Excessive Adverse Effects

Attention to the above points - which are virtually the only ones the blaster has any control over anyway - will minimize problems due to airblast. To a great extent the stemming release pulse can be controlled, as can, to a rather lesser degree, the gas release pulse. Apart from terrain and weather variables, this only leaves the dominant effects of the air pressure pulse, and to a lesser extent, the rock pressure pulse. Since these both tend to be at lower and less audible frequencies, the overall impact of airblast will be greatly reduced.

FLYROCK

Flyrock occurs when the blast is improperly designed or loaded. Incorrect burden for the explosive load and the geology assures a flyrock problem. A burden too small for the drill hole size and rock type could result in fly from the face. In the same manner, excessive burden or rows of holes without relief will result in violence in the collar zone. Loading holes through zones of weakness, or into voids, will result in "blow outs". Flyrock can also be caused, or contributed to, by geological conditions which can not always be detected prior to the shot.

One technique that is receiving particular attention these days is "casting". This is, as has already been stated, the deliberate use of explosives not merely to fragment the rock, but to move overburden to a spoil pile without, or with minimal rehandling. The mine is trying to control and direct the throw of material so that as much as 65% of the overburden is displaced to the spoil pile. By the controlled application of some of the causes of flyrock, the mine can move large volumes of material. Poor application of casting techniques will result in adverse effects, with flyrock being the greatest, closely followed by excessive airblast.

The main control that can be applied to the blast design is to ensure proper burden and stemming, together with loading the explosives into the borehole to place the energy release at the points where it is required to break the rock. Generally, it is considered that a burden dimension less than 25 times the diameter of the explosive charge can result in long flyrock distances, while excessively large burdens can cause violence in the collar zone (Bu. Mines IC 8925, p.77). Where blasting must take place, and it is difficult to ensure proper burden and stemming relationships, then blasting mats or spoil cover must be used to control flyrock. The above considerations together form the best control solutions to the flyrock problem.

Flyrock and airblast are closely related, and proper techniques to control flyrock will greatly assist in reducing airblast problems. By knowledgeable placement of the explosive in relationship to the face, the collar, and to the known zones of weakness, flyrock can be effectively controlled.

GROUND MOTION

Excessive ground motion is caused by improperly designed blasts, excessive - or insufficient - explosive charge weights, excessive confinement and too short time periods between successive delays.

The fundamental control available to blasters has for years been based on the simple relationship between charge weight and distance. Reducing the charge weight, or increasing the distance, or both, results in a smaller ground vibration. Since confinement and breakage also have a very considerable effect, the above is an oversimplification, but if it is also stated that excessive ground motion equates to wasted energy, it is easier to visualize the following:

A properly designed blast will give lower ground motion per pound of explosive than one that is poorly designed. For a given weight of explosive that is detonated, a certain fixed amount of energy is released. If that energy is used in breaking rock into fragments, there is less "waste energy" available at the end of the reaction to go into the ground as excess vibration. A badly designed shot, where good breakage is not obtained, will generally produce higher levels of ground motion. This fact must also be remembered when specifically high confinement shots are being designed (e.g. pre-splitting) because in these cases any "site-specific" attenuation formula that has been developed may not apply. In fact, when developing such attenuation formulas for any particular mine site, it is normally necessary to divide data into groups: "OVERBURDEN", "COAL" and "OVERBURDEN PRE-SPLIT", etc. Separate formulas would have to be developed for each category. This subject will be discussed fully in Chapters 9 and 10.

The U.S. Bureau of Mines, in IC 8925, outlines the following five techniques that can be used to minimize ground motion:

1. Reduce the charge weight of explosives per delay period. This is most easily done by reducing the number of blastholes fired on each delay. If there are not enough delay periods available, a sequential timer blasting machine can be used, or a combination of surface and in-hole nonelectric delays. The manufacturer should be consulted for advice when using the sequential timer or complex delay systems. If the blast already employs only one blasthole per delay, smaller diameter blastholes, a lower bench height, or several delayed decks in each blasthole can be used. Delays are often required when presplitting.

2. Overly confined charges such as those having too much burden or too much subdrilling should be avoided. The primer should not be placed in the subdrilling. Where it appears that a later row of blastholes will not have adequate relief, a delay period should be skipped between rows.

3. The length of delay between charges can be increased. This is especially helpful when firing large charge weights per delay at large blast-to-structure distances. However, this will increase the duration of the blast, and may cause more adverse reactions from neighbors.

4. If delays in a row are arranged in sequence, the lowest delay should be placed in the hole nearest the structure of concern, except at very short distances when other considerations apply. In other words, the shot should normally be propagated in a direction away from the structure.

5. The public's perception of ground vibrations can be reduced by blasting during periods of high local activity, such as the noon hour, or shortly after school has been dismissed. Blasting during typically quiet periods should be avoided, if possible.

Very recent research ("Geologic Factors Affecting Vibration from Surface Mine Blasting", USBM 1985, See Bibliography) has shown that it is possible to reduce ground vibration levels, particularly low frequency vibrations, by the proper selection of delay periods. Firing times are chosen by analyzing the vibration response created by the detonation of a single blasthole. This response is a function of the geology at the blast site, the vibration travel path, and the geology at the recording location. Blast firing times can be selected to create "out of phase" vibrations with adjacent holes. Significant reduction of vibration levels (up to 50%) have been achieved in controlled tests.

Tables 1 and 2, pages 27 and 28 in Chapter 3, summarize the factors which influence ground motion and airblast to one extent or another. The influence might be to increase or decrease the effect of the vibration, as in the case of confinement. Highly confined blasts will tend to produce high ground vibrations and low airblast. Unconfined blasts will cause low levels of ground motion, but very high overpressures, with high frequencies, audible over long distances.

CHAPTER 7

VIBRATION MONITORING

The Bureau of Mines Reports of Investigations, RI 8506 and 8507 are the current standards for defining methods of monitoring ground motion and airblast respectively. There are many different monitoring instruments available; some used more in a research capacity, and others used basically for compliance and effect control. In this chapter, and in the later chapter devoted to instrumentation, focus will be upon the specialized instruments produced specifically for blast vibration compliance and control. The majority of these instruments are portable.

AIRBLAST MONITORING

The basic choices open to the operator are:

- Peak only vs. entire time history recording instruments.
- Permanently or semi-permanently installed vs. portable, operator set-up and/or attended.
- Monitoring by consultants.

Any instrument with a frequency response listed within the requirements of Section 816.67(b) can be used, and because the OSMRE regulations regarding airblast do not relate to the predominant frequency of the airblast itself, peak reading instruments alone are satisfactory for compliance. In instruments which also record ground motion, the airblast may be reported simply as a peak instead of a full waveform. It may be, however, that instruments that record the entire time history waveform would be considered to be preferable, since:

- A waveform of the entire event can frequently help to identify causes of excessive airblast.
- A waveform, by its "signature", can permit discrimination between blast and non-blast overpressure events. This can be of particular importance where remotely installed "constant-recording" instruments are concerned.

Permanently installed "constant-recording" instruments can be more convenient than portable operator attended or set-up instruments. They do not require the labor expense of an operator. They will record any event of a recordable magnitude (generally over about 100 dBL) if they are of the peak recording type, and any event over a preset trigger threshold level if they are of the acoustic/seismic triggered variety. This is an advantage in favor of the peak recording instruments, and a slight disadvantage of the automatically triggered instrument - certainly if it is considered desirable that every event, no matter how minor it might be, should be put on record.

This last disadvantage of triggered instruments may not be immediately apparent. However, if it is remembered that complaints can and will arise from any humanly perceptible blasting event, and that in such circumstances (for the unit failed to receive the minimum vibration that would have been necessary to trigger it) the total lack of a record may prove difficult to explain to an attorney. A flat trace, supported by testimony that the instrument was operating at the time of the blast, is at least a record, albeit of non-measurable vibration. This can be of real value when a complaint situation is at issue.

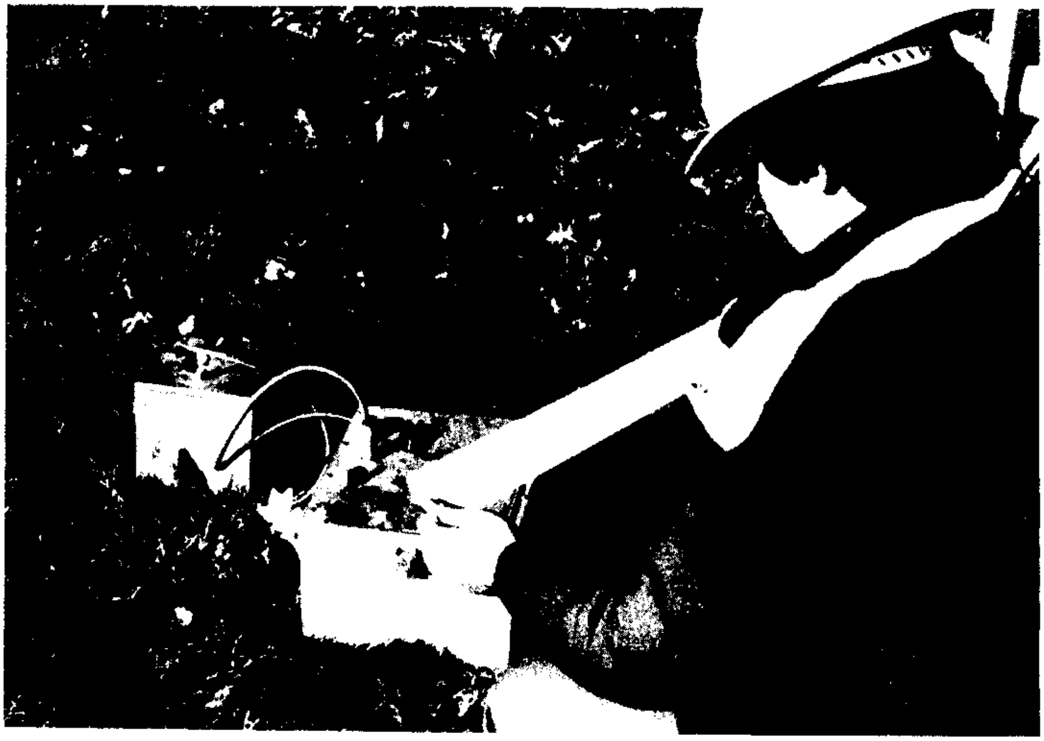


Figure 19.
Field Monitoring.

Portable operator-attended instruments require someone to set them up at a specific location, and to retrieve them following the blasting event. They do not necessarily require critical timing, nor do they always require the operator to be physically present during the actual shot, particularly the magnetic tape recording instrument which will run unattended for up to a half hour or so. Some of these portable instruments can also be of the seismically or acoustically triggered variety, though at closer distances, missing a shot due to non-triggering is normally less of a problem. Nevertheless, care has to be exercised to ensure that the trigger threshold level is set appropriately: nct so high that there is a risk of missing an event, and not so low that passing traffic, etc., might cause spurious events to be recorded.

The portable instruments tend to be more versatile, and offer more practical uses than the remotely installed instruments, since they can be moved to any location, and can collect both high and low level data. This is of lesser importance when monitoring airblast, because of the difficulty in applying predictive techniques to airblast data. For airblast monitoring, portable instruments can be moved to any position inside or at the the perimeter of the permit area, and to any outside point of concern or complaint site.

All instruments used for airblast monitoring should be equipped with windscreens over the microphones, which should be placed in an area not masked by trees or buildings, at least 5 ft. to the side of any structure, and 3 ft. to 5 ft. above the ground.

When monitoring both ground motion and airblast at a structure, it is desirable to employ an instrument that records the ground motion and airblast as full waveform time histories. In case of excessive adverse impacts, or persistent complaints, the airblast and ground motion time histories may then be compared in order to identify the major cause of any problem. At boundary limits, for compliance monitoring [Section 816.67(b)(2)] or for verification, a peak reading airblast monitor is adequate.

When employing consultants to carry out airblast monitoring programs, be particularly careful that the consultant is, in fact, a specialist in blasting vibrations. It might seem that this caution is unnecessary, however one proposed local airblast ordinance was recently based on the study of a professional engineer who was not only apparently unaware of the differences between 'sound' and 'airblast', but did not seem to fully understand the difference between a steady state and an impulsive event. He attempted to use the noise study parameters such as dBA, Leq, and d', and also based his conclusions on measurements made of only two events at a single location in mountainous terrain! Should any prospective consultant prepare to monitor a shot, displaying any of the above tendencies, or using a "sound level decibel meter", it should be taken as an immediate warning that he is not sufficiently experienced or competent in blast vibration monitoring and control. Be very careful when selecting a consultant.

GROUND MOTION MONITORING

Whenever ground motion needs to be recorded for whatever reason, by the mine operator, independent consultant or regulatory authority, the actual placement of the instrumentation is the primary consideration. Adequate time should be allowed for the proper set-up of the instrumentation at the chosen location, before the detonation of the blast. Hurried instrument set-up can lead to imperfect orientation and sensor-to-ground coupling, and will often result in less than adequate results.

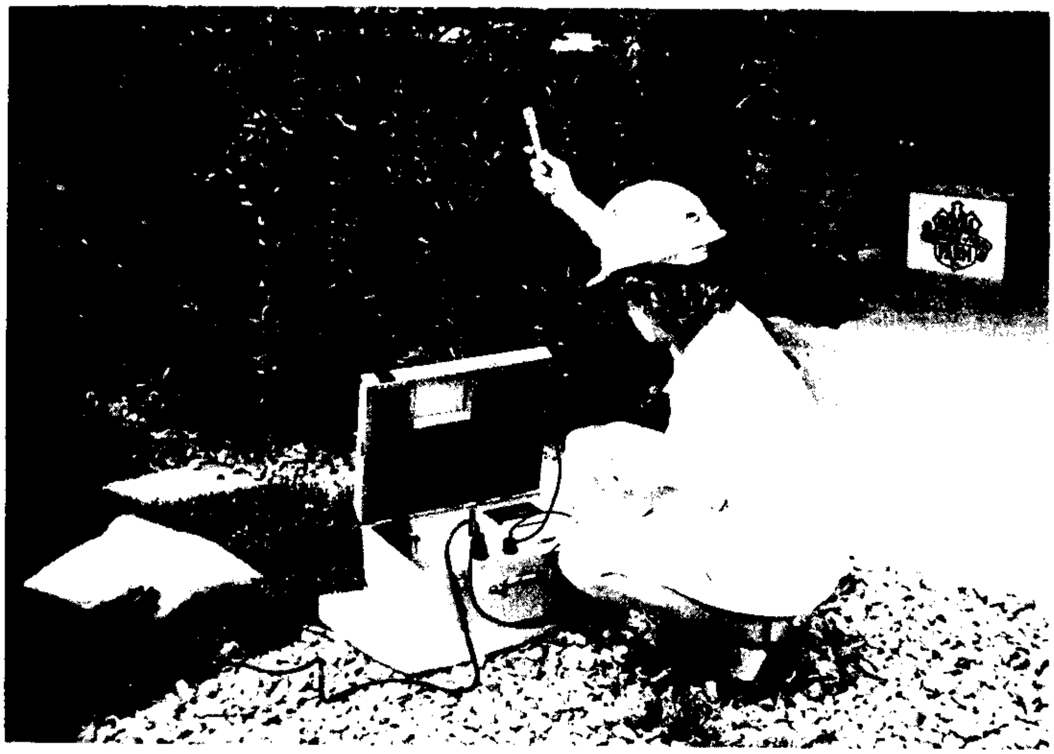


Figure 20.
Monitoring ground motion and air blast.

The first consideration in terms of instrument placement is the actual location of the ground motion sensor, or transducers. This placement has to be decided both in terms of distance from the blast site, and, at a structure, in terms of the transducer placement relative to the structure.

Distance from the blast is not always a matter of choice. If it is necessary to monitor ground motion at the particular structure then obviously distance from the blast is dictated by the distance that structure is from the blast. If this limitation does not apply, then it is essential to remember that the most useful data will be collected at as widely different scaled distances as possible. The distance to the blast decision, if open, will be dependent upon recent monitoring history: if large scaled distance data is already available, then the aim should be to collect data at small scaled distances. Attempt, as far as possible, to collect data at as low a scaled distance as is safe and prudent, and at as high a scaled distance as is measurable. In between these extremes, it is desirable to have as even a distribution of data as possible. Whenever the choice of distance is open to the operator, the temptation to set-up the instrument in the same, easy, convenient spot where it was last time must be avoided. Vary the data, and the extra effort will be found to be well worth while when the need to predict vibration arises, as sooner or later it surely will.

The second consideration in terms of instrument location concerns the local placement of the transducers with reference to the structure itself, and the actual connection of the transducer head to the ground, or "coupling".

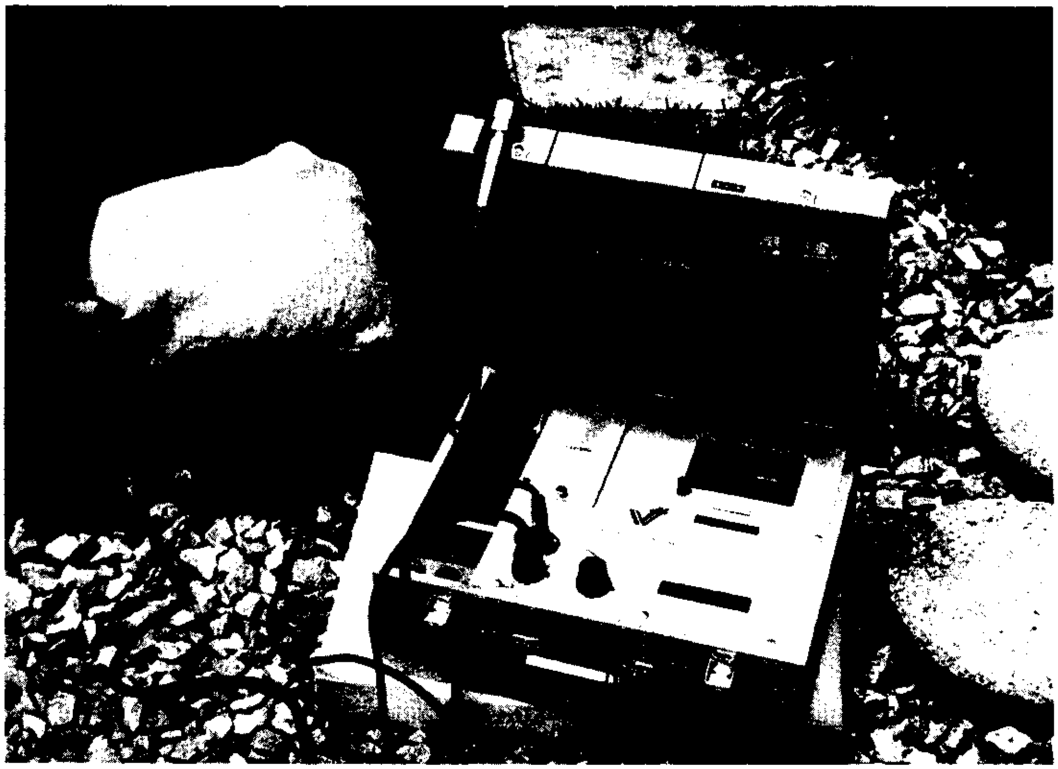


Figure 21.
Instrument placement.

The placement of the transducer head should be outside any building or structure of concern, since the vibration limits are for effects at the point of entry to a structure. Locations which are also influenced by an incidental or background vibration - heavy rotating machinery, compressors, etc. - should be avoided. It is quite common for a householder to request that the instrument be placed inside a house, or on a window sill. In most cases these requests are made because this location is where the vibration was most strongly experienced. This request should always be resisted, explaining that any location other than outside the structure will not measure incoming ground motion, but only structure response, and that structure response was carefully considered when the OSMRE drafted the ground motion regulations. There is no need to be reluctant to admit that structure response is sometimes higher than the incoming ground motion. If the insistence on an internal structural measurement is so great that this request is conceded to, make absolutely certain that in these cases any internal monitoring is backed up by a proper external ground motion measurement as well.

Sometimes, however, particularly in the case of constant recording remotely installed instruments, it is desirable to place the instrument inside the structure simply in terms of weather protection. A common placement for the transducer in such cases will be an internal mounting on a concrete foundation or basement wall. In such circumstances it is important to place the transducers at approximately the outside surface level on an outside concrete basement wall or foundation, preferably at the corner intersection that is closest to the blast. A partition wall is not suitable because it has a tendency to resonate.

Normally, the transducers should be placed on a compacted earth or soil surface, as close to the foundation of the structure as possible, correctly leveled and oriented towards the blast, following the instrument manufacturer's instructions. This requirement is so that the planes of measurement are kept in a proper and consistent relationship, i.e. that the longitudinal (or radial) component is indeed measured longitudinally, and not transversely, to the blast. Some transducer heads have a small bubble level to indicate a level position, on other instruments a satisfactory calibration cannot be achieved if the heads are not in a sufficiently level position. Exact, precise leveling is not necessary.

Coupling is the single most important transducer head placement consideration. If the manufacturer provides a ground coupling spike to be attached to the underside of the transducer head, it should always be used providing the ground is at least soft enough for the spike to be pushed fully into place. In addition to this, if at all possible, and even when the vibration levels are expected to be quite low, it is always good practice to cover the transducer unit with a loosely filled 15 - 25 lbs. sandbag. Burial of the transducer unit is sometimes advocated, with soil compacted around the transducer head to a depth of at least 2/3 the transducer height, but digging a hole will sometimes disturb the soil on which the transducer is placed to such an extent that in effect the transducer is placed on loose uncompacted soil, and the ground to transducer coupling will suffer accordingly.

Figure 22.
Sandbag and spike transducer head
to achieve good coupling.

When high vibrations are expected, special considerations apply. Obviously, the risks of ground to transducer decoupling are increased, and careful thought must be given to ensuring continuing and complete coupling. Some transducer heads are provided with a through hole: if a threaded stud is fired or cemented into an exposed rock outcrop, the transducer head can be securely bolted down, using the storage mounting bolt supplied with the instrument. Other methods of secure transducer placement in such circumstances include cementing or gluing in place. A very suitable and cheap material for this is plaster of paris. This is not only very quick, but the bond can easily be broken at the conclusion of operations, and the excess plaster remaining can easily be removed from the transducer head with no risk of damage to the instrument. Care must also be taken to protect the body of the instrument from direct exposure to airblast and vibration. It should be placed on a soft foam rubber pad, and shielded from direct exposure to the incoming airblast shock wave.

Occasionally, in special circumstances, transducers have to be mounted sacrificially with no possibility of retrieval following the operation. In such circumstances, it is wise not only to check the cost of such a sacrificial transducer, but also to remember that when being fitted with a new transducer head, in all probability the instrument will have to be recalibrated. Such recalibration costs can be quite significant, sometimes several hundred dollars.

Loose or smooth surface transducer placement should be avoided without some sort of coupling support under all circumstances, even when the velocities expected will be low, but when acceleration levels are expected to be over .2 g's.

If any decoupling or slippage occurs the results of any measurements will be gravely in error. If peak reading instruments are used, this will be hard to detect, although with time history recordings, such decoupling is normally immediately apparent, visible in the waveform "signature".

Once these basics are complied with, the choices are much as were open to the operator for airblast monitoring.

- Peak only vs. entire time history.
- Permanently or semi-permanently installed vs. portable.
- Monitoring by consultants.

The first option, however, is restricted, because of the frequency responsive ground motion limitations in the OSMRE regulations. Apart from secondary, or backup peak readings taken in conjunction with a second time history recording instrument, the only times 'peak only' reading instruments are acceptable are: (a) when the instruments are used to monitor velocities at points within the permit area, when compliance is not an issue anyway, and (b) when compliance is being sought under the requirements of Sections 816.67(d)(2)(i) and 816.67(d)(3)(ii).

Similar considerations apply to the decision to use permanently installed "constant-recording" instruments, versus portable operator attended or set-up instruments, as in the case of airblast monitors. An important consideration in the case of ground motion, however, is the existence of instruments which may be set-up in the field either in a portable or in a "constant-recording" mode. Instruments of this type can offer increased versatility. They provide the advantages of variable and varying data collection in the portable mode, as well as the convenience of use in a 24 hour per day monitoring situation, in a fixed location for week or a month, or for whatever period might be necessary to deal with any particular complaint or concern situation.

The arguments discussed under AIRBLAST MONITORING concerning the relative advantages and disadvantages of seismically triggered instruments are also identical. Only the operator can decide just what type of instrument is best suited to his needs. Very often the use of instruments on a rental basis is the most convenient answer to this problem; either because of the ease of switching to another instrument without a significant capital expenditure, or, as a prelude to purchase, a rental period to serve as a practical field trial.

Since many of the instruments available today offer a full airblast recording capability along with seismic monitoring, all the airblast considerations already discussed are pertinent in a seismic, or ground motion recording mode.

Consultants should still be chosen with a great deal of care. Ground motion is far better understood among the non-specialist consulting engineers than is airblast, but nevertheless, if the decision is taken to retain a consultant for monitoring, it is wise to make certain that he is experienced and known in the field.

The result is a form of bar graph, on which are recorded deflections from a baseline occurring for each blast or other vibration-producing event. By knowing the sensitivity of the recorder, and the rate of movement of the chart paper, both the peak recorded values and their times of occurrence can be determined over periods as long as 30 to 60 days. Even if a peak recorder is able to continue to operate unattended for such long periods, it is advisable to remove the records on a much shorter time cycle, in order that excessive vibrations are recorded in a timely fashion, and do not go uncorrected.

The major advantage of the peak recorder is the low cost and simplicity of the equipment, as well as the fact that it can operate with minimal attention and manpower expense.

Its major disadvantage is that no frequency information is recorded. Because the potential for structural damage is frequency-related, the data obtained is of limited value, except in cases where the vibration levels are so low that damage will not occur regardless of frequency. Compliance with OSMRE regulations would only be fully satisfied if the peak particle velocity was lower than 0.2 inches per second, or if compliance was being sought under Section 816.67(d)(2)(i) or (3)(ii).

Another problem with peak recording instruments is that non-blast events, such as bumping the geophone or slamming a nearby door, cannot be distinguished from blast vibrations even though the differences in their waveform 'signatures' are quite distinct. Therefore, because of these possible interpretative doubts, the value of these records in damage determination and litigation situations is somewhat limited. In general, the application of these instruments should be limited to situations where the vibration levels are certain to be low and the potential for complaints is also minimal. Peak recorders restrict the choice of the operator in terms of vibration level compliance options.

Although peak recorders produce only one trace, containing only peak information, they nevertheless have to record ground motion in all three planes. The ground motion sensors, therefore, still must incorporate three mutually perpendicular geophones. Although the trace will not identify in which plane the peak occurred, OSMRE regulations will be satisfied since the requirement is for maximum velocity in any plane. See Note 3/ to Section 816.67(d)(2)(i). Some of these instruments provide a vector sum peak reading. This is also acceptable, since the vector sum velocity will always exceed or equal the maximum any plane velocity.

Instrumentation

THE WAVEFORM RECORDER

These instruments are the most commonly-used blast monitors. They are distinguished by their capability of producing a particle velocity analog of a ground vibration waveform. Some have features which allow more sophisticated and accurate computerized techniques for damage prediction. However, the minimum requirements for waveform instruments are as follows:

1. Three mutually perpendicular geophones which can be oriented to sense vibration in the vertical direction, along a horizontal line between the blast and the geophone (longitudinal or radial), and along a horizontal line at right angles to the other two (transverse). This assures that all components of ground vibration are sensed by one or more of the geophones and can be added vectorally if necessary. This also complies with OSMRE regulations, Note 1/ to Section 816-67(d)(2)(i).

2. The capability of responding to ground vibration frequencies of 4 Hz or lower, at ±3dB, or down to 5 Hz at ±1 dB. This assures that all vibration energy within the 4 to 12 Hz fundamental frequency range of residential structures will be accurately recorded.

3. The ability to reproduce all frequencies up to at least 50 Hz. This enables the accurate determination of both the amount of energy in the fundamental frequency range of residential structures as well as that energy causing resonance of individual walls and other structural elements. This also permits compliance with the Blasting Level Chart option, Section 816.67(d)(4)(i).

4. The capability of recording peak ground vibration levels at frequencies up to 200 Hz to conform with USBM recommendations.

5. A dynamic response range from at least a minimum of .05 inch per second to a maximum of no less than 2.0 inches per second.

6. An internally-generated calibration signal which tests the entire system, including the geophones, for accurate operation. The instrument's response to this calibration signal should be displayed on the record as proof of proper operation and to allow for corrections when necessary. Failing this, the instrument should have recent (within one year) factory calibration records, showing calibration traceable to the National Bureau of Standards.

Instrumentation

7. Unless a separate airblast recorder is used, there must be a capability of recording peak airblast with an upper frequency limit of at least 200 Hz to comply with Section 816.67(b)(2)(ii). The low frequency limits may vary in accordance with the requirements set forth in Section 816.67(b)(1)(i).

The output of the blast monitor should be in the form of a particle velocity time history record of the event. This time history may be generated on-the-spot by an onboard printer or may be put on photographic film, tape, diskette or other memory device and analyzed at a later time. There are always advantages and disadvantages with any system that need to be considered.

To assure proper analysis and maximize credibility, legal experts recommend and some regulatory agencies (but not OSMRE) require that independent vibration consultants perform the analyses of vibration records. Regardless of whether a record is on film, magnetic tape or a field-generated strip chart, all records should be analyzed, or at least verified for validity, by a qualified person not connected with the mining operator or explosive contractor.

A recent innovation in blast monitoring instrumentation is the microprocessor-based unit. This provides a field record by sampling the vibration wave at a high rate, storing the sampled values in its memory and then printing out these values as strings of points on a strip chart so that an approximation of the original waveform is drawn. At the same time the peak values sampled from the geophones and microphone are printed out with the waveform to provide a peak particle velocity and airblast analysis of the blast.

This "instant" analysis has the advantage of timeliness, and provides a certain amount of information regarding the frequency content of the vibration wave. The expense of monitoring is also reduced, as long as the operator is not inclined or required to obtain a formal verification of the results by an independent vibration analyst.

If evidence of conformance to a single-number particle velocity criterion is the only requirement, this method may be satisfactory. Low velocities, or velocities measured in accordance with Section 816.67(d)(2)(i) or (3)(ii) will conform in these terms.

Vibration waves are, in general, a complex mixture of many frequencies. Visual examination of a vibration printout is usually a rather crude method of determining which frequencies are important from the standpoint of structural damage potential. For instance, a particle velocity peak may be the result of the addition of several frequencies having different significance in terms of structural response. On the other hand, important frequencies from the standpoint of structural response may not be apparent by visual examination, because they are masked by other less significant frequencies.

The implication of this is that conformance to the OSMRE frequency dependent criteria shown in Figure 12, page 24, (Fig. 1, OSMRE Regulations) can most conveniently and accurately be accomplished by a computer technique which separates the vibration wave into its component frequencies. There are several methods which can be used to accomplish this. It is only through the use of such a technique, however, that a valid correlation between amplitudes and frequencies can be plotted directly against the variable particle velocity limits shown on this graph.

The seismic information gathered by present-day digital onboard waveform printing instruments cannot be supported in this way. After the stored digital points are used to plot the particle velocity waveform, the digital information is discarded and no further analyses can be performed, except for example by "hand-digitizing" the waveform for further separate analysis by computer. In such instances, however, hand digitizing error can be additive to normal instrument error: great care must be exercised with these techniques.

Future instrumentation of this type will no doubt result in more relevant and sophisticated analyses than are currently available. Such capability is, in fact, within the realm of present-day technology. When it becomes implemented into this type of instrument, it will provide the blaster or his consultants with a far better insight into the damage potential of ground vibration than is currently available using onboard printing instruments.

Another point to consider is that the need for seismic instrumentation goes far beyond the basic control of ground vibration levels and the fulfillment of OSMRE regulatory requirements. Civil lawsuits are a common result of blasting operations, and the vibration data gathered by the mine operator can be crucial in determining the extent to which he may be judged liable.

When property damage lawsuits do occur, it is imperative that the mine operator be able to produce seismic evidence that is accurate, complete and provable. Opportunities for falsification, suppression or other tampering of seismic evidence must be kept to a minimum by whatever means are practical. Evidence demonstrating proof of non-damage is of paramount value: in most states, lawsuits only have to prove a causatory connection between the blast and the damage. Negligence does not have to be proven: it is usually not an issue.

Instrumentation

Experience of lawyers, vibration consultants and other experts in the area of blast damage liability has shown that certain data-gathering procedures and instrumentation requirements are important in establishing the credibility of seismic and airblast evidence in litigation proceedings, as follows:

1. Proof of Calibration: Most instruments have a built-in calibration test circuit which checks the continuity and accuracy of all data channels. The response of each channel to the calibration input signal is printed out, either automatically or on command of the operator. The calibration test response pulse should be included with every blast record to indicate the accuracy of the recording system.

All seismic instruments should also be shake-table calibrated by a competent vibration testing facility at least once a year, and a current certification of calibration should be provided, traceable to the National Bureau of Standards.

2. Third-Party Analysis: Blast recordings which provide an on-the-spot analysis, or are analyzed by the mine operator, may be subject to questions regarding their admissibility in civil actions. This question of credibility may, at times, become a very important issue because of the potential for a conflict of interest on the part of the mine operator.

This is the reason why it is desirable that the analyses of blast records be made by an independent third-party expert. Besides minimizing the potential for conflict of interest, an expert analyst is able to identify problems in recording procedures, instrument operation, and blast design that may otherwise go unnoticed.

Third-party expert analysis is a key facet of any blast monitoring and structural damage protection program. Even when "instant analysis" type instruments are used, review of these records by an independent expert is highly advisable to assure the validity of the results and to identify possible problems.

3. Witnesses: Whenever a blast is recorded, an individual other than a representative of the mining company should, if possible, be present to observe the operation of the instrument. Ideally, the witness should be familiar with the operation of a blast monitor such as a regulatory inspector. However, a homeowner, tenant or other interested party might also be asked to observe any blast recording to at least substantiate the fact that a recording was made. Sometimes local government officials or employees can be prevailed upon to undertake this function, as can members of the local media.

SUMMARY OF BLAST VIBRATION MONITOR SPECIFICATIONS AND CAPABILITIES.

Company; Model; Type;	Sensitivity Ranges: Seismic: ips, (Air: dB)	Frequency Response: Seismic: Hz (Air: Hz)	Manual, Seismic or Air Trigger	Recording Format:	Country of Origin:	OSM "Option No." Suitability:	Record/Recall Capabilities:	Availability of Frequency Information:	Power Requirements:	Wgt. (lbs)	Fig. No.
Dallas Instruments: BR-2-3 / VS-3 PEAK;	0-2, 0-4, (NA)	1-200 (NA)	M	Bar graph on 30 day strip chart.	U.S.A.	1 and 3	Max component continuous recording. Vector sum optional.	None.	3 x 6V Lantern battery. Ext.DC power plug.	25	23
Dallas Instruments: BT-4 WAVEFORM;	0-4 (100-137)	1-200 (5-200) (2-200 Opt.)	M	Magnetic Tape Cassette[1]. Peak-hold meter readout.	U.S.A.	1 and 3, also 4 if computer analysed.	3 component seismic and air data stored on tape[2].	Visual estimate thru seismogram. Computer analysis[2].	3 x 6v Lantern	28	24
Dallas Instruments: SM-4 WAVEFORM;	0-4 (100-137)	1-200 (5-200) (2-200 Opt.)	M S(Opt)	Magnetic Tape Cassette[1]. LCD display of peak readings.	U.S.A.	1 and 3, also 4 if computer analysed.	3 component seismic and air data stored on tape[2].	Visual estimate thru seismogram. Computer analysis[2].	12V rechargeable battery. Ext. DC power.	28	N/A
Dallas Instruments: ST-4 WAVEFORM;	0-4 (100-137)	1-200 (5-200) (2-200 Opt.)	M,S	Magnetic Tape Cassette[1]. LCD display and BCD printout of summary data.	U.S.A.	1 and 3, also 4 if computer analysed.	3 component seismic, air and summary data stored on tape[2].	Visual estimate thru seismogram. Computer analysis[2].	12v rechargeable battery. Ext. DC power.	30	25
Dallas Instruments: ST-4D WAVEFORM;	0-4 (100-137)	1-200 (5-200) (2-200 Opt.)	M,S,A	Magnetic Tape Cassette[1]. LCD display of summary data.	U.S.A.	1 and 3, also 4 if computer analysed.	3 component seismic, air and summary data stored on tape2. 94 event summ. data printed out with peripheral equipment.	Visual estimate thru seismogram. Computer analysis[2].	12v rechargeable battery. Ext. DC power.	30	26
Digital Vibration: TELEBLAST WAVEFORM;	0-2 (100-140)	5-200 (6-200)	S,A	Portable printer and terminal for summary data. Remote based computer/plotter for waveform data.	U.S.A.	1,3 and 4	3 component seismic and air. Dial-up phone link central computer/printer /disc data storage.	Direct data interface with computer for time-history, Fourier & response analysis.	110V AC with standby 24V battery.	42	27(a) 27(b) 27(c)
Instantel DS-377 WAVEFORM;	0-8 (100-140)	2-250 (2-250)	M[4],S,A	Waveform and summary by pen printer/plotter. Computer type keyboard.	CANADA	1 & 3, +4 if manually digitized into computer.	3 component seismic, air and summary data on paper printout. 50 event auto. recording. Continuous recorder optional.	Visual estimate thru seismogram. Manual digitizing req. for computer analysis.	8V rechargeable battery. Ext.DC power plug. 2nd 8V battery req. for opt. heater.	42	N/A
Philip R. Berger & Associates: SSU II WAVEFORM;	0-2 (Max 145)	5-200 (6-200)	M	Waveform by direct photo print chart recorder. LED readout of seismic peaks.	U.S.A.	1,3 and 4	3 component seismic and air on paper printout.	Visual estimate thru seismogram. Manual digitizing required for computer analysis	12V rechargeable battery.	26	28
Philip R. Berger & Associates: SSU 1000D WAVEFORM;	0-4 (110-140)	2-256 (2-256)	S,A	Waveform and summary data by onboard dot-matrix thermal printer. Typewriter style keyboard panel.	CANADA	1 and 3, also 4 if computer analysed.	3 component seismic, air and summary data on paper printout. 40 event automatic recording per paper	Visual estimate thru seismogram. Manual digitizing req. for computer analysis.	6V rechargeable battery. External DC power.	29	29
Slope Indicator S-2 / S-35 WAVEFORM:	0-20 (Max 162) (5 gain settings)	5-150 (1-350)	M	Waveform by onboard direct photo print 7-channel chart recorder.	U.S.A.	1,3 and 4	Two 3 component seismic channels and optional air on paper printout.	Visual estimate thru seismogram. Manual digitizing required for computer analysis	12V rechargeable battery.	50	30 & 31
Slope Indicator S-6 WAVEFORM:	0-30 (Max 168)	5-200 (5-400)	S,A	Wave form and summary data by onboard strip chart. LCD display of summary data. RS232C interface for external printer or computer.	U.S.A.	1,3 and 4	Two 3 component seismic channels & optional air. Three storage/recall modes.	Spectral energy recorded within 11 frequency bands.(13 for air) Direct computer interface for analysis of waveform data.	12V rechargeable battery.	26	32
Sprengnether Instruments: VS-1200 WAVEFORM:	0-5[3] (Opt.)	2-200 (Opt.)	M	Waveform by onboard photo print chart recorder.	U.S.A.	1 & 3, +4 if manually digitized into computer.	3 component seismic on paper printout.	Visual estimate thru seismogram. Manual digitizing required for computer analysis	12V rechargeable battery.	52.5	33
Sprengnether Instruments: VS-1600 WAVEFORM:	0-6.4 (Max. 140)	4-200 (2-200)	M,S	Waveform by onboard photo print chart recorder. LCD display of summary data	U.S.A.	1 & 3, +4 if manually digitized into computer.	3 component seismic on paper printout.	Visual estimate thru seismogram. Manual digitizing required for computer analysis	12V rechargeable battery.	30	34
Vibra-Tech/ VME: Vibra-Tape® GMS-4 Series 2000 WAVEFORM:	0-4 (100-140)	2-200 (5-250)	M	Magnetic tape cassette[1]. Peak-hold meter peak data capture. Voice on sound channel capability.	U.S.A.	1,3 and 4	3 component seismic and air data stored on magnetic tape[2].	Visual estimate thru seismogram. Direct computer analysis available.	2 x 6V Lantern batteries.	28	35
Vibra-Tech/ VME: Vibra-Tape® Series 5000 EVERLERT WAVEFORM;	0-4 (100-140)	2-200 (5-500)	S,A	Digital grade magnetic tape cassette. LCD readout of summary data. Tape readback facility.	U.S.A,	1,3 and 4	3 component seismic, air and summary data stored on tape. Field recall of all summary tape data including time & date.	Visual estimate thru seismogram. Direct interface with computer for complete analysis.	2 x 6V rechargeable Lantern batteries. Ext. DC power supply & charger unit.	30	36
Vibra-Tech/ VME: SEISTECTOR PEAK;	0-.5,1 or 2 Factory set (N/A)	5-200 (N/A)	M	Bar graph on 30 day strip chart, with hourly timing marks.	U.S.A.	1 and 3	Max. component (or vector sum) continuous recording.	None.	110VAC with 8 hr standby battery (supplied) or 12V ext. battery	10	37
Vibra-Tech/ VME: VR Model F WAVEFORM;	0-4 (Max 140)	5-200 (5-200)	M	Waveform by onboard photo print chart recorder.	U.S.A.	1 & 3, +4 if manually digitized into computer.	3 component seismic and air on paper printout.	Visual estimate thru seismogram. Manual digitizing required for computer analysis	12V rechargeable battery.	35	38
Vibra-Tech/ VME: VR Model G WAVEFORM:	0-4 (NA)	5-200 (NA)	M	Waveform by onboard photo print chart recorder.	U.S.A.	1 & 3, +4 if manually digitized into computer.	3 component seismic on paper printout.	Visual estimate thru seismogram. Manual digitizing required for computer analysis	12v rechargeable battery.	35	39

Notes:
[1] 30 minute tape normally recommended by manufacturer.
[2] Time history, frequency spectrum, building response and computer analyses per OSM and USBM frequency responsive criteria available through consultants.
[3] Selectable velocity, displacement and acceleration output. Six gain settings.
[4] 7 second recording period in manual mode.
[5] Model S-3 has selectable velocity, displacement and acceleration outputs.

Table 4.

Instrumentation

Table 4, on page 61, is a summary of most of the instruments found in the field today including general descriptions of their important features, advantages and limitations. It is important to emphasize that these descriptions are, of necessity, very general. Many subtle differences exist in the design details of similar type instruments. Some of these differences may be insignificant for one application but vitally important in another. Engineering changes are also made regularly within given models to improve their operation and take advantage of technology advances. This is particularly true for the newer microprocessor-based models where software changes can be made which change their capabilities without any change in hardware.

It is therefore recommended that whenever instrument capabilities are in question, the manufacturer or the appropriate consultant should be contacted to obtain information regarding a specific instrument and the suitability of its intended application.

The illustrations contained in the following pages show almost all of the instruments described in Table 4 on page 61, and are referenced in the last column of that table.

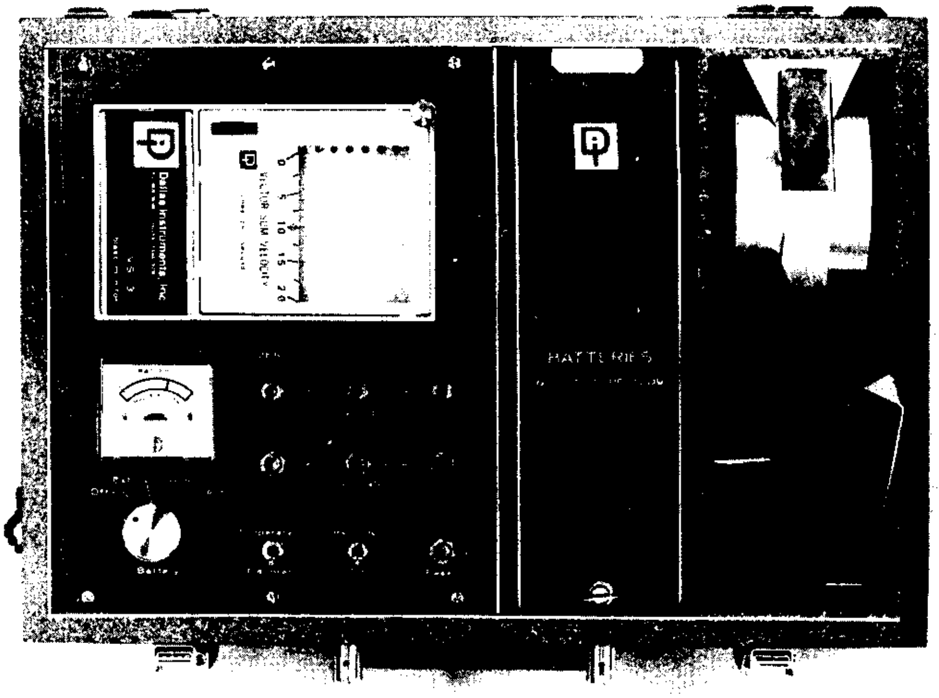


Figure 23.
Dallas Instruments VS-3.

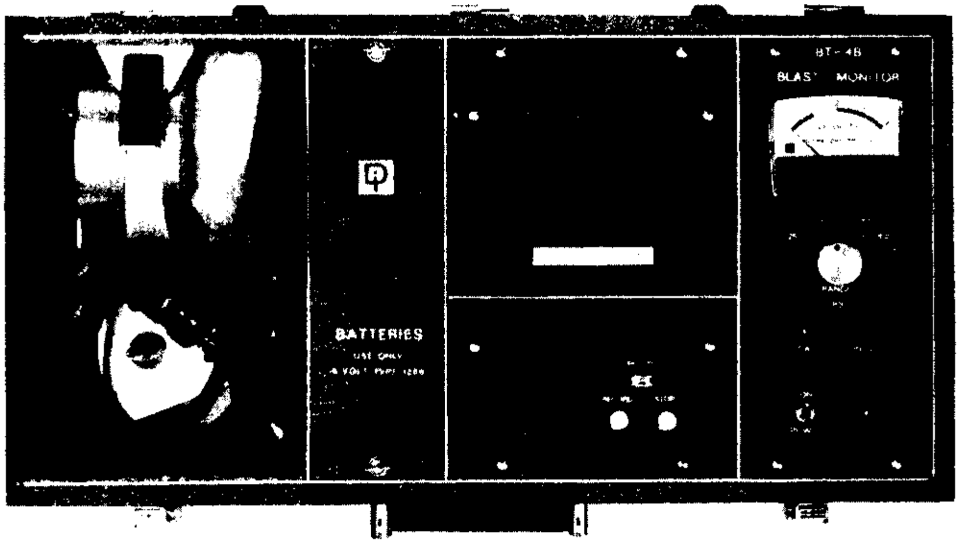
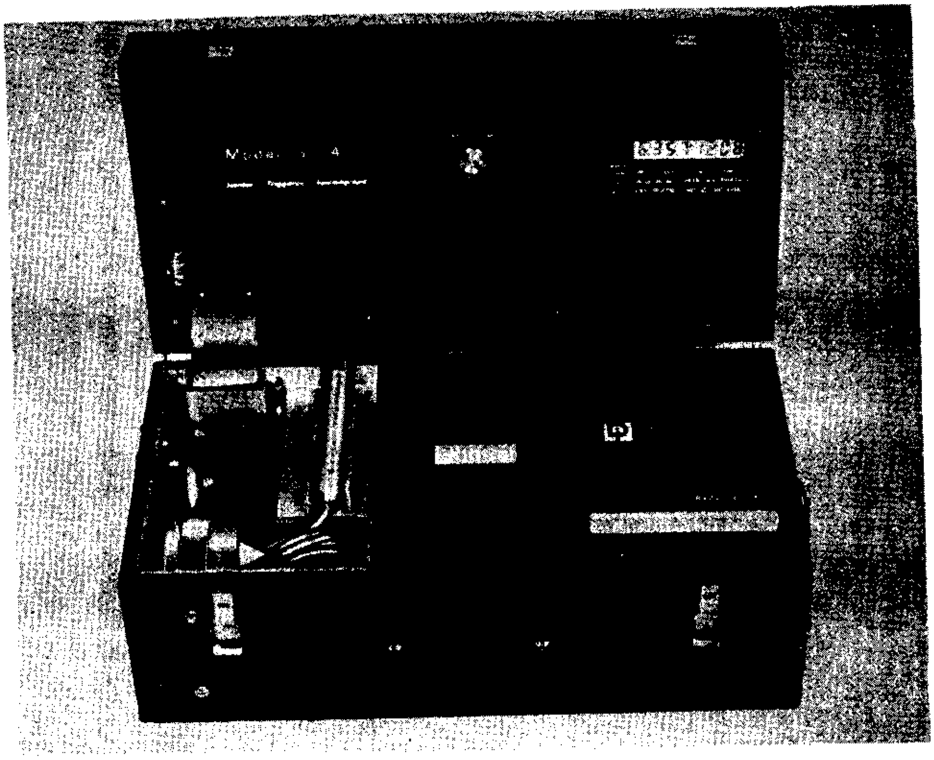


Figure 24.
Dallas Instruments BT4-B.



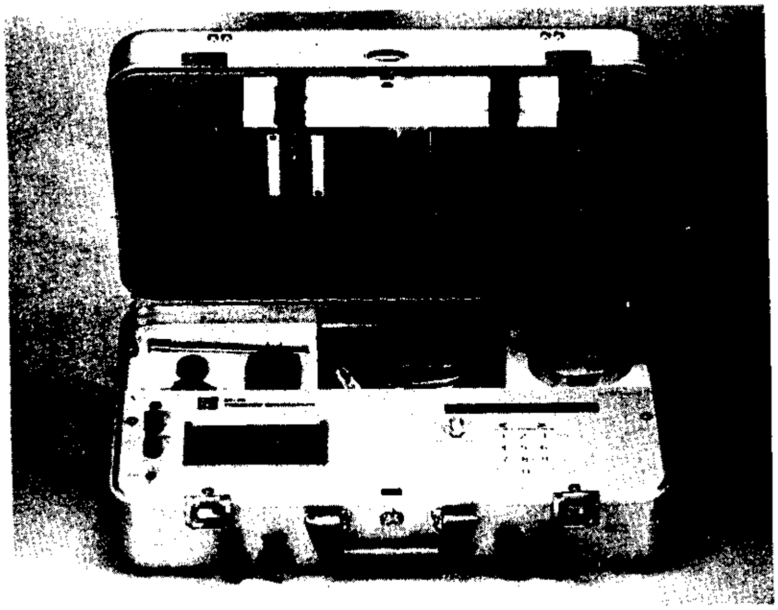


Figure 26.
Dallas Instruments ST-4D.

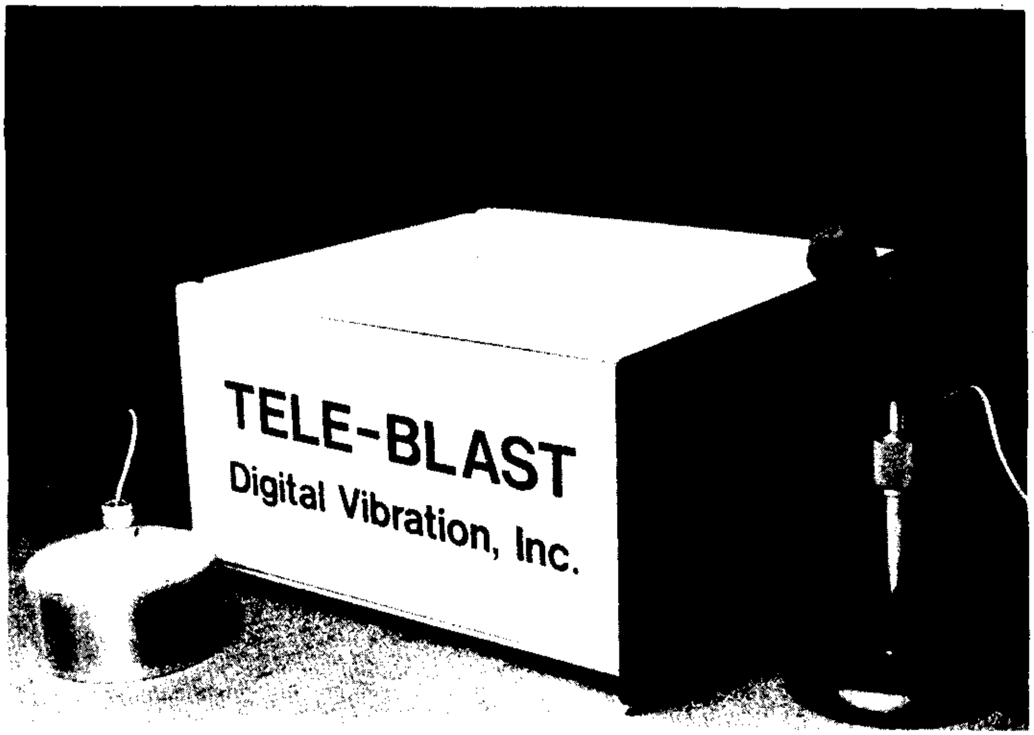


Figure 27(a).
Digital Vibration Teleblast.

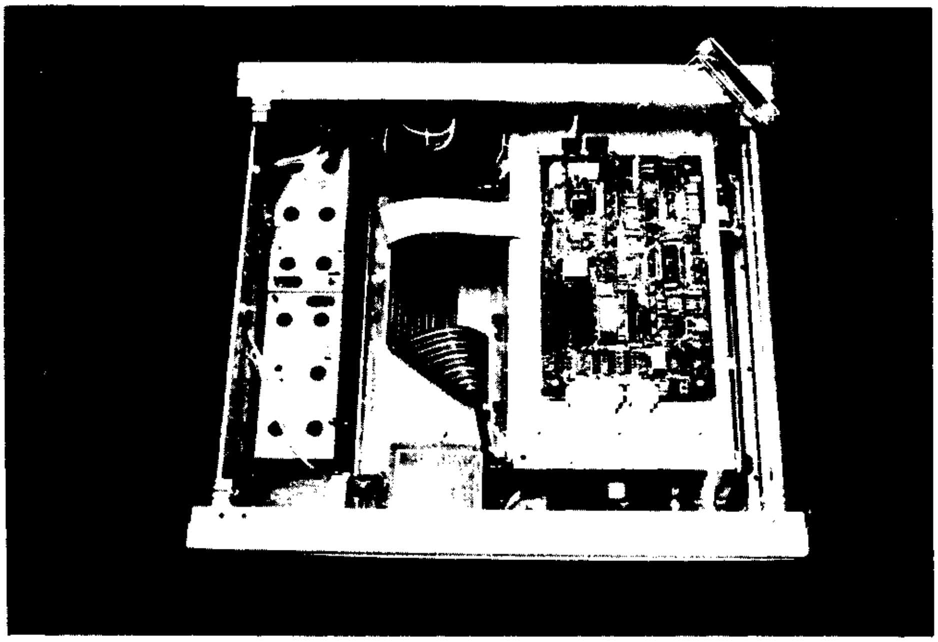


Figure 27(b).
Digital Vibration Teleblast.

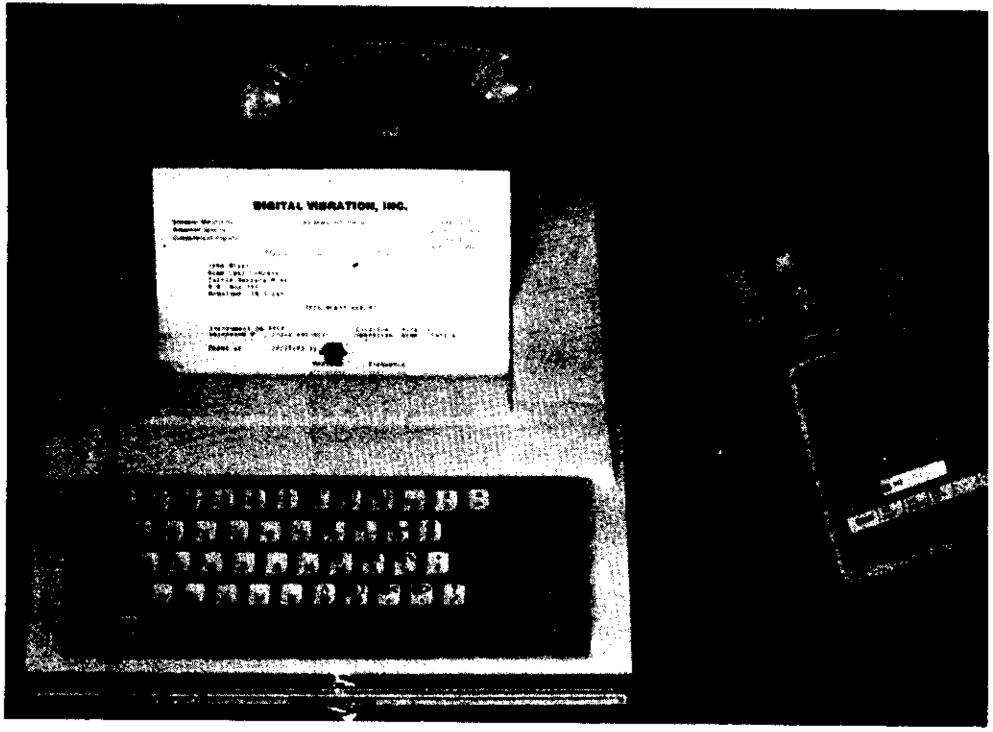


Figure 27(c).
Digital Vibration Teleblast.

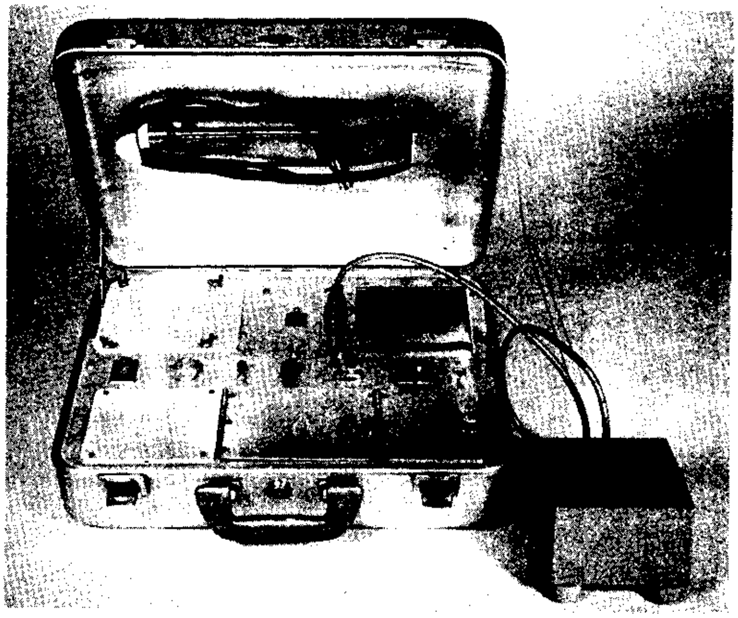


Figure 28.
Philip R. Berger & Associates SSU II.

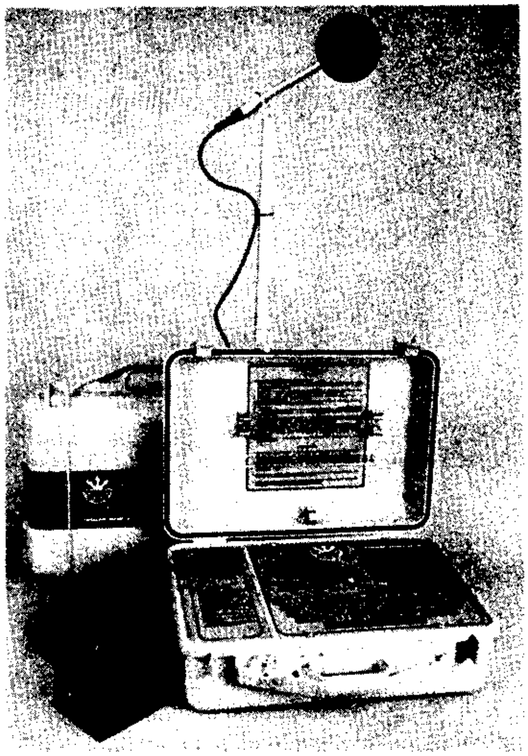


Figure 29.
Philip R. Berger & Associates SSU 1000D.

Figure 30.
Slope Indicator S-2.

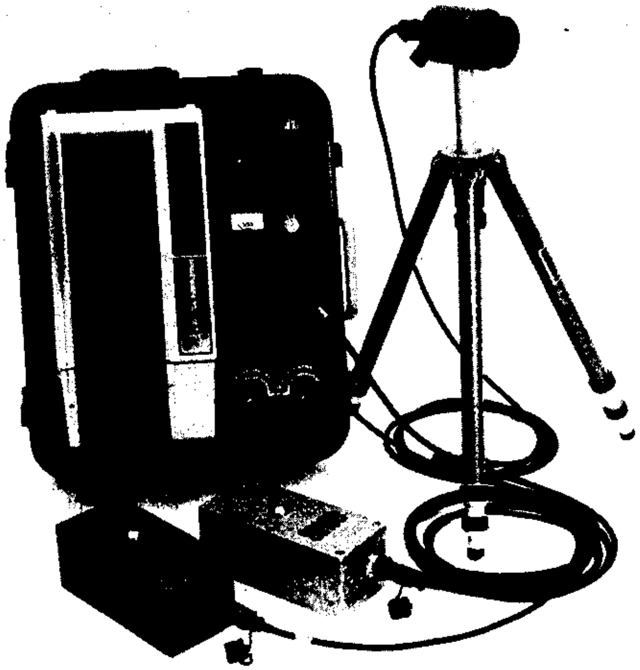


Figure 31.
Slope Indicator S-3.

Figure 32.
Slope Indicator S-6.

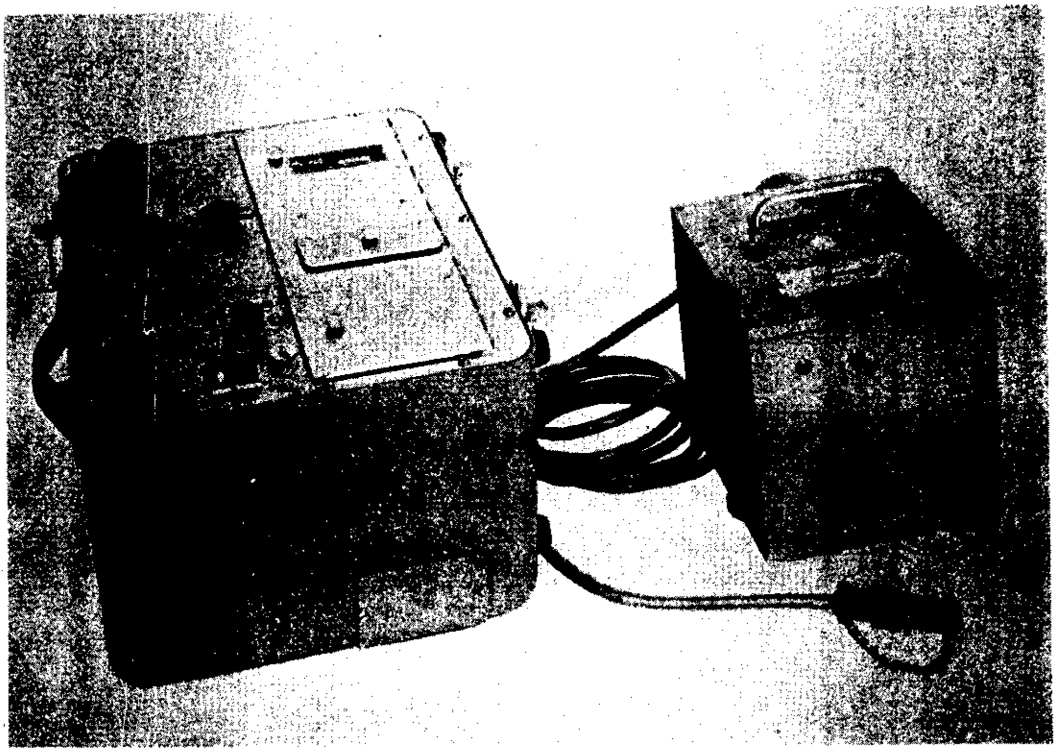


Figure 33.
Sprengnether Instruments VS-1200.

Figure 34.
Sprengnether Instruments VS-1600.

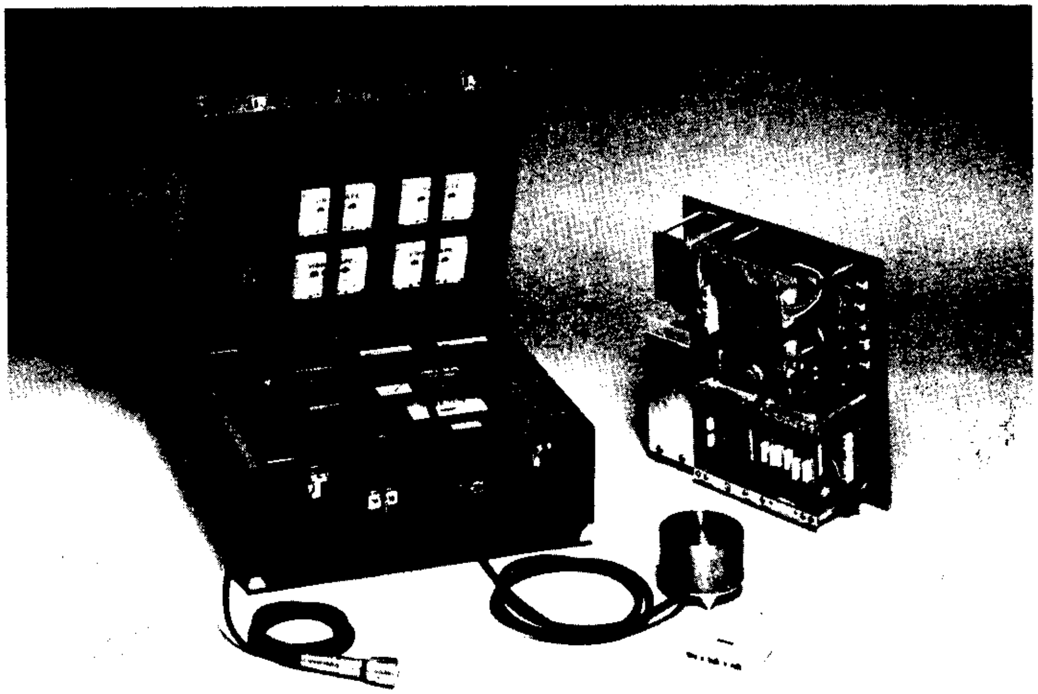


Figure 35.
Vibra-Tech/VME Vibra-Tape® GMS-4.

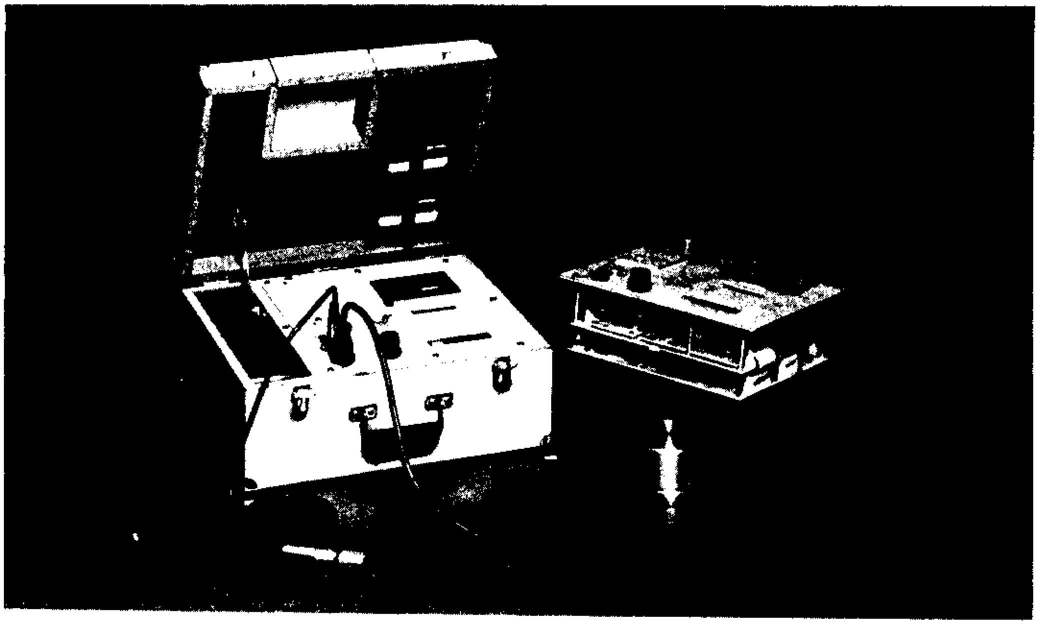


Figure 36.
Vibra-Tech/VME Vibra-Tape® Series 5000.

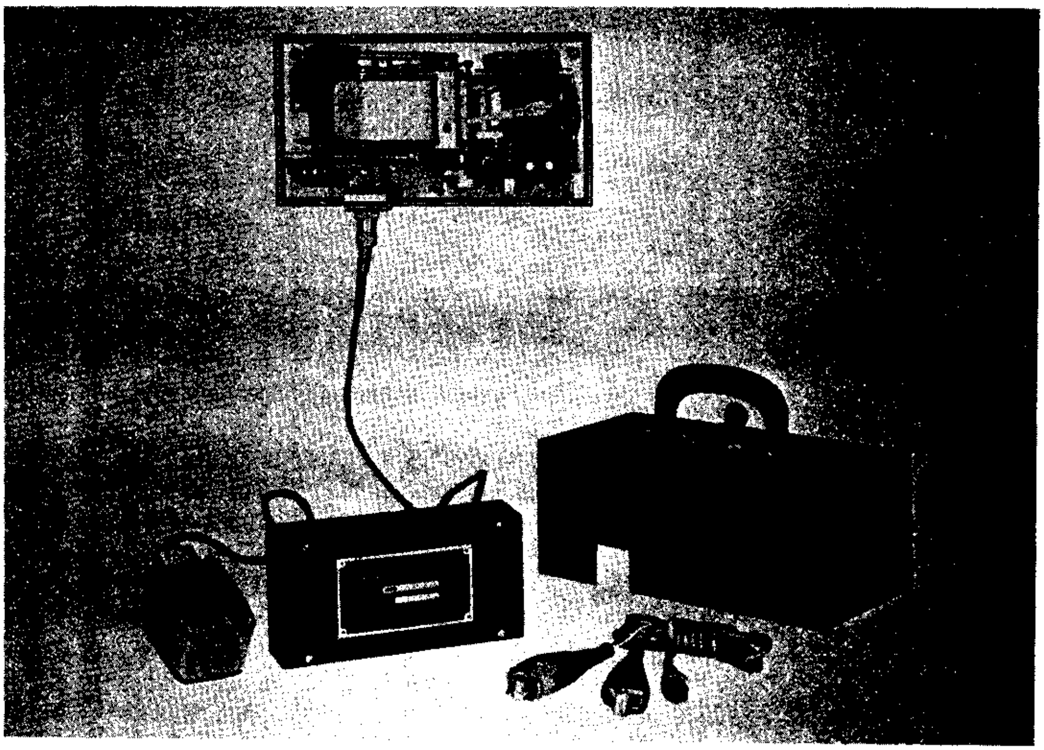


Figure 37.
Vibra-Tech/VME Seistector®.

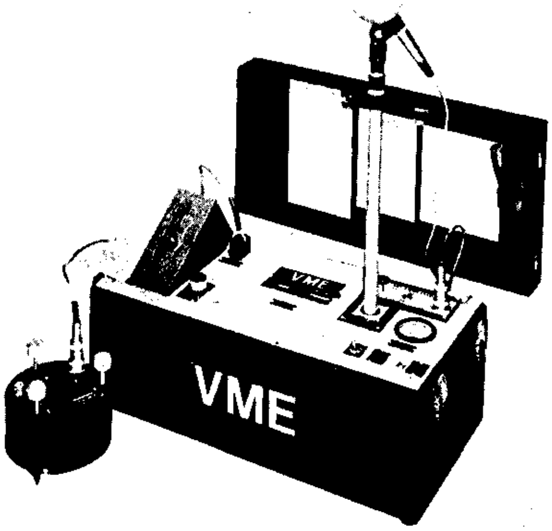


Figure 38.
Vibra-Tech/VME VR Model 'F'.

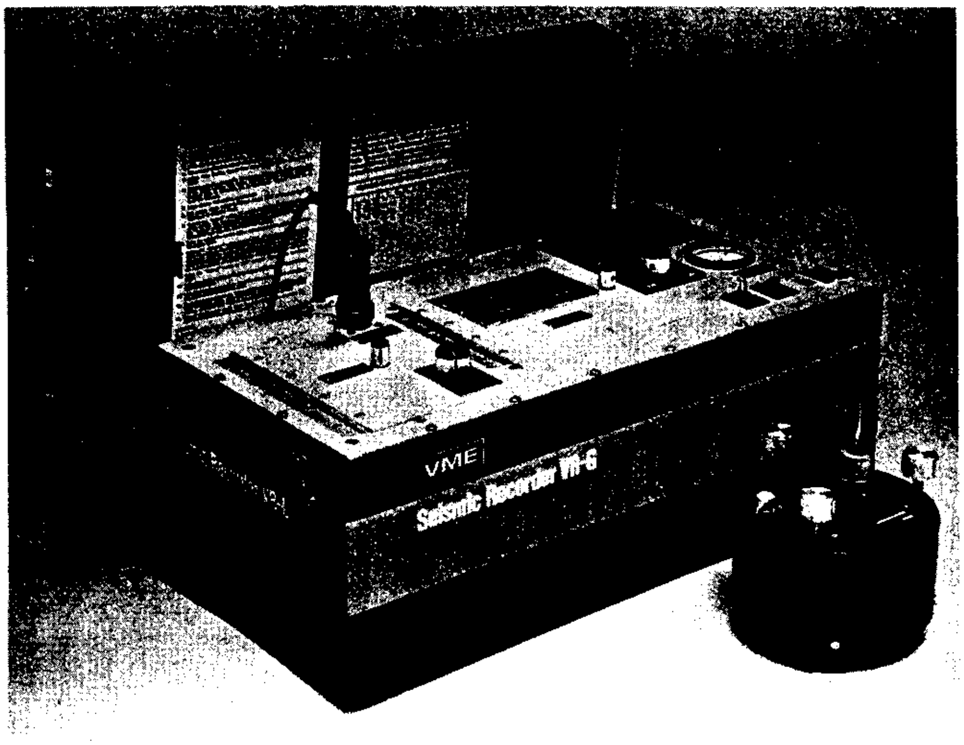


Figure 39.
Vibra-Tech/VME VR Model 'G'.

CHAPTER 9

COMPLIANCE OPTIONS AVAILABLE TO THE OPERATOR

GROUND MOTION

The OSMRE regulations allow the operator to choose from four optional methods to control ground vibration:

1. Section 816.67(d)(2)(i) Maximum Peak Particle Velocity: Providing that each shot is monitored, and a seismograph record is provided, this first option is DISTANCE related, and requires merely that:

(a) From 0-300 ft. distance: max. PV = 1.25"/sec.

(b) From 301-5000 ft. distance: max. PV = 1.00"/sec.

(c) From 5001 ft. to beyond: max. PV = 0.75"/sec.

2. Section 816.67(d)(3)(i) Scaled Distance Equation: This method does not require that blasts be monitored, but it relates a permissible MINIMUM SCALED DISTANCE (Ds) to DISTANCE, and requires adherence to these as follows:

(a) From 0-300 ft. distance: min. Ds = 50

(b) From 301-5000 ft. distance: min. Ds = 55

(c) From 5001 ft. to beyond: min. Ds = 65

3. Section 816.67(d)(3)(ii) Modified Scaled Distance: This is not distance related, but is based upon the collection of site specific data, and the statistical analysis of this data, using the predictive methods covered in the "PREDICTION AND CONTROL METHODS" Chapter in this manual.

4. Section 816.67(d)(4)(i) and (ii) Blasting Level Chart: This is the most precise, and also the most unrestrictive option available to the operator. It requires the monitoring, recording and analysis techniques that provide complete frequency information, since the vibration limitations imposed, up to 2.0 inches per second, are frequency related.

Discussing these options in order, and referring to them throughout this manual, and in Table 4. (Page 61, Instrumentation) as Options 1, 2, 3 or 4, it is possible to detail them, together with their advantages and disadvantages.

OPTION 1: MAXIMUM PEAK PARTICLE VELOCITY

This option, and option 2, Scaled Distance equation, might at first sight appear to be illogical in that the closer a structure is to the blast, the higher the velocity (or lower the scaled distance) that is allowed. Common sense would seem to advise the reverse. However, because of the fact that higher frequencies are less damaging to structures than lower frequencies, and that the closer to a blast, the higher are the frequencies, this regulation is, in fact, perfectly reasonable.

Option 1 is the simpler of the options that require monitoring on a permanent basis, and will permit the second highest vibration levels. It only requires peak effect monitoring, without any frequency reference, and all of the measurements can be made at, or outside, the permit area, usually at the particular structure of concern.

OPTION 1 ADVANTAGES:

- "Peak only" reading instruments are acceptable.
- No frequency information is needed.
- Little operator expense involvement.
- Maximum PV of up to 1.25"/sec. are allowed at short distances (when higher maximums may be more useful).
- Generally permits shorter distances and/or higher charges per delay than the scaled distance options.

OPTION 1 DISADVANTAGES:

- Every shot must be monitored.
- Does not permit the maximum velocities allowed under option 4.
- Each shot might have to be monitored in two or more separate locations, dependent on distances.
- If peak only reading instruments are used, will not assist in identifying potential blasting problems.

OPTION 2: SCALED DISTANCE EQUATION

Option 2 is the only non-site specific option, and therefore, being based on generalized data collected over the whole of the U.S., it is the most restrictive, although it is undoubtedly the simplest of all the ground motion compliance options. It requires only that the distance from the shot to the point or structure of interest is related to the maximum charge weight per delay, as a square root scaled distance, thus:

$$Ds = D/W^{\frac{1}{2}}$$

Where D = the distance, in feet; and

W = the maximum charge weight per 8 ms. delay period, in lbs.

Since this formula can be rewritten:

$$W = (D/Ds)^2$$

then, substituting Ds according to the regulation and the actual distance, it becomes easy to calculate a maximum charge weight per delay allowable at that distance.

The following table shows allowable maximum charge weights per delay under this regulation, at various distances:

DISTANCE-FT	MINIMUM Ds	MAX. CHARGE WT/DELAY, LBS.
100	50	4.0
300	50	36.0
310	55	31.8
330	55	36.0
500	55	82.6
1,000	55	330.6
2,000	55	1,322.3
5,000	55	8,264.5
5,100	65	6,156.2
5,900	65	8,239.1
6,000	65	8,520.7
10,000	65	23,668.6

The above figures naturally show some anomalies at the regulatory Ds change distances of 301 ft. and 5001 ft.; however, since it is most likely that when this option is adopted the conditions will not be critical, and the distances will probably be over 2 or 3 thousand feet, this is of no great consequence. The regulation itself is written to allow blasting at distances less than 300 ft., with no minimum distance stipulated, provided that the requirements of Section 761.11(e) are complied with (mainly that the owner of any occupied dwelling within a radius of 300 feet has provided a written waiver consenting to such operations). Although the regulation allows a minimum scaled distance at these short distances, the charge weights per delay permissible are usually too small to permit any practical production mine blasting. Really effective control of blast vibrations at short distances is far better left to Option 4, the Blasting Level Chart.

Whenever blasting is carried out, and instruments are not used to record the vibrations, it becomes increasingly important for the operator to take all possible steps to reduce ground motion and airblast. It is therefore imperative, when monitoring is not being done, that utmost care be taken to minimize vibrations. (See pages 33, 35, 40, 41, 42, 43 and 44, and Figures 14 to 17 in this manual).

OPTION 2 ADVANTAGES:

- No monitoring is required.
- Simple scaled distance control only.
- Minimum cost.

OPTION 2 DISADVANTAGES:

- The most restrictive of all the options.
- Not related to actual velocities: least effective protection in the event of complaint situations.
- Impractical at short distances.
- Only effective under non-critical distance/charge weight relationships.
- Will not assist in identifying potential blasting problems.

OPTION 3: MODIFIED SCALED DISTANCE

This, and option 4, are far more effective under more critical conditions than is option 2. Both options 1 and 3 rely on site specific measurements, but option 3 translates these measurements into a statistically predictive scaled distance, with a confidence level of 95%. This avoids the need for regular monitoring of every shot, although it must be stated here that once a modified scaled distance is authorized by the regulatory authority, it must be subject to periodic review and renewal. This is discussed specifically later in this chapter.

The methods by which the site specific vibration measurements are converted into a scaled distance formula are detailed in this manual's Chapter 10 on PREDICTION AND CONTROL METHODS. Computer and calculator programs are provided in Appendix 'A' (pages 135 to 165) for those who wish to process their own data, although it is recommended that this type of predictive work be done, if possible, by experienced blast vibration consultants, because of the many pitfalls that can beset the inexperienced venturer in this field.

For the purposes of this section, however, these methods will be described only in outline, with emphasis being placed on compliance, and their relative advantages and disadvantages to the operator, as has already been done for options 1 and 2.

The first point that must be firmly established regarding option 3 concerns the amount of data that is needed to assure authorization of a modified scaled distance. The answer to this is complex:

It must be realized that when statistical sources are consulted for the answer to this question, they only provide the information that the 'n' value, the number of data pairs required for a valid statistical analysis, should be "large". For the purposes of this manual's guidance, 30 or more data pairs will be considered a suitably large 'n' value. Therefore, the following qualified answer is offered:

<u>If the data is good; a minimum of 30 data pairs are acceptable.</u>

Obviously, the real qualifier is the goodness of the data. There is a simple solution to the problem, however, based on the fact that the prediction methods used work very well provided the data used is collected sensibly, accurately, and consistently. Therefore, when embarking on a program to collect data to form the basis for an authorized modified scaled distance, these basic rules must be adhered to:

1. Remember that the data pairs needed are peak particle velocity versus scaled distance. So as to properly utilize options, scaled distance data must be collected as distance in feet with maximum pounds of explosive per delay period.

2. When collecting scaled distance data, do so on the basis of:

(a) Measured distances (NOT GUESSED).

(b) Measured explosive weights (NOT GUESSED).

Careful explanation to the blasting crew of the methods and purposes will help here. Do not simply rely on the figures written on the reports; check personally to see that they are factual.

3. When recording blast vibration data, do so on the basis of the maximum peak particle velocity that occurred in any plane, for each shot. One instrument recording is required for each velocity data point. If more data is required, per blast, then more instruments must be used.

4. Separately identifiable data should be recorded for coal shots and overburden shots. Sometimes the characteristics will be close enough between the two to permit a common scaled distance formula, but frequently this is not the case. Other similar significant geological variations will also require separation of the data in this way.

5. Collect data at as wide a range of scaled distances as possible: see remarks on this subject on Pages 48 and 49, and also on Page 133, Appendix 'A'. In any event, data MUST be collected at at least as low a scaled distance as it is hoped will be authorized and preferably lower than this.

6. Collect data at an even spread of scaled distances between the highest and the lowest.

7. Collect data consistently, using the same instrumentation, recording it in the same geological formations, and avoiding interposed features that might cause higher or lower than normal results, such as streams, hills or excavated areas, etc. (See Figure 56. in Appendix 'A', page 131.)

8. Exclude data where it is known that conditions were not normal. For example, if it were known that propagation occurred, or if there were misfires, etc.

Once these rules are observed, it will be found that the collected data is good. If problems persist in terms of getting good data, then it is time to start looking for problems that may not be known to exist. The fact is that careful monitoring can lead to a more efficient and trouble-free operation, and this should be encouragement and motivation in itself.

The final results of these calculations, together with the supporting data, must be submitted to the regulatory authority for approval. Authorization for a modified scaled distance will be forthcoming, as long as the data is good; as long as there are sufficient data pairs, and if the calculations are correct.

Once a modified scaled distance has been authorized, it must be reviewed and renewed from time to time. This is one point that is not covered by the regulations, although it is of great importance. Particularly on the larger surface mines, the area in which today's operations are taking place may be a significant distance from the area in which last year's operations took place. The geographic and geological differences can well mean that the site specific formula for last year is no longer specific to this year's site.

It is recommended that modified scaled distances be reviewed, updated if necessary, and re-authorized at least annually. The data required for this would be as for any initial modified scaled distance application.

Although this third option would seem to require a great deal of effort and application, it provides a site specific velocity attenuation formula that can be of inestimable value in the event of complaints from unexpected quarters - and sometimes great distances. Where it might have been thought quite unnecessary to monitor, a complaint situation frequently will cause the operator to wish he had had the foresight to have taken some readings at the complaint site. The existence of a site specific attenuation formula will offset this omission to a very large degree, since instead of a site specific measurement, a calculation based on the attenuation formula can often establish clearly that a damage situation was not possible.

OPTION 3 ADVANTAGES:

- No regular monitoring required.
- "Peak only" instruments acceptable.
- No frequency information needed.
- Maximum of 1.25 inches per second allowed at short distances, based on the site specific rather than general data.
- Provides reasonable protection in complaint situations.

OPTION 3 DISADVANTAGES:

- Does not offer minimum restriction to operations.
- Must be reviewed and renewed at least annually.
- Offers less complaint or lawsuit protection than frequency responsive methods.

OPTION 4: BLASTING LEVEL CHART

This is undoubtedly the least restrictive of the four available options and although it may appear to be the most costly, it can offer the most in side benefits and cost savings to the operator.

Every shot must be monitored, and a frequency responsive instrument must be used. As has already been discussed, however, the advantages that accrue from the use of such instruments should not pose too great an additional burden in this respect. In addition to this, the latest computer analysis techniques provide an easy to understand (and easy to verify) graphic representation, so that compliance can be checked at a glance. Figure 40, which shows a typical computer analysis printout for a Vibra-Tech GMS-4 Analog blasting seismograph, illustrates this point. For each of the three planes, the computer will print out a particle velocity versus frequency graph, very similar to the Figure 1. (OSMRE Regulations) Blasting Level Chart, complete with the frequency responsive maximum velocity indication on it. As long as the velocity versus frequency graph lies below the maximum velocity limit line, it is a clear indication that the vibrations are in compliance.

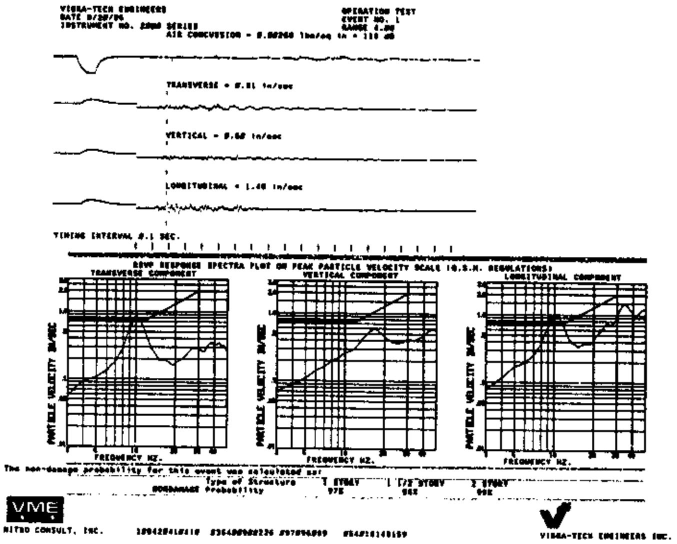


Figure 40.
Typical computer printout of blast vibration waveforms.

The data gathered when this option is exercised are also the most useful, both in terms of protection from damage claims and lawsuits, and also for predictive purposes. Since the frequency at which the maximum vibrations occur is known, in all three planes, the possible effects will also be much easier to demonstrate and to predict.

When more critical conditions are approached, at closer distances, the predominant frequencies of the ground motion tend to get higher. Therefore, in general, it will be found that the closer the blasting is to a structure, the higher are the permitted velocities. When at or over 30 Hz, 2 inches per second is permitted. When this higher velocity limitation is coupled to the fact that any predictive exercises are based on current site specific information, it will be realized how far less restrictive to the operator this last option is.

It should be noted at this point that frequency determination is not a simple procedure, as careful scrutiny of Figure 40 will confirm. If reference is made to the preamble to the Rules and Regulations (Federal Register, Vol 48, No.46, Tuesday March 8, 1983) on page 9802 OSMRE states:

> "Commenters requested clarification as to what was required to evaluate blast vibration frequency. They wanted to know whether visual inspection of seismographic records was adequate or whether electronic analysis of frequency would be required. Under Section 816.67(d)(4), which requires regulatory authority approval of the method of analysis of the predominant frequency contained in the blasting records, visual inspection may be adequate if traces are distinct and only a few frequencies are contained in the wave-form. However seismographic consultants have found that various waves with multiple frequencies typically are contained in the blasting record. In those cases, electronic analysis is necessary to separate the wave traces and analyze each intensity and frequency. OSM does not intend to mandate electronic analysis; rather the determination of what type of analysis is appropriate should be made by the regulatory authority .... Except when the criteria of Section 816.67(d)(4) are used, the final rule leaves frequency analysis to the discretion of the regulatory authority. OSM recognizes its value as an indicator of vibration damage probability, but also recognizes the complexity and expense in its application ...."

This fourth option can be most usefully employed if it is used in conjunction with the predictive techniques described in Chapter 10, PREDICTION AND CONTROL METHODS. Quite apart from the benefits that these techniques provide when unexpected or unusual complaint situations arise, they are the only methods that permit blasts to be detonated, knowing in advance that velocity limitations will not be exceeded. Once that capability is properly understood, and these techniques are utilized to the full, the guesswork and uncertainty in blast design can be virtually eliminated, certainly as far as vibrations are concerned. A distance will be known, and it will be known from previous records just what the predominant frequencies will be. The maximum permissible peak particle velocity can then be found, and, using the regression techniques mentioned, a safe scaled distance, relative not only to those exact site characteristics, but to that particular shot, can be established. Once that is known, the blaster can be told his maximum permissible charge weight per delay. He is then totally free to design his shot, with an absolute minimum of restrictions. He can always, therefore, work to the optimum conditions. The shot is monitored, for confirmation of compliance, and the new data is added to the old data and run through the predictive techniques once more, so that the next shot will again be based on totally up-to-date and current predictive information.

Notwithstanding the apparent - and actual - effort involved with this option, it will be found that this effort will be amply repaid in terms of minimum restrictions, optimum blasting efficiency, maximum protection and complete compliance.

OPTION 4 ADVANTAGES:

- Least restrictive: permits highest velocities, maximum loadings and shortest distances.
- Permits greatest freedom in blast design.
- Greater freedom in blast design can result in lower drilling costs, optimum drilling and blasting efficiency.
- Maximum liability protection.
- Complete compliance.
- Greatest total savings.
- Employs OSMRE encouraged use of response spectra (see page 81).
- Provides OSMRE approved evidence of regulatory compliance and damage potential.

OPTION 4 DISADVANTAGES:

- Every shot must be monitored.
- The instrument must be frequency responsive.
- Highest cost, neglecting possible savings offset.
- Needs careful and thorough implementation.

When considering any of the above options, only the operator can really decide what is best for his own particular situation. The simplest and cheapest options tend to be more restrictive, and do not offer the side benefits that frequently moderate the apparent cost and effort involved in the less restrictive options.

CHAPTER 10

PREDICTION AND CONTROL METHODS

When any monitoring methods are carried out that collect vibration data against distance and explosive weight data, it is possible to analyze that data in such a way that it becomes an indicator of the vibration effects for future blasting and not merely a record of past events. Since it is obviously better to know in advance whether blast vibrations will be excessive, rather than merely to record them hopefully, these prediction and control methods are presented as the core of efficient, safe and responsible blasting operations.

Whether the purpose is to develop a modified scaled distance, for compliance under Section 816.67(d)(3)(ii), or to ensure that the limits imposed under Section 816.67(d)(2)(i) or (4)(i) and (ii) will not be exceeded, or simply to control critical blasting effects, the basic technique is the same. The underlying principle is that each mine or blasting site is different from another, and that minor differences exist within each site, such as the geology and techniques of blasting, hole size and depth, drill and blast pattern, and blast hole loads, in addition to the location and distance to structures of concern.

Scaled Distance (Ds) is a fundamental relationship between distance in feet from the blast to the recording instrument or point of concern and the maximum explosive charge weight in pounds per 8 ms delay period. It is expressed as the distance, feet, divided by the square root of the charge weight per delay, pounds, thus:

$$Ds = D/W^{\frac{1}{2}}$$

When statistical analysis techniques are applied to blast vibration data pairs, peak particle velocity against the scaled distance at which that velocity was measured, a site specific velocity attenuation formula can be developed. The technique is known as a least squares regression analysis, and the velocity attenuation formula takes the form:

$$V = H(Ds)^{-\beta}$$

where V = peak particle velocity, inches/second,

H = particle velocity ('y' axis) intercept at $Ds = 1.0$,

Ds = scaled distance, and

β = curve slope (decay exponent - always negative).

The variable values H and β are constants for each particular site: each regression analysis carried out on the PV/Ds data pairs will determine a specific value for each of these terms. Generally speaking, H can vary between perhaps as low as 20 or 30 to as high as 1000 or more. The slope β will normally be no lower than -1.1 or -1.2 or so, and will sometimes be as high as -2.2 or -2.4. The often quoted and referenced general use velocity attenuation formula published in the DuPont Blasters' Handbook (16th Edition, p. 426) is:

$$V = 160(Ds)^{-1.6}$$

This is of course, very conservative, and is not site specific, being derived from data obtained over a very wide range of geographically and geologically different blasting sites. Conservative as this formula is, it is not as conservative or limiting as the dictates of Section 816.67(d)(2)(i) and (3)(i). The following table relates the two and indicates the need for proper site specific velocity determination and prediction techniques, whenever the local conditions are anything more than completely non-critical:

DISTANCE	Ds(3)(i)	PV(2)(i) (Permitted)	PV (DuPONT FORMULA) (Probable max. actual)
0-300 ft.	50	1.25"/sec.	0.30"/sec.
301-5000 ft.	55	1.00"/sec.	0.26"/sec.
5000 ft. +	65	0.75"/sec.	0.20"/sec.

It is this type of restriction - essential when no monitoring is to take place - that can be circumvented and replaced by site specific, factual and far less restrictive compliance options when prediction and control methods are fully exploited.

A plot of particle velocity versus scaled distance is a complex curved line on linear graph paper. To show this relationship as a straight line, and to compress a wide range of values onto a single sheet, the plot is made on logarithmic co-ordinates. The slope of the curve, being negative, shows that as the scaled distance increases, the peak particle velocity decreases.

The data pairs, carefully and systematically collected as discussed in Chapter 9 (Compliance Options: Modified Scaled

Distance) are input to the regression analysis calculation, which can be performed on any small computer, or even a programmable calculator. The resultant equation is for a geometric curve in the form:

$$y = ax^{b}$$

or:

$$\log y = \log a + b \log x$$

which shows a linear relationship between both x and y in terms of logarithms. Drawn on 3 cycle "log-log" paper, the curve can be represented as a straight line, and can accommodate a scaled distance range of 1 to 1000, and a peak particle velocity range of 0.01 to 10.0 inches per second.

The statistical confidence level adjustment procedures described in this manual are those commonly used throughout the blast vibration control profession, and therefore:

- If the data collection methods recommended in this manual are closely adhered to,
- If at least thirty data pairs are obtained (preferably in excess of thirty),
- If the data is properly distributed,
- If appropriate distinction is made between coal, overburden, and presplit blasts, and
- If the topography between the blast and seismograph is sensibly considered,

then the regulatory limits will not be exceeded.

To assure the reliability of the equation, the attenuation formula must be adjusted statistically to a 95% confidence level, and the 'goodness of fit' or coefficient of determination (r^2) of the data should be no less than 0.7. The standard deviation, used in establishing the confidence level, should be as close as possible to zero. In actual fact, it is not likely under practical conditions that the standard deviation will be less than 0.2, but it should not be much greater than 0.5 or so.

If the standard deviation becomes too large, the H variable of the attenuation formula will increase to the point that the 95% confidence level will only be attainable at large scaled distances, approaching the non-site specific scaled distances allowable under Section 816.67(d)(3)(i). In order to derive maximum benefit, in this respect, the standard deviation should be reasonably low.

When the goodness of fit is too low, below 0.7 or so, this is an indication that there is some problem or inconsistency in the data. When this occurs, a review of the data and test procedures is advisable, and a series of additional tests must be carried out.

Even if the data is not usable in a predictive manner, or if a modified scaled distance cannot be established in this way, the results are still of great value. This might be the situation where the analysis, while not providing the looked for results, has nevertheless made a clear statement that must not be ignored:

> "THE DATA IS NOT GOOD! Look for a problem that may exist in the data collection, recording methods, drilling and blasting procedures, or blast design."

While this may not actually identify the problem, it has alerted the operator to the fact that a problem exists. If he then reviews his records and procedures, if he then looks for the difficulty, the chances are very good that some sort of inconsistency or deviation will be found. Once identified in this way, corrective action can be taken, and a problem will be resolved which otherwise would have gone unrecognized.

The resultant information should never be regarded as final, as long as some ongoing vibration monitoring is to take place. As soon as new data becomes available, it may be added to the old, and the attenuation formula, and supporting information, constantly updated for optimum reliability.

PREDICTIVE DATA: USAGE FOR MODIFIED Ds

Once a minimum of 30 data pairs has been collected and the regression analysis performed, by the mine operator or by an independent consultant, the analysis and supporting data must be submitted to the appropriate regulatory authority. On approval, a specific attenuation formula will be authorized for use at the location where the data was collected.

In order to determine exactly what modified scaled distance must be used in planning the blast, the distance to the structure of interest or concern must be known, so that the appropriate maximum peak particle velocity may be arrived at under Section 816.67(d)(2)(i).

Let it be supposed, for example, that the distance in question was 1385 ft. From the regulation, at this distance the maximum allowable peak particle velocity would be:

1.00 inch/second.

Let it also be supposed that the site specific attenuation formula derived from the collected data was:

$$V = 149.2(Ds)^{-1.51}$$

Since this formula can be rewritten:

$$Ds = (149.2/V)^{1/1.51}$$

substituting the allowable 1.0 inch per second velocity for V will give, at the distance of 1385 ft., a modified scaled distance of:

27.5

NOTE: This scaled distance is for this shot only, in terms of a maximum of 1 inch per second velocity, at the structure of interest, at a distance of 1385 ft. It has to be recalculated for every other shot, dependent on the distance to the structure of interest, which in turn dictates the allowable velocity.

Since the scaled distance formula:

$$Ds = D/W^{\frac{1}{2}}$$

can also be rewritten as:

$$W = (D/Ds)^2$$

again, using this example's values for substitution, it can therefore be calculated that using the modified scaled distance, the maximum explosive charge weight per delay that could be detonated at 1385 ft. distance would be:

2536 lbs.

Using the Section 816.67(d)(3)(i) scaled distance regulation alone, at 1385 ft., a scaled distance of 55 would have been permitted, allowing a maximum explosive charge weight per delay of only:

634 lbs.

Obviously, this is only a hypothetical example, but the attenuation formula selected for the argument is not in any sense extraordinary. The increase in allowable charge weight, according to circumstances - and care in collecting the base data - may be less, even considerably less, but it could even be more. What this example does try to illustrate, however, is that the potential to remove, or lighten the restrictive load on the operator is a very significant one. From being restricted to no more than 634 lbs. per delay to over 2500 lbs. per delay does not mean that the operator has to shoot 2500 lbs. per delay, but it does mean that he can design his blast up to that charge weight per delay in terms of drilling costs, optimum breakage, and blasting efficiency, rather than simply to comply with the regulations.

Appendix 'A', between pages 135 and 149, contains a complete computer program, written in BASIC, that will run on the majority of small IBM and IBM compatible computers, from the IBM PCjr., through the PC to the AT. This program is designed specifically to embody all the requirements of the OSMRE regulations, and to permit all the necessary steps to be taken to prepare a modified scaled distance application to be submitted to the regulatory authority. Also included in this appendix is a reference to a general use regression analysis program that will permit complete and versatile control of blasting vibrations, without specific reference to the OSMRE regulations, and a similar, but simpler, hand calculator program, on pages 164 and 165.

PREDICTIVE DATA: USAGE FOR COMPLIANCE WITH SECTION 816.67(d)(4)(i) - BLASTING LEVEL CHART - AND FOR GENERAL AND CRITICAL PREDICTIVE PURPOSES.

For compliance, the collected data must be frequency responsive, as already discussed. While the basic techniques are the same, the maximum permissible velocity is based on the predominant frequency of the vibration, rather than on the distance alone.

Let it be assumed that the data collection and regression analysis provided the same attenuation formula as in the previous example. Taking a critical, close distance example, for comparison purposes, let the distance from the blast to the structure be 275 ft., permitting a maximum of 1.25 inches per second under (2)(i), and let it be assumed that in the case of the frequency responsive data, the predominant frequencies at this short distance were in excess of 30 Hz, allowing a maximum velocity under (4)(i) of 2 inches per second.

Under (2)(i) the modified scaled distance would become 23.7, allowing a maximum explosive charge weight per delay of:

134.6 lbs., at 275 ft.

If compliance were sought under (4)(i), while the operator must still monitor every shot for both velocity and frequency, the scaled distance that could be used to design the next shot would be:

$$Ds = (149.2/2)^{1/1.51} = 17.4$$

allowing, at 275 ft. distance:

$$W = (275/17.4)^2 = 250 \text{ lbs. per delay.}$$

Again, using precisely the same attenuation formula, and only changing the method of compliance - the operator's option - it is clear that nearly twice the weight of explosive can be detonated! At close distances, under critical conditions, this kind of difference can truly be said to provide relief from restriction. Efficient and practical blasting methods can indeed be used at close distances, and the operator will remain in complete compliance with OSMRE regulations. Care must be exercised, however: though these calculations are based on the statistical probability of NOT exceeding 2.0 inches per second at a confidence level of 95%, and it is therefore likely that recorded vibrations will be well below this level, nevertheless IF a velocity in excess of 2.0 inches per second were recorded then the operator would be subject to a violation.

Quite apart from considerations of compliance or not, these methods offer complete control and protection when:

- Blasting has to be carried out within short distances of sensitive structures well within the permit area.
- Allegations of blasting damage are made at locations, distant or close, where no vibration measurements had been made. The maximum possible effects can be accurately calculated.

These methods and applications are discussed fully in Appendix 'A', together with examples of typical calculations.

CHAPTER 11

FREQUENCY CONSIDERATIONS

It is important to be able to determine the frequency content of a ground vibration signal because the response of structures to blasting vibration is dependent on both particle velocity and frequency. Frequency is the number of oscillations per second that the ground surface vibrates as the seismic energy created by a blast passes by a particular location. Frequency is usually expressed in units called Hertz (Hz). (1 Hz = 1 oscillation per second.)

A structure, like a tuning fork, will vibrate at a fundamental natural frequency when excited. The maximum response of a house to blasting vibration occurs when the frequency of the ground motion matches the natural frequency of the house. On the other hand, when there is a mismatch between the ground vibration frequency and the natural frequency of the house, very little energy is transmitted into the structure.

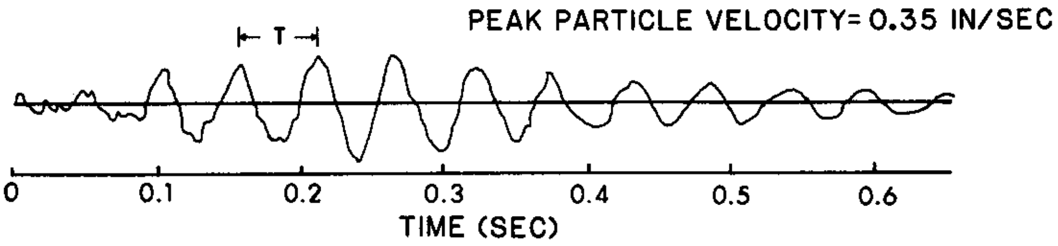
This dependence on both particle velocity and frequency is the rationale for the OSMRE blast vibration regulations. Recent US Bureau of Mines research has determined that the fundamental natural frequency of low rise (1 or 2 story) residential structures is in a range of 3 to 12 Hz. These low frequencies are more predominant at greater distances from a blast, and this is the reason for the more restrictive particle velocity limit of 0.75 inch per second at distances beyond 5001 ft. from the blast site. At close in distances, up to 300 ft. from a blast, high frequencies (above 40 Hz) predominate the vibration record. These higher frequencies are well above the fundamental natural frequencies of residential structure, so a higher particle velocity limit of 1.25 inch per second is allowed.

When the ground vibration frequencies can be shown to be higher than 30 Hz, then the blaster would be permitted a peak particle velocity of 2 inches per second regardless of the distance away from a blast, by using the Alternative Blasting Level Criteria shown in Figure 1 [Section 816.67(d)(4)(i)&(ii)], Figure 12 in this Manual, page 24.

The Alternative Blasting Level Criteria permit the most accurate prediction of blast vibration effects, provide the best defense in the event of litigation and offer minimum restrictions on blasting procedures and therefore, the optimum potential efficiency and cost savings, while still offering maximum protection to the homeowner. In order to be able to use these Alternative Blasting Level Criteria, it is necessary for the explosives user to determine the frequency content of the blasting vibrations.

Frequency Considerations

The frequencies present in a ground vibration seismogram are a result of three effects: the source, the geology of the travel path from the source to the seismograph, and the geology of the seismograph location. The blast frequency spectrum may be quite simple with the energy concentrated in one narrow frequency band. Such a condition would obtain at larger distances from a blast, when higher frequency components have been attenuated. Figure 41 is an example of such a relatively simple waveform. As can be seen, it is only necessary to determine the time interval between two adjacent peaks in order to calculate the frequency.



PERIOD = T = 0.054 SEC

FREQUENCY = 1/T = 1/0.054 = 18 Hz

Figure 41.
Calculation of frequency for a simple waveform.

For such simple waveforms, the frequency can easily be determined by measuring the time required for one oscillation of the waveform.

A more sophisticated method to determine the frequency content of a blast vibration recording would be a Fourier analysis. Because a blast vibration recording is not a continuous event, that is, it starts at a specified time and has a limited duration, it is called a discrete signal. In addition, the particle velocity levels are not necessarily periodic in that the peak values do not remain constant from one cycle to another, but vary, usually having the largest peaks early in the waveform and decreasing with time later in the waveform. As a result of having these properties, the Fourier transform will calculate only the relative amplitudes of the vibration frequencies contained in a waveform, but will not enable one to assign a peak particle velocity to any particular frequency. The plot of a Fourier amplitude spectrum normalized to the maximum peak particle velocity of the entire waveform can be used to estimate the particle velocity contributions for the various frequencies present. Such an estimate would be conservative, in that the overall waveform peak particle velocity is a result of contributions from all the frequency components present. This subject will be discussed in greater detail later in this chapter.

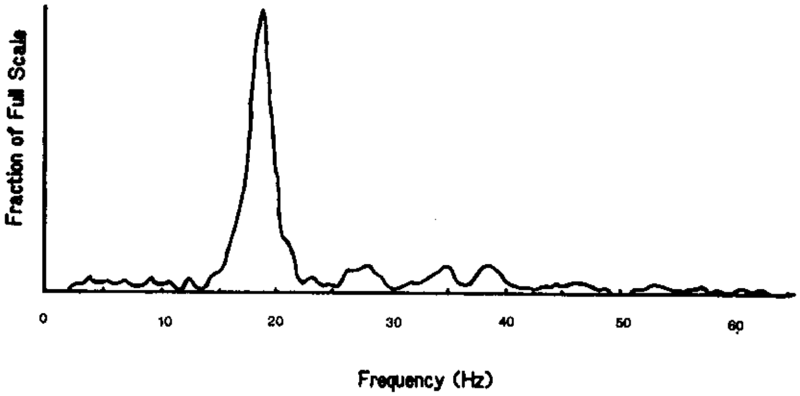


Figure 42.
Fourier amplitude spectrum for a simple waveform.

The plot of the Fourier amplitude spectrum for the simple waveform previously discussed is shown in Figure 42. It can easily be seen that the amplitude at 18 Hz predominates the spectrum. The overall peak particle velocity of the entire waveform was 0.35 inches per second. For this specific particle velocity recording, the 0.35 inches per second can be assumed to be almost entirely composed of 18 Hz energy.

A complex waveform results when two frequency components are present. These frequencies could represent the between hole and between row delay periods, or one frequency could be from the effects of soil thickness at the seismograph location, and the second frequency from a repetitive firing time in the blast design.

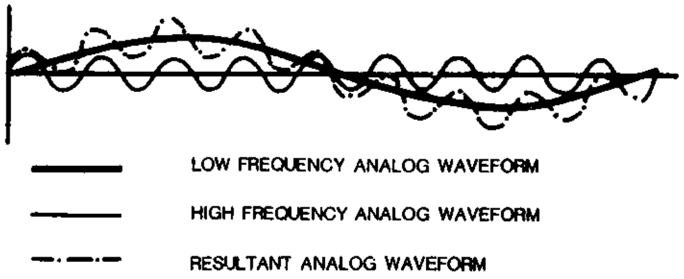


Figure 43.
Analog waveform with high and low frequency components.

Figure 43 shows a waveform made up of a high frequency and a low frequency component. The particle velocity of the low