

**REPORT
OF
RELATING SURFACE COAL MINE
SCALED DISTANCES
TO DEEP MINE ROOF
PEAK PARTICLE VELOCITIES**

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ABSTRACT

The 2006 legislative report dealt with the protection of endangered bat hibernacula while surface coal mine blasting progressed. The National Park Service (NPS) and U.S. Fish and Wildlife Service (USFWS) requested the West Virginia Department of Environmental Protection (WVDEP) to monitor abandoned mine portals potentially being used by endangered bats. This request was to ensure that a USFWS vibration limit of 0.30 inches per second (ips) was maintained. Research ultimately focused on a method to predict roof vibrations in inaccessible areas of abandoned underground coal mines by monitoring an active deep mine roof while surface blasting occurred overhead.

Our endeavor was expanded in 2007 as it was determined additional data was needed to more accurately determine surface blasting vibration effects under a variety of geologic conditions. If these effects could be accurately modeled, it has great potential for determining vibration levels in underground mines or caves. For example, surface coal mine blasting within 500 feet of an active underground coal mine requires a specific blast plan to safeguard underground miners and mine roof stability. Additionally, blasting restrictions could be placed on permittees through the Endangered Species Act that may require the protection of those species or their habitat. Difficulties arise when certified blasters are required to submit site-specific blast plans to regulatory agencies with minimal knowledge of the relationship between surface blast designs and ground vibration impacts on underground mine roofs. Due to this lack of data, it is also a difficult endeavor for regulatory personnel to review these plans to ensure they will accomplish this task.

Due to the lack of data, more research is needed on the effects of surface blasting on underground mines. WVDEP continued to monitor the effects at the active underground mine and is proposing to monitor additional underground mines under various geologic conditions. It is intended that this work be used as an introduction for further research into the effects of surface blasting upon underground mines and caves.

INTRODUCTION

The 2006 Office of Explosives and Blasting (OEB) legislative report discussed surface blasting and the possible effects on bat hibernaculum. One research goal was to determine vibration levels from surface mine blasting on an inaccessible mine roof. Seismograph geophones were bolted to an active underground coal mine roof and separate geophones placed directly above on the surface. The purpose of this research was to determine the differences between surface and underground peak particle velocities (PPV) generated from surface coal mine blasts. It was hypothesized that this information could help estimate an underground roof vibration based upon a surface seismic measurement.

The research site is located in Boone County, West Virginia and involves multiple seam mining of the Middle Kittaning Rider (MKR), Middle Kittaning (MK), Lower Kittaning Rider (LKR), and Lower Kittaning (LK) surface seams. These coal seams are positioned between 209 feet and 316 feet above an active underground coal mine (Coalburg seam). Seismographs, bolted to the Coalburg seam roof, were located approximately 1,000 feet apart. The seismograph locations are shown in Figure 1 (underground mine map) and Figure 2 (plan view). These locations represent an underground and corresponding surface seismograph.

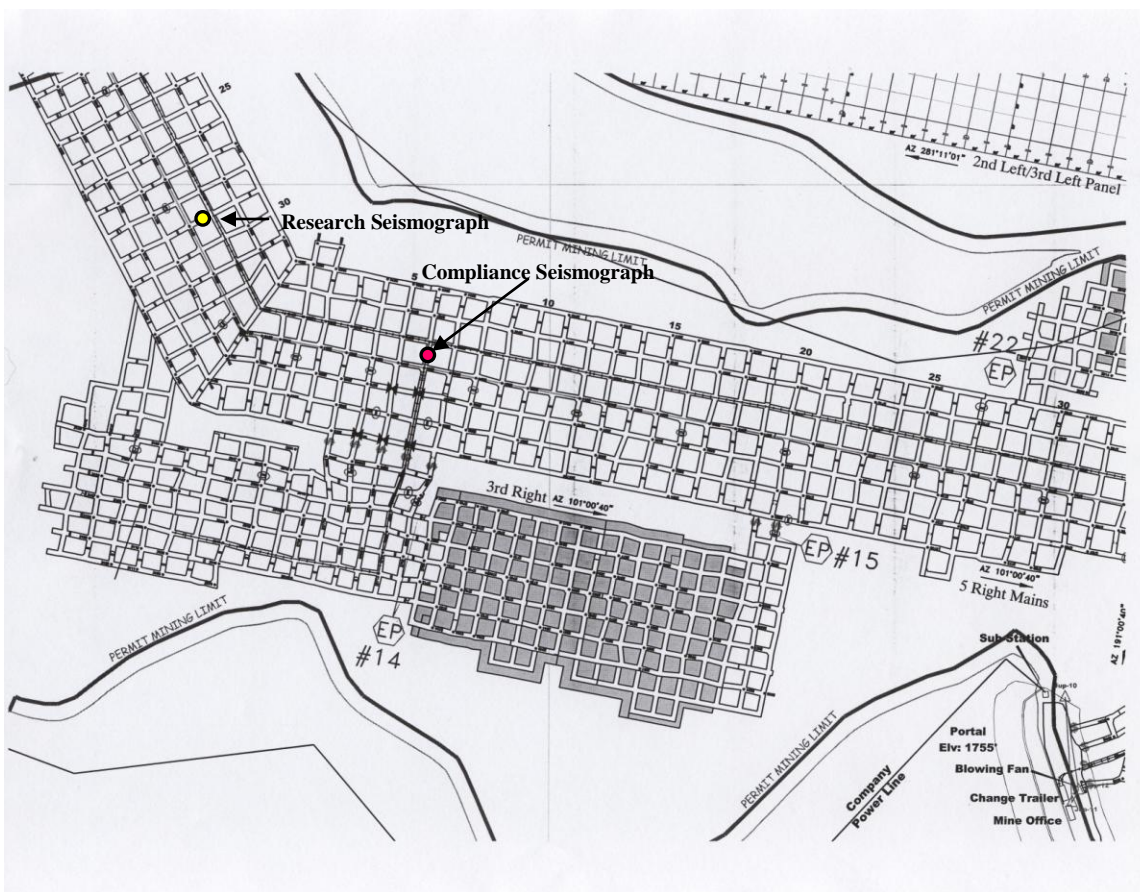
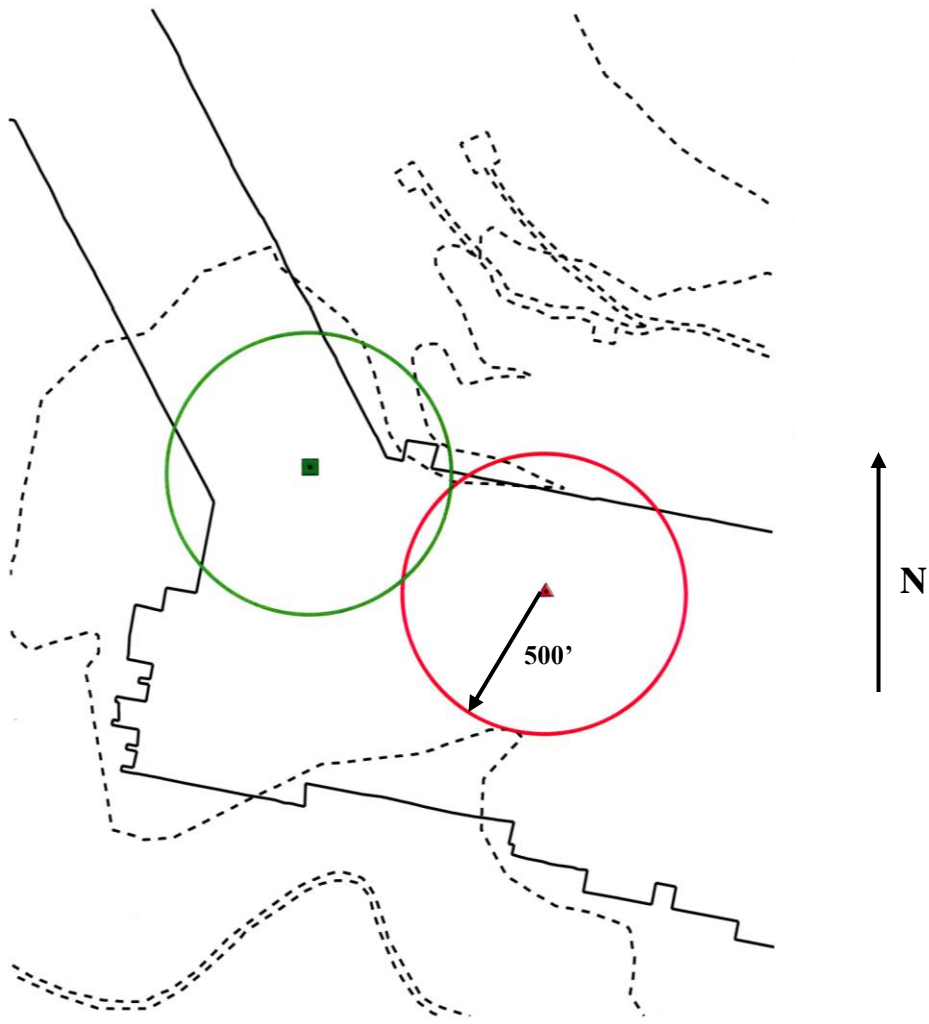


Figure 1



LEGEND





-  Underground Research Seismograph
-  Underground Compliance Seismograph
-  Underground Mine Boundary
-  Surface Mine Boundary

Figure 2

The underground compliance seismograph was installed on the mine roof as part of the permittee's blast plan and required that a vibration level of 1.00 ips not be exceeded. This seismograph location was based upon safe underground access and surface mine advancement towards the seismograph (east to west). The trigger level for this underground unit was 0.02 ips. The surface research seismograph located above the underground unit has trigger levels to record blasts between .02 ips and 10.00 ips, depending upon the blast location .

An underground research seismograph was established based upon safe underground access while the surface research seismograph located originally above the underground compliance seismograph was moved to a point directly above the underground research seismograph. This new research location was well ahead of surface mine advance and allowed more blasts to be recorded before the removal of the surface unit. Since OEB has seismographs with higher gain (more sensitive) capabilities, trigger levels were set at 0.005 ips for the underground unit. As mining progressed towards the surface unit, it was programmed to record a maximum of 10.0 ips. Blast times occurred regularly at 3:30 PM so seismograph timers were set to turn on at 12:00 PM and off at 5:00 PM. Bi-weekly trips were made to download the research and compliance seismographs. The underground seismograph set-up is shown in Figure 3.



Figure 3

During the 2006 and 2007 research, there were 107 blasts recorded with corresponding surface and underground seismic measurements. Vertical distances between the underground and surface geophones varied between 375 and 389 feet. An analysis of the seismic data sets recorded revealed the surface PPV to underground PPV ratios varied from 2.0 to 9.7 with 90 percent of the blasts having ratios between 2.0 and 6.0. This data is represented in Figure 4.

Surface to Underground PPV Ratios vs Number of Blasts

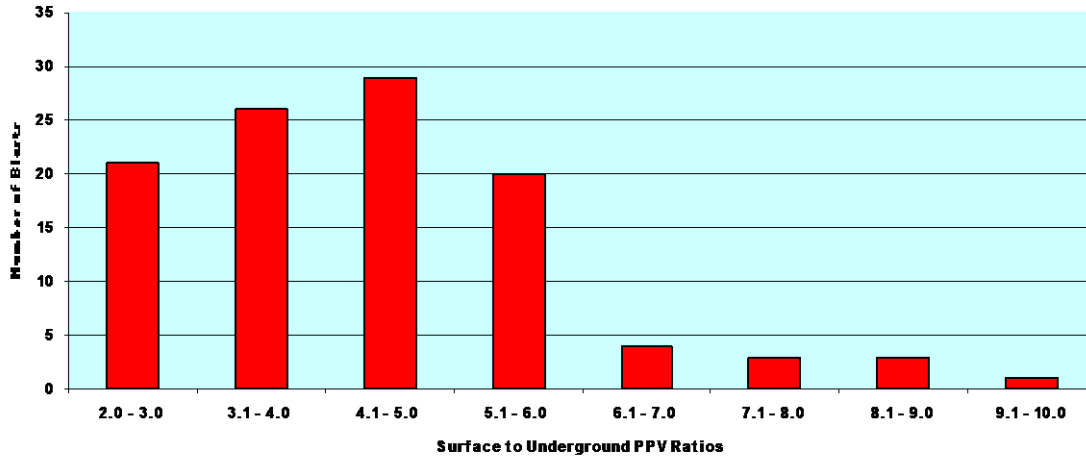


Figure 4

The 2.0 to 9.7 PPV ratio spread can be partly attributed to the measurement of surface and body seismic waves on the surface seismograph while the underground seismograph generally measures body waves. This conclusion is similar to an observation in previous research that concludes, “The observed [surface] particle velocities represent the vector sum of motions from several wave types (compressional, shear, surface) and are further complicated by reflected and refracted arrivals resulting from local geologic conditions and the mine structure.”¹ Surface and body waves are discussed later in this report.

As the surface mine advanced, blasting locations became very close to the surface research seismograph. The last surface research seismograph reading was 8.4 ips from a blast located approximately 75 horizontal feet away. Interestingly the underground seismograph, also located 75 horizontal feet and 361 vertical feet below, had no seismic trigger for this same blast. OEB seismographs perform a self-diagnosis and calibration check every 82 hours of active operation. Through these calibration records, it can be shown that the seismograph was in good working condition during the course of this blast.

Due to this unexpected result and the desire for additional data, the underground research seismograph was kept in place. This decision was made to obtain more seismic data that could have potential in establishing relationships between surface mine blasting and mine roof vibrations. Between May 16, 2006 and October 10, 2007, 295 blasts were recorded

on the underground research and/or the compliance seismographs resulting in 399 seismic records.

A 2007 OEB research goal was to establish the relationship between scale distance values and roof vibrations. As more data is collected here and in different geologic conditions, it is believed that the relationship between surface blasts and underground vibrations may be refined.

SCALED DISTANCE FORMULA AND REGRESSION ANALYSIS

The Surface Coal Mining and Reclamation Act (SMCRA) 38CSR2-2.119 defines a structure as “any man-made structures within or outside the permit areas which include, but is not limited to: dwellings, outbuildings, commercial buildings, public buildings, community buildings, institutional buildings, gas lines, water lines, towers, airports, underground mines, tunnels and dams”. By this definition, OEB is required to protect underground mines from the effects of surface blasting.

A common method of relating surface blast intensities is the use of the scaled distance (SD) formula. This formula is regularly used by blasters to protect structures from ground vibration damage if they do not use a seismograph to monitor. It establishes a relationship between distances and the maximum pounds per delay (lbs/del.) detonated for allowed scaled distance as follows:

$$SD = D / W^{1/2}$$

Where

SD = Scaled Distance

D = Distance from the blast to structure (ft.)

W = Maximum pounds per delay of detonated explosives

SMCRA 38CSR2-6.5.i. and West Virginia 199CSR1-3.6.h. stipulate minimum scaled distance factors or maximum allowable PPV to be used for the protection of structures. These requirements are:

Distance from blast to structure (ft.)	Scaled Distance factor	Maximum PPV allowed (ips)
0 - 300	50	1.25
301 – 5,000	55	1.00
5,000+	65	0.75

These minimum scaled distance factors were developed by the United States Bureau of Mines (USBM) to protect low-rise residential structures and based upon PPV measurements and distances obtained over time and various geologic conditions. If it is used as a compliance option, it is recognized that no damage should occur at a low-rise residential structure because of surface mine blasting vibration.

Rupert and Clarks² study relating surface blasting and underground coal mines states “It was postulated that the peak particle velocity for damage would be in the vicinity of 2.0 in./sec, depending upon the geologic structure, and the strength of roof, pillars, and the

floor of the mine”. There is little other definitive research on scaled distances or PPV levels needed to protect an underground mine roofs. Therefore, the scaled distance table above is applicable to underground mine roofs unless a blasting waiver is obtained.

Scaled distance is also used in regression analysis. It is used in the following form:

$$PPV = k * (D / W^a)^B$$

Where

PPV = Predicted Peak Particle Velocity (ips)
k = Intercept of the regression line at D / W = 1
D = Distance between blast and geophone (ft)
W = Maximum pounds per delay
a = Scaling exponent on maximum pounds per delay
B = Slope of the regression line

This equation can be used to predict maximum vibrations that a blast would generate by inputting distance and maximum charge weight per delay information.

Large data sets can be studied by plotting scaled distance values with corresponding PPV. It is accomplished by graphing these data sets on log-log paper and is called least squares regression analysis. It allows the prediction of PPV attenuations over distance if the following rules are observed for the data sets:

- 1) Use a minimum Correlation Coefficient (R) of 70 percent;
- 2) Use a 95 percent confidence interval;
- 3) Use a minimum of 30 blast events (scaled distance and corresponding PPV); and
- 4) Use distributed and wide range of scale distance values.

Currently, OEB uses a regression program developed by White Seismology. Data is typed into this program and values for k and B are determined. The program also determines the upper and lower 95 percent confidence interval and correlation coefficient.

A literature search revealed that the scaling exponent (a) is usually between 1/3 (cube root) and 1/2 (square root). As noted above, a square root value of 1/2 is used for ground vibration compliance. Air overpressure predictions are based upon the use of 1/3 as a cube root “a” value. The application of either value in underground vibration predictions is partly based upon how well the data is grouped on a regression line. The Jenny Mine¹ underground research report written in 1979 under contract for the USBM, states, “Snodgrass and Siskind compared the results of mine roof vibrations from underground blasting at four sites and found that while cube root scaling provided the best grouping in some cases, only small errors resulted in the use of square root scaling instead”. Rupert and Clarks² report, also written under contract for the USBM in 1977 states, “a cube root law is more applicable in massive rock and a square root law in bedded rock”. The Jenny Mine report and the scaling exponent are reviewed later in this report.

SEISMIC WAVEPATHS AND SITE GEOLOGY

When blasts are detonated, shock and stress waves propagate from the origination point. These waves are defined as surface and body waves. Surface waves travel along the surface and have a slower velocity than body waves and unless a seismograph is very close to the point of detonation, surface waves are recorded on seismographs after body waves. Body waves are classified as compression and shear waves. The compression or P wave is the fastest wave to propagate through a given medium. Because it is considered a compression wave, it will travel through mediums resistant to compression such as liquids, solids, or gasses. A shear or S wave is created when a P wave encounters a geologic change. The S wave can only travel through a solid material.

When a P wave encounters a geologic layer change, part of the energy is reflected back to the surface while the remaining energy is transmitted across the anomaly (refraction). This is symbolized in Figure 5.³

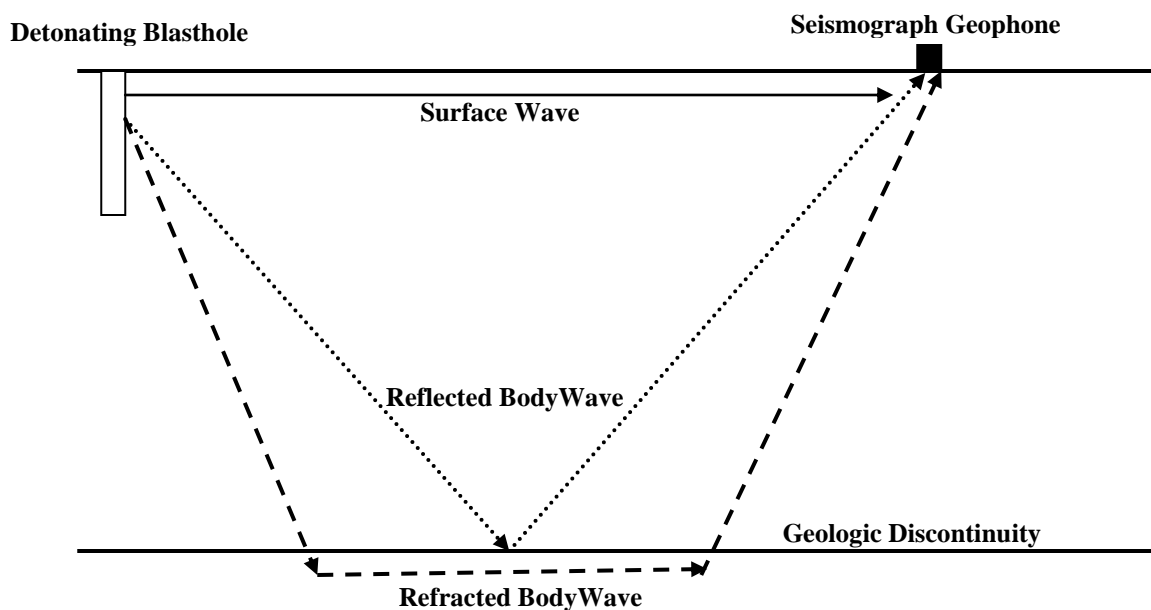


Figure 5

This is a simplistic explanation of a more complex situation as various layers of geologic materials are encountered between a surface coal mine and underground works. Multiple layers of strata with different thicknesses and densities will cause the compression wave to reflect and refract with different intensities. The amount of energy reflected or refracted depends upon the rock densities (ρ) and seismic wave velocities (V). These parameters are related to a rock mass acoustic impedance (Z) where: $Z = \rho * V$.

The relationship between the two acoustic impedances determines how the compressive wave will be partitioned. If a softer material (Z_1) overlays a harder material (Z_2), or Z_1 / Z_2 is less than 1.0, some of the compressive energy is reflected and some is transmitted into the harder material. Both the reflected and refracted energies are considered compressive waves. If the impedance ratio is greater than 1.0, some of the energy is transmitted to the softer underlying material as a compressive wave while the reflected energy is in the form of a tensile wave. If the impedance ratio is equal to 1.0, all of the energy is transferred into the lower rock mass.

The amount of energy reflected is determined by the equation³:

$$\% \text{ Reflection} = (Z_2 - Z_1)^2 / (Z_2 + Z_1)^2$$

As an example, a layer of shale ($\rho_1 = 150$ pounds per cubic ft. and $V_1 = 9,000$ feet per second) overlays a sandstone layer ($\rho_2 = 160$ pounds per cubic ft. and $V_2 = 11,000$ feet per second). The acoustic impedance of the shale (Z_1) would equal 1,350,000 lb/ft²/sec while the sandstone impedance (Z_2) would equal 1,760,000 lb/ft²/sec.

In this particular example, the amount of reflected energy is calculated as $(1,760,000 - 1,350,000)^2 / (1,760,000 + 1,350,000)^2 = 0.017$. This represents a 1.7 percent reflection and implies that 98.3 percent of the energy is transmitted across the interface between the two layers.

A second important parameter that dictates how the compressive wave will split when imparting a different geologic layer is the critical angle of incidence. The critical angle of incidence (i_c) is defined by the equation: $\text{Sin } i_c = V_1 / V_2$ where V equals the seismic wave velocity of each geologic layer. The example above would calculate as $\text{sin}^{-1}(9,000 \text{ fps} / 11,000 \text{ fps})$ that equals 54.9° . If the incident angle is greater than 54.9° , then all the energy is reflected back into the top geologic layer. This is illustrated in Figure 6⁴.

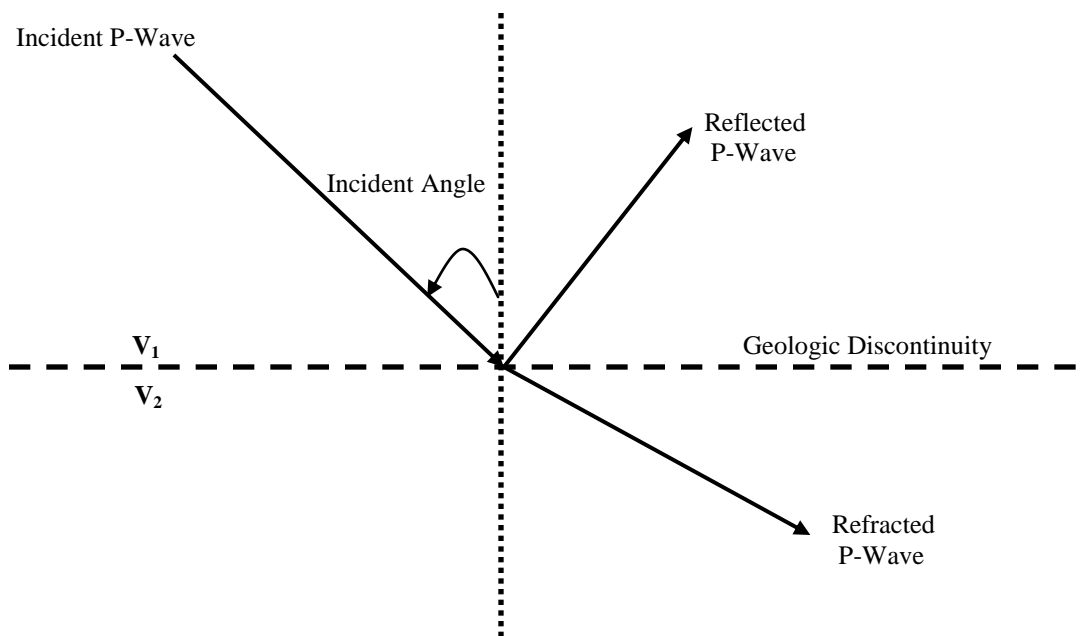


Figure 6

A third important parameter that affects the attenuation and reflection of body waves are cracks or air gaps. The reflection intensity encountered at an air gap is defined as³:

$$(Z_1/Z_2 - Z_2/Z_1) / \text{SQRT} (4 * \cot^2 (2\pi t/\lambda) + (Z_1/Z_2 - Z_2/Z_1)^2)$$

Where

Z1 = Layer 1 acoustic impedance

Z2 = Air acoustic impedance

t = Air gap thickness

λ = wavelength of the wave traveling through air = (V / frequency)

One aspect this equation signifies is a lower frequency seismic wave decreases reflection and has greater ability to transmit through an air gap than a higher frequency wave. Although seismic wave frequencies and their effects upon surface structures have been documented by various researchers in detail, underground frequencies were not analyzed for this report.

It is apparent that seismic wavepaths are very complex, especially when considering multiple geologic layers, thicknesses, and subsurface cracks between the blast and an underground seismograph. It is also evident that as surface mining of multiple coal seams progresses and vertical distances decrease, there is potential for less energy to reflect back to the surface and the possibility exists for increased vibration levels on an underground mine roof. Geologic structure location and identification is paramount for the interaction of body waves and can influence the effects of surface blasting vibrations upon deep mine roofs or other underground voids.

Geologic sections were obtained from the surface and underground mine permits. Core hole V-790C was located 163 feet from the compliance seismograph and corehole V-791C was located 182 feet from the research seismograph. Geologic strata from these sections are represented from the mine surface to Lower Kittanning coal seam and are included in the surface mine permit. Geologic information from the Lower Kittanning seam to the Coalburg coal seam were obtained from corehole V-585C in the underground mine permit. This corehole is located 750 feet from the compliance seismograph and 1,750 feet from the research seismograph. The following table represents these geologic layers.

and pillar) to the surface mine. The cracks are due to subsidence and are believed to have influenced PPV recordings on the underground mine roof. Photos of these cracks are shown below.



Surface Crack #1



Surface Crack #2

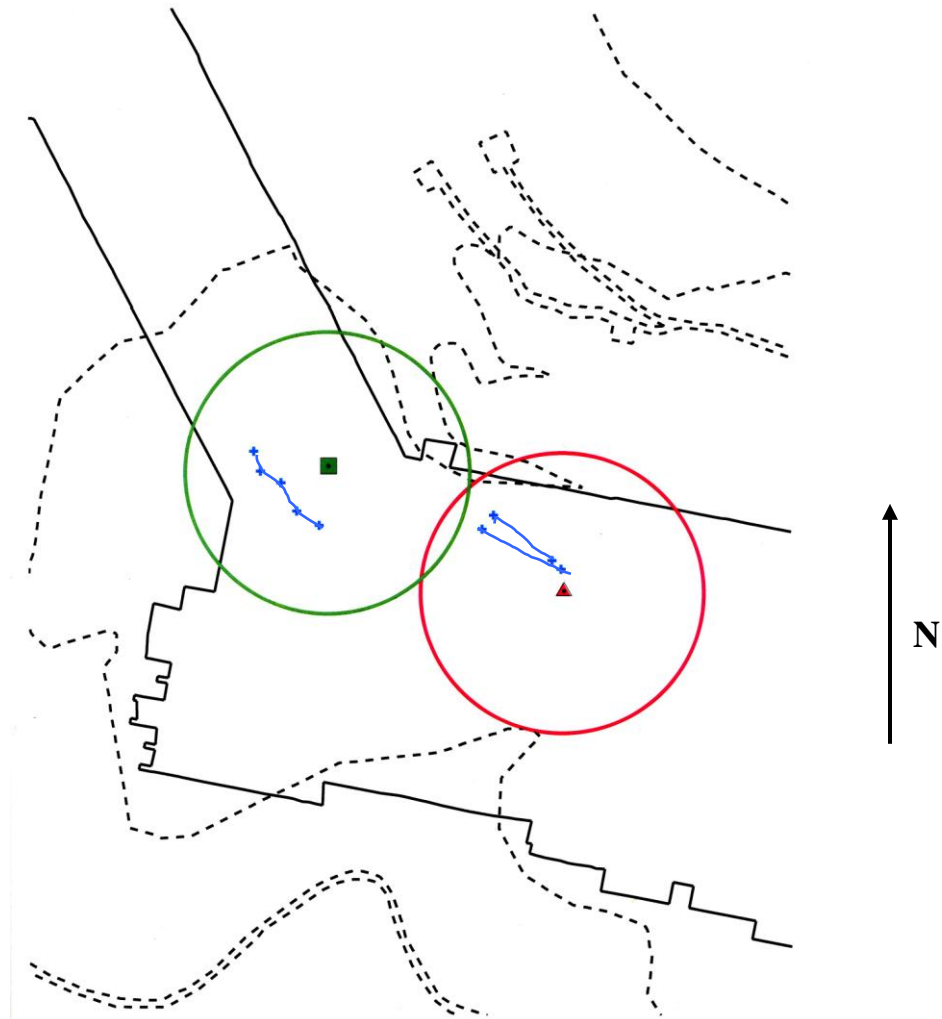


Underground Roof Crack



Surface Sediment on Coal Ribs

Large surface cracks were observed early in the research and were documented with a Global Positioning System (GPS). Other cracks became more evident as mining progressed. These positions are shown on Figure 7.



LEGEND






-  Underground Research Seismograph
-  Underground Compliance Seismograph
-  Underground Mine Boundary
-  Surface Mine Boundary
-  Surface/Subsidence Crack Location Location

Figure 7

JENNY MINE STUDY

The most comprehensive study found in the Appalachian coalfield regarding surface blasting and the effects upon deep mine roofs is entitled "Underground Vibrations From Surface Blasting At Jenny Mine, Kentucky". This research was funded by the USBM in 1979 and its purpose was twofold. First, to determine the relationship between underground vibrations and roof damage and secondly, to predict vibration levels underground based upon surface mine blasts.

Seismographs on the mine roof, mine floor, and surface locations recorded 31 surface blasts. Seventy-four mine roof seismic impulses were documented in the study. These measurements were taken from surface blasts located 150 to 180 feet above the underground mine workings. Geologic strata consisted of layered shales, sandstone, fire clay, and coal beds between surface blasting and the underground roof.

Although surface blasts generated roof seismic impulses as high as 17.5 ips, no visible damage could be linked to surface blasting. Since normal failures of the mine roof were not documented before surface blasting began, no damage criteria for underground mine roofs could be determined from this study. An interesting attempt was made to estimate roof zones of crushing, compressive failure, and spalling at the Jenny Mine. An equation derived by G.B. Clark⁵ in tunnel closure studies is defined as:

$$R_i = K_i * W^{1/3}$$

Where

R_i = radius of zone damage

W = yield of explosive source expressed as pounds of chemical exposure (lbs/del.)

K_i = an empirically determined constant which is a function of rock type and other variables.

K_i average values for sandstone are 1.3 (zone of crushing), 3.3 (zone of compressive failure), and 5.1 (zone of spalling) also based upon the work of G.B. Clark and others. Although this equation is based upon a concentrated spherical explosive charge, which is different from a surface mine blast, the authors of the Jenny Mine study used the equation for comparison purposes. The assumption was made that calculations based upon this equation could possibly be considered as a worse case scenario as to any effects occurring at the Jenny Mine. The maximum of 12,000 lbs/del. at the Jenny Mine site estimates a zone of spalling out to 117 feet from the blast. Since blasting at the Jenny Mine occurred at a minimum of 150 feet over the deep mine, no spalling should have occurred on the mine roof. This same equation used at the OEB research site with the maximum of 1,585 lbs/del. initiated 209 feet above the Coalburg seam would produce a zone of crushing, failure, and spalling from the surface down to a depth of 59 feet. Although spalling of the ribs at the OEB research site occurred prior to any blasting, no spalling of the roof from surface blasting has been observed or reported by mine management.

Dr. David Siskind states, “A general observation is that major failure such as roof collapse and pillar failure would require vibrations greater than about 12 in/s. In some cases, loose pieces were dislodged at lower vibration levels of about 1.2 to 5 in/s. Low-level vibrations, certainly below 1.0 in/s have been found to be totally harmless to underground workings, even active ones where rockfalls are a personal hazard.”⁶ This statement is based upon nine studies that had various geologic conditions and structure including an underground limestone mine, sandstone tunnel roof, granite tunnels and underground coal mines. Blasting parameters such as charge weight, hole diameter and vertical distances varied widely in these studies.

The second research goal at the Jenny Mine study of predicting mine roof vibration levels from surface mine blasts proved more fruitful. Blast/seismic data obtained from the report were analyzed by OEB using regression analysis in the following form:

$$PPV = k * (D / W^a)^B$$

Where

- PPV = Predicted Peak Particle Velocity (ips)
- k = Intercept of the regression line at D / W = 1
- D = Distance between blast and geophone (ft)
- W = Maximum pounds per delay
- a = Scaling exponent on maximum pounds per delay
- B = Slope of the regression line

Using 74 seismic data sets from the report and a scaling factor of 1/2, a regression analysis was performed shown in Figure 8. Distances between the blast and mine roof were calculated as slope distances. (i.e. 200 feet horizontal and 180 feet vertical equals a slope distance of 269 feet).

Jenny Mine Research

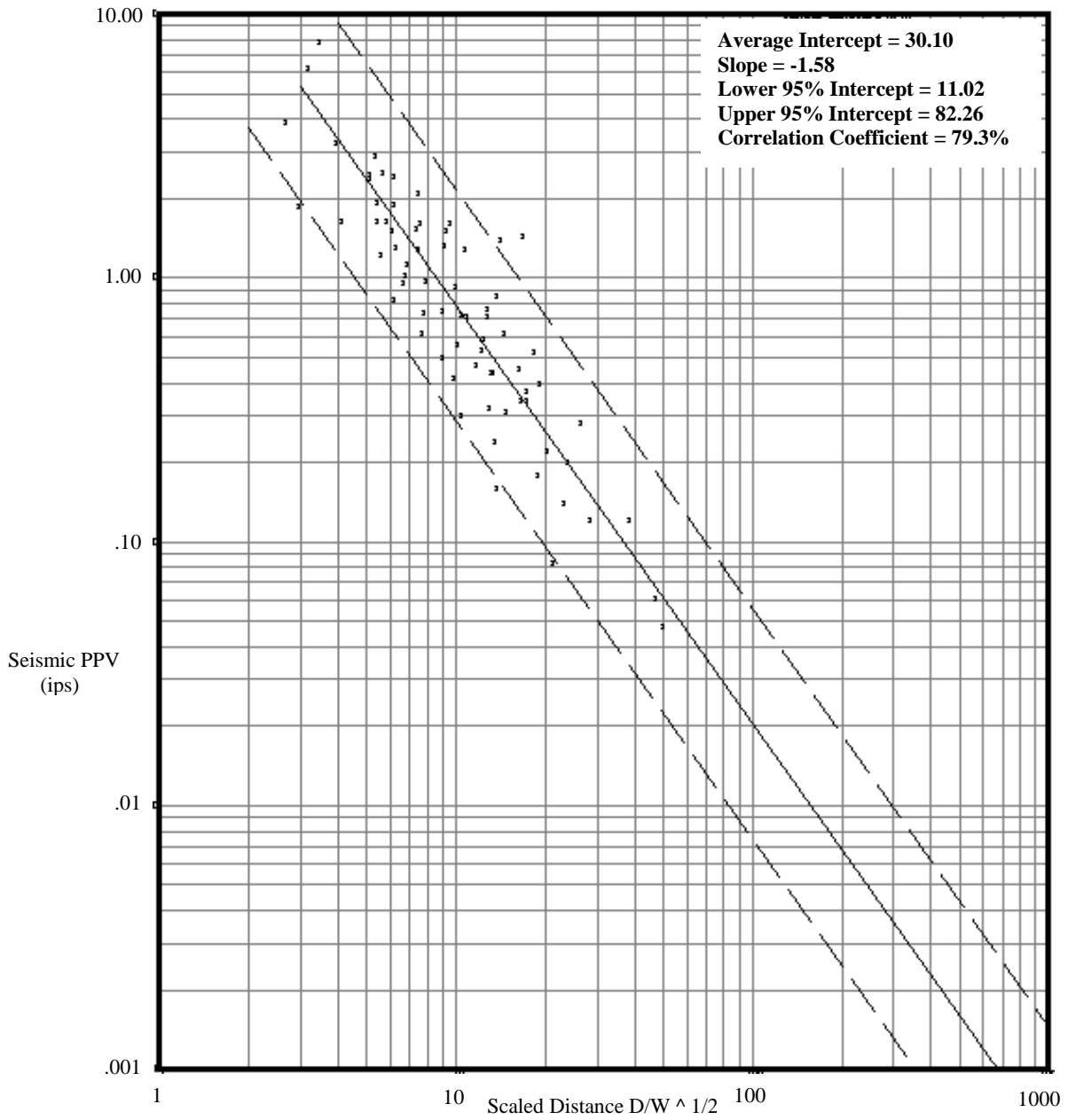


Figure 8

A 95 percent confidence interval predictive equation of $PPV = 82 * (D / W^{0.5})^{-1.58}$ was generated. The quality of the data is sufficient as the coefficient of determination exceeds 70 percent. **Using this formula, a surface scaled distance of 16.3 would predict an underground roof vibration of 1.00 ips.** Data sets were not sorted by separate geologic layers or vertical distances.

Dr. Siskind's equation⁶ for predicting blasting vibration on underground mine and tunnel roofs is as follows:

$$V = 15.1 * (D / W^{0.5})^{-1.45}$$

Where

V = Predicted Peak Particle Velocity (ips)
D = Distance between blast and measurement location (feet)
W = Maximum charge weight per delay (pounds)
 $D / W^{0.5}$ = Scaled Distance

Using this formula, a surface scaled distance of 6.5 would predict an underground mine or tunnel roof vibration of 1.00 ips. This equation represents a “mean” value and not a 95 percent confidence interval. No data is given by Dr. Siskind for a 95 percent regression confidence interval regression equation.

The Jenny Mine study is considered a basis for further research into the effects of surface blasting upon deep mine roofs. Relevant observations and conclusions from this study are as follows:¹

- 1) A significant reduction in data scatter is obtained by scaling rather than simply plotting velocity versus distance. However, only minor differences in parameters result from the use of square root scaling, cube root scaling, or scaling by the fractional root determined directly from the data by multiple regression analysis.
- 2) Peak particle velocities measured at the mine roof are best grouped by using cube root scaling. Velocities measured on the mine floor and at the ground surface are best grouped by square root scaling. The reason for the difference in scaling factors is not defined by these observations.
- 3) The results of analysis of the data measured at the mine roof are similar to those of previous studies where vibrations from underground blasts were measured on the roof of the underground mine or tunnel.
- 4) Vibration levels measured on the mine floor were generally lower than those measured at the roof.
- 5) Roof vibration levels are consistently less than those measured at the surface at equal scaled distances.
- 6) Predictions of roof vibration levels from surface measurements would be conservative at low levels but less conservative at higher levels.
- 7) Only limited conclusions can be drawn regarding the relationship between damage and vibration levels as there were no observed underground failures attributable to the surface blasting. However, it is significant that no apparent damage occurred even at the peak measured particle velocity of 17.5 in/sec.

- 8) Strain as well as particle velocity should be measured underground.
- 9) It is recommended that vibrations at the ground surface and on the mine floor be measured as well as on the roof. Hopefully, this will lead to a simplified method of evaluating roof vibrations in general observations.
- 10) It would be desirable to begin as soon as possible to develop a model for damage produced by blasting over an underground mine. Data from the Jenny Mine study and information from the literature could be used as a starting point. The model could then be altered as additional data became available until such time as researchers were satisfied that it indeed reflected actual physical conditions. At that point, the model could be made available for general use by the industry and its consultants, much as the model developed in USBM Bulletin 656 is used for potential damage to surface structures from surface blasting is a concern.

Other research issues common to the Jenny Mine study and OEB research are:

- 1) Blasting parameters were determined by the surface mine operator. Therefore, the blasts were designed and scheduled to be consistent with efficient surface mining procedures and were not part of the research program design.
- 2) Collected data shows less regression scatter on the mine roof compared with surface measurements.
- 3) Accurate determination of charge weight is essential.
- 4) A pre-blast survey of a small area of the mine roof should be conducted before surface blasting begins.

Research parameters that differed between the Jenny Mine study and OEB research include:

- 1) The location of each Jenny Mine blast was estimated in the field by compass and pace survey and by plotting on a small scale topographic map. Surface blast locations in the OEB research were obtained with Global Positioning Systems (GPS).
- 2) Jenny Mine seismographs were located on the mine roof, mine floor, and surface location. Surface seismographs were not directly above the underground geophones. This differed from OEB's approach of the same coordinates for surface and underground geophones. OEB did not place any seismographs on the mine floor.
- 3) The Jenny Mine study used downhole seismograph arrays, extensometers and modified Philadelphia surveyor's rod for roof-floor convergence measurements, and a borescope for their study. OEB did not use any of these techniques or equipment for research.
- 4) Seismographs for the Jenny Mine study were dependant upon a four conductor shielded cable connected to a recording van located near the mine portal. To record low levels of vibration, Jenny Mine seismographs had to have a shunt resistance to obtain the lowest recorded PPV of 0.02 ips. OEB has 2 gain, 4 gain, and 8 gain seismographs that can easily be programmed to trigger and monitor for a wide range of vibration levels (0.002 ips to 10.000 ips).

OEB FIELD DATA

A common dilemma for analyzing blasting vibration and effects on structures is blast record accuracy. One of these problems is getting an accurate location of the surface blast. This was true for the Jenny Mine study and this endeavor was no exception. The only requirement on OEB's blast log for shot location is a notation of a blasting grid square from a blasting map. Since these grid scales are generally 250 feet by 250 feet, it is possible to have distance errors of more than 200 feet. The use of a GPS is crucial for accurate spatial relationships. The purchase of a GPS by the surface mine was instrumental in determining accurate horizontal distances between the blasts and seismographs. Vertical locations are another issue of great importance. Recording of the elevation or seam(s) on the blast log is critical for calculating slope distances to the underground seismograph. The notation of the surface mine seam also assists in any regression analysis for each seam being mined and any changes in scaled distance values needed to maintain a consistent vibration level on the mine roof.

The use of ammonium nitrate and fuel oil (ANFO) enhances the accuracy of the pounds per delay, as the density range is smaller (0.84 – 0.88 g/cc) than that of emulsion blends (0.90 – 1.34 g/cc). Unless density checks are made on the emulsion blends in the field, blasters have more potential for errors in their explosives charge weight calculations. The smaller density range of ANFO translates into a more accurate pounds per foot of borehole calculation. The Jenny Mine and OEB's research site used ANFO as their main explosive charge in each borehole.

Blasters at OEB's research site had good control over the spatial relationships and charge weights, but did not have any influence over cap scatter. Cap scatter occurs during the course of pyrotechnic burning in the detonator delay element. It can account up to +/- 10 percent scatter in the nominal detonator firing time. This makes it difficult to determine actual pounds per delay because more than one hole could be detonating at the designed firing time, which ultimately affects the scaled distance calculation. The increased use of electronic digital detonators in the West Virginia coalfields will minimize this problem in future research projects. This newer technology allows a blaster to program a detonator with a precise firing time, usually within +/- 1 millisecond.

Although not all of the blast events at OEB's underground research site triggered the seismograph, all surface blast log data with associated underground seismic events were analyzed using White Seismology regression program. Maximum pounds per delay, distances, and PPV were input into the program. Both square root and cube root scaled distances were calculated to determine the best grouping of data. Although the cube root had a slightly higher Correlation Coefficient (CC) than the square root, 76 percent versus 75 percent respectively, it was decided to use the square root factor in the ensuing analysis. This is attributed to the following:

- 1) Past research shows little error between the use of cube and square root in mine roof regression calculations;
- 2) Past research also indicates that bedded rock, such as the geology above the Coalburg seam, is represented better by the square root factor; and
- 3) Blasters are more familiar with the square root calculation in ground compliance calculations.

Since the Correlation Coefficient of 70 percent was exceeded, a 95 percent confidence interval equation of $PPV = 89 * (D / W^{0.5})^{-1.54}$ was generated from the regression program. **Using this formula, a surface scaled distance of 18.4 would predict an underground roof vibration of 1.00 ips.** This scaled distance value is a little more conservative than the Jenny Mine study (scaled distance = 16.3) conducted in 1979. This could be attributed to geologic strata differences between the research mine roof and the Jenny Mine. Jenny Mine blasting occurred at 150 feet above the deep mine, while OEB research observed blasting no closer than 209 vertical feet. One would expect the Jenny Mine scaled distance (16.3) to be higher than OEB's scaled distance (18.4), but this was not the case. The geologic layering below the Jenny surface mine was not available from the research report and could not be used to compare against geologic cross sections from OEB's research site. A graphical representation of OEB's regression data is shown on Figure 9.

OEB Research

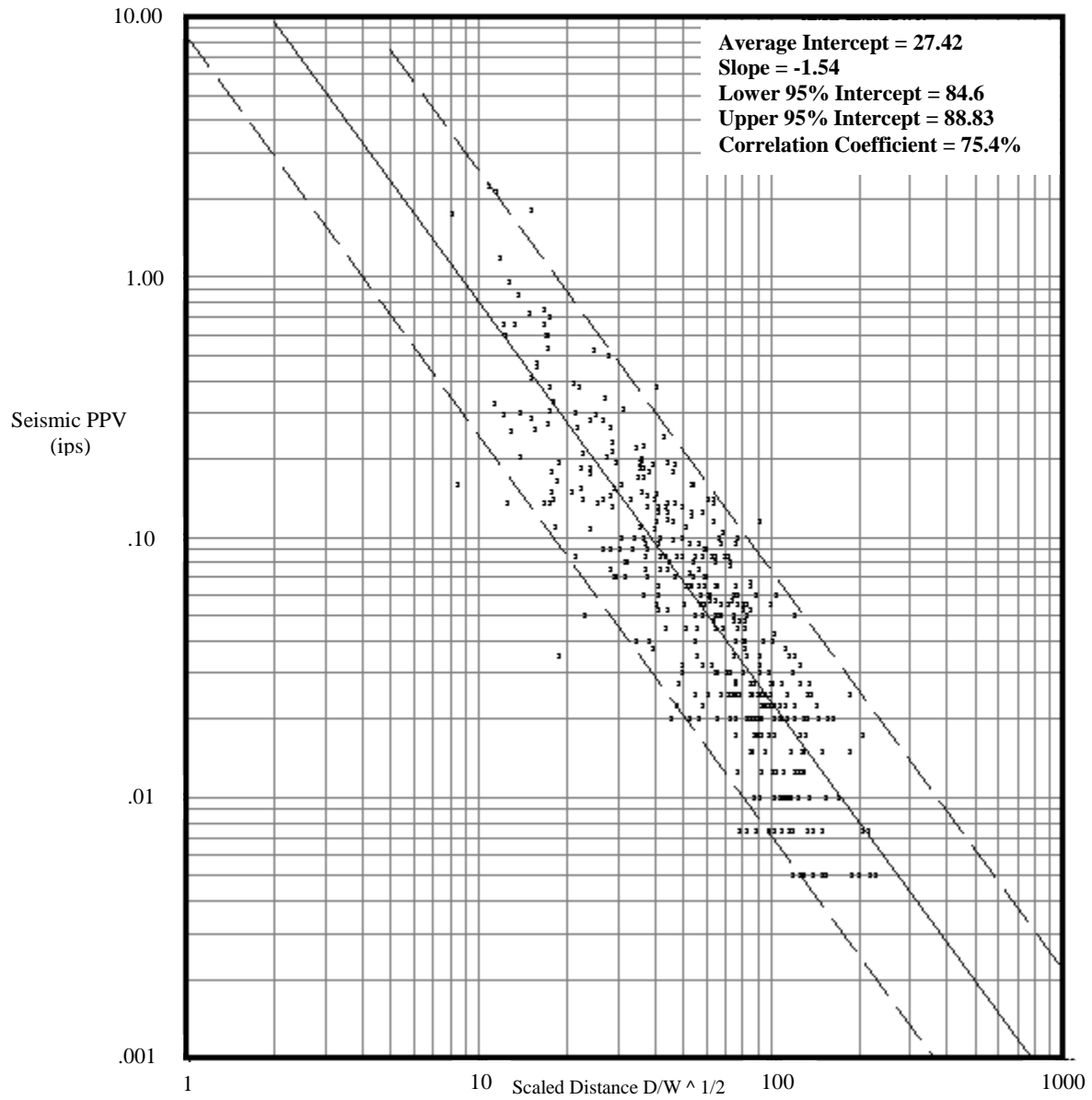


Figure 9

To determine the scaled distance effects of vertical changes (blasting to different surface coal seams), data was sorted by coal seam elevations. Since this report considers scaled distances from various surface coals seams, many data sets were eliminated from this analysis unless coal seams being mined were documented on the blast logs. Since this is not a regulatory requirement and not listed on the OEB approved blast log, many times the blaster just forgot to include this information. OEB’s current proposed legislation will require coal seam data be recorded on the blast log which should help eliminate this problem in the future. GPS may also give elevations of surface coal seams that can be used in vertical depth calculations, but must be calibrated beforehand. Blasters were more consistent as the research progressed as they realized the value of the data being collected. If coal seams were discerned on the blast log but blasts were tied together on various coal seam benches, the data sets were also eliminated from the analysis. These constraints reduced the 399 recorded underground seismic events for scaled distance analysis to 110 events. After the data sets were sorted and analyzed, the following was discovered:

**Compliance
Seismograph**

Coal Seam	Vertical Dist.	# Geologic Layers	Data Sets	CC	95% SD
MKR	296	32	11	76%	11
MK	273	27	9	4%	NA
LKR	236	17	24	67%	14
LK	209	11	36	73%	22

**Research
Seismograph**

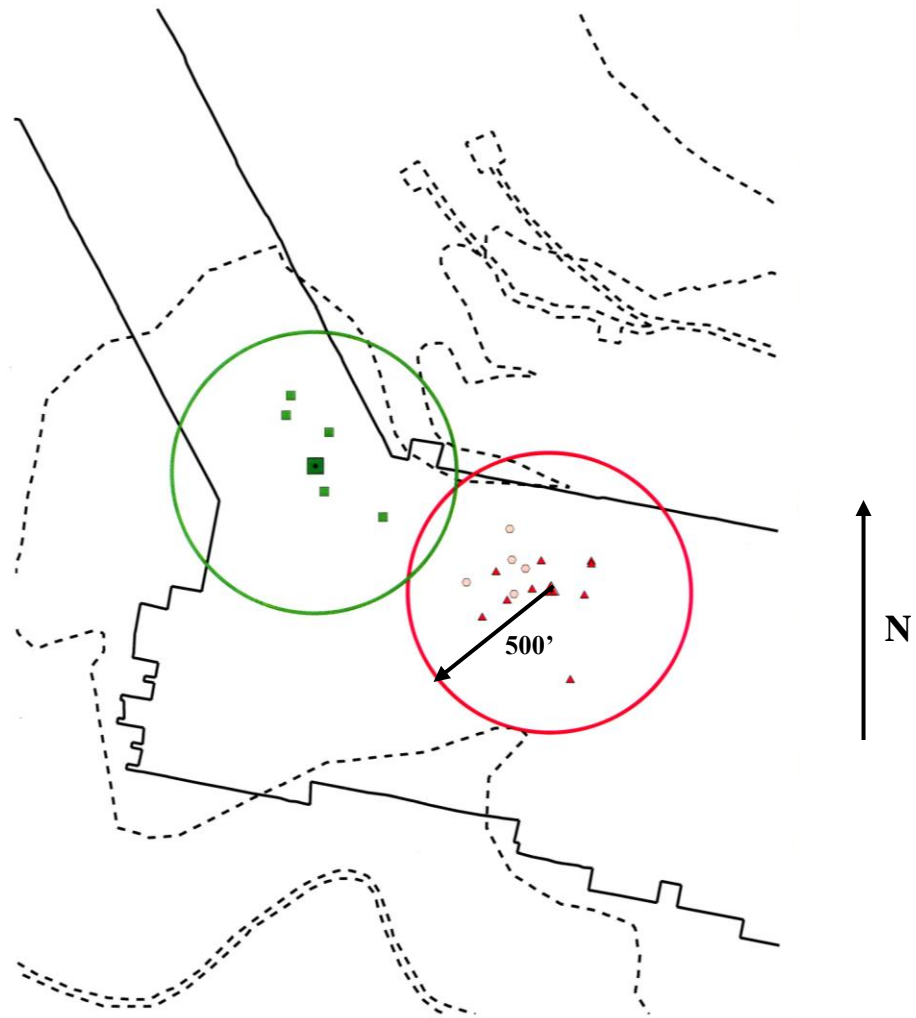
Coal Seam	Vertical Dist.	# Geologic Layers	Data Sets	CC	95% SD
MKR	316	25	9	68%	31
MK	282	21	3	27%	NA
LKR	245	15	8	88%	19
LK	209	11	22	77%	24

Using the regression rules of at least 30 blast data sets and a minimum correlation coefficient of 70 percent, the Lower Kittaning compliance equation predicts a true surface scaled distance of 22 that would generate an underground vibration of the regulatory default limit of 1.00 ips on a mine roof. The 36 data sets analyzed have scaled distances between 11 and 77.






A further analysis found that 19 seismic records had a mine roof PPV of 0.50 ips or greater. Scaled distances for each blast were reviewed. They are as follows:

Slope Dist.(ft)	PPV (ips)	SD	Slope Dist.(ft)	PPV (ips)	SD
534	0.50	28	289	0.72	15
476	0.52	25	260	0.75	17
347	0.53	17	348	0.86	14
337	0.60	13	227	0.95	13
343	0.60	17	272	1.18	12
334	0.60	18	205	1.74	8
215	0.66	12	253	1.80	15
255	0.66	13	231	2.14	12
251	0.66	17	218	2.22	11
336	0.70	18			

These locations are plotted onto WVDEP's ArcGIS mapping software and shown on the in Figure 10.



LEGEND

- 
0.50 – 1.00 ips at Underground Research Seismograph
 - 
0.50 – 1.00 ips at Underground Compliance Seismograph
 - 
1.00 ips+ at Underground Compliance Seismograph
- 
Underground Mine Boundary
 - 
Surface Mine Boundary

Surface Blast Locations




- 
0.50 – 1.00 ips at Underground Research Seismograph
- 
0.50 – 1.00 ips at Underground Compliance Seismograph
- 
1.00 ips+ at Underground Compliance Seismograph

Figure 10

Collected data indicated that all blasts exceeding the permittee's blast plan compliance limit of 1.00 ips had corresponding scaled distance values between 8 and 15. General observations show that a majority of the higher PPV values at the compliance seismograph occurs to the west of the seismograph. This includes all recordings over the default limit of 1.00 ips. Since these blasts were located in a 175 foot by 250 foot area of the permit, a post-blast review of the deep mine roof was conducted. Although roof cracks were observed near the blast locations, it could not be determined if these cracks were present before blasting began. If the cracks were present before blasting, no size characteristics were measured therefore no effects of various PPV can be determined. Future research should focus on roof crack locations and size before surface blasting commences. The research seismograph recorded higher PPV values mainly along the ridgeline NW to SE. These blast locations appear to run parallel with the major subsidence/surface cracks as shown in Figure 7.

Another unexpected trend observed was no seismic triggers at the closest seismograph, but recordings at the more distant seismograph. Some of these can be attributed to the underground seismograph ground trigger sensitivity. The research seismograph is set at a 0.005 ips trigger level while the compliance seismograph is set at 0.02 ips. Although there are 180 seismic events with vibration levels between 0.005 and 0.02 ips that are to be analyzed at a later date, all blast locations with seismic recordings greater than 0.05 ips from either machine were reviewed for spatial relationships and PPV recordings. Seismic anomalies between the compliance and research seismographs are shown in the following table. NT denotes no trigger of a seismograph.

Horizontal Blast Distance From Compliance Seismograph (ft.)	PPV (ips)	Horizontal Blast Distance From Research Seismograph (ft.)	PPV (ips)
911	0.19	350	NT
613	0.15	502	NT
798	0.08	311	NT
850	0.13	339	NT
855	0.11	170	NT
985	0.06	24	NT
969	0.13	141	NT
1,051	0.16	258	NT
649	0.18	381	NT
1,174	0.08	214	NT
688	0.14	323	NT
766	0.08	236	NT
805	0.08	232	NT
1,099	0.09	202	NT
1066	0.07	62	NT
1066	0.09	62	NT
1285	0.05	286	NT
948	0.06	451	NT
775	0.18	253	NT
951	0.19	130	NT
1,085	0.08	102	NT
1,207	0.05	201	NT
1,085	0.06	224	NT
1,051	0.19	404	NT
895	0.08	365	NT
1,085	0.08	418	NT
954	0.13	142	NT

Seismic anomalies between the research and compliance seismographs are shown in the following table.

Horizontal Blast Distance From Research Seismograph (ft.)	PPV (ips)	Horizontal Blast Distance From Compliance Seismograph (ft.)	PPV (ips)
1,046	0.15	96	NT
1,046	0.05	96	NT
940	0.10	67	NT
987	0.07	11	NT

Data plots shown in Figure 11 indicates that there are a significant amount of blasts that triggered the compliance seismograph but did not trigger the research seismograph; even though the research seismograph was closer and had a lower sensitivity. This unexpected result is hypothesized to be geologic influences concentrated near the underground research seismograph.



LEGEND



Underground Research Seismograph



Underground Compliance Seismograph



Underground Mine Boundary



Surface Mine Boundary



Seismic Trigger at Underground Research Seismograph



Seismic Trigger at Underground Compliance Seismograph

Figure 11

Site-specific geologic conditions appear to affect mine roof vibrations from surface blasting. As such, it is important to have a very large database of underground PPV measurements that are affected by the multitude of blasting and geologic variables encountered during surface blasting.

As stated in the Jenny Mine conclusions, underground vibration data obtained in future research should be added to the Jenny Mine project to ultimately generate a general vibration model that can be used by industry and blasting consultants. OEB combined the Jenny Mine and OEB data conducting a least squares regression on the 473 seismic events. The resulting 95 percent confidence equation of $PPV = 86 * (D / W^{1/2})^{-1.53}$ is very similar to the OEB regression equation except the combined data's higher correlation coefficient (85 percent). **Using this formula, a true surface scaled distance of 18.3 would predict an underground vibration regulatory default limit of 1.00 ips on a mine roof.** Figure 12 represents the combined Jenny Mine and OEB least squares regression equation.

Jenny Mine & OEB Research

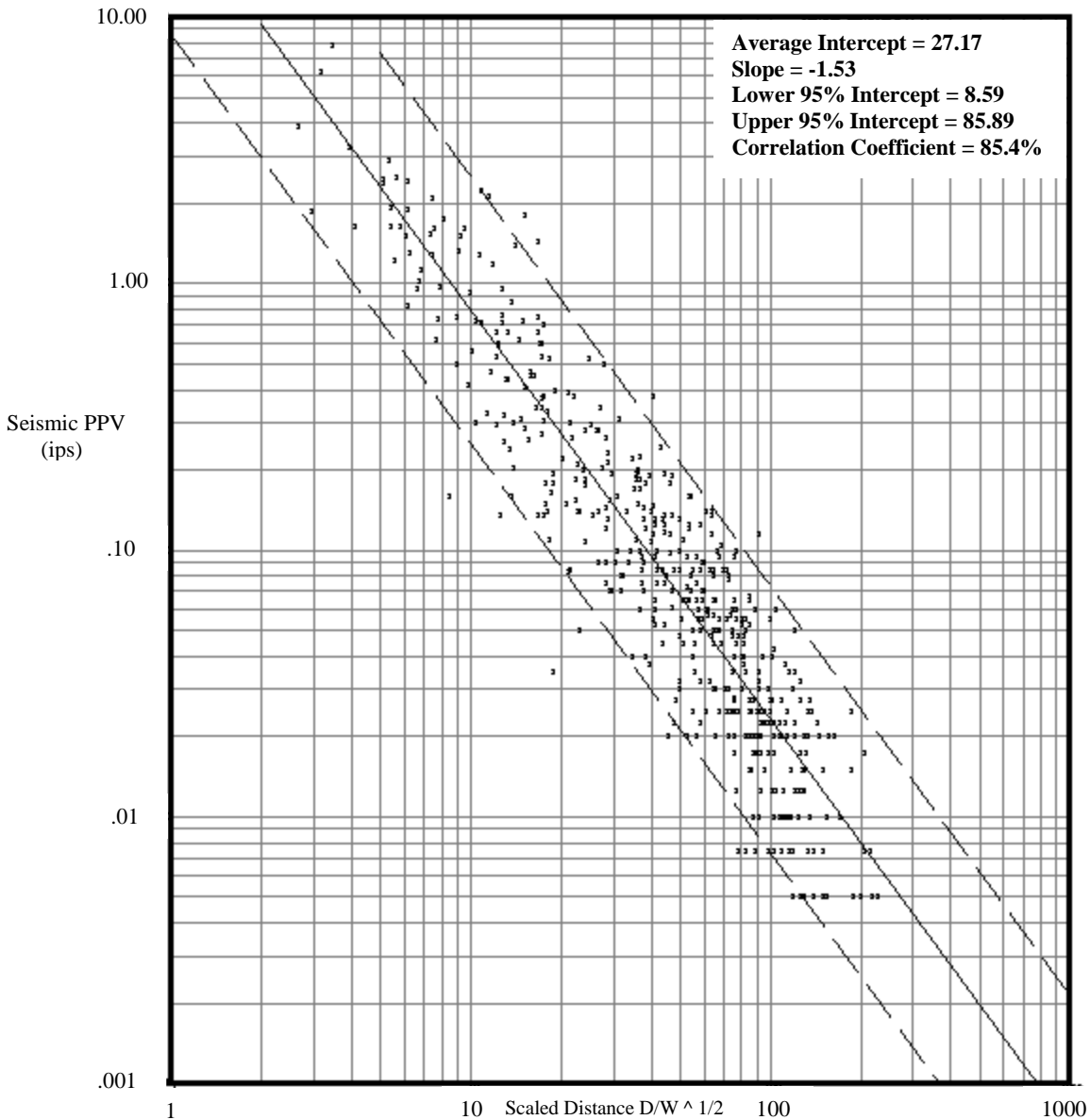


Figure 12

This combined regression equation is the next step in the development of an overall predictive vibration model for surface blasting over deep mines and other underground voids.

CONCLUSIONS

Continuation of the 2006 research yielded additional information on relationships between scaled distances and vibration levels on deep mine roofs. Additional literature search revealed a research project conducted at the Jenny Mine with the goal of determining vibration levels that damage deep mine roofs and the ability to predict mine roof vibration from surface blasts. OEB's research goal of determining the relationship between scaled distance and deep mine roof vibrations compliments the Jenny Mine study. These two projects are the basis for renewed research activity. Conclusions, observations, and recommendations concerning OEB research are as follows:

- 1) One hundred seven seismic impulses from surface blasts were recorded on both surface and underground geophones to compare the PPV values. An analysis of the seismic data sets recorded revealed the surface PPV to underground PPV ratios varied from 2.0 to 9.7 with 90 percent of the blasts having ratios between 2.0 and 6.0. Although surface waves are known to act differently than body waves, this data has potential for the development of a method to more accurately predict roof vibrations and a surface monitoring method for inaccessible underground mines or caves.
- 2) Literature review shows geologic structure such as rock density and propagation velocity, thickness, faults, voids, water saturation and cracks has a big influence on the intensity of reflected and refracted seismic wavepaths. Multiple layers of strata, depths between the surface blast and an underground mine, and blast design can affect the intensity of a seismic wave impacting a mine roof.
- 3) Regression analysis of the combined Jenny Mine and OEB data resulted in a 95 percent confidence interval predictive ground vibration equation of $86 * (D / W^{1/2})^{-1.53}$. This equation estimates that a surface blast designed with a scale distance of 18.3 should not exceed OEB's regulatory default protection limit of 1.00 ips on a deep mine roof. This research shows that the USBM scaled distance formula used for surface structures is generally not applicable for predicting the effects of surface blasts on the roofs of underground voids.
- 4) In multiple seam surface mining, scaled distance values needed to maintain a consistent PPV on a deep mine roof will generally increase when vertical distances decrease. Although these results were expected, there were several unexplained occurrences where the surface seismograph recorded a PPV while the working underground seismograph, directly under it, did not register the same blast event.
- 5) Difficulties arise when attempting to determine surface blast intensities that will damage or cause failure of an underground mine void roof. Research is generally conducted in active mine settings where worker safety and compliance are of primary importance. The Jenny Mine¹ study concluded that their maximum vibration of 17.5 ips did not appear to affect the stability of the underground mine roof. Another USBM contracted research report² postulated that the PPV for damage would be approximately 2.0 in./sec, depending upon the geologic structure, and the strength of roof, pillars and the floor of the mine. The maximum underground vibration encountered during OEB research was 2.22 ips with no

adverse effects to the mine roof identified by underground mine personnel. To date, there has been no established vibration level threshold for coal mine roof failure.

RECOMMENDATIONS

- 1) More research is needed to obtain additional seismic and blast data from surface blasts and underground roofs with varying geology between them to validate this research. This may be accomplished by investigating underground mines that currently have seismographs installed on the mine roof for compliance purposes. The addition of OEB equipment and research personnel can compliment the data accumulated by the existing underground seismographs.
- 2) Measuring changes in underground roof cracks from surface blasting could be pursued using extensometers, strain gauges, and other equipment. Due the geologic stresses and strains associated with underground mining, this equipment would be installed prior to the influence of surface blasting for control purposes.
- 3) Sites that utilize electronic digital detonator (EDD) initiation systems and GPS location devices on surface blasts should be given research priority due to the greater accuracy for scaled distance calculations.
- 4) Research should be continued in this area with the goal of creating a general equation or scaled distance values for use in predicting vibrations that would be registered on underground void roofs. This would be similar to standard scaled distance values created by the USBM for the protection of above ground structures.
- 5) Future research should be conducted to determine vibration levels that cause underground roof failures. This will be difficult at best and dependant on accessibility of the underground voids and the proximity of surface mine blasting to gather data.

GLOSSARY⁷

ANFO – non water resistant explosive ideally composed of 94.0 to 94.3 percent ammonium nitrate (AN), and 5.7 to 6.0 percent fuel oil (FO).

acoustic impedance – the product of the compression wave velocity and density of a material. It characterizes a material as to its energy transfer properties.

air blast – the airborne shock wave generated by an explosion.

angle of incidence – angle at which a compressive wave reflects at a discontinuity

attenuation – decrease in amplitude of a wave as a function of distance of propagation from its source.

blast log – a written record of information about a specific blast as required by regulatory agencies.

blast vibration – the energy from a blast that manifests itself in earthborne vibrations that are transmitted through the earth away from the immediate blast area.

body waves – compression and shear waves that propagate in the interior of an elastic solid.

borehole – a hole drilled in the material to be blasted, for the purpose of containing an explosive charge.

compression wave – a mechanical wave in which the displacements are in the direction of wave propagation. Because this wave shows the highest velocity, it is called the primary wave (P-wave).

correlation coefficient (R) – a number expressing the fitness of a curve to measurement data. R varies between 0 – 1 where 1 represents the case when all measurement points are located on the fitted line.

elasticity – the property of a material to regain its original size and shape upon complete unloading after it has been deformed.

emulsion – a water resistant explosive material containing substantial amounts of oxidizers, often ammonium nitrate, dissolved in water and forming droplets, surrounded by fuel oil and stabilized by various emulsifiers. An emulsion blend has various amounts of prilled ANFO mixed with an emulsion.

ground vibration – shaking of the ground, by elastic waves emanating from a blast; usually measured in inches per second of particle velocity.

millisecond – one thousandth of a second

peak particle velocity (PPV) – a measure of the intensity of ground vibration, specifically the time rate of change of the amplitude of ground vibration.

portal – the surface entrance to a tunnel or an underground mine.

scaled distance – a factor relating similar blast effects from various size charges at various distances. It is obtained by dividing the distance of concern by a fractional power of the weight of the explosive materials.

seismograph – an instrument useful in monitoring blasting operations, that records ground vibration and airblast.

shock wave – a transient pressure pulse that propagates at supersonic velocity.

spall – fragment of rock broken from a free surface by the tensile stress wave which is usually created by the reflection of a compressive wave at the free surface

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