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GROUND MOTIONS AND THE INFRASOUND SIGNAL: A NEW MODEL AND THE DISCOVERY OF A SIGNIFICANT CAVITY REBOUND SIGNAL

**Eric M. Jones
Frederick N. App
Rodney W. Whitaker**

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GROUND MOTIONS AND THE INFRASOUND SIGNAL: A NEW MODEL AND THE DISCOVERY OF A SIGNIFICANT CAVITY REBOUND SIGNAL

Eric M. Jones, Frederick N. App, and Rodney W. Whitaker
Earth and Environmental Sciences Division
Los Alamos National Laboratory

ABSTRACT

A model is presented that relates infrasound signals from underground nuclear tests to the peak vertical velocity at surface-ground-zero. For the most part, agreement between the model and observations is good, the exceptions being events conducted in shallow tuff layers in Yucca Flat. These events all have low values of the peak surface velocity. We have determined that the lack of agreement for these events is due to an unusual, second spall event. A stress-wave calculation is presented that reproduces the second-spall phenomenon and indicates that it is due to interference of a cavity-rebound-associated signal with the initial ballistic motion of the surface layers. The effect of the rebound signal is to increase the amplitude of the infrasound signal and thus make low velocity events more detectable.

I. INTRODUCTION AND SUMMARY

The sequence of events which led to the development of a physics-based model of infrasound amplitudes and to the subsequent recognition of the cavity rebound signal can be summarized as follows. Adapting the methodology of Bannister (Ref. 1), we used analytic descriptions of ground motions to predict the pressure histories that would be detected by a near-field observer located along a propagation-path that would eventually lead to the LANL infrasound station at St. George, Utah. Next, an examination of these near-field pressure predictions led to a model of the dependence of the infrasound amplitudes on the peak ground-motion velocity at surface ground zero (SGZ). Subsequently, a comparison between the model and data showed that, while there was good agreement at high values of the peak velocity, for virtually all low-velocity Yucca Flat tests for which both ground motion and infrasound signals are available, the infrasound amplitudes were higher than the model

predictions. An examination of the SGZ ground motion records for these shots then showed that virtually all exhibited two episodes of ballistic motions - that is, two intervals of -9.8 m/s^2 acceleration - separated by an acceleration spike resembling a spall-closure (slapdown) signal. Finally, a calculation was performed of a typical case, one for which subsurface acceleration records were available. Although an exact match with the ground motion data - surface and subsurface - was not achieved in this first calculation, all of the essential features were reproduced and the calculation clearly showed that the distinct character of these tests is the result of a cavity-rebound signal arriving at the surface during the initial spall phase of surface motion. This arrival produces a premature spall closure and a re-acceleration of the surface, which in turn produces enhanced coupling to increase the amplitude of the near-field pressure signal.

II. GROUND MOTIONS AND NEAR-FIELD SIGNALS FOR HIGHER YIELD TESTS

The SGZ ground motion for a typical higher-yield test conducted in saturated tuff is shown in Figure 1. This acceleration record has an initial, three-phase positive pulse consisting of an elastic wave followed by a plastic wave and, finally, a cavity rebound signal. By "plastic wave" we mean the remnant of the wave formed by inelastic processes near the explosion. A calculational study of a similar test has been reported by App and Brunish (Ref. 2). By the end of this initial pulse, the near-surface layers have spalled and, for the next second or so, the ground surface motion is determined solely by gravity. This ballistic phase ends abruptly with spall closure and the resulting slapdown pulse. Generally, the amplitudes of all three components of the positive pulse decrease with range from surface ground zero (SGZ), with the plastic and rebound components often being absent at stations removed from SGZ. The duration of the ballistic phase, τ_b , can be obtained from the ballistic equation

$$d_0 + v_0 \tau_b - 4.9 \tau_b^2 = 0 \quad (1)$$

where d_0 and v_0 are the ground-surface displacement and velocity, respectively, at the start of the ballistic phase. Because d_0 and v_0 decrease with range from SGZ, τ_b also decreases with range. Readers should note, however, that because the time of the first elastic

motion increases with range from SGZ and the duration of the ballistic phase decreases, the time of slapdown can actually decrease with range from SGZ. As an example, for the event shown in Figure 1 the time of first elastic arrival increases from about 0.34 s at SGZ to about 0.47 seconds at a horizontal range equal to the depth of burial; and the time of slapdown decreases from 2.1s to about 1.2s.

For an near-field observer, low in the atmosphere, the acoustic signal produced by an underground nuclear explosion is given by

$$P(t) = \frac{\rho_0}{2\pi} \int_{Area} a(t - \frac{R}{c}) \frac{d\sigma}{R} \quad (2)$$

where a is the ground motion acceleration evaluated at the retarded time, $t - R/c$; R is the slant range from the observer to the area element, $d\sigma$; c is the speed of sound in air; and ρ_0 is the atmospheric density. Note that we assume a constant air density along the path from the surface to the observing point. In a series of model calculations, we have used analytic descriptions of the components of the initial positive pulse, the duration of the ballistic phase, and the amplitude and duration of the slapdown pulse to predict the near-field pressure signal for this and other cases. For the case shown in Figure 1, the signal expected at an observing location 18 kilometers from SGZ at an elevation angle of 33 degrees is shown in Figure 2. The dominant features of the pressure history are (1) a broad, deep negative phase which is associated with ballistic-phase arrivals from a relatively small area around SGZ, and (2) a sharp positive phase associated with slapdown arrivals. Because of the slow variation of the time of slapdown with range from SGZ, the arrivals contributing to the near-field positive phase come from areas relatively far removed from SGZ.

III. A MODEL FOR THE NEAR FIELD NEGATIVE PHASE

Experiments were performed with the near-field prediction program in which contributions to the pressure signal were calculated only for a small circle surrounding SGZ. In Figure 3 the amplitude of the resulting near-field negative phase is plotted as a function of the circle radius, r . Clearly, the negative phase amplitude increases as the square of circle radius out to a limiting radius, r_{max} .

of about 220 meters, beyond which there is a small decline and then an approach to an asymptotic value. In Figure 4, we show the near-field pressure signal resulting from an integration out to a radius of $0.5 r_{\max}$. The flat bottom in the negative phase is an important clue to the cause of the observed behavior.

We note that, for the case under consideration, the ground motion signal does not vary significantly over distances of 200 meters. Indeed, for present purposes we can assume that the ground motion signal is identical at all points closer than $r_{\max}$. Let us now consider arrivals from different points on a selected circle at some smaller distance from SGZ. As illustrated in Figure 5, there will be an interval of time during which arrivals from all points on and within the circle will be ballistic phase arrivals. The start of this interval will correspond to the first ballistic arrival from the point on the circle farthest from the observer; and the end of the interval will correspond to the last ballistic arrival from the nearest point on the circle. Clearly, there will be a limiting radius beyond which there will be no interval of purely ballistic arrivals. An integration to this radius should produce a maximum amplitude for the near-field negative phase and should correspond to $r_{\max}$.

We are led, then, to the following model for the near-field negative phase. The limiting integration radius can be estimated from the expression

$$t_2(r_{\max}) + R_+/c = t_3(r_{\max}) + R_-/c \quad (3)$$

where t_2 is the starting time of the ballistic phase, t_3 is the ending time, R_+ is the slant range from the observer to the far point on the circle, and R_- is the slant range to the near point. The duration of the ballistic phase can be approximated as

$$\tau_b = t_3 - t_2 = 2 v_0/g . \quad (4)$$

This expression can be combined with algebraic approximations for R_+ and R_- based on the fact that both are much greater than $r_{\max}$. The result is

$$r_{\max} = R_0 c v_0 / g H \quad (5)$$

where H is the horizontal range from SGZ to the sub-observer point. For the case shown in Figure 1, we have $v_o = 4.9$ m/s and, consequently estimate $r_{\max} = 200$ m, in good agreement with the graphical result. The results of the numerical experiment indicate that, for integration radii less than $r_{\max}$, we can express the amplitude of the negative phase as

$$P_- = \frac{\rho_o g}{2 \pi R_o} \pi r^2 \quad (6)$$

where R_o is the slant range from the observer to SGZ and g is the acceleration of gravity. Finally, we can combine this expression with our prior expression for $r_{\max}$ and obtain

$$P_- = \frac{\rho_o R_o c^2}{2 g H^2} v_o^2 \quad (7)$$

IV. COMPARISON WITH INFRASOUND DATA

At the moment, we have a total of 33 NTS tests for which we have both infrasound and ground-motion data. The analysis of the previous section indicates that, to the extent that the negative near-field phase is representative of the observed wind-corrected amplitude (WCA) of the infrasound signal, we would expect a quadratic dependence of WCA on the peak velocity. However, rather than do a fit of WCA versus v_o , we have found it instructive to scale our expression for P_- via the approximate relation

$$\text{WCA } (\mu\text{bars}) = 10 P_-(\text{mks}) \left(\frac{R_o}{D} \right)^{1.15} \quad (8)$$

where D is the distance from SGZ to the St. George infrasound station, typically 240 kilometers. Consensus estimates (Ref. 3) for the exponent in this relation vary from 1.1 to 1.2; and we note that, with $R_o = 18$ kilometers, this uncertainty in the loss corresponds to a 30% (full width) uncertainty in WCA.

In Figure 6 we compare WCA versus peak velocity ($v_{pk} = v_o$), showing both the data (solid dots) and the model (solid line). Obviously, there are some significant differences between the data and the model, and we discuss those differences below. Nonetheless,

the overall comparison is very satisfying; and we believe that, for the first time, we have a physical basis for understanding the relationship between infrasound WCA and ground motion.

At high values of v_{pk} the values of WCA tend to lie above the model relationship. As noted above, these tests tend to produce a strong slapdown component in the near-field signal. Although we have not yet developed a model for this slapdown component, a fit made to the results of the higher-yield, near-field calculations indicates that the slapdown component increases as v_o^4 . Because the amplitude of the negative phase increases only as v_o^2 , the total amplitude should and does make a transition from negative-phase dominance to positive-phase dominance. The two terms are equivalent at about $v_o = 5$ m/s.

Below the model line, we find four shots which, thus far, have defied explanation. All have substantial yields and quite normal ground motions for their yields and depths. Three are Pahute Mesa shots and the other was fired in Yucca Flat tuffs just above the static water level. We have found no reason why they should have produced such low infrasound signals.

At lower values of v_{pk} , virtually all of the points lie above the line. For these shots, an examination of the ground motion records has led to an explanation.

V. GROUND MOTIONS FOR THE LOW YIELD TESTS

In Figure 7, we show the SGZ ground motions (acceleration, velocity, and displacement) for a low-yield test conducted in Yucca Flat. This shot was fired in the Ammonia Tanks tuff unit which underlies the alluvium. There was an elastic wave which produced a peak acceleration of about 2 g, followed by a lower-amplitude "plastic" wave. The peak velocity (v_o) of 0.8 m/s occurred at about 0.3 seconds and the displacement (d_o) at that time was about 0.06 meters. In the absence of any further arrivals, slapdown would have occurred at about 0.52 seconds. However, as indicated in the Figure 7, for this shot a slapdown-like pulse occurred at about 0.47 seconds, a time when the surface still had a displacement of about 0.06 meters. Although it is possible to imagine a number of explanations for this apparently-early spall closure, the most significant feature of

the phenomenon is that the pulse was strong enough to produce a positive surface velocity and a second interval of ballistic motion. Indeed, the combined duration of the two ballistic periods is about twice as long as would be expected on the basis of the amplitudes of the elastic and plastic waves. Ground motions measured at stations at various distances from SGZ show a similar behavior and, consequently, the observed enhancement of the near-field amplitude is, perhaps, not surprising.

Virtually all of the other low-yield tests plotted in Figure 6 had similar ground motion behavior. Many showed two distinct intervals of ballistic motion while, for others, neither the first pulse nor the late arrival was strong enough to produce purely ballistic motion. However, as is illustrated in Figure 8 for the case of a second test conducted in the Ammonia Tanks tuff, all of these shots produced acceleration records with the same general features. In each, there is a first positive pulse, an interval of negative acceleration, an intermediate positive pulse, a second interval of negative acceleration, and a final slapdown pulse. Clearly, an understanding of the source of this behavior is important to an understanding of the infrasound signals and, in the following section, we present the results of a stress wave calculation which indicate that, for these shots, the second interval of ballistic or quasi-ballistic motion is the result of a strong signal associated with cavity rebound.

VI. CALCULATIONS

We have performed a stress-wave calculation for the low yield Ammonia Tanks event discussed above in conjunction with Figure 7. The computational mesh is shown in Figure 9. The calculation was performed using a Los Alamos-modified version of the Sandia National Laboratory TOODY finite-difference stress wave code (Ref. 4) that solves the Lagrangian equations of motion in two dimensions. By employing symmetry about the vertical axis, we achieve a true three-dimensional representation of a horizontally layered site, which to a first approximation, is typical of events in Yucca Flat. For the event in question, there were accelerometers emplaced in the backfill of the emplacement hole at depths of 94 and 113 m to complement the surface motion measurements at SGZ and at surface ranges from SGZ of 99 and 244 m. As indicated above, the calculation is preliminary in that the material response models are not refined to the point that all features of the wave forms are

replicated by the calculation. However, the calculation does capture the essential features of the observed surface and subsurface motions.

Figure 10 shows a comparison between calculated and measured vertical particle-velocity wave forms at the surface locations. The measured (dashed) wave form at SGZ is the same as that of the center panel of Figure 7, but at a different plot scale. Note that the pulse which produces the second ballistic interval is present in the calculation, albeit more impulsive than in the measurements. Figure 11 is a "ladder" plot of the particle velocity wave forms from 140 m depth to the surface (104 to 244 m range from the WP), with the line of zero velocity for each station plotted at the station depth. Again the dashed lines represent measurements. The amplitude and timing of the peaks are off, but the presence of an upward propagating "second pulse" is clearly evident in both the measurements and the calculation. This second pulse is the cause of the "premature" first spall closure observed at the free surface.

Figure 12 shows the calculated particle velocity field at times of 160 and 180 ms. Vectors are plotted to indicate the direction of motion at each mesh point, with lengths that are linearly proportional to the velocity. The heavy arrows indicate the general sense of motion. The initial upward propagating stress wave reaches the surface at about 170 ms. At 160 ms, the motion is everywhere outward from the WP. At 180 ms, rebound is beginning to occur beneath the WP as evidenced by the motions directed inward toward the WP. A dynamically formed cavity in an infinite elastic medium would oscillate symmetrically with a period that is dependent on the size of the cavity and the elastic properties of the surrounding medium. For an actual underground nuclear explosion, the cavity is in a half space, confining pressure and material properties vary with depth and the oscillations are influenced by both elastic and inelastic processes. The cavity oscillations are asymmetrical with initial rebound occurring beneath the WP because of the increased impedance to outward motion in that direction.

Figures 13 through 16 show the evolution of the velocity field and spall from 280 ms to 1 sec. The regions undergoing spallation (stippled) are on the left. The corresponding velocity fields are on the right. By 280 ms (Figure 13), the main stress wave has reflected from the free surface and a region of spall has formed to a depth of about 60 m beneath SGZ, and to a surface range of about 200 m. At

this same time an inward, cavity-rebound-associated horizontal flow has just developed that becomes quite strong by 320 ms. Near the axis of rotational symmetry, the rebound flow separates into upward and downward components. The downward component is responsible for the cavity rebound just above the cavity, which in turn is important to the underground containment of the explosion. The upward component eventually produces the "premature" spall closure at the free surface. The effect is especially evident at 400 ms (Figure 14); the motion of the spalled material is downward but the motion of the underlying, unspalled material is strongly upward. The resultant collision is quite violent. By 520 ms the first spall closure is complete. By 600 ms (Figure 15), the rebound signal has reflected from the free surface (as a tensile rarefaction) and the second spall phase begins. There are no additional signals being generated near the cavity to interfere with normal spallation so the second ballistic phase follows its normal course to completion. Figure 16 simply shows that motions are dying down. There is a slight third spall but it is of little extent or consequence. The calculation is approaching a state of static equilibrium.

Because geologic bedding is not perfectly flat and horizontal, a perfectly symmetrical convergence of the horizontal rebound pulse (Figure 13) on axis will not occur naturally and any cavity rebound signal would therefore not be as distinct or impulsive as it is in the calculation. Consistent with this, the measurements show the existence of the rebound signal, but it is not as impulsive as in the calculation, especially at the free surface.

We believe the phenomena responsible for the second spall observed on relatively shallow events in Yucca Flat is due to the interference of the rebound-associated signal with the spall that was created by the initial stress wave interaction with the free surface. The strength and timing of the rebound pulse is known to be a strong function of material properties, especially shear strength, so shallow events in other media may not exhibit the same behavior at the surface. Such cases are amenable to modeling.

VII. NEAR-FIELD AMPLITUDES COMPARED WITH WIND CORRECTED AMPLITUDES

In the discussion of Figure 6, we noted that the systematic deviation of the higher velocity shots from the model line was due to the importance of a positive, slapdown-associated signal. For the low velocity shots, we have now demonstrated that the second interval of ballistic motions is produced by a strong cavity rebound signal and, in this final section, we discuss the results of near-field calculations for these and other shots.

For the low velocity tests, we have included an analytic description of the cavity-rebound signal. Guided by in part by the ground motion data and in part by the calculation described in the previous section, we have modeled the cavity rebound signal as having a simultaneous arrival at all stations, but with an amplitude which, like the first pulse components, has a power-law decay with increasing slant range from the burst point. Although we have not yet fully analyzed the results of these calculations, it is clear that the implied wind-corrected amplitude can be quite sensitive to the details of the ground motion model used for each shot. In Figure 17, we show the near-field signal predicted for the case presented in Figure 7 and find that there is a resemblance to the higher velocity cases in that there is a well defined minimum followed by a positive spike which probably represents coherent arrivals from the cavity rebound signal. In Figure 18, we show the near-field prediction for the case presented in Figure 8; and, here, we find a complex signal which completely lacks a dominant negative phase.

Because the predicted near-field signals at low velocity can be quite sensitive to details of the assumed surface motion and also lack the systematics of predicted signals at higher velocities, it is perhaps not surprising that a comparison of the predicted near-field signals with the measured wind-corrected amplitudes shows considerable scatter at the low end. The comparison is presented in Figure 19. Readers will note the four shots plotted as filled circles which have anomalously low WCAs for their near-field amplitudes. These are the four shots which were discussed previously, all of which have large peak velocities and well-defined, single ballistic phases. Readers will also note that, for WCA greater than about 2, the agreement between the near-field and wind-corrected amplitudes is quite satisfactory. However, below $WCA = 2$, there is a considerable scatter in near-field amplitudes, reflecting the difficulty of defining the ground motions with sufficient accuracy.

Although there is still much work to be done in refining our predictive capabilities at lower velocities, one final point seems worthy of emphasis. If we take the negative-phase model presented earlier as a baseline for the prediction of wind-corrected amplitudes, most tests produce values which are either near or significantly above those which would be expected from the model. Higher velocity shots have greater amplitudes than those that would be expected from the peak velocity because of the coherent spall arrival; and lower velocity shots have larger amplitudes because of such things as strong cavity-rebound signals. Indeed, because the two ballistic intervals seen in these shots have about the same duration, the resulting infrasound amplitudes should be about twice those predicted from the single ballistic-phase model. Generally we find this to be true. This result suggests the interesting possibility that, although it may prove difficult to predict peak velocities for low amplitude shots, these extra effects make detection of signals from this class of events more likely.

ACKNOWLEDGMENT

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REFERENCES

1. J. R. Bannister, "A Program for Predicting Ground Motion Induced Air Pressures", Rept. SAND 78-2361, Sandia National Laboratories, Albuquerque, NM, March 1979.
2. F. N. App and W. M. Brunish, "Stress Wave Calculations of Four Selected Underground Nuclear Tests: Merlin, Hearts, Presidio, and Misty Echo", Rept. EES-NTC-91-03, Group EES-3, Los Alamos National Laboratory, Los Alamos NM, January 1991.
3. ANSI S2.20-1983, "Estimating Airblast Characteristics for Single Point Explosions in Air, With a Guide to Evaluation of Atmospheric Propagation and Effects", American Institute of Physics, 1983.

4. Swegle, J. W., "TOODY IV - A Computer Program for Two-Dimensional Wave Propagation", Report SAND-78-0552, Sandia National Laboratories, Albuquerque NM, September, 1978.

Figure 1. Ground motion accelerations measured at surface ground zero (SGZ) for an underground nuclear test with a relatively high yield that was fired in saturated tuffs in Yucca Flat. The first pulse consists of three arrivals: an elastic wave, a plastic wave, and a cavity rebound signal. This positive phase is followed by an interval of ballistic motions and then by spall close and the slapdown pulse. The peak positive velocity for this case is about 5.6 m/s.

Figure 2. Near-field pressure history predicted for the case shown in Figure 1. This is the signal which is expected for an observer located 18 kilometers from SGZ at an elevation angle of 33 degrees. The broad negative phase is the result of coherent arrivals produced by ballistic motions in a region near SGZ, while the sharp positive phase is the result of coherent arrivals produced by slapdown motions at locations removed from SGZ.

Figure 3. Near-field, negative-phase amplitudes for integrations to a finite radius, r , centered on SGZ. These integrals are done for the case shown in Figure 1. The radius producing the largest negative-phase amplitude is designated $r_{\max}$.

Figure 4. Near-field pressure history produced by an integration to a radius of $0.5 r_{\max}$ for the case shown in Figure 1. The flat-bottomed region is the result of coherent arrivals of ballistic phase motions. The two positive regions flanking the flat-bottomed region are due to coherent arrivals produced by the first pulse and by the slapdown pulse. Note that the slapdown-related maximum comes earlier than the sharp, positive peak in Figure 2.

Figure 5. Pressure arrivals produced by motions at various points on a circle centered on SGZ and with a radius less than $r_{\max}$. The interval of coherent ballistic arrivals is bounded by the start of the ballistic arrival from the farthest point on the circle and by the end of the ballistic arrival from the near point. Coincidence of these two arrivals defines $r_{\max}$.

Figure 6. Measured infrasound wind-corrected amplitudes (WCAs) versus peak SGZ velocity. The solid curve is a representation of the ballistic model for the negative component of the near-field signal. At high peak velocities, WCAs tend to exceed the model predictions because of the positive phase associated with slapdown. At low peak velocities, the points also tend to lie above the model line, in part because of a cavity rebound signal described in this paper. Readers should note the four tests with $\log v_{pk}$ between 0.5 and 0.7 which fall well below the model line. All four have well-defined ground motions with substantial intervals of ballistic motion. The reason why low values of WCA were measured for these shots is not understood.

Figure 7. SGZ ground motions for a shot showing two intervals of ballistic motion separated by a signal resembling spall closure. Note, however, that this signal begins at a time when the surface displacement is still positive.

Figure 8. SGZ ground motions for a second case with two intervals of negative accelerations separated by a strong, slapdown-like signal. In this case, neither the first positive pulse nor the extra signal was strong enough to produce purely ballistic motion.

Figure 9. Computational mesh at 460 ms. Shows layering at the site, measurement station locations and fully grown cavity. Mesh lines within cavity are removed for clarity.

Figure 10. Calculated (solid) and measured (dashed) vertical particle velocity waveforms at the free surface.

Figure 11. Ladder plot of subsurface particle velocity waveforms from 140 m depth to the surface. Line of zero velocity for each station is plotted at the station range. Measurements at stations BFB, BFC and GM1 are dashed. Stippled and solid-filled peaks identify the "second" pulse in the calculations and measurements respectively.

Figure 12. Calculated velocity fields at 160 and 180 ms. Indicates direction of motion at each mesh point, with lengths linearly proportional to the velocity. Heavy arrows indicate general sense of motion. Long vectors originating from near the WP are associated with cavity gas, and should be ignored.

Figure 13. Spall and velocity field plots at 280 and 320 ms. Stippled regions on the left are regions of zero stress (spall). Velocity vector plots on the right indicate the direction and magnitude of motion (see Figure 12 caption).

Figure 14. Spall and velocity field plots at 400 and 520 ms. Stippled regions on the left are regions of zero stress (spall). Velocity vector plots on the right indicate the direction and magnitude of motion (see Figure 12 caption).

Figure 15. Spall and velocity field plots at 600 and 700 ms. Stippled regions on the left are regions of zero stress (spall). Velocity vector plots on the right indicate the direction and magnitude of motion (see Figure 12 caption).

Figure 16. Spall and velocity field plots at 800 ms and 1 sec. Stippled regions on the left are regions of zero stress (spall). Velocity vector plots on the right indicate the direction and magnitude of motion (see Figure 12 caption).

Figure 17. Near-field pressure signal expected for the case shown in Figure 7. Here, the sharp, positive phase may be associated with the cavity rebound signal.

Figure 18. Near-field pressure signal expected for the case shown in Figure 8. This case illustrates the complex nature of the signals which can result from shots with low velocity maxima. The predicted WCA for such cases are sensitive to details of the assumed ground motion histories and distributions.

Figure 19. WCA versus scaled near-field signals calculated for 33 shots with both measured ground motions and measured infrasound signals. In each case, the measured ground motions have been used to construct ground motion models used to predict near-field pressure histories. The near-field amplitudes were then scaled according to Eq. 8 so that they could be compared directly with the measured WCAs.

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