Conf - 93 - 2

LA-UR-93- 1615

Title: Modelling of Nuclear Explosions in Hard Rock Sites

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Submitted to: Numerical Modeling for Underground Nuclear Test Monitoring Symposium
March 23-25, 1993
Durango, CO

Los Alamos
NATIONAL LABORATORY

Modelling of Nuclear Explosions in Hard Rock Sites

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This study represents part of a larger effort to systematically model the effects of differing source region properties on ground motion from underground nuclear explosions at the Nevada Test Site. In previous work by the authors the primary emphasis was on alluvium and both saturated and unsaturated tuff ([1], [2], [3]). We have attempted to model events on Pahute Mesa, where either the working point medium, or some of the layers above the working point, or both, are hard rock. The complex layering at these sites, however, has prevented us from drawing unambiguous conclusions about modelling hard rock.

In order to learn more about the response of hard rock to underground nuclear explosions, we have attempted to model the PILEDRIVER event. PILEDRIVER was fired on June 2, 1966 in the granite stock of Area 15 at the Nevada Test Site. The working point was at a depth of 462.7 m and the yield was determined to be 61 kt. Numerous surface, sub surface and free field measurements were made and analyzed by SRI [4]. An attempt was made to determine the contribution of spall to the teleseismic signal, but proved unsuccessful because most of the data from below shot level gauges was lost. Nonetheless, there is quite a bit of good quality data from a variety of locations.

Our previous modelling efforts have indicated that it is difficult to characterize how hard rock will respond to ground shock from the traditional methods of laboratory tests on core, and geophysical logging. Hard rock tends to have inhomogeneities in material properties on a fairly large scale, due mainly to fractures and faults. The core samples, therefore, tend not to be representative, particularly with regard to sound speed and shear strength. In order to obtain reasonable agreement with the waveform data obtained from a nuclear underground test, it is typically necessary to model the rock as being considerably weaker in shear than the core values indicate. Also, the sound speed, based on the times of arrival of accelerometer or velocity gauges, is often lower than the values obtained from core, presumably due to the influence of faults and fractures. The rock may also undergo considerable damage from the strong shock, so that its response, after the passage of the outgoing shock wave, may indicate even further weakening of the rock mass. This study attempts to confirm and better quantify these effects. Our preliminary results indicate that the granodiorite at the PILEDRIVER site is not significantly stronger than the welded tuffs and rhyolites present on Pahute Mesa. In fact, the granodiorite may be more subject to fractures and joints, making it more easily damaged and weaker after damage. In particular, the near surface layers seem to be severely weathered, resulting in lower strength and greatly reduced sound speed.

A schematic diagram of the PILEDRIVER shot and most of the ground motion stations is shown in Figure 1. The data quality is, for the most part, very good. For several locations we have velocities both from integrated accelerometer traces and from velocity transducer gauges, and the agreement is generally excellent. The surface stations shown were all on a line bearing N58E from surface ground zero (SGZ). A few other gauges located at a bearing of S5E were situated across the Boundary Fault from SGZ to investigate possible motion along the fault. We have not included these gauges in our study at this time.

We have performed a series of calculations with different layering, physical properties and material properties in an attempt to determine which properties are most important in shaping the observed waveforms. Although this study of hard rock is far from exhaustive, and we have so far only looked at the PILEDRIVER waveforms, some conclusions are already apparent.

The treatment of damage is extremely important, i.e., the amount of shear the rock can support after the passage of the initial "shock" wave, as well as the strength of the shock required to damage the rock. Calculations were performed for HARDHAT, in a similar granodiorite to that found at PILEDRIVER, by Wagner and Louie [5]. they found that despite numerous variations in the way the equation of state of the rock was modeled, they were unable to match the slow drop of the trailing end of the velocity waveform. They concluded that "shock conditioning" was an important missing component of their model. More recent work by Rimer et al. [6] among others, has confirmed the importance of how damage is modeled on the resulting waveforms.

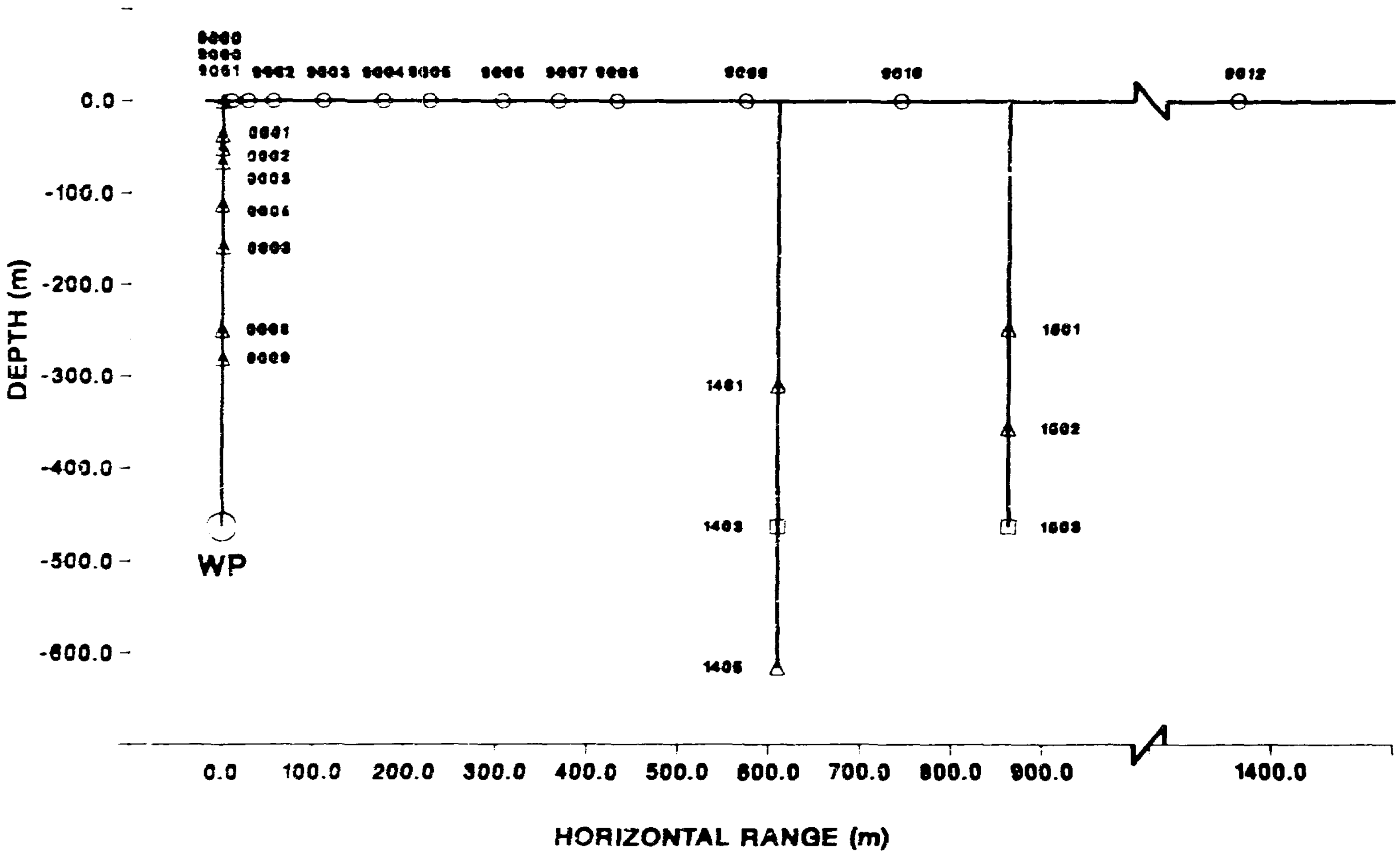

Figure 1. PILEDRIVER ground motion stations

Another important aspect is the presence of the near-surface weathered layers. Both the dispersion in the waveforms themselves and the arrival times at the near surface stations confirm the degraded condition of these layers. The arrival times for the stations in the "zero" hole indicate that while the sound speed at depth is near 6000 m/s, the sound speed within 50 m of the surface drops down to about 1600 m/s. An intermediate layer has an acoustic velocity, based on arrival times, of about 4500 m/s.

In the calculations we performed for the present study, we varied the strength, the amount of damage and the compressibility of the working point layer, and the thickness, the sound speed, the compressibility and the shear strength of the weathered layers. Some of the more important parameter variations are shown in Table 1.

Some of the results for the aforementioned calculations are shown in Figures 2 through 5. In all of the plots, the solid lines are the calculational result and the dashed lines (or symbols in Figure 3) represent the experimental data.

Figure 2 shows best vertical velocity waveform matches achieved so far (for calculation PD12 as shown in Table 1). In Figure 3, we show a comparison of peak vertical velocity versus range for this calculation and the PILEDRIVER data.

Figure 4 shows the waveforms obtained when we use "good quality" granite, as described by Hoek and Brown [7], for the working point material (calculation PD11). This is the same material response model used by App [8] in his 1-D study of material property effects on the seismic source function. The calculated waveforms are much more impulsive and lack the broad tail seen in the experimental data. The granodiorite at PILEDRIVER, based on the characteristics of the recorded waveforms, is considerably weaker than the type of rock that is usually characterized as granite. Apparently the PILEDRIVER medium is not "good quality" granite.

Figure 5 shows some of the surface ground motion for the PD12 "baseline" calculation and for a calculation (PD18) where the weathered layers were modeled as significantly slower and weaker than the working point material. The weak near surface layer spread out the waveform. Also, we see in the data that the overall

Table I.
PILEDRIVER calculation material properties

	Calculation		
	PD11	PD12	PD18
Weathered layer:			
thickness (m)	35	150	50/150
initial crush pressure (kb)	0.10	0.10	0.10/0.05
sound speed (m/s)	2100	2100	1600/4700
Working point layer:			
max unconf. strength* (kb)	2.52	0.945	0.945
initial crush pressure (kb)	0.10	0.40	0.40
sound speed (m/s)	4000	5500	5500

PD11 - "good quality" granite
PD12 - weaker, easily damaged granite
PD18 - like PD12 but thicker, weaker surface layers

* maximum stress difference material can support in triaxial loading

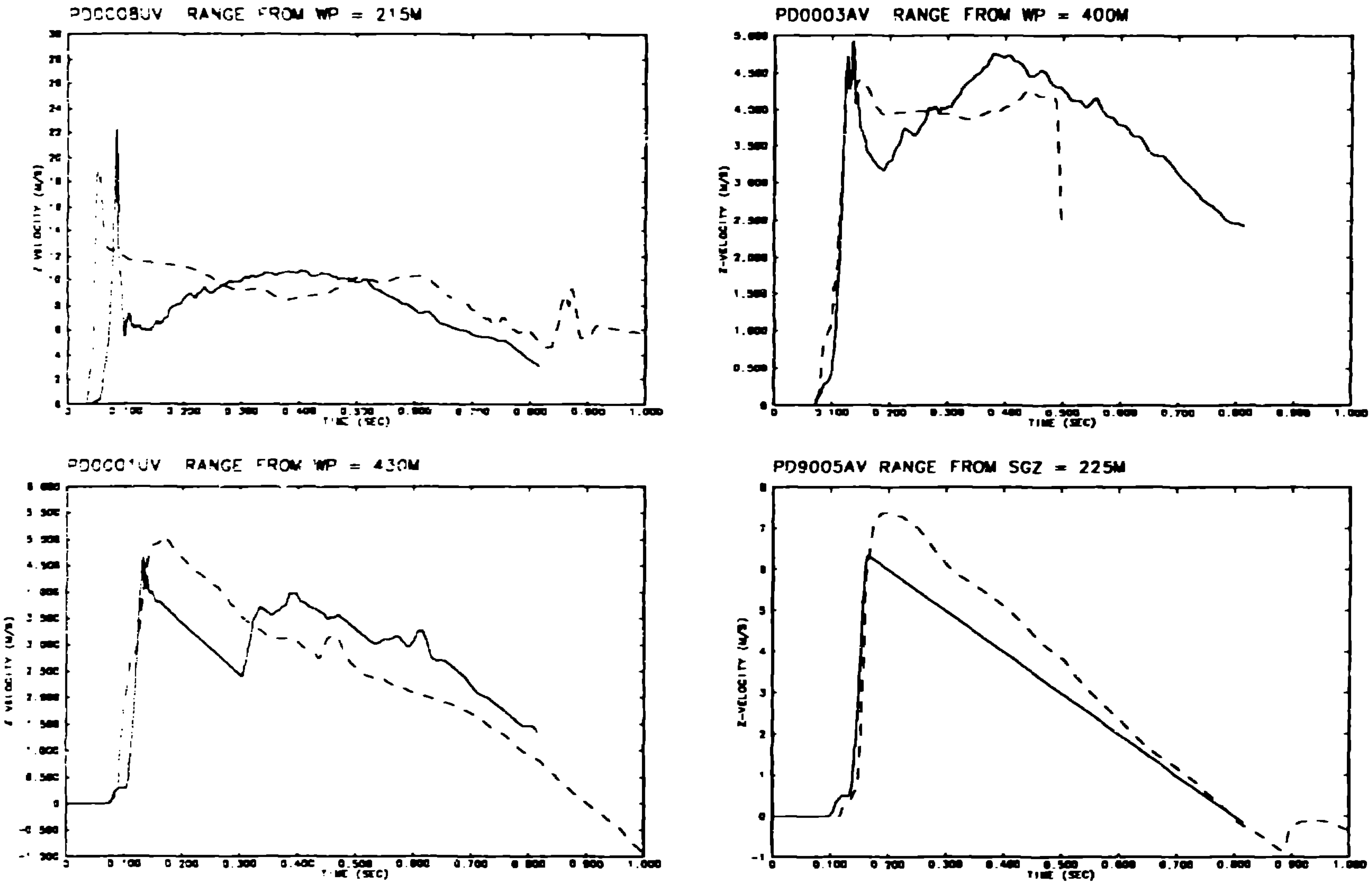

FIGURE 2. BEST MODEL (PD12)

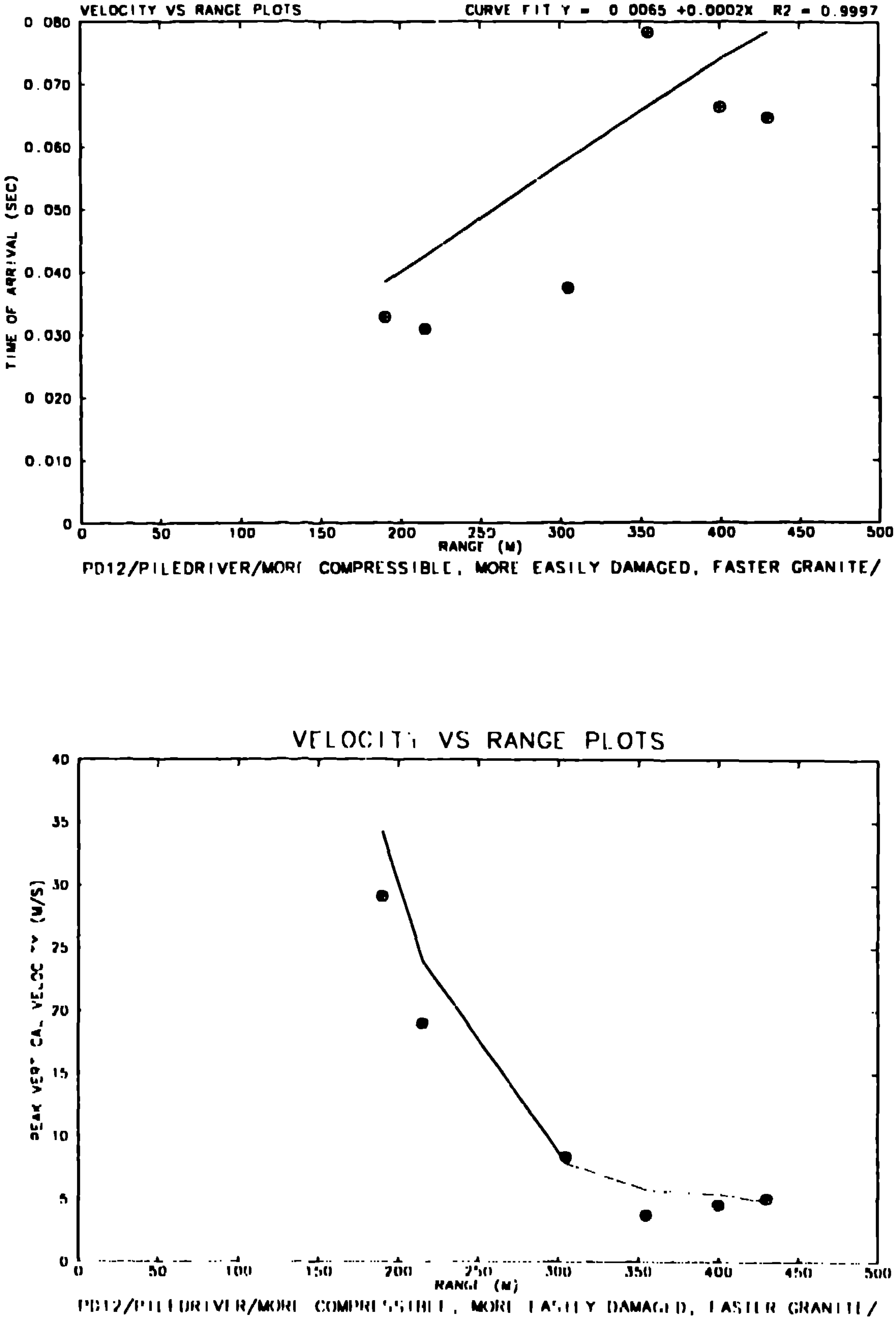
VELOCITY VS RANGE PLOTS
CURVE FIT Y = 0 0065 +0.0002X R2 = 0.9997
TIME OF ARRIVAL (SEC)
0 080
0.070
0.060
0 050
0.040
0.030
0 020
0.010
0
0
50
100
150
200
250
300
350
400
450
500
RANGE (M)
PD12/PILEDRIVER/MORE COMPRESSIBLE, MORE EASILY DAMAGED, FASTER GRANITE/
VELOCITY VS RANGE PLOTS
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
350
400
450
500
RANGE (M)
PD12/PILEDRIVER/MORE COMPRESSIBLE, MORE EASILY DAMAGED, FASTER GRANITE/

Figure 3

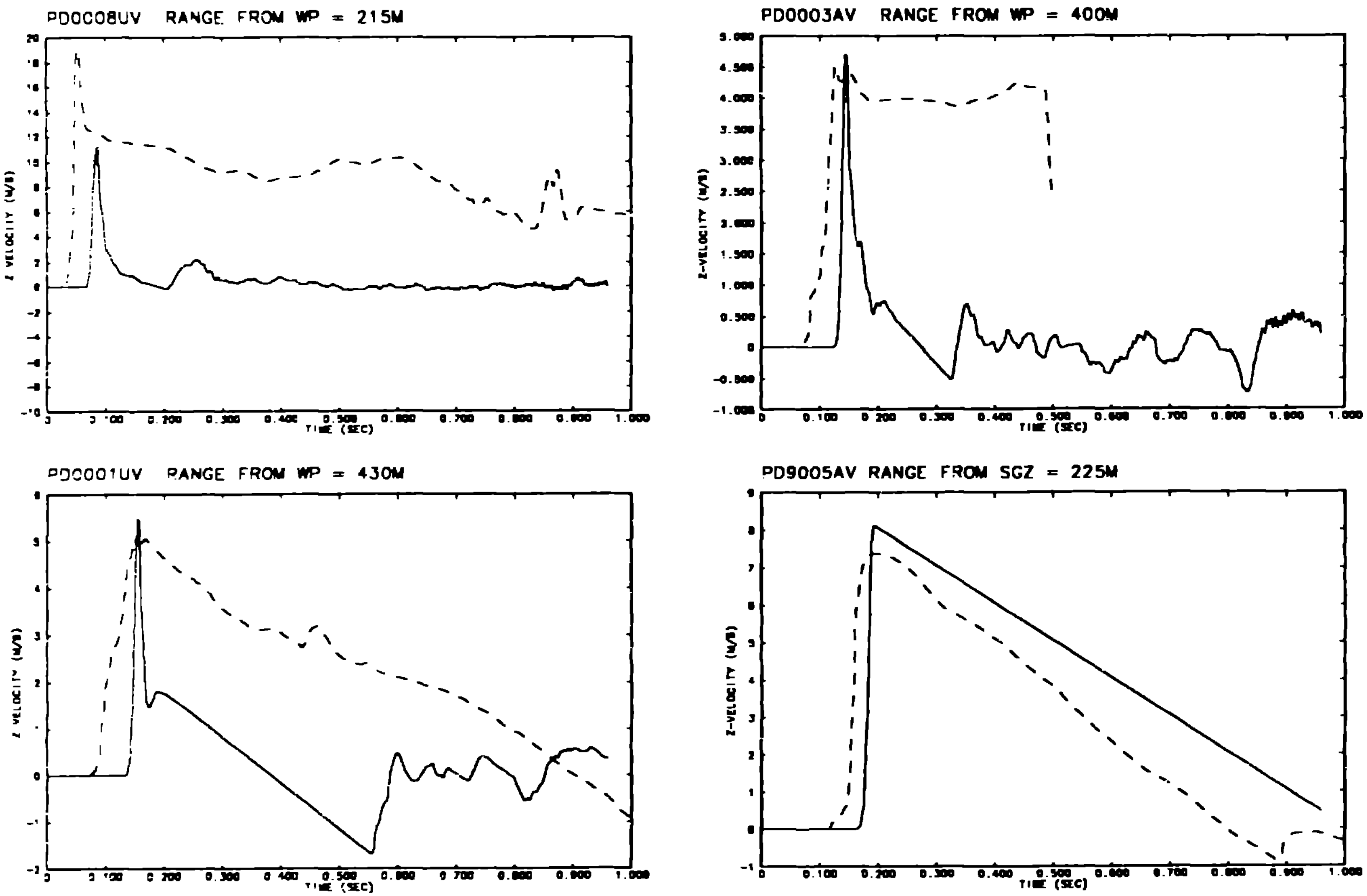

FIGURE 4. GOOD QUALITY GRANITE MODEl (PD11)

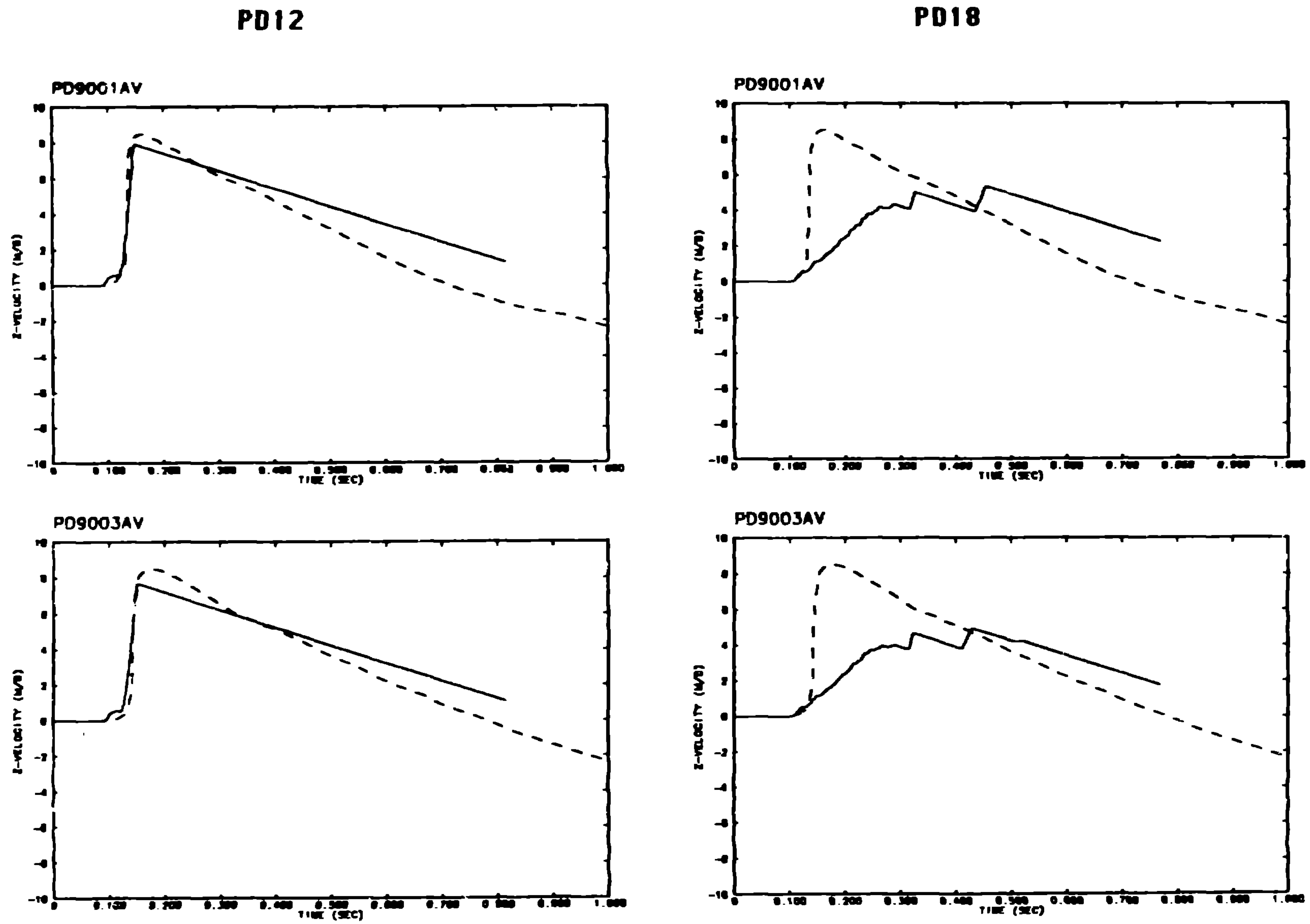

FIGURE 5. PILEDRIVER SURFACE MOTION: PD12 AND PD18 COMPARISON

slope of the velocity decrease is not consistent with a -1 g spall signal, although portions of it may be. In the baseline calculation, we do see a -1 g spall. The calculation with the weaker surface layers does roughly replicate the less than -1 g spall, although the rise time and peak values do not match the data. Obviously we are not correctly modeling the contributions of the weathered layers to the surface waveforms. The behavior seen here is similar to our earlier calculations of the MERLIN event in alluvium ([1], [2], [9]), where we found that the spall closure acceleration was less than -1 g if the near-surface material was weak enough to fail due to the reflected shock.

We have been able to obtain relatively good agreement with the experimental PILEDRIVER waveforms. In order to do so, we had to model the granodiorite as being considerably weaker than "good quality" granite, and it had to undergo considerable weakening due to shock damage as well. In addition, the near-surface layers had to be modeled as being weak and compressible and as have a much lower sound speed than the material at depth. The is consistent with a fractured and jointed material at depth, and a weathered material near the surface.

The authors would like to thank Tom Tunnel and Albert Martinez of EG&G for the rapid and excellent digitization of the PILEDRIVER waveforms. We would also like to extend thanks to Charles Snell for providing us with copies of many reports on ground motion in hard rock. Thanks are due to Norton Rimer for supplying us with information about some of his calculations and for helpful discussions. We are grateful to Jack House and the Nuclear Test Containment Program and to Tom Weaver and the Source Region Program for supporting this work. And thanks to Marie Kaye for her help in preparing this paper. This work was performed under the auspices of the U. S. Department of Energy by Los Alamos National Laboratory which is administered by the University of California under contract W-7405-Eng-36.

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