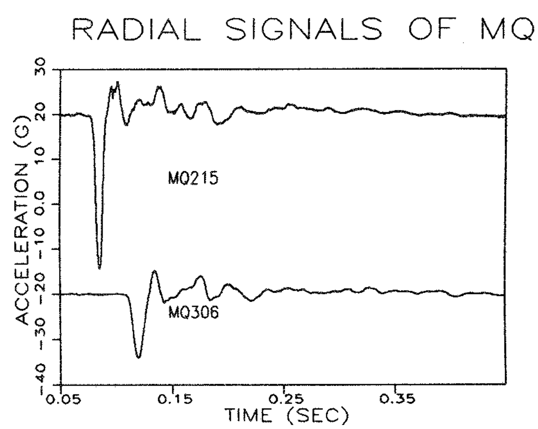

Figure 3: MINERAL QUARRY Radial Signals at 215 and 306 m

The vertical signals are predictably much smaller than the radial amplitudes. This is an indication that the gauges were aligned fairly well. The initial peak at 215 m is about 4 g and only .3 g at 306 m. These signals show much more structure than the radial data along with greater amount of variation among themselves.

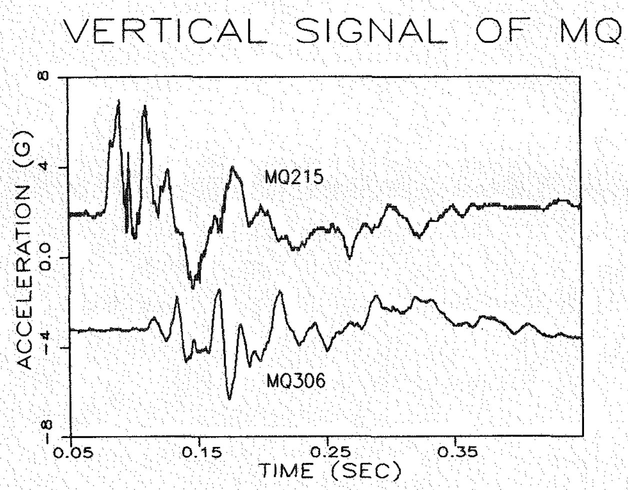

Figure 4: MINERAL QUARRY Vertical Signals at 215 and 306 m

The tangential signals are also smaller than the radial data. This is the case at the 215 m range and the peak is of the order of the vertical signal. However the tangential signal at 306 m appears to be contaminated with non-seismic noise. The initial coda has large, late arriving peaks which are not only greater than the radial signal, but have a different spectral content. In addition, the frequency of the signal beyond 0.2 seconds is 60 Hz reflecting the difficulty we experienced with shielding the cable. This leads us to suspect that the tangential component at 306 m is unreliable.

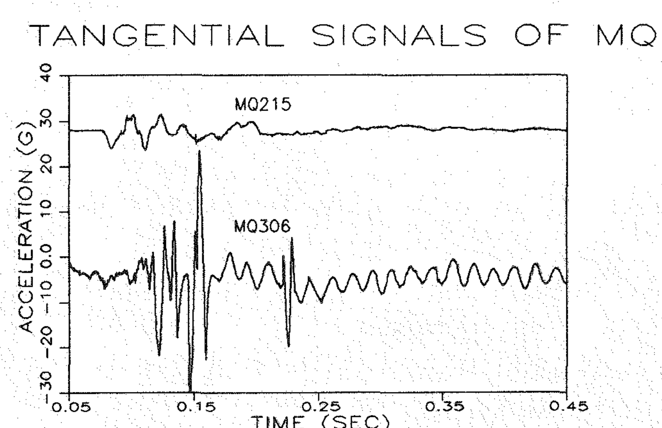

Figure 5: MINERAL QUARRY Tangential Signals at 215 and 306 m

As a final comparison, consider the MISTY ECHO event. MISTY ECHO recorded signals from gauges located at ranges of 170, 350, and 363 m. Figure 6 is a comparison of 350 m radial data to the acceleration record of MINERAL QUARRY at 306 m. Both of these signals are used in the decoupling analysis and the wave forms are quite similar to each other.

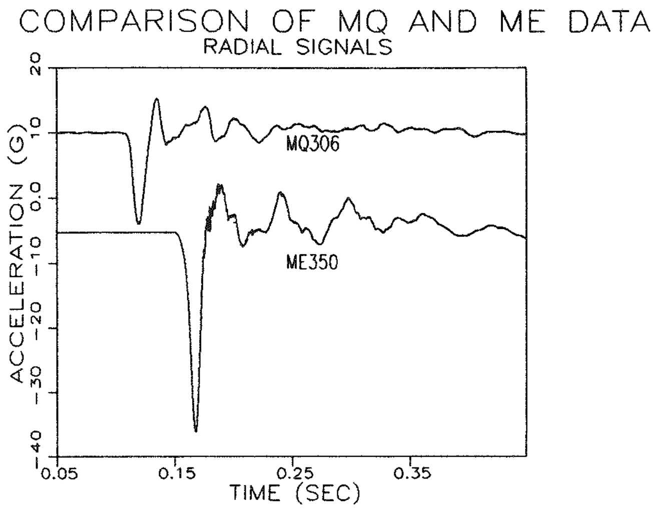

Figure 6: Radial Acceleration Comparison

ANALYSIS

Before the decoupling analysis can begin, some operational definition of the phenomenon should be made. This is done by setting up an idealized experiment. Suppose we measure the ground motion at due to a tamped device of a known yield with gauges located at various ranges. After the data has been obtained from this tamped reference event, suppose a cavity is excavated about the working point of the explosion. Place another device located at the same point as the tamped explosion and repeat the experiment using the same gauges located at the same ranges. Ignoring the changes in the medium due to the first explosion, decoupling is defined as the spectral ratio of the ground motion due to a reference event to that of a cavity event with the same yield detonated at the same location with instruments at the same ranges. The above experiment satisfies the requirements of the definition but obviously, this idealized state is never achieved since tests are not dedicated to decoupling. In general, the tests differ in all three aspects of yield, location, and range. Thus, to make an estimate, the reference data (MINERAL QUARRY) is cube root scaled to the yield of the cavity explosion, i.e., MISTY ECHO. The general relationship for scaling acceleration is:

$$u_s\left(r_{mq} / s, t / s\right) = s * u\left(r_{mq}, t\right) \quad (2)$$

where: u = measured MINERAL QUARRY acceleration,
u_s = MINERAL QUARRY acceleration scaled to MISTY ECHO,
r_{mq} = range of gauges with respect to the WP,
t = time,

and the scaling factor s is given as:

$$s = (W_{mq} / W_{me})^{1/3} \quad (3)$$

W_{mq} = MINERAL QUARRY yield,
W_{me} = MISTY ECHO yield.

The procedure first requires obtaining the Fourier Transforms for both MINERAL QUARRY and MISTY ECHO radial signals. By scaling the time before the transforms are applied, it can be shown that the spectral amplitude is automatically compensated. However, there is still an additional geometric spreading factor for which compensation must be made. This arises from the difference in the scaled range (r_{mq}/s) and the MISTY ECHO range. After scaling, the Fourier Transform of MINERAL QUARRY represents its response at the range r_{mq}/s. This must be converted to the MISTY ECHO range by the relation:

$$u_s(r_{me}, \omega) = u(r_{mq} / s, \omega) * r_{mq} / s / r_{me} \quad (4)$$

where: r_{me} = MISTY ECHO range,
r_{mq} = MINERAL QUARRY range,
ω = circular frequency.

The ratio of $|u_s \ / \ u_{me}|$ gives the decoupling as a function of frequency. Note that there are no corrections for losses due to attenuation since the scaled MINERAL QUARRY ranges are near MISTY ECHO ranges. Perret and Bass[6] express peak attenuation as a power law with acceleration degraded with the square of the range. This would have the effect of reducing decoupling because $r_{mq} < r_{me}$. A more accurate description (the above is a far-field approximation) would have the following replacement:

$$|ik / r| \Rightarrow |ik / r + 1 / r^2|$$

where: k = wave number.

This technique is applied only to acceleration data and avoids difficulties with the permanent displacement in the near field. A Fourier Transform of a finite window with a permanent offset will introduce leakage problems unless a tapered window is applied. This would produce a false representation of the spectra at low frequencies. In addition, the data is recorded as acceleration; and to obtain displacement, one must perform a double integration. To avoid unrealistic displacements any linear trends and off sets in the data are removed before the integration. One of the conditions to be satisfied is the requirement that the velocity tends to zero at large times. Whether 0.8 seconds is sufficient time for the signal to die out is questionable. Also, the integration procedure is subjective and non-unique. In spite of these reservations, figure 7 is the result of one such integration.

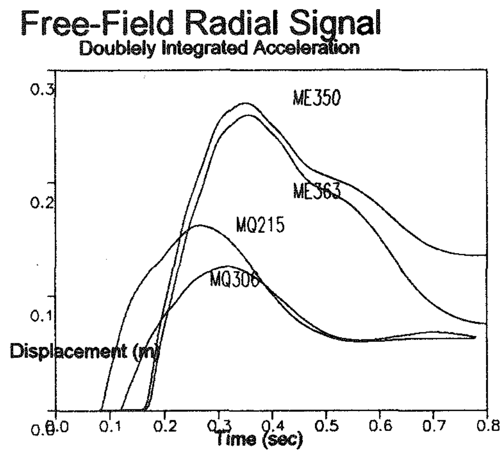

Figure 7: Displacements in MISTY ECHO and MINERAL QUARRY

The value of the scaling factor s is determined from the yields as given by the sponsoring lab. This produced a scaling factor near 1. The calculated decoupling curve is given in Figure 8. This particular plot is an average over four possible pairs of ratios (2 MISTY ECHO, 2 MINERAL QUARRY signals). The data at 170 m in MISTY ECHO is not included because it may be in the nonlinear range. The two outer curves are the 1 standard deviations of the four pair averages at each frequency. The straight line is the average decoupling over the total frequency range shown. Note that this curve's average is less than 1 which implies coupling enhancement.

The accelerometers were calibrated on a shake table and have a flat response from 10-1000 Hz. No dynamic calibration could be done below 10 hz, but static tests still indicated a continuation of the flat response to dc. However, the calculations at low frequencies are suspect for several reasons. First, the time window is only 0.8 sec which limits the frequency resolution. The high frequencies dominate the signal to such an extent that the low frequencies are near the resolution of the recording system. Finally, any dc offset or trend will contaminate the low frequency amplitudes.

The decoupling given in Figure 8 exhibits a constant ratio over the large frequency range. Previous experimental analysis has shown low frequency decoupling to be significantly higher than at the lower frequencies. MILL YARD was decoupled by a factor of 70 near 3 Hz and only 10 at 30 Hz. There is a theoretical basis for assuming the low frequency decoupling is higher. If a standard Sharpe model is assumed for an infinite homogeneous space, the spectral response of the displacement is

$$d = \frac{p(\omega)a^3(ik/r + 1/r^2)}{\mu(Z - \{ka\}^2 - ikaZ)} \exp - ik(r - a) \quad (5)$$

where:

d = displacement,
p(ω) = time source response at elastic radius,
a = elastic radius,
m = shear Lame' constant,
Z = 4/3 for a Poisson solid,
k = Compressional wave number.

Using the expression above, it can be shown that the decoupling ratio at low frequencies ($\omega \rightarrow 0$) is:

$$DC(0) = (p_r/p_c)(a_r/a_c)^3. \quad (6)$$

In a similar manner, the decoupling ratio at high frequencies $\omega \rightarrow \infty$ is:

$$DC(\infty) = (p_r / p_c)(a_r / a_c) \quad (7)$$

The source functions (p) are assumed to have the same functional form so the frequency dependence cancel in the ratio. The subscript r denotes the reference event and c the cavity explosion. For a fully or partially decoupled explosion, it is reasonable to assume that the elastic radius of a cavity explosion is less than a fully tamped explosion.

$$a_r/a_c > 1$$

Under this condition;

$$DC(0) = DC(\infty)(a_r / a_c)^2 \quad (8)$$

or

$$DC(0) > DC(\infty)$$

If it is assumed that DC(∞)= 1/2 and the pressures are equal at the elastic radii, equation 7 implies that $a_c = 2a_r$. The cavity elastic radius at twice the size of the scaled reference elastic radius is opposite of what is expected for a decoupled event.

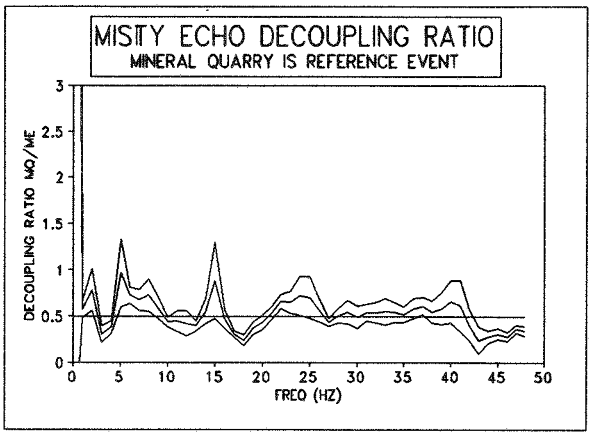

Figure 8: MISTY ECHO Decoupling, MINERAL QUARRY Reference Case

In addition to the above analysis on the displacement, calculations were also done using the Reduced Displacement Potential (RDP). This quantity is defined by the relation:

$$d(r,t) = \frac{\partial}{\partial r}\left[\frac{\phi(\tau)}{r}\right] \quad (9)$$

where ϕ is the Reduced Scalar Potential
d = radial displacement
$\tau = t - r/c$
t = time
r = range
c = p-wave velocity

The form of the RDP plots are similar to the displacement result. The RDP curves are shown in Figure 9. Because of the permanent offsets at late times, the Fourier Transforms are not calculated directly. Instead, curves are fit to the RDP shown in Figure 9 using the Haskell[5] expression. This is given as:

$$\Phi(\omega) = \Phi(\infty)[1 - \exp(-\kappa\tau)f(\kappa\tau)] \quad (10)$$

$\Phi(\infty)$ is related to the permanent radial displacement $u(\infty)$ by:

$$\Phi(\infty) = r^2\, u(\infty) \quad (11)$$

The function f(x) is given as:

$$f(x) = 1 + x + x^2/2 + x^3/6 + Bx^4 \quad (12)$$

For these relations to be useful, three constants need to be determined, $\Phi(\infty)$, κ and B. $\Phi(\infty)$ can be found either by the late time value of $\Phi(\tau)$ or through the expression (11). κ and B are determined by the RDP peak amplitude and time. They are related by the expression:

$$B=1/(1+0.25\kappa\tau_p) \quad (13)$$

τ_p is the reduced time that the peak amplitude occurs. This expression is substituted into equations (12) and (13) and κ can be determined. The Fourier Transform of equation 10 can be written as:

$$(i\omega)\Phi(\omega) = \Phi(\infty)\frac{\{i(1+B)\omega/\kappa+1\}}{(i\omega/\kappa+1)^5} \quad (14)$$

An average spectral function is found for both MISTY ECHO and MINERAL QUARRY. MINERAL QUARRY is scaled and the ratio taken. Figure 10 is the RDP spectral ratio of the two events. The high frequencies have decoupling values near the acceleration analysis. The low frequencies are higher but still less than 1, indicating coupling enhancement. This analysis is subject to the same low frequency criticisms expressed with acceleration.

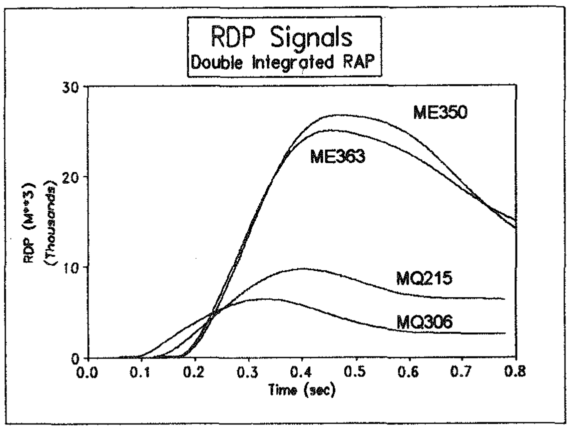

Figure 9: Reduced Displacement Potential in MISTY ECHO and MINERAL QUARRY

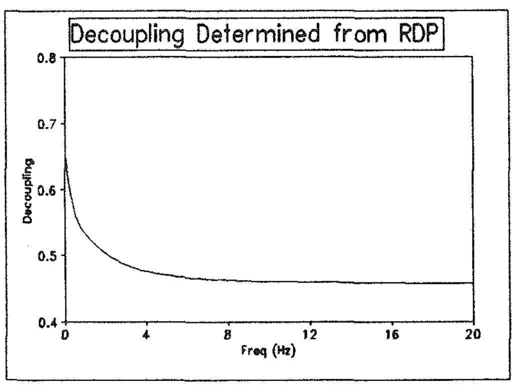

Figure 10: MISTY ECHO RDP Decoupling, MINERAL QUARRY Reference Case

Explosive coupling is not just a function of whether it occurred in a cavity. Granite is a better coupler than tuff. However, the material properties of MINERAL QUARRY and MISTY ECHO are quite similar. Table I is a list of some of these properties with the corresponding values. One important property that is missing in this table is the material strength. However, the properties that are listed are almost identical although the two explosions occurred about 1 km apart. This gives added weight that signal enhancement is due to the cavity.

Table I

Physical Properties of MISTY ECHO and MINERAL QUARRY

	MINERAL QUARRY	MISTY ECHO
Tunnel	U12n.22	U12n.
Depth	389.4 m	400.2 m
Medium	Tuff	Tuff
Lithologic Unit	Tunnel Bed 4	Tunnel Bed 4
Density (Grain)	2.46 Mg/m^3	2.45 Mg/m^3
Density (Bulk)	1.88 Mg/m^3	1.91 Mg/m^3
Water Content Vol.%	20.1%	19.1%
Porosity Vol.%	39.0%	36.7%
Saturation Vol.%	97.0%	99.4%
Sonic Velocity	2920 m/sec	2860 m/sec

ATTENUATION

Although the seismic experiment was designed to obtain free-field reference data, the layout of the accelerometers lends itself to calculation of attenuation. The MINERAL QUARRY sensors were located relatively co-linearly with respect to the WP. The advantage of this straight line geometry lies in the analysis' independence of the source. This is because spectral ratios are taken and the source function cancels. Thus, if there is a non-uniform component to the radiation pattern it should have no effect on my calculations.

Two different techniques are used to estimate the Q-factor. One is a standard spectral ratio method. The other is similar, but it attempts to produce a time series of a signal at one range by using the signal at another as its driving function. It assumes a constant Q and through trial and error, finds a Q that fits the first peak of the data at the other location. The compressional wave can be represented by the equation;

$$Z(\omega) = \frac{A(\omega)}{r^2}(1 + ikr)\exp(-ikr) \quad (15)$$

where Z(w) is the spectral acceleration,

A(w) is the spectral amplitude independent of range,
$k = k_0(1+i/2Q)$ is the complex wave number,
$k_0 = \omega / c$,
r is the range.

The ratio of this equation at two different ranges r_1 and r_2 is:

$$\frac{Z_1(\omega)}{Z_2(\omega)} = \left(\frac{r_2}{r_1}\right)^2 \left(\frac{1+ikr_1}{1+ikr_2}\right) \exp - ik(r_1 - r_2) \quad (16)$$

This equation is used as the basis of propagating a signal at one range to another. If Z_2(w) is known from the data, Q given, then Z_1(w) may be calculated along with its time series. In the present case Z_2(w) is the spectral response at 215 m and the spectral response at 306 m is calculated for various values of Q. The WP velocity is near 2900 m/sec and Figure (11) shows the comparison of the actual data to that propagated using equation (16). In this case, the initial peak is forced to fit the recorded signal, but the calculated curve follows the data fairly well at later times. Note that Q is 8. McCartor[7] et al estimated Q at 10 from the SALMON ground motion data. This is quite low when compared to Q values determined from lower amplitude signals. Mitchell[8] estimates the crustal shear Q below NTS at 90. This is a compressional Q near 200. Der et al[9] gives Q at 400-2000 in the upper mantle.

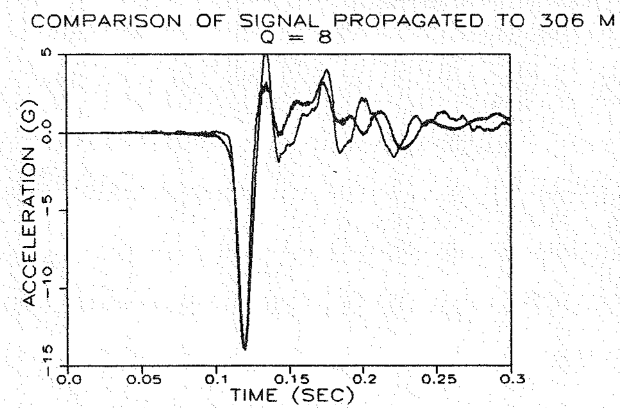

Figure 11: Comparison of signal at 215 m propagated to 306 m

The spectral ratio method uses the same equation (16) but in a different form. Taking the log gives a quasi straight line representation of equation (17) of the spectral ratio.:

$$\mathrm{Log}\left(\left|\frac{Z_1(\omega)}{Z_2(\omega)}\right|\right) = k_0(r_1 - r_2)/2Q + S(\omega) \quad (17)$$

where:

$$S(\omega) = Log\left(\left|\left(\frac{1+ikr_1}{1+ikr_2}\right)\left(\frac{r_2}{r_1}\right)^2\right|\right).$$

S(ω) is a slowly varying function of ω, the straight line fit will yield the value of 1/Q from the slope. Figure (12) is such a fit over the frequency range from 5 - 100 hz. The slope gives a Q of 7. If the frequency range is limited 5 to 50 hz, again, as shown in Figure (12), Q is increased to 14. In either case, Q is much smaller than normal seismic Q values which are about 50 to 100. This may be due to the high stress conditions produced by the explosion.

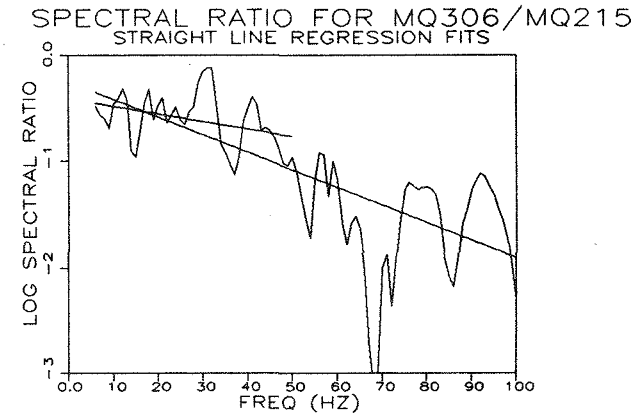

Figure 12: Plots of spectral ratios used in the straight estimates of attenuation

SUCCESS OF EXPERIMENT

One of the prime objectives of the MINERAL QUARRY seismic experiment was to obtain ground motion data in the free-field to investigate the possibility of partial decoupling in previous cavity events. This part of the experiment has been a success. Using spectral ratios of the cube root scaled reference event (MINERAL QUARRY) and MISTY ECHO indicate a coupling enhancement of 2. The RDP calculated for each event was fit to a Haskell type source function yielding similar results. Whether this is due to the cavity or material properties is unclear, but most of the media properties of the two events are almost identical. The low frequency data does not reveal the expected higher decoupling which may be attributed to the window length and offset or trends in the records. Additional work will be done on source characterization and attenuation.

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