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THE UTILIZATION OF EXPLOSIVE LOADING AS A NONDESTRUCTIVE EVALUATION TOOL IN GEOLOGIC MATERIALS

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Abstract—This paper describes the use of a small explosive charge to evaluate geologic material in a non-destructive manner. One-dimensional computations have been performed using the Lagrangian finite difference code WONDY to investigate the effects that open joints and weak layers of unconsolidated material have on the propagation of stress waves resulting from the detonation of an explosive charge. Data from testing conducted by others in models or in full scale in a number of different materials have been collected and examined. Several findings of importance were noted. The computational results indicate that the characteristics of a stress pulse after passing through an open joint are significantly different from those of a stress pulse that has passed through a weak layer. The examination of data from various explosive tests in different media has yielded a way of determining the type of material that the stress pulse has passed through. These preliminary results indicate that it is theoretically possible to excite a geologic medium with a small explosive pulse and determine the type of rock and the extent to which it contains either open joints or weak layers of unconsolidated material.

INTRODUCTION

This work was motivated by the need to identify the size and type of an explosive source from signals recorded at distances from the source. As the work has developed it is anticipated that the results can be used to assess the state of a geologic material prior to underground construction. Since one of the concerns of the verification program for nuclear testing was the possibility of disguising a nuclear explosion by shielding the event with open fissures and layers of unconsolidated material (sandy layers), we were interested in the effects of such discontinuities on signals generated.

COMPUTER SIMULATION

We used WONDY V, a one-dimensional finite difference wave propagation computer code, to estimate the effects that weak layers and open joints might have on stresses, velocities and displacements at points in a geologic material subjected to the passage of a stress wave. We were interested in the open joints and weak layers since an examination of the tuff in the vicinity of the Nevada test site had revealed the presence of such discontinuities. The code we used was developed by Sandia National Laboratories and did not incorporate either strain rate effects or material damage models. That is, static properties obtained in standard laboratory testing were used as input to the code with no increase in strength for higher rates of loading and likewise no decrease in strength due to the material being damaged at high load levels.

Figure 1 shows the model used in the calculations. The geometry was spherical with a charge of 3/8 g pentaerythritol tetranitrate (PETN) in the center surrounded by a spherical rock core of a strong geologic material (limestone). A weak layer or an open joint of various dimensions separated the central core from an outer core of the same strong material. The first row of numbers in the figure for each material indicates the failure envelope input data and the second row of numbers are the values for the elastic and the critical crush pressures used in the numerical simulations of the weak layer situation. The failure values for the weak material were about one-sixth of the value for the strong material at a mean stress of

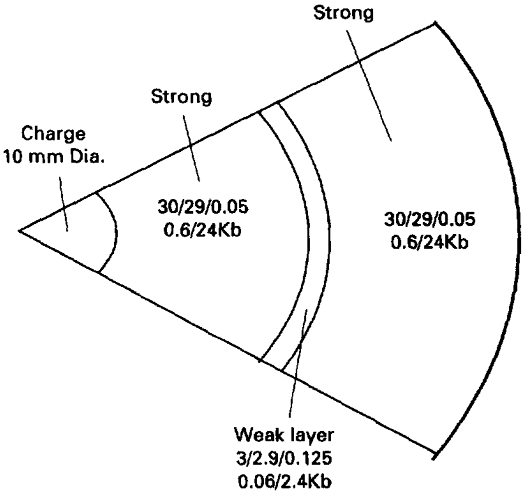


Fig. 1. Model used in the numerical simulation.

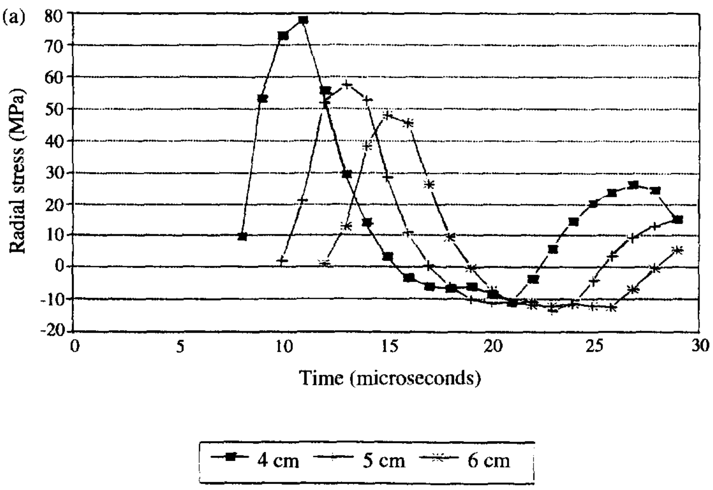
10 Kbar. As shown in the figure, the elastic and critical crush pressures for the weak material were one-tenth those of the strong material. For the simulations of the case where open joints were present a gap of given width was placed between the two strong layers.

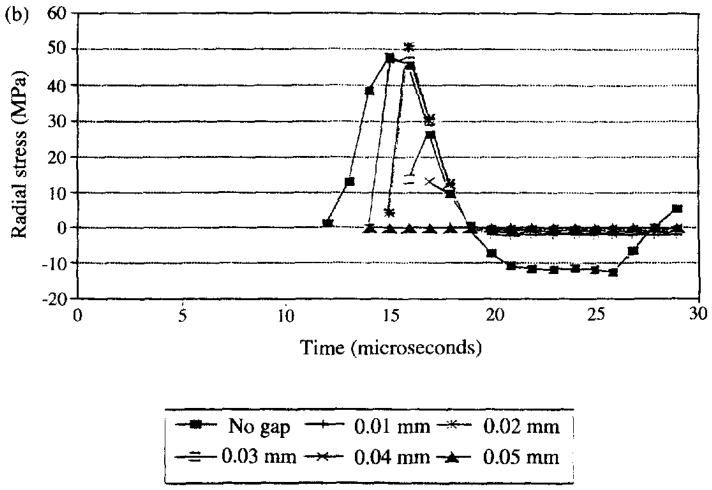
Figure 2 shows results obtained from the calculations. Figure 2(a) shows the stress–time plots obtained for the case where no weak layer or open joint was present. The stress results are shown for locations of 40, 50 and 60 mm from the explosive. Figure 2(b) shows stress results obtained at the 60 mm location when open joints of various widths were present at a location of 50 mm from the explosive source. Figure 2(c) shows stress results obtained at 60 mm when weak layers of various widths were present at a location of 35 mm from the charge center. Of interest in the figures is the fact that for open joints the main effect is a significant decrease in pulse width with an increase in gap width and for the weak layer the main effect is a significant decrease in the magnitude of stress and little or no change in pulse width. More details of these computational results can be found in Fourney *et al.* (1993) and Dick *et al.* (1993). Keep in mind that the changes indicated above are with respect to what would be predicted if the open joints or the weak layers had not been present.

EXPERIMENTAL RESULTS

Figure 3 shows results obtained from measurements made in testing with nuclear charges. Figure 3(a) shows how the magnitude of the acceleration versus time pulse changes in volcanic tuff with increased range from the explosive source. As is evident from looking at the figure, there is normally a significant decrease in acceleration amplitude with an increase in range from the explosive source. Figure 3(b) shows that as range from the charge increases the width of the acceleration pulse increases. Even though the results shown are from nuclear testing, the same trend is present with ordinary chemical explosives. The amount of decrease in amplitude and increase in pulse width is of course dependent upon the geologic material in which the explosive is detonated.

At Maryland, we conducted tests to evaluate the effects of open joints and weak layers on the amplitude of stress and velocity as they propagate into the material beyond the interface. We have been using a quick setting gypsum cement in our tests—a product sold commercially under the name of Hydrocal. This material is similar to volcanic tuff in its response to loading, especially in its response to static loading. It is also similar to tuff with regard to density and porosity. In our testing we used magnetic velocity gages to record the response of the material to explosive loading. With this technique a length of wire is embedded in the material and the model is then tested while located in a constant magnetic field. As the particle (and the wire) moves through the magnetic field an electric current is


Stress versus time
4, 5 and 6 cm from charge


Stress versus time
6 cm from charge

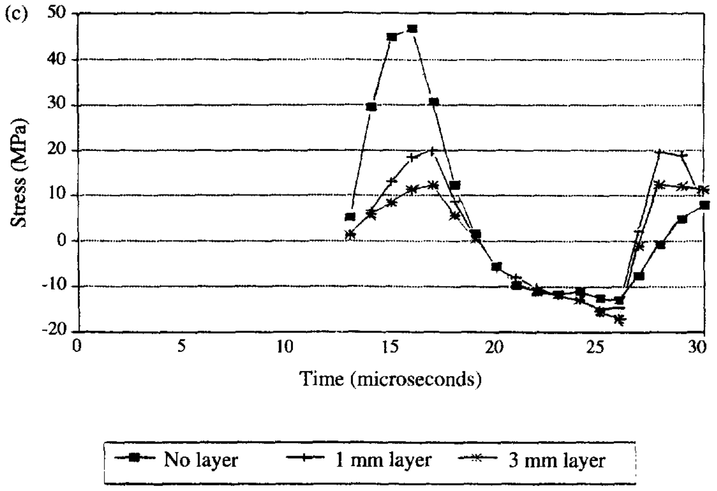
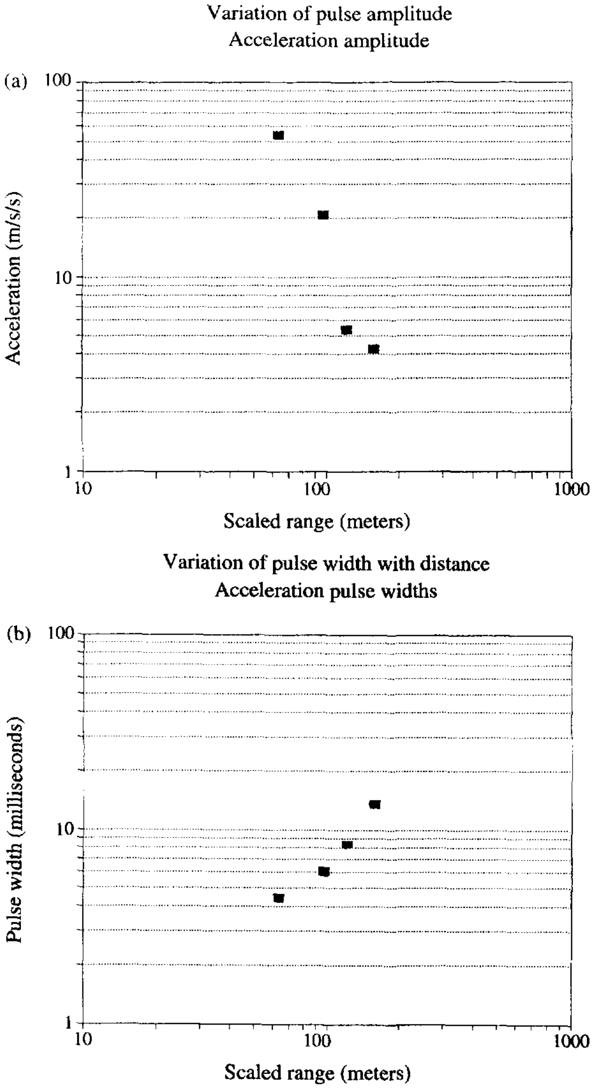

Stress versus time
At 6 cm layer @ 3.5 cm

Fig. 2. Results from numerical simulation—3/8 g of PETN. (a) Stresses at 40, 50 and 60 mm from charge. (b) Effect of open joints on stresses. (c) Effect of weak layers on stresses.



Variation of pulse amplitude
Acceleration amplitude

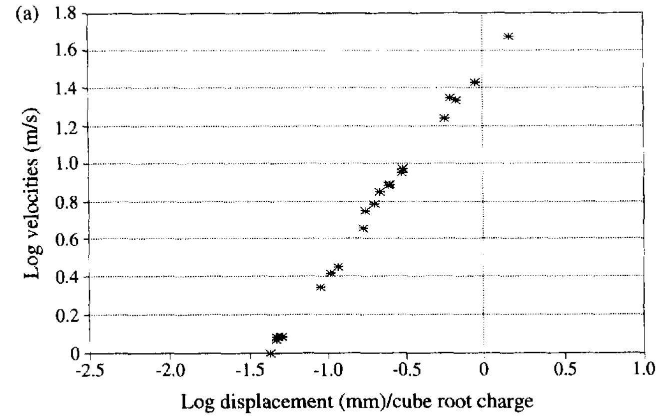
Variation of pulse width with distance
Acceleration pulse widths

Fig. 3. Variation of acceleration amplitude and pulse width with distance from source. (a) Decrease of amplitude with range. (b) Increase of pulse width with range.

induced into the wire which is directly proportional to the velocity (Young *et al.*, 1983). We therefore record velocity as a function of time of a particle positioned at the location of the wire segment. In some cases we used a loop of wire which was equidistant from the explosive source and oriented in the magnetic field so as to measure radial velocity. In other instances we used only a segment of wire that was about 25 mm in length and measured the velocity over the 25 mm length. The direction of the velocity measured depends upon the orientation or the magnetic field.

We prefer to analyze our results by plotting the peak positive velocity (the maximum value of velocity away from the explosive source) versus the peak value of positive displacement (the maximum value of displacement away from the explosive source). Since the positive displacement is the area under the velocity curve up to the time when the velocity becomes negative, we felt that this way of plotting the data would give an indication of information about the pulse shape. That is, if the velocity pulse was of high magnitude and narrow pulse width the value of velocity would be high compared with the value of displacement. Likewise if the pulse was of low magnitude and had a long pulse width the value of velocity would be low compared with the displacement. We also felt that this way of plotting the data would permit us to account for any effects that changes in pulse magnitude and pulse width as shown in Fig. 3 might have on the outward travelling wave.

Velocity versus displacement
Hydrocal models



Velocity versus displacement
Hydrocal models

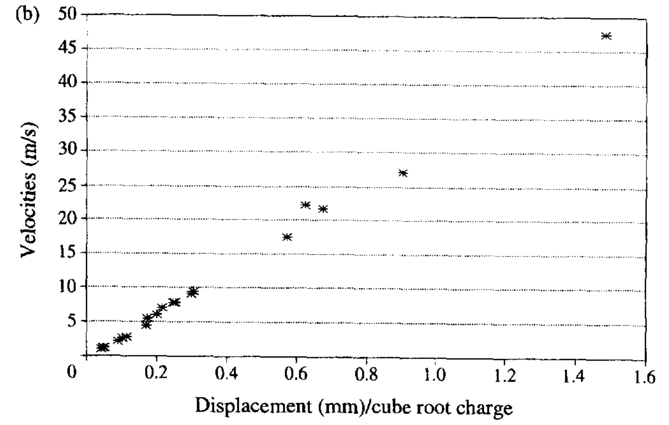


Fig. 4. Velocity versus displacement from tests conducted in Hyrodcal at the University of Maryland. (a) Velocity versus displacement in log–log space. (b) Velocity versus displacement in normal space.

Figure 4(a) shows some sample results from the testing at Maryland. The points shown in the figure are from multiple tests and are plotted in log–log space. Notice that all of the results fall on a single line. The points at the lower end of the line are from velocities measured at greater ranges, while the points on the upper end of the line are from positions located closer to the explosive charge. The fact that all of the points seemed to define a single line in log–log space [and almost a straight line in normal velocity displacement space—see Fig. 4(b)] was of great interest.

Figure 5(a) shows velocity–time traces measured by scientists at Stanford Research Institute (SRI) (Nagy and Florence, 1985; Miller and Florence, 1991) for granite, limestone and tuff. The traces for granite and limestone were measured at a distance of 10 mm from the explosive source—a 3/8 g charge of PETN. The one for tuff was measured at a slightly larger distance of 12.5 mm. The velocity gages used in these tests were wire loops and the velocities shown are radial velocities. The granite pulse is high in amplitude and narrow in width. The limestone pulse is not quite as high in amplitude and is nearly twice as big with regard to pulse width. The tuff record is intermediate to the other two in terms of amplitude and is again nearly twice as large again in pulse width as the limestone pulse. Keep in mind the fact that the tuff result is for a location that was farther from the charge than the other two. Figure 5(b) shows velocity–time traces which compare results obtained from tuff [the same test as shown in Fig. 5(a)] and Hydrocal models tested at Maryland. The tests at Maryland used a 1.0 g charge of PETN and the results shown in the figure are scaled so as to normalize the results. The scaling used was with regard to charge size to the one-third power and was applied only to the time variable since it is not necessary to scale velocity.

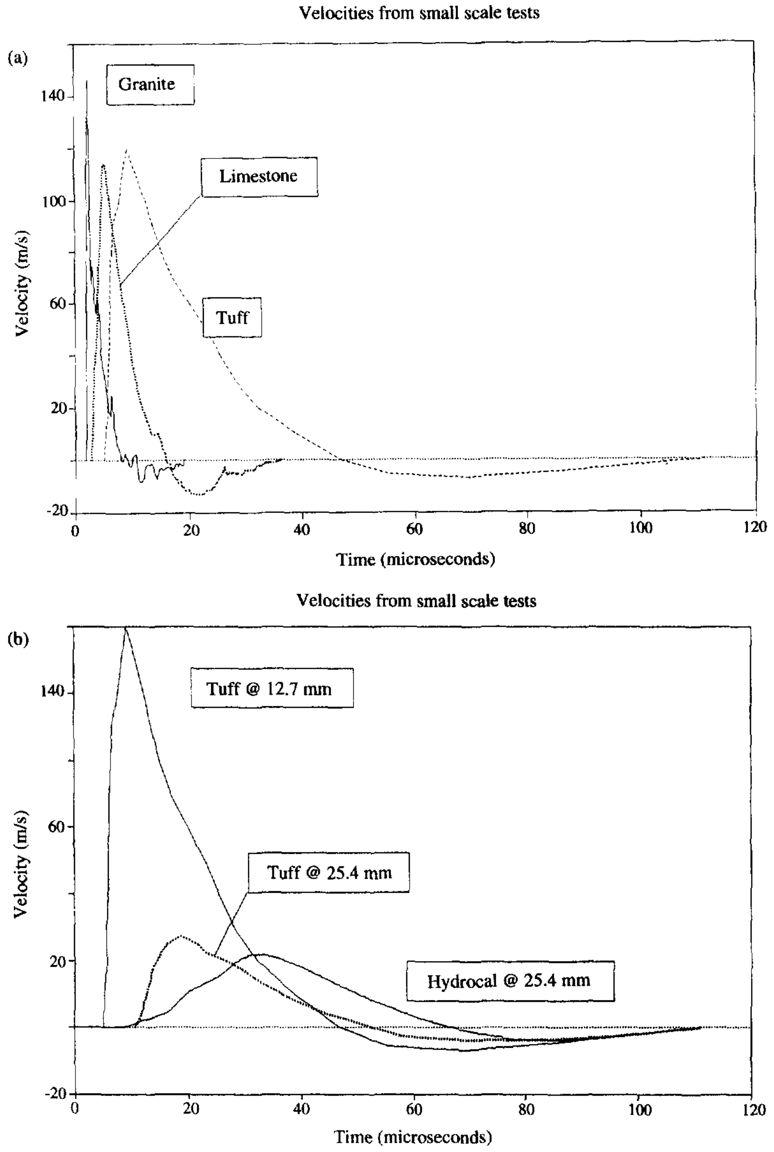


Fig. 5. Velocity versus time traces for four rock types. (a) Velocity versus time for granite, limestone, and tuff. Granite and limestone at 10 mm, tuff at 12.5 mm. (b) Velocity versus time for tuff and Hydrocal.

Notice from the figure that the responses of the tuff and the Hydrocal are similar from the standpoint of velocity amplitude and total pulse width. They are dissimilar with regard to rise time and the pulse width of the positive peak. The rise time of the tuff is considerably quicker than the rise time of the Hydrocal. The width of the positive pulse of the Hydrocal is greater than that of the tuff.

Figure 6(a) shows a plot in log–log space for results obtained in testing of granite, limestone and tuff. Most of the data were obtained by SRI in small scale testing (3/8 g of PETN) but some points are from nuclear tests with charge sizes in the kiloton range. The data fall on a straight line in velocity–displacement (log–log) space, and of more interest is the fact that the data from the different materials are separated quite nicely in the plots. The scatter in the data shown in the figure is due, in part, to the fact that the conditions of the materials differed from test to test. That is, the granite was tested both at room temperature and below freezing temperatures in both dry and saturated conditions. The limestone was tested both in the dry frozen and the saturated frozen state. Some of the scatter in the tuff data is also possibly due to differences in saturation. The data for the three materials shown in the figure are almost on a straight line when plotted in normal

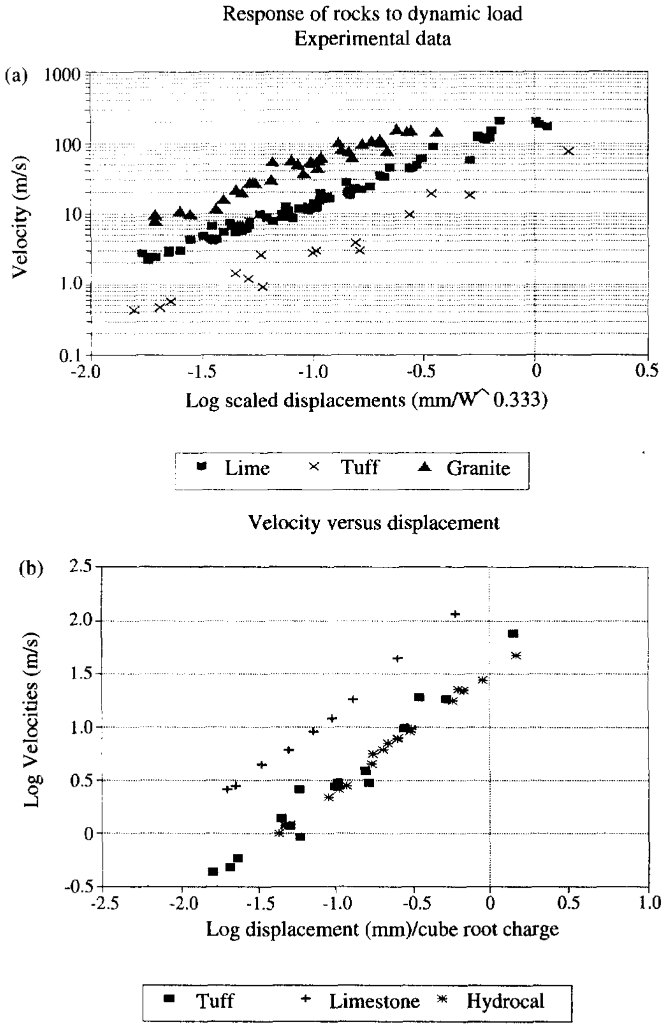


Fig. 6. Velocity versus displacement for four rock types in log–log space. (a) Velocity versus displacement for granite, limestone and tuff. (b) Velocity versus displacement for limestone, tuff and Hydrocal.

space. Figure 6(b) shows similar results for the Hydrocal tested at Maryland and gives a comparison of those results with limestone and tuff. The difference between the tuff and the Hydrocal is not great, but their velocity–time traces were also similar.

DISCUSSION

The straight lines in log–log space imply that the relationship between peak velocity and peak displacement can be expressed as a power relationship. Since the peak velocity being zero implies that the peak displacement is also zero the following relationship holds between velocity and displacement:

$$V = bD^{a} \tag{1}$$

where V is the peak velocity, D is the peak displacement and b and a are constants. As indicated above, for tests involving charges of different types and sizes, the displacement needs to be scaled, whereas the velocity does not, to normalize the data.

If a is equal to one, then the relationship in normal space is a straight line and the b value is the slope of the line. A least-squares fit to the data shown in Figs 6(a,b) gave the values shown in Table 1 for the constants in the equation.

The least-square fits to the data are very good with R^2 values ranging from a low of 0.929 to a high of 0.995. The values of the constant a range between 1.01 for the saturated

Table 1. Material response parameters obtained from experimental results

Material	a	b	Condition	R^2
Granite	1.07	2.922	Frozen	0.929
	1.01	2.877	Saturated (RT)	0.995
	1.14	3.055	Dry (RT)	0.997
Limestone	1.12	2.278	Dry (frozen)	0.994
Tuff	1.17	1.644	Saturated (RT)	0.959
Hydrocal	1.10	1.525	Dry (RT)	0.995

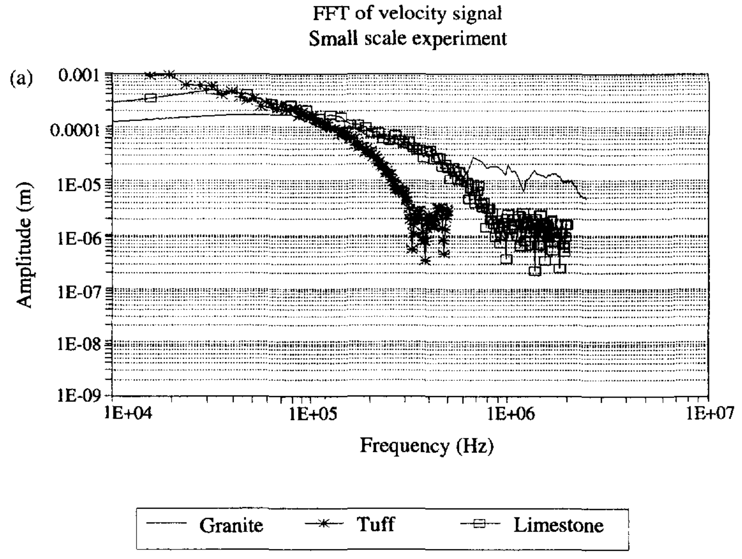
granite at room temperature (RT) to 1.17 for the tuff. The value of the constant a, as indicated above, is related to the curvature of the velocity displacement curve in normal space. The material with the most linear relationship in normal space is the saturated granite at room temperature. The most non-linear relationship was found for the saturated tuff at room temperature.

The b values which are the intercept values in log–log space are quite different with a low of 1.525 for Hydrocal and a high of 3.055 for the dry granite at room temperature. It should be pointed out that the limestone data plotted in Fig. 6(a) are for both dry and saturated materials in the frozen conditions but the coefficients given in Table 1 are only for the dry frozen condition as plotted in Fig. 6(b).

We were interested in determining a better way to distinguish the response of different materials to the explosive loading. One can, of course, look at the pulse shapes shown in Fig. 5(a) and see differences, but these measurements were all made at about the same distance from a similar charge. In the case where the measurements would be made with different size charges and at different distances, this difference would not be apparent. We performed fast Fourier transforms (FFTs) on the velocity pulses shown in Figs 5(a,b) to determine how the frequency contents compare. Figure 7 shows the results of this analysis. Figure 7(a) shows a comparison of the results for the limestone, granite and tuff shown in Fig. 5(a). As can be seen from the figure, the spectra are quite similar. All are nearly identical at the lower frequencies. The spectra are not plotted out to the same value of frequency and this is due to the data that were used as input into the FFT routine. The time points input into the routine for the granite and the limestone pulses were much more closely spaced than were the points for the tuff (0.2 μs compared with 1.0 μs). Figure 7(b) shows spectra from three gages from the same small scale tuff test and give an indication of the type of variation that can be expected with distance from the same material. As expected, the amplitude of the spectra decreases as the range from the charge increases. In the case of the results shown in the figure the behavior is similar at the lower frequencies but some unexpected variations begin to appear at the higher frequencies.

Figure 7(c) shows a comparison of the spectra obtained from gages located 25.4 mm from the explosive source for testing in Hydrocal and in tuff. These results are from the velocity–time traces shown in Fig. 5(b). The spectra are quite similar. Figure 7(d) presents the results of a FFT on results from two gages from the same Hydrocal test that were located only 12.5 mm from one another. It is our opinion that the differences in the FFT spectra shown in Figs 7(a,c) between the four tests in the different rock types are no greater than the differences between the gages in the same materials at different locations as shown in Figs 7(b,d). Our conclusion from performing the FFT analysis on the velocity pulses from the four materials is that such an analysis does not offer a very good way of distinguishing easily the response of different materials to explosive loading.

We have presented the results in a velocity versus displacement space because at Maryland and at SRI the measurements during the tests were velocity versus time. We could just as easily have used acceleration–velocity space or for that matter acceleration–displacement space. All provide a way to distinguish the behavior of one material from another. Figure 8 shows results from nuclear testing in both acceleration–velocity space and in velocity–displacement space. The intercept and the power of the curve are of course different in acceleration–velocity space from those obtained in velocity–displacement space. For the tuff data shown in Fig. 8, the intercept value was found to be 1.033 in acceleration–



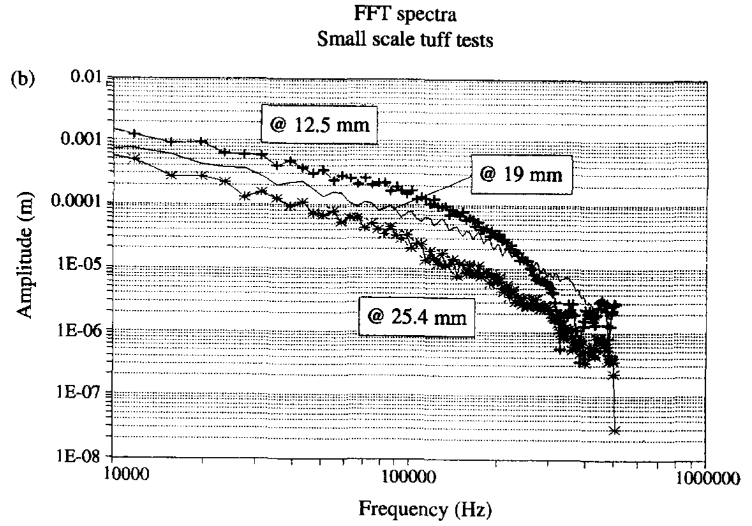
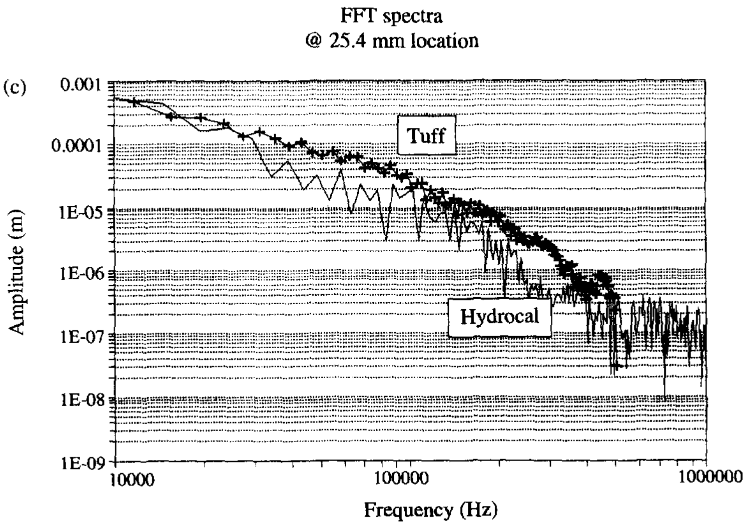


Fig. 7. FFT spectra for four rock types. (a) FFT spectra for granite, limestone and tuff—from velocity time traces in Fig. 5(a). (b) FFT spectra for tuff. (c) FFT spectra for tuff and Hydrocal results from 25.4 mm. (d) FFT spectra for Hydrocal results from 25.4 mm and 38 mm.

velocity space and 1.531 in velocity–displacement space. The power of the acceleration–velocity relationship was found to be 1.52 while the power of the velocity–displacement curve was 1.081. The value obtained for the power of the velocity–displacement curve differs from the value shown for tuff in Table 1 since the saturation was different.

What appears to be important in using this technique to distinguish between types of materials is that the measured variable is plotted against the area under the time curve for that variable. We have had limited success using stress versus "impulse"—the area under the stress–time curve. In the case of stress the integration becomes difficult since the stress normally does not return to zero due to a plastic zone that remains after the stress pulse passes by the measurement point. Also it is more difficult to work with stresses since the gages used to measure the stress do not seem to be as robust as do the accelerometers or the velocity gages and the stress gages do not survive for a long enough period of time after the test to obtain good integrated values.

At Maryland, we are testing Hydrocal models with and without open joints and weak layers. The testing is not yet complete enough to substantiate or refute completely the computational results obtained from the WONDY code. We have, however, obtained preliminary results which are encouraging. Figure 9 shows the variation of pulse width


FFT spectra
@ 25.4 mm location

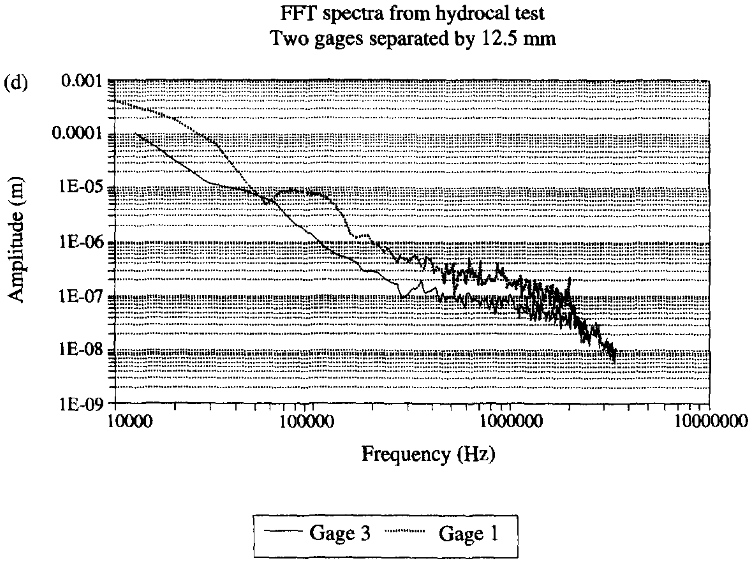
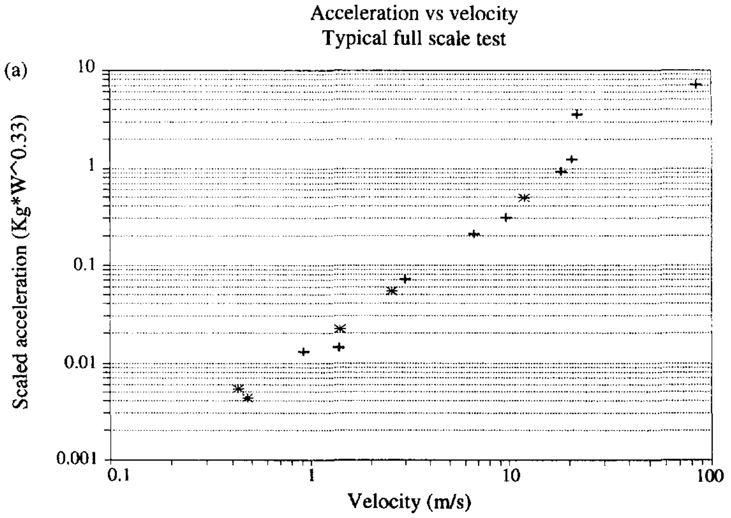

FFT spectra from hydrocal test
Two gages separated by 12.5 mm

Fig. 7. *Continued.*

measured in one of our Hydrocal models without either an open joint or weak layer. For these tests we used wire loops in an almost identical fashion to those utilized by SRI to measure radial velocity. As seen from the figure, the increase in pulse width is not large with range. A doubling in range from 25 mm to 50 results in only an increase in pulse width from around 58 μs to about 62 μs. Figure 10 shows results obtained in Hydrocal models with various widths of open joints. In this case the width of the open joints varied from 0.05 to 0.254 mm. The magnetic field and the wire segments (25 mm in length) were oriented in such a fashion that measured velocity was normal to the open joint. The test arrangement provides for three normal velocities to be measured before the interface and three after the interface. Note from the results that there is a very definite decrease in pulse width as the velocity pulse propagates across the open joint—just as was predicted by the computer code.

CONCLUSIONS

Model testing and computer simulation have been used to develop a means of performing non-destructive evaluation of a geologic medium. We have shown that a simple plot in log–log space of velocity versus displacement (or acceleration versus velocity) can distinguish the response of different materials to explosive loading. This way of looking at



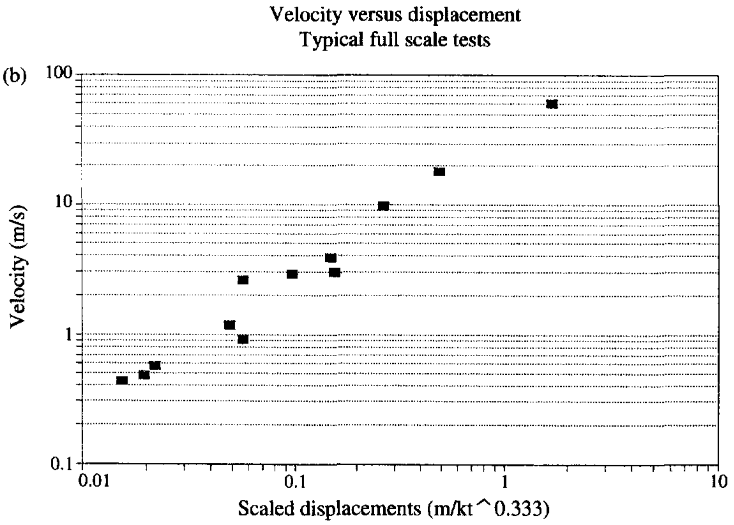


Fig. 8. Acceleration versus velocity and velocity versus displacement results from nuclear testing. (a) Acceleration versus velocity in log–log space. (b) Velocity versus displacement in log–log space.

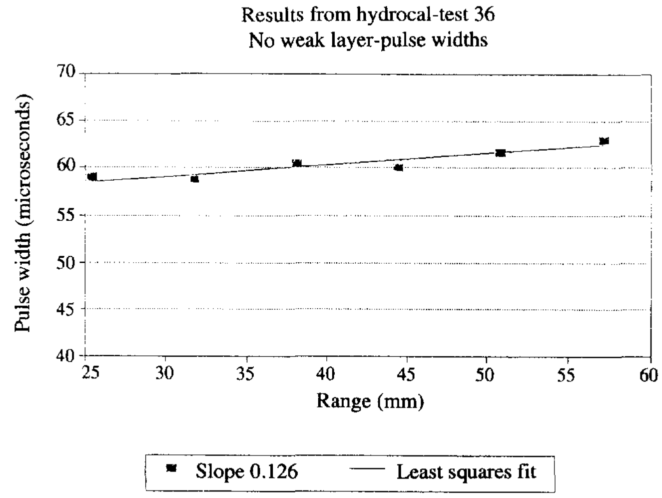


Fig. 9. Pulse width versus range for Hydrocal tests when no open joints or weak layers are present.

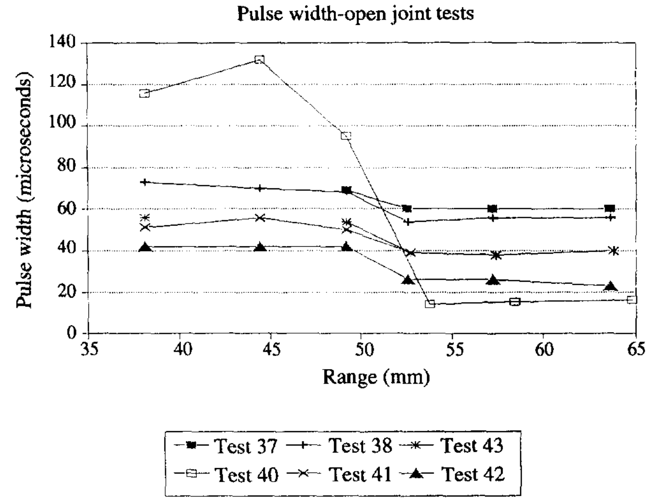


Fig. 10. Pulse width versus range for Hydrocal tests when open joints of various sizes are present in models.

the data appears to be much quicker and distinguishes between the various materials in a much clearer fashion than does a FFT analysis.

The results of computer simulations have also indicated that one can distinguish the presence of open joints and weak layers from the effects these discontinuities have on the velocity pulse as it travels through the material. An open joint appears both from the results of the computer simulation and very preliminary model testing to affect the velocity (or stress) pulse primarily from the standpoint of pulse width. Computer simulations indicate that the presence of weak layers, on the other hand, appears to affect only the magnitude of the velocity pulse. We are currently conducting model testing when weak layers are present to determine whether the results of the computer simulation are accurate.

In theory, it is possible to excite a geologic medium with a small explosive load prior to beginning construction and through the use of a few transducers placed in appropriate locations to determine what lies ahead of the construction path—both from the standpoint of material type as well as open joints or weak layers. The results do not allow the identification of each and every open joint or weak layer but rather would give an integrated effect of the discontinuities. In fact, the results obtained might prove very effective in establishing a way of determining material damage from the passage of a high amplitude stress wave through a geologic material (Godfrey, 1974). Using the suggested techniques it might be possible to determine the damage parameter used in many cases to account for prior excessive loading.

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