GROUND MOTIONS FROM DETONATIONS IN UNDERGROUND MAGAZINES IN ROCK

Twenty-Fifth DOD Explosives Safety Seminar
Anaheim, CA
18-20 August 1992

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1992**	2. REPORT TYPE	3. DATES COVERED **00-00-1992 to 00-00-1992**

4. TITLE AND SUBTITLE **Ground -Motions from Detonations in Underground Magazines in Rock**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Waterways Experiment Station,3909 Halls Ferry Rd,Vicksburg,MS,39180-0631**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA260985, Volume II. Minutes of the Twenty-Fifth Explosives Safety Seminar Held in Anaheim, CA on 18-20 August 1992.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**17**	

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This paper discusses the problem of determining ground motions resulting from the detonation of munitions stored in underground magazines in rock. Six sets of ground motion test data from decoupled detonations in rock are compared, including the China Lake Shallow Underground Tunnel/Chamber Test (1989) and the Camp Stanely Validation Test (1990). The data are presented in two consistant forms which are used to discuss analysis and prediction techniques. Current techniques for predicting ground motions from decoupled events are compared and a peak particle velocity prediction equation based on a fit of available data is presented.

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INTRODUCTION

The U.S. Army Engineer Waterways Experiment Station (WES) is currently conducting a research program to investigate underground munitions storage concepts. The goal of this research effort is to investigate techniques for mitigating the blast effects (primarily, airblast and debris) that would escape out the entrance portal in the event of an accidental detonation of munitions stored in individual magazine chambers. A secondary concern is the effect on nearby structures of direct-induced ground motions generated by such an explosion. If the research program is successful in developing designs which significantly reduce external airblast and debris hazards, then it appears likely that the controlling blast effect for establishing hazard areas around such facilities will be ground motion. The purpose of this paper is to review available test data, including recent data from actual blast effects tests for underground munitions storage facilities, and current techniques available for calculating ground motion levels from decoupled detonations in rock.

BACKGROUND

The detonation of a store of munitions in an underground facility represents a complex explosion environment in which a number of parameters have a significant affect on the resulting long-range ground motions. The dominant factor is the amount of explosive contained in a storage chamber of given volume, referred to as the loading density. Other factors include the type and distribution of explosives (distributed along the length of a long chamber or concentrated), the amount of venting between the chamber and tunnel system, and the properties of the rock surrounding the facility. In general, the only factors which are accounted for in current prediction techniques are the loading density and the properties of the material, with the latter limited to material constants.

A ground motion hazard criterion is usually defined as a peak particle velocity at which a certain level of damage is expected. The current U.S. (DOD 6055.9-STD, 1984) and NATO (NATO Document AC/258-D/258, 1991) explosives safety standards quote 11.5 cm/sec and 23 cm/sec in soft and hard rock, respectively, as the maximum acceptable levels for inhabited buildings.

Techniques for predicting peak particle velocity are generally of two types. Each takes a different approach to account for charge decoupling (i.e., the fact that there is an air void between the explosives and the surrounding rock medium). The first relies on an estimate of the initial cavity pressure to calculate the maximum strain or velocity of the cavity wall, which is then used as an initial condition for calculating velocities at increased ranges. This technique was used (Drake, 1974) to develop an elastic solution to a spherical one-dimensional approximation of the problem. Another equation was developed (Smith, 1989) based on 1:75 scale model test data, using the same technique.

The second type of prediction technique relies on fully-coupled peak particle velocity data, and uses a reduction or decoupling factor to account for the decoupled charge configuration. The decoupling factor is defined as the ratio of peak particle velocity at a given distance from a decoupled detonation to that from a fully-coupled detonation of the same charge weight. The velocity from a decoupled detonation is calculated from the equation:

$$V_d = D*V \tag{1}$$

where V_d is the decoupled velocity, D is the decoupling factor, and V is the fully-coupled velocity. This formula is used in both the U.S. and NATO standards. The benefit of this technique is that equations that predict fully-coupled motions can be used in conjunction with the decoupling factor to predict motions resulting from decoupled charge configurations. The drawback is that little data exits to verify that the decoupling factor is accurate.

Dimensional analysis and cube root scaling (Ambraseys and Hendron, 1968) indicate that empirical equations derived from fits to peak velocity data should be of the form

$$\frac{V}{c} = K\left[R\left(\frac{\rho c^2}{W}\right)^{1/3}\right]^n \tag{2}$$

where V is the peak particle velocity, c is the seismic velocity of the rock, ρ is the mass density of the rock, W is the charge weight, R is the range, and k and n are constants determined from a fit of the data. Odello (1980) indicates that the equations in the U.S. and NATO standards, from which the Inhabited Building Distance equations for ground shock are derived, originate from Mickey (1964), and are of the form

$$V = K\left(\frac{R}{W^{4/9}}\right)^{-2/3} \tag{3}$$

where K is a constant dependent upon the medium and V, R, and W are as previously defined. This equation is not consistent with cube root scaling or dimensional analysis.

COMPARISON OF DECOUPLED DATA WITH PREDICTION EQUATIONS

A search for available data from decoupled underground detonations in rock revealed six sets of data, listed in Table 1. Four of the sets represent data from actual underground magazine tests; the KLOTZ II test (Hultgren, 1987, and Vretblad, 1988), the WES 1:75-scale model tests (Smith, 1989), the China Lake shallow underground magazine test (Joachim, 1990), and the Camp Stanley 1/3-scale validation test (Ensco, 1991). The Cowboy test data (Murphey, 1960) were gathered from a series of experiments designed to evaluate the extent to which underground explosions could be concealed by detonating charges in chambers. The Cowboy data are unlike the others, since both the charges and chambers were spherical and non-vented. The final set of data was collected by the U.S. Bureau of Mines (Atchison, 1964). The Bureau of Mines tests used elongated charges placed in vertical bore holes. The KLOTZ, Cowboy and Bureau of Mines data included both fully-coupled and decoupled data, allowing calculation of decoupling factors.

The above data are presented in two forms, such that comparisons can be made to the two types of prediction equations described previously. In order to compare the data to Drake's and Smith's equations, the decoupled velocity data were normalized by the chamber wall velocity, which was calculated from the equation

$$V_c = \frac{1000 * P_o}{\rho c} \tag{4}$$

where V_c is the peak particle velocity (m/sec) of the chamber wall, P_o is the maximum gas pressure (MPa) in the chamber, ρ is the mass density of the rock (kg/m^3), and c is the seismic velocity of rock (m/sec). This is an approximation based on one-dimensional elastic plane wave theory, which is not strictly accurate for the data presented, especially for higher loading densities. The chamber pressure (MPa) can be estimated (from Smith, 1989) by the relation

$$P_o = 1.11\left(\frac{W}{V_1}\right) \quad (5)$$

where W/V_1 is the loading density (kg/m^3). The range is normalized by dividing by the chamber radius. The data from all six test series are plotted together in Figure 1, along with Smith's (1989) and Drake's (1974) prediction equations. Considering the range of test conditions, loading densities, rock types, explosive types and configurations, and measurement types, the scatter in the data are quite acceptable.

Smith's (1989) prediction equation was derived as an upper bound of the data from the WES 1:75 scale model tests, and from some of the Bureau of Mines tests. The equation has the form:

$$\frac{V_d}{V_c} = 0.85\left(\frac{L}{A}\right)^{1.5}\left(\frac{R}{A}\right)^{-2} \quad (6)$$

where V_c is as previously defined, V_d is the decoupled velocity, L is the chamber length, A is chamber radius, and R is range, all in compatible units. The plot of Equation 6 in Figure 1 is with respect to the L/A ratio of the WES 1:75 scale model tests, which was 23.6. The other tests had L/A values ranging from 1 to 16.8 (see Table 1). The fact that Equation 6 provides a reasonable upper bound fit to all the data indicates there may not be a strong dependence upon L/A for these data.

Drake's (1974) equation is of the form:

$$\frac{V_d}{V_c} = \frac{A^2}{R^2} + 0.0128\left(\frac{P_e}{P_l}\right)^{2/3}\frac{A}{R} \quad (7)$$

where V_d, V_c, R, and A are as previously defined, P_e is the explosive density, and P_l is the chamber loading density. The cavity wall particle velocity is estimated by Drake (1974) as

$$V_c = V_o \left(\frac{P_l}{P_e} \right)^{1.2} \tag{8}$$

where P_l and P_e are previously defined and V_o is the peak particle velocity of the cavity wall for a fully-tamped charge, which may be estimated from

$$\frac{V_o}{c_e} = 0.75 \left[1 + \frac{(\rho c)_r}{(\rho c)_e} \right]^{-1} \tag{9}$$

where c_e is the detonation velocity of the explosive, $(\rho c)_r$ and $(\rho c)_e$ are the impedances of the rock and explosive, respectively. Equation 7 cannot be plotted uniquely in Figure 1 due to a nonlinear dependence on the loading density. The plot of Equation 7 in Figure 1 is with respect to the Cowboy test parameters (i.e., rock and explosive properties, Nickols, 1960) and a loading density of 16.4 kg/m^3. The equation fits the Cowboy data and the Bureau of Mines data quite well, but falls below all the other data sets, for all ranges of R/A. Plots of Equation 7 for larger loading densities would fall below this line, while those for lower loading densities would fall above it.

The six data sets were also represented in another form in order to compare them to prediction techniques which rely on scaled distance and decoupling factors as input parameters. In order to collapse the data for comparison at various loading densities, the decoupled velocity was divided by the decoupling factor, which then essentially represents the decoupled data as fully-coupled data. The decoupling factor used to normalize the test data was derived from the plot of available data shown in Figure 2. The data are calculated from peak velocity measurements, recorded at the same distance from both a fully-coupled and a decoupled charge of the same weight, and in the same medium, using the relation

$$D = \frac{V_d}{V} \tag{10}$$

where D is the decoupling factor, V_d and V are as previously defined. The decoupling factor is represented as a function of the relative loading density, which is the actual loading density divided by the density of the explosive material (see Figure 2). This allows data from various explosive types to be presented on the same plot. A fit of the data provided an expression for the decoupling factor as

$$D = \left(\frac{p_l}{P_e}\right)^{.38} \tag{11}$$

This expression takes into consideration data from four sources, but still represents relatively few data points. The decoupling equation used in the U.S. and NATO standards is also plotted in Figure 2, in terms of a relative loading density, for comparison. This equation was derived from only the Cowboy data, and ignored the data points below 16 kg/m^3, which equates to a relative loading density of 0.0016 for the Cowboy explosive (Odello, 1980).

The six sets of data are plotted in Figure 3 in terms of dimensionless variables. This representation accounts for variations in loading density through the use of the decoupling factor, and for variations in charge weight and materials through the use of dimensionless variables. The scatter of the data is less than the previous representation, and again is reasonable for the variations in the test parameters included. A fit of these data provides an equation of the form

$$\frac{V_d}{Dc} = 910\left[R\left(\frac{\rho c^2}{W}\right)^{1/3}\right]^{-1.70} \tag{12}$$

For comparison, the equation for the fully-coupled detonations (developed from the

KLOTZ tests) is also plotted in Figure 3. This equation is an upper bound to all the data and, as expected, provides a good fit to the KLOTZ data. The equations in the U.S. and NATO standards which are used to define the inhabited building distance for ground shock cannot be compared to the data in this form, since the equations are not consistent with cube root scaling.

CONCLUSIONS AND RECOMMENDATIONS

Velocity data from underground detonations of decoupled charges in rock have been presented and compared to several prediction techniques. Equations developed by Smith and Drake rely on a calculation of initial chamber pressure instead of a decoupling factor to account for decoupled detonations. This technique is attractive, since explosive types and geometries can be considered in a calculation of the maximum chamber gas pressure, but a more accurate technique is needed than that currently used for calculating gas pressure. An additional drawback is the simplifying assumption that elastic plane wave theory can be used to estimate the initial velocities of the chamber wall. Smith's equation provides an upper bound to the experimental data. Drake's equation requires additional properties of the explosive and cannot be directly compared with Smith's equation, but was shown to compare well with data from the decoupled tests of Project Cowboy.

A better representation of the velocity data from decoupled explosions appears to be provided by an empirical approach, with the data plotted with respect to dimensionless variables. A fit of the data provides a means to predict peak particle velocities from decoupled detonations in rock. The most useful form of the equation is

$$V_d = 910\ D\ R^{-1.70}\ W^{+0.57}\ \rho^{-0.57}\ c^{-0.13} \tag{13}$$

where V_d is the decoupled velocity (m/sec), D is the decoupling factor, R is the range (m), W is the charge weight (Kg), ρ is the mass density of the medium (Kg/m^3), and c is the seismic velocity of the medium (m/sec).

The equation for decoupled detonations presented in this paper requires verification by additional test data. There are indications that the coupling factor may be dependent upon range from the detonation, in addition to loading density.

The above equation is a fit of predominantly radial velocity (at depth in rock) data, but also includes vertical and horizontal surface velocity measurements, and resultant motions of triaxial measurements. It is not strictly accurate to compare these various types of motions on the basis of wave propagation theory. Future testing and analysis should attempt to distinguish between these various types of motions.

ACKNOWLEDGEMENT

The analysis presented herein was performed by the U.S. Army Engineer Waterways Experiment Station. We gratefully acknowledge permission from the Chief of Engineers and the test sponsors to publish this paper.

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TABLE 1 - Test Data Related to Ground Motions from Decoupled Underground Explosions

Test Series	Scale	No. Tests	Loading Density (kg/m^3)	Type of Data[a]	Range $m/kg^{1/3}$	Range R/A	L/A
Klotz	FULL	8	3.3 - 25	V_{xyz}, V_v	1.0 - 5.0	5.6 - 30.1	16.8 13.9
WES 1:75	1:75	18	1.6 - 405	S_r, V_r	0.4 - 6.3	5.2 - 31.2	23.6
China Lake	1:2	1	66.4	S-V_v, S-V_h	0.4 -14.7	5.2 - 173	7.8
Camp Stanley	1:4	1	5.2	S-V_v	2.7 -11.1	7.6 - 30.8	7.7
Cowboy	Full	17	0.2 - 33.6	V_r	0.6 -18.7	1.6 - 76.9	1
Bureau of Mines	-	6	197 - 352	S_r	1.5 -25.0	30 - 520	16

NOTE: [a]

V_{xy} = Three components of velocity, triaxial measurement.
V_v = Vertical velocity.
S_r = Radial strain.
V_r = Radial velocity.
S-V_v = Surface velocity, vertical.
S-V_h = Surface velocity, horizontal.

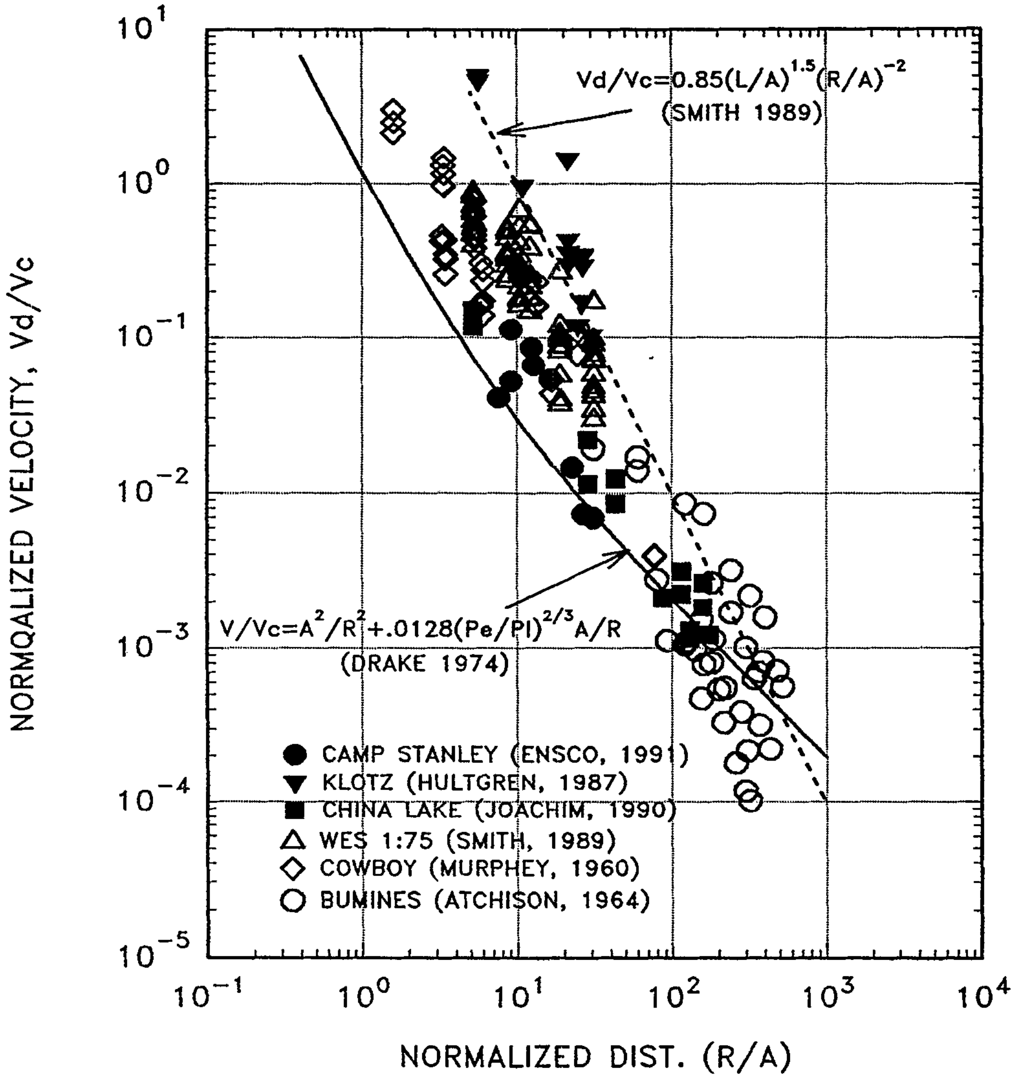

Figure 1. Comparison of Smith's and Drake's prediction equations with test data from decoupled detonations in rock. Data are plotted in terms of actual velocities divided by chamber wall velocities (normalized velocity) and normalized distance (range over equivalent chamber radius).

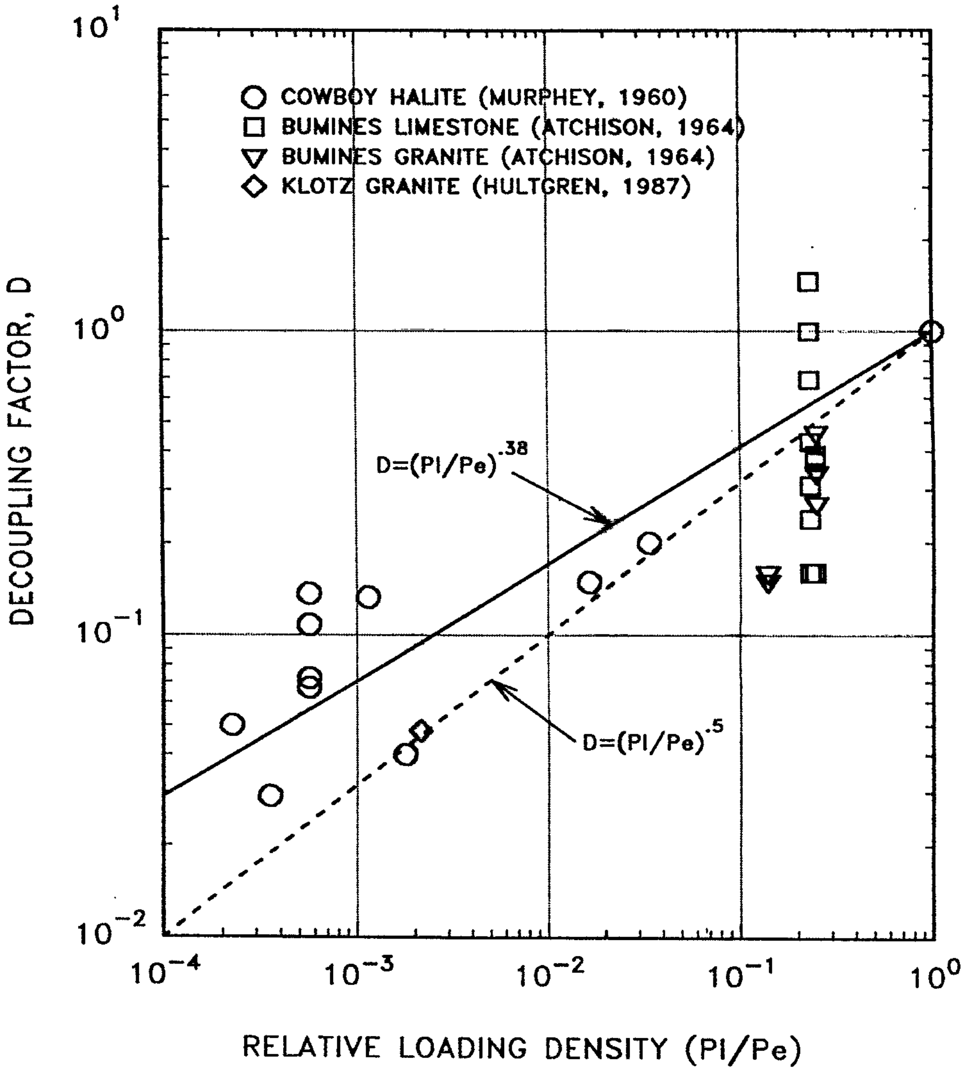

Figure 2. Decoupling factor data plotted with respect to relative loading density (actual chamber loading density over explosive material density) including a best fit expression (solid line) and the expression currently used in the U.S. and NATO safety standards.

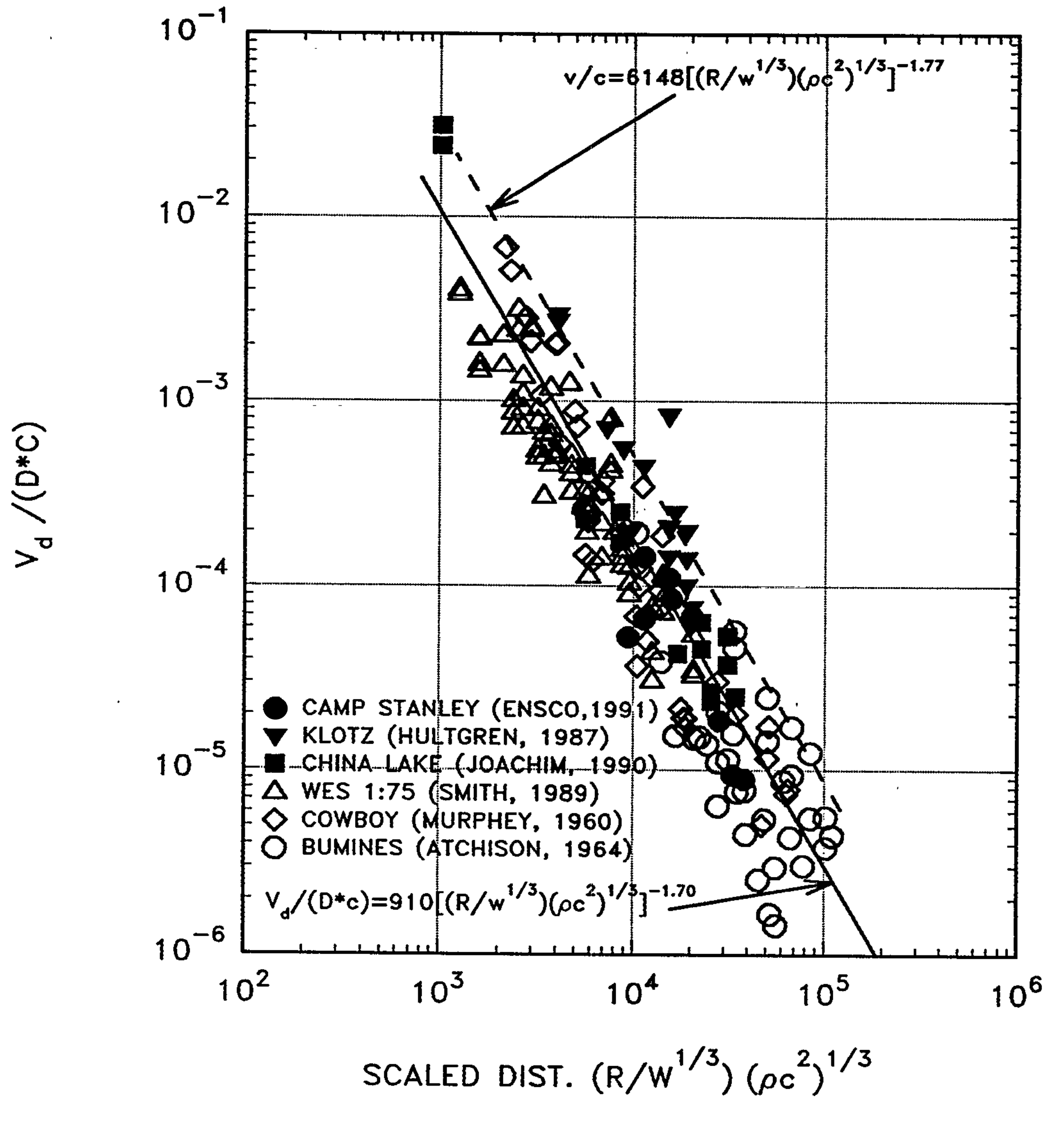

Figure 3. Peak particle velocity test data from decoupled detonations in rock plotted in terms of dimensionless variables and normalized by the decoupling factor D. Included are a best fit expression (solid line) and an expression for fully-coupled detonations (dashed line) developed from the KLOTZ tests.