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# VIBRATION: ITS EFFECT & MEASUREMENT TECHNIQUES AT OR NEAR DWELLINGS

by

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## ABSTRACT

The effects of vibrations on close surroundings has been studied in Europe and the United States extensively in the past three to four years due to the ever increasing demands of environmental control. Therefore, "routine measurements" or "standard vibration consulting services" are being carried out by numerous firms with widely different qualifications.

Without good practice, the danger of deterioration in the quality of the data has increased. Therefore standards of workmanship must be set.

Since, when pre and post blast inspections are made, one can be ensured that the final inspection will never show a similar number of cracks. An investigation of damage to buildings as a function of the magnitude of the vibrations and the ageing of the building must be established.

To assist the industry, guidelines are outlined for measurement techniques, based on the simple relationship:

$$PPV = (k)\,(SD)\ \hat{}\ (-\beta)$$

Using an example based on an occurrance and standard proceedures which are normally followed and inhered to by the mining and quarrying industry a number of easy but misleading answers can be arrived at. Only by understanding and employing the CONDITIONS that affect vibration and the response of instrumentation and structures can effectual answers to the vibration problem be presented.

These CONDITIONS are:

Geology and Building Response
Attenuation with Distance
Frequency with Distance
Focusing and Dispersion
R-wave Amplitude with Depth
Vibration of Foundations

Understanding the physical CONDITIONS is of essential importance, but the analysis and interpretations of the measurements made is equally important. In this matter the optimum usage can be made of the available data.

Fast Fourier Transform Analysis is the primary tool for developing the answers which for years have gone unanswered in their entirety. Applying the results from such a study will make for the most efficient blasting results attainable.

## INTRODUCTION

Numerous quarries have over time experienced complaints and alleged damage allegations even when they have faithfully followed the recommendations of experts. Likewise the operators who have observed the U.S. Bureau of Mines recommendation as outlines in:

(1) Bulletin 656 "Blasting Vibrations And Their Effects On Structures."

(2) RI 8168 "Noise And Vibrations In Residential Structures From Quarry Production Blasting."

have to their discomfort joined their other misfortunate associates in the web of blasting complaints. ?

One hears consistently that RI 8507, "Structure Response And Damage Produced By Ground Vibration From Surface Mine Blasting" applies only to surface coal mine operations and not to hard rock or industrial type operations such as quarries. This is not true and many quarry operators have to re-evaluate their thoughts concerning vibration and the effects on neighboring structures. The Introduction to RI 8507 states on page 4 of the report that:

> "The damage criteria presented herein were developed to quantify the response of and damage to residential-type structures from small to intermediate-sized blasts as used in mining, quarrying, construction, and excavation. Application of these criteria by regulatory agencies will require an analysis of social and economic costs and benefits for the co-existence of blasting and environmentally conscious society."

? WHAT IS THIS ?

Overburden roll, the norm in the major coal fields is seldom considered a problem in areas of thick limestones or other quarryable rock, but investigations have assessed that the phenomenon is present and as much a problem as in the documented coal mine sites noted in RI 8507. The solution then is to make the explosive user understand that damaging structural response due to surface wave motion can occur at the most unexpected sites and from small diameter blast hole shots to the large hole production blasts of the area strip mines.

A fictional case history is presented in this report to demonstrate the complexity of the blast vibration topic and the methods to deal with it, and a probable solution.

## CASE HISTORY

A residential community was developed in the vicinity of a stone quarry that has been located in the area for some fifty years. The new home owners have in the last two to three years complained and alleged that various damages have occurred, that one would not notice in other environments.

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The quarry is disturbed, since older neighbors have made little, of the ongoing operational activities. In addition, over the years the quarry has changed their blasting procedures so as to conform to Bulletin 656 and regulatory criterias. The allowable pounds per delay have been calculated using the Scaled Distances of 50 till 1978 and currently the value of 60 is used and complaints, rare during the past are an every day occurrance presently.

Convention has it, that at a Scaled Distance of 60, one can expect values of peak particle velocity between 0.20 to 0.40 inches per second. The situation at this site is different since measurements have approached the 1.00 inch per second level, which for a quarry is exceedingly high and unexpected.

A request for assistance led the quarry to lease a seismograph and take a number of measurements. Upon analysis, the data supplied by the quarry was questioned and two measurements were made by an experienced technician. One being inside a selected residence, the other at the foundation of the closest residence.

Figure 1 depicts the relationship between the blast site and the instrumentation location. A straight line distance, measured from an aerial photograph, of 600 feet was used to determine the Scaled Distance of 64. This blast along with that monitored at a Scaled Distance of 40.3 confirmed the data was acceptable and a problem did exist which needed further investigation.

The residential area's homeowner association based their complaint on the assumption that their homes responded to the vibration since they rested on the "same ledge" as the quarry. Therefore a pipeline was transmitting the energy without dispersion or absorption, and only by closing the quarry would they have satisfaction. It was explained that if the conditions seen at the quarry site was present at the home sites the expected values would be much lower than the actual, since a higher frequency wave would be much lower than the actual, since a higher frequency wave would be the norm, rather than what was being experienced.

It was only then that the quarry supplied information that a radical change in rock type occurred only a few hundred feet east of the operation. Some ten years ago, in order to expand reserves the present residential area was core drilled. It was found that a major contact zone and dipping of the beds occurred so softer rocks existed above the limestone under the subdivision. Figure 2 shows this as a cross section in the northeastern direction from the blast location.

Currently the practice is to drill a rectangular pattern of 12 feet of burden and 14 feet of spacing with 5 feet of subdrill using a 5 inch diameter drill bit on a 40 foot bench (Figure 3). The borehole is normally a full column or two deck load depending on the distance relationship to a Scaled Distance of 60. For the measurement being considered a full column load of 225 pounds of ANFO was placed in each borehole (Figure 4) and a delay sequence between holes of 75-ms. (Figure 5) was used.

The how and why the results obtained occurred and finally the improvements made are the major topics of discussion and follow.

## THEORETICAL DISCUSSION ON GROUND VIBRATIONS

### Response of Geological Formation to Seismic Waves

Quarry or construction blasting generates ground vibrations which propagates through the ground in the state of seismic waves. These waves are of different types and propagate with different velocities in different geological environments. Each of the waves affects soil or rock masses by a characteristic particle motion pattern.

In figure 6 the following wave types are presented:

- the fastest wave, the P-wave, characterized by radial particle motion, dilatates and compresses the ground materials (figure 7)
- the secondary wave, the S-wave, is characterized by a transverse particle motion which can be polarized in vertical or horizontal direction. This motion results in shearing (figure 7)
- The L-wave, is a form of the shear (S-wave) but is bound to the surface as a surface wave.
- The R-wave, the surface wave which is a cooperation product of the P- and the S-waves.

Eliptical particle orbit (generally retrograde motion) is characteristic for the R-wave (figure 6). Since all the waves travels with different velocities and the number of delays gives variety of event durations, it may happen that all the waves interact with each others in the same time and the same space.

The analysis of such complicated motions requires a 3-component time history record as shown in figure 6.

The propagation velocity of the P-, S- and R-waves depends on such elastic constants of ground materials as E - elasticity modulus, G- shear modulus, $\rho$ - density and $\nu$ - Poisson's ratio.

$$1. \quad Cp \doteq \sqrt{\frac{E\,(1-\nu)}{\rho\,(1+\nu)(1-2\,\nu)}}$$

$$2. \quad Cs \doteq \sqrt{\frac{G}{\rho}} \doteq \sqrt{\frac{E}{2\,\rho\,(1+\nu)}}$$

If we denote $Cp/Cs = \varkappa$ , then the relationship between wave velocities and $\nu$ - Poisson's ratio will be as shown in figure 8. Consequently the "soft" geological formations of overburden as clays, silts and sands will respond to low propagation velocities. Rocks and consolidated harder formations will result in higher propagation velocities.

However, when the formation is layered or jointed the wave fronts will reflect and difract at the discontinuities as shown in figure 9 and wave velocities will be changed because of different wave paths. Even in the homogenious but layered formations, the phase velocity change will occur corresponding to change in the layer thickness.

This can be shown in figure 10 accordingly to F. Press (ref. 1).

The geometry and nature of the geological formation can also change the wave type and subsequently the direction of particle motion.

The reflection and diffraction of P-wave fronts as shown in figure 11 change the direction of particle motion from radial to nearly vertical with increasing distance from shot point in the overburden materials.

Since P-waves and SV-waves (a type of S-wave) are coupled waves, each reflection of one wave type at the discontinuity border will result in reproduction of new wave types as shown in figure 12. This phenomena and generally occurring anisotropy contribute to a very complex response of geological formation to vibrations.

## Frequency of Ground Vibrations

The measurements of vibrations close to the detonating charges have shown high frequency content and filtering of those high frequencies with the distance. The observed relationship is presented in figure 13 where comparison between blasting and other vibration sources is shown.

Long distance observations of ground vibrations due to blasting (ref.2) contributed to the diagram in figure 13. The spectral analysis Fast Fourier Transform (FFT) and response spectrum of the same signals have shown that the different wave types are subdivided into certain frequency bands as presented in figure 14. Studies of R-waves behavior (ref.3) and vibrations from vehicular traffic (ref.4) contributed to validate the relationship between the dominating frequency and the thickness of the overburden clay sediments. The result of the observations is shown in figure 15.

## Dispersion

Since the R-wave is dispersive and studies (ref.4) have shown numerous deviations in the dispersion curves (see figure 16), it is evident that at least two or more R-wave fronts with different frequencies will interact at given distances from the shot point.

This will create minima and maxima in the attenuation curve which is an expression of vibration at various Scaled Distances. Depending on where the measurements are done, such maxima and minima will be localized and analysed otherwise the difference will be treated as a scatter or error.

## Attenuation With Distance

As mentioned, the appearance and characteristics of a wave usually change when it propagates. There are several reasons for such changes:

### Decrease in amplitude due to geometric attenuation

The energy of a cylindrical and spherical wave are scattering over a surface that increases linearly by the radius and square of the radius respectively. Results of attenuation measurements from various field tests are shown in figure 17.

Dispersion, the phenomenon due to the velocity of propagation for certain types of waves which varies with the wave-length.

Absorption, which is the actual damping due to part of the energy of the wave being transformed into heat by interior friction.

NO!
STRICTLY EMPIRICAL

Use of scaling laws for the prediction and control of blasting operations is based on assumption of the same wave form and propagation pattern. For that reason the linear regression is used with sigma ( $\sigma$ ) representing scatter as shown in figure 18. In another study of attenuation parameters the effect of absorption has been taken into consideration as shown in figure 19.

In figure 20 an improved curve fitting is used for more secure estimation of maximum values. The deviations from the regression curves as shown in figures 19 and 20 can have several explanations.

- Dispersion effects which give maxima and minima at different distances.
- Different wave types which can dominate at certain distances. If the scaling law is based only on a peak value detector then the different waves can give maximum amplitudes at various distances.
- Focusing of seismic wave.

## Focusing of Seismic Waves

Interaction of seismic waves in time and space leads to focusing, which gives higher or lower attenuation values than those theoretically calculated.

The topography and the geometry of geological formations leads often to reflection and concentration of wave front in an area where focusing will give significantly increased values. Example of such a formation are shown in figure 21.

## R-Wave Amplitude Variation With Foundation Depth

Studies of R-waves (ref.3) (ref.4) from blasting operations show that the theory of amplitude distribution with depth can be successfully applied in practice. An example of such distribution in the state of time histories is shown in figure 22. (Ref.14)

Similar distribution, measured in field during test blastings is shown in figure 23 in the state of a R-wave amplitude profile. Numerous measurements, on the ground surface close to the foundation, in the soil along the foundation and corresponding measurements on the foundation itself (ref.5) shows that the foundation is mainly affected by the R-wave acting at the foundation depth. This means that great differences can occur when comparing close ground observations with vibrations of the foundation itself. The difference of magnitude depends on the relation between the foundation depth and the wavelength of the R-wave. (ref.4)

FIELD TESTS? HOW ABOUT DATA?

Consequently, the preferable method of measurement should be to measure on the building foundation if possible, otherwise the measurement on the ground should be corrected with respect to the reduction factors.

In Sweden, such reduction factors have been calculated for three types of low structure foundations, in clay formations.

THEORETICAL?

A. Reinforced plate (slab) on ground

Depth 1 m    Factor 0.62

B. Foundation with basement

Depth 2-3 m    Factor 0.40

C. Foundation supports or piles to bed rock

Depth 10 m    Factor 0.40

FOUND. VIBR = F x GROUND VIBR

The formula used is VF = VG·RF where VG is the value measured in the ground surface close to the foundation (1 - 3 m). RF is the reduction factor, and VF is the value of the vibration on the foundation.

## Vibration of Building Foundations

Studies of interaction between building foundations and soils are plentiful in earthquake engineering. In practical blasting engineering it is, however, difficult to find application for advanced interaction study mainly for the following reasons.

- Vibration levels are in general low and do not lead to interaction processes of interest at distances greater than 10 m.

- The results of interaction studies depends greatly on the computer model used and input values which must be collected in the field. For this reason good geophysical approach is needed involving several expensive investigation methods.

- Industry requires simplified models and simplified formulas which can be followed in practice without involving high costs.

- Simplified Finite Element Method (FEM) analysis i.e. (ref.6) have been found to follow well the theory of damage criteria (ref.7) and seem to give good modelling possibilities

The Response Spectra analysis have been widely used and applied since 1950 in earthquake engineering. The analysis is based on a system with a single degree of freedom and seems to be too simple to reflect the whole complexity of motion within the building when considering i.e. construction blasting. In comparison with i.e. the Energy Spectral Density (ESD) approach presented in figures 24 and 25, the response spectra does not consider duration time, which is essential when comparing effects of different rounds, delays, ignition systems and explosive type and distribution.

The analysis presented in figures 24 and 25 is based on the same event, but the observation has been done in the rear and front of the foundation. Distance is approximately 100 meters to the blasting site.

The comparison between the ESD-spectra show difference in the frequency band which dominates the motion. Figure 24 represent the rear part of the foundation setting on a thin layer of sediment close to the rock surface (0.5 m). The dominating frequency band ranges between 75 - 125 Hertz.

Figure 25 shows a ESD spectrum recorded on the front of the same foundation placed on soil-rock mixed fill. Which is approximately 2 m. thick and consequently the frequency, ranges from about 25-80 Hertz.

This difference in the frequency of the motion shows that the foundation moves unequally and can not be accurately evaluated by the response spectra approach which represent equal motion of the system with one degree of freedom.

## Building Response

The dominating frequency of ground vibrations corresponds to the wave type and the thickness of overburden. In cases where the building natural frequency is close or equal to the dominating frequency in the ground resonance and severe magnification effects can occur. Schematically this relationship is shown in figure 26.

The vibrations within a building can be magnified due to the floor response as in case of figure 27 where magnification of about 9 times have been observed.

Magnification due to resonance might also arise if the intervals of the detonators create vibration frequencies close to the resonance frequency of the floor beams, or wall plates of a low or intermediate rise structure.

Resonance frequency for the beams of the floor can be calculated in advance as per the equation:

$$F = \frac{\pi}{2} n^2 \left[ \frac{EI}{\rho L^4} \right]^{1/2} = \frac{\pi}{2} n^2 \left[ \frac{Ebh^3}{12 \rho L^4} \right]^{1/2}$$

WHERE:

f = Resonance Frequency
E = Modulus of Elasticity
I = Moment of Inertia
b = Width
h = Height
L = Length
= Density
n = 1, 2, 3 ........n
T = Period

After derivation and logarithmation of the equation we get:

$$\left| \frac{\Delta f}{f} \right| = \frac{1}{2} \left| \frac{\Delta E}{E} \right| + \frac{1}{2} \left| \frac{\Delta b}{b} \right| + \frac{3}{2} \left| \frac{\Delta h}{h} \right| + \frac{1}{2} \left| \frac{\Delta \rho}{\rho} \right| + 2 \left| \frac{\Delta L}{L} \right|$$

where ahead of every term there is a factor, which principally shows the importance of different characteristics of the beam, when it comes to the determination of resonance frequences.

The resonance frequency for the whole floor can also be obtained by means of a rather simple vibration measurement and analysis.

The best and most recommendable method to determine the magnitude of vibrations in floor surfaces is a prognosis based on test blasting, which can be controlled by means of vibration measurements of the following:

- Registration and analysis of dominant frequency range on the foundation of the building and the floor.
- Calculation of scaling-laws for the foundation and the floor.
- Calculation of the transfer function between the foundation and the floor.
- Calculation of duration and damping of the vibration in the floor.

Building foundation response is frequency dependent and the frequency content can be easily analysed by Fast Fourier Transform, (FFT) application. It seems that this uncomplicated approach can successfully solve resonance and magnification problems.

FFT analysis is comparable with response spectra of zero damping and is found to give valuable information at low costs about the foundation behaviour. FFT informs in practice about what frequency band, and responsible wave length is needed to be omitted for avoiding damage and disturbances. FFT analysis which is the less costly and simplest way today can be utilized practically for blast design.(Ref.8).

Energy Spectral Density analysis can also be used for more accurate evaluation and comparison between different blasting techniques.

## PRACTICAL ASPECTS ON GROUND VIBRATIONS

Traditionally seismic monitoring reports have been used to handle complaints and alleged damage cases in courts of law. Therefore monitoring records were and still are a must.

This demand is still relevant but belief currently is that monitoring reports should serve more immediate needs and be used as a profitable tool. Our view is that high ground or sound vibration is a sign of miscalculation resulting in blasting below peak efficiency.

## Waveform Analysis

The character of the wavetrain to be analyzed directs, to a certain extent, the interpretation procedure to be employed. Are the waveforms simple or complex? Is event interference present: e.g., a low-amplitude, high frequency waveform superposed on a low frequency, high amplitude wavetrain? Has a narrow or wide range of frequencies been recorded? That is, are sharp transients present revealing a wide spectral make-up or, are the traces essentially sinusoidal indicating a rather limited spectal base? Is the baseline stable before and after the recorded event? These and other similar factors should be ascertained from a simple visual inspection of the seismogram. They indicate to the interpreter whether or not a routine analysis is adequate. Additionally, they reveal much useful information about the nature of the vibrations that have been recorded.

There are a number of techniques used for the analysis of a wavetrain but the two most common methods are:

- Steady-state sinusoidal analysis

- Fast fourier transform

The steady-state sinusoidal analysis is applied extensively in routine blast seismogram analysis. This technique assumes that the analyzed part of the ground motion is a steady-state sinusoidal vibration.

Under this assumption we also assume that the motion parameter for the seismograph is velocity and the zero-to-peak trace amplitude for each peak is proportional to the ground motion velocity. The frequency of the particular wave from which the amplitude measurement is calculated from the period length in between two successive peaks.

The above mentioned procedures apply to analog time histories, which is a record of, for example, particle velocity variations with time.

The Time History (figure 28) shows the particle velocity versus time for the three directions. As observed in the figure the maximum peak particle velocity is 1.21 in/sec. for the transverse wave.

The Trace Diagram (figure 29) gives the frequency range for the wave train. In this case one can see that the maximum peaks occurs within a frequency range of 10-20 Hz.

When we have a high amplitude and/or a more complex signal the Fast Fourier Transform analysis is to be recommended. (figure 30). The Fourier Transform, as used for waveform analysis, is a powerful tool for solving problems and analyzing data in Rock Engineering.

The Fast Fourier Transform for the transverse wave (figure 30) gives us the supplemental information that we have three main peaks in the wavetrain. Maximum occurring at 9.8 Hz. and minor peaks at 26.0 and 40.0 Hertz compared to the Trace Diagram (figure 29) where peaks were in the frequency ranges of 10 - 15, 15 - 20, 20 - 25, and 35 - 40 Hertz.

Compare the maximum frequency 9.8 Hz. with the delay time in the typical blasting pattern (figure 5) in which 75-ms. gives a forced frequency of 1000/75 = 13.3 Hertz.

During the test period data was compiled and the following diagram was developed:

> The Maximum Response Diagrams (figure 30) indicates that we are above the USBM RI 8507 alternative blasting level criteria in the frequency range of 5 to 25 Hertz.

## Proposed Changes in Blasting Techniques

The goal is to decrease the peak particle velocity in order to match USBM RI 8507 proposed limits (figure 31). It is possible to do that in two ways:

1. Reduce the maximum cooperating charge.
2. To shift the peak values toward higher frequency ranges by using a shorter delay interval between the charges.

? * HOW WAS COMPARISON MADE! SHOWN IN FIG 31

In this case you have the maximum peak particle velocity of 1.21 in/sec but want to be below 0.75 in/sec in the frequency range of 4 to 16 Hertz.

An important factor in regulating the vibration output from a blast is the "Maximum Cooperating Charge". In a blast where only one charge is detonated at each interval, the maximum cooperating charge is simply the largest single charge in the blast. Where several charges are detonated by detonators having the same nominal delay time, the maximum cooperating charge is the total charge detonated within any eight millisecond delay period. That means that the maximum cooperating charge for one delay number in each blast or those charges detonated within the eight millisecond nominal delay time.

The calculation method is based on the fact that the ground vibrations depend on the maximum cooperating charge in the following ways:

- Ignition Pattern
  Check that if possible just one charge is initiated by each detonating period. Ultimately, the maximum cooperating charge will be equal to the largest single charge in the blast.

- Deck Charging
  Use two or more charges with different delay periods in the same drill hole.

- Reduced burden and spacing
  If the charge in any one drillhole is greater than the maximum allowed cooperating charge, to reduce the charge weight per foot of drillhole by increasing the number of drillholes and decreasing the charge weight in each hole.

- Divided Bench
  Reduce the bench-height and/or the drill bit diameter to keep the charge weight per drillhole below the maximum allowed cooperating charge weight. This is the most expensive method, because of the decrease in productivity.

The Scaled Distance Curve (figure 32) from the test program indicates that with 95% probability we will be below the solid line if we use the following formula:

$$PPV \doteq (204.40)(SD) ^\wedge (-1.32)$$

where:

$PPV \doteq$ Peak Particle Velocity (in/sec.)
$SD =$ Scaled Distance

If $PPV = 0.75$ in/sec.
$SD \doteq 70$

$$SD = D/W ^\wedge 0.50$$

where:

$D =$ Distance (ft.)
$W =$ Maximum Charge per delay (Lb.)

If $D = 600$ ft.
$W = 73.50$ Lbs.

The changes made in drilling and blasting procedures (figure 33) was done according to Deck Charging. From the solid charge column of 225 pounds it was decided to use three decks of 70 pounds each which is with in the limiting allowable charge weight of 73.5 pounds.

We also changed the ignition pattern (figure 34) so that we got 30 ms between each charge.

Theoretically the forced frequency for the delay time 30-ms. will be:

$$1000/30 = 33 \text{ Hz.}$$

Which is in a more favorable range than the 13.3 Hz we had when we used 75-ms. delay time.

Result After Changes

Vibration measurements from the same measuring point gave us the following data:

- Time History (figure 35)
  The highest peak particle velocity 0.65 in/sec came from the vertical wave and was well in the predicted range of 0.75 in/sec.

- Trace Diagram (figure 36)
  The peak frequency was in the range 35 to 45 Hz. which is above the critical 16 Hz. The highest particle velocity below 16 Hz. was 0.4 in/sec.

- Fast Fourier Transform (figure 37)
  The peak frequency range was about 30 to 50 Hz. which confirms the figures from the trace diagram.

## CONCLUSION AND RECOMMENDATIONS

Taking into consideration the inpacts of all the variables on the magnitude and the frequency of seismic wave from shot point to monitoring site at one operation, one can foresee that the difference in intensity and response from various detonations will vary. The variance can be so great, that the uninformed will associate this difference in values with instrumentation error or misinformation on the part of the analyzer. With this great variance at one monitoring point, the difference is magnified when numerous sites at one operation for a single or many blasts are analyzed.

Likewise, the variance from site to site within a geological unit, and finally to outside one structural element to another can cause one to question the competence of the most reputable "expert" or firm.

To ensure that the neighbor as well as the user gets the most factual information available, a thorough investigation should be considered with calibrated instrumentation. But, since cost and time are of concern to the majority of the users of explosives or to those affected by vibrations an analysis using the Fast Fourier Transform and associated techniques would give the most effectual and efficient analysis per unit cost.

A follow up or continuing use of the Steady-state sinusoidal analysis will ensure compliance with the majority of governmental regulations or ordinances that concern themselves with limiting ground vibration to levels they (bureaus, agencies, etc.) consider SAFE or acceptable.

Therefore, it is our recommendations that to obtain maximum usage from vibration monitoring one should:

- Realize that frequency is of importance and can aid on in reducing complaints or potential damaging levels of vibration.
- Monitor on the foundation itself preferable if at all possible.
- Estimate and use "Reduction Factors" if the monitoring site is on the ground next to the foundation.
- Be knowledgable of the approximate thickness of soils beneath structures in question to maximize/minumize velocities, frequencies and responses.
- Keep current data available for projecting vibration levels in the near future.
- Use the vibration data, velocities and frequencies to design delay sequencies to assure a non-damage or SAFE vibration level for structures, pipelines, wells or underground facilities.

## SUMMARY

Vibration is a complex topic that can be controlled by relatively simple techniques with the assistance of the explosive user when care and concern is expressed; and the benefit is not only happy neighbors but a more efficient use of explosive energy and savings in dollars.

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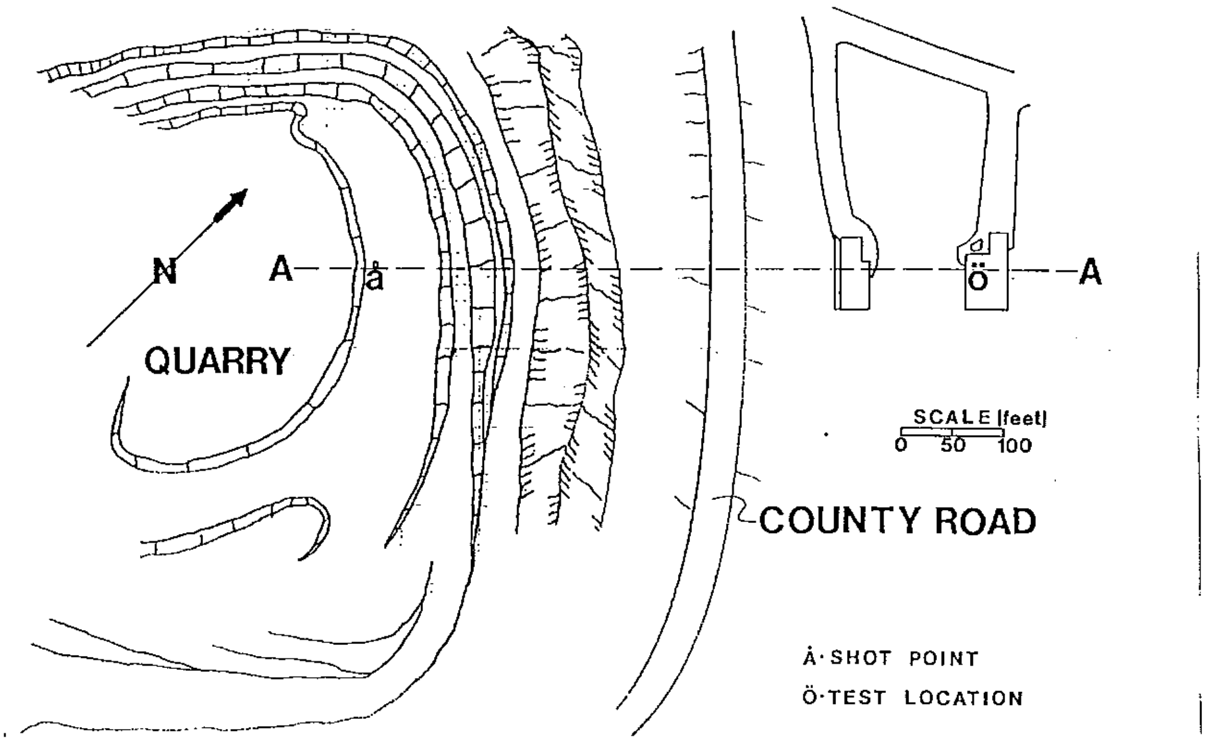


FIGURE 1 - OVERVIEW

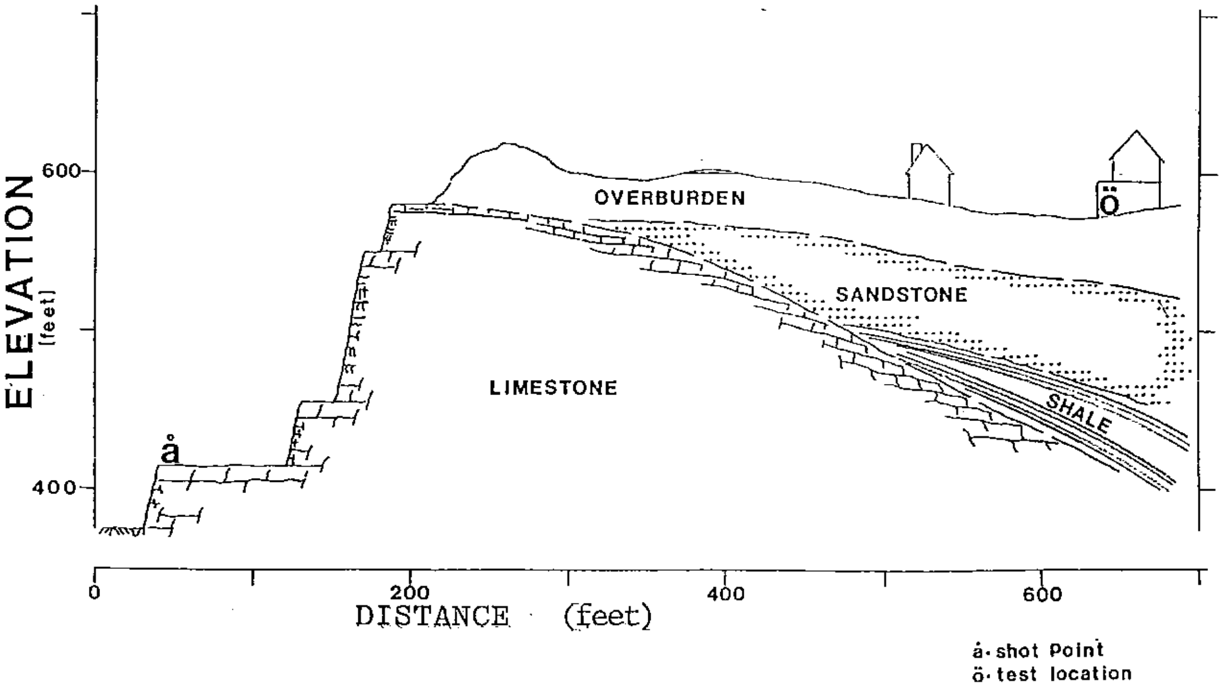


FIGURE 2 - PLAN VIEW

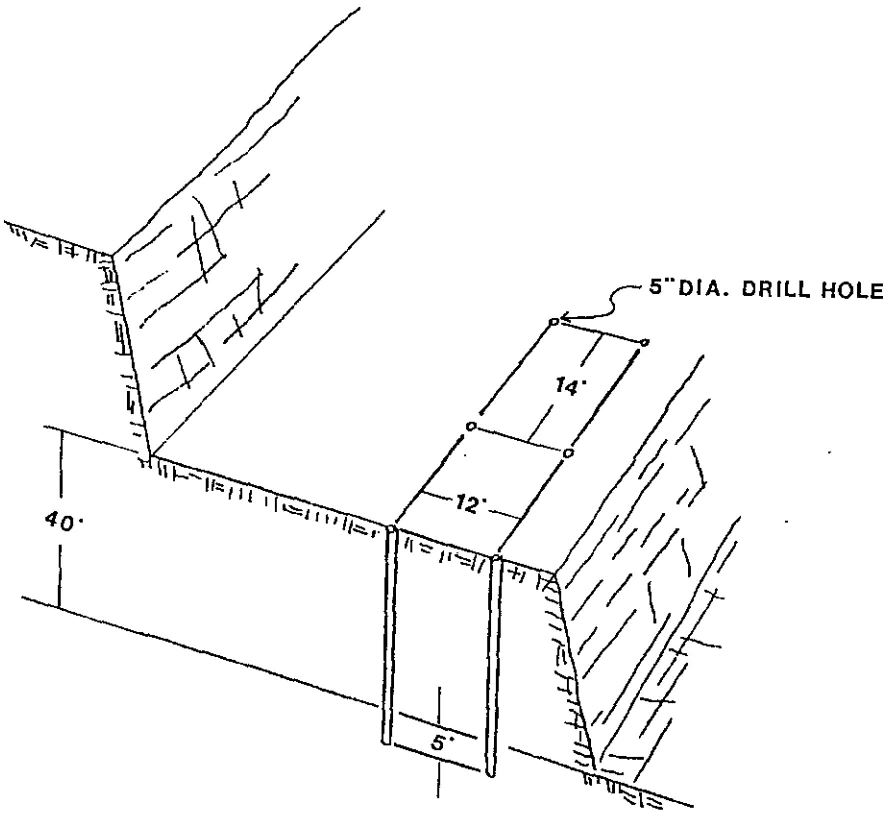


FIGURE 3 - DRILL HOLE PATTERN

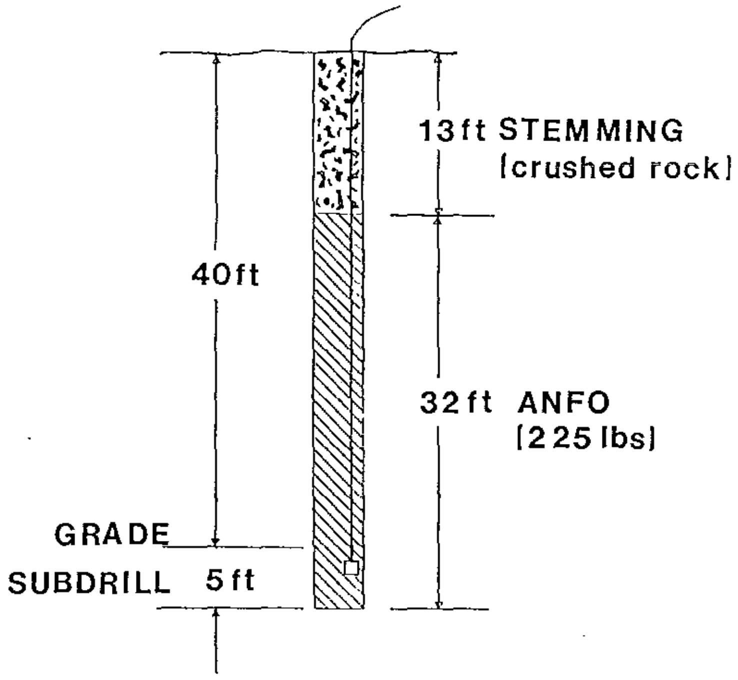


FIGURE 4 - TYPICAL HOLE LOADING

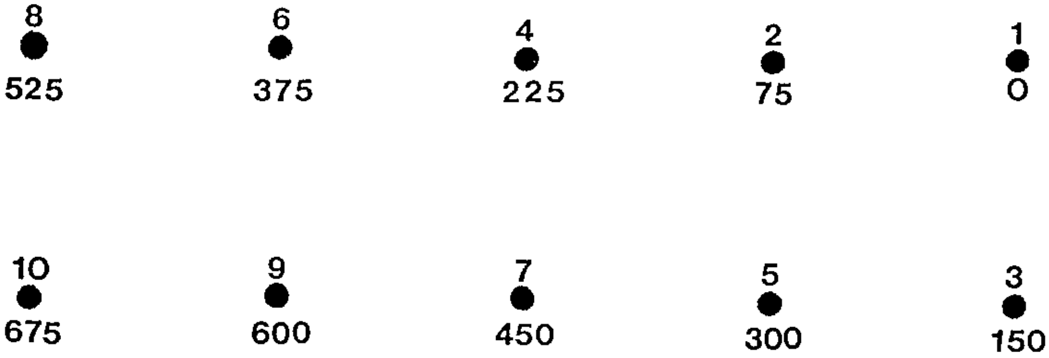


FIGURE 5 - TYPICAL DELAY PATTERN

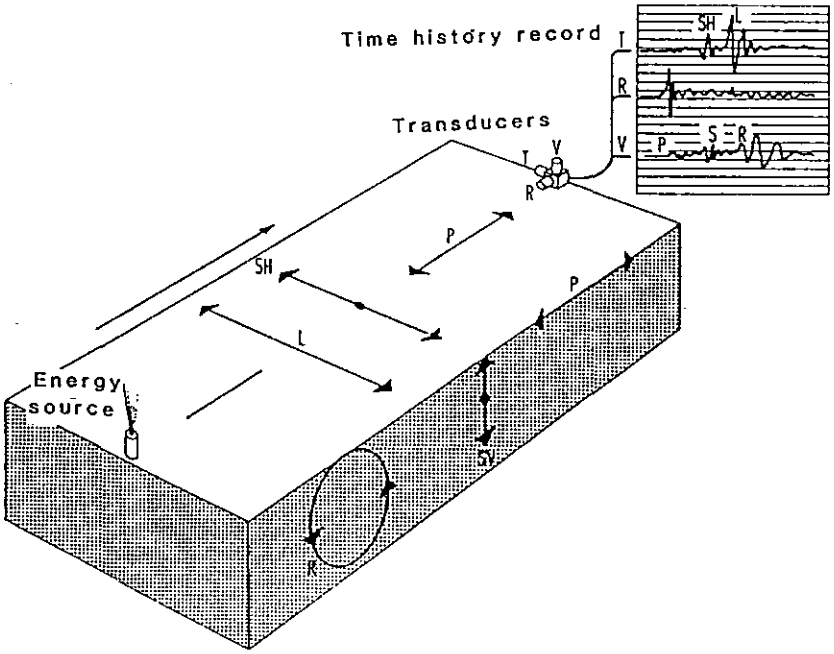


FIGURE 6 - DIFFERENT WAVE TYPES

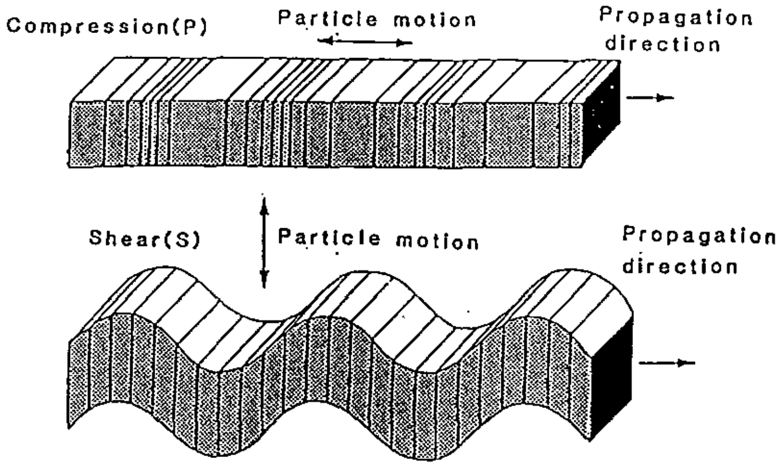


FIGURE 7 - COMPRESSION AND SHEAR WAVES

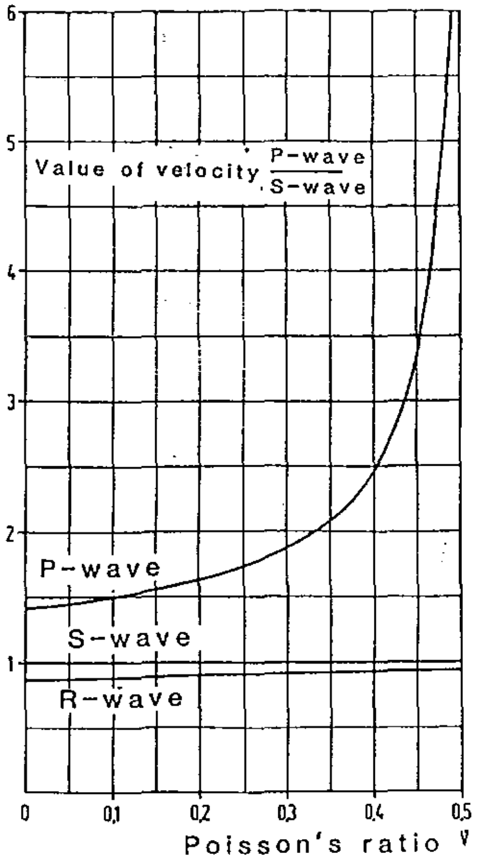


FIGURE 8 - RELATION BETWEEN WAVE VELOCITY AND POISSONS RATIO

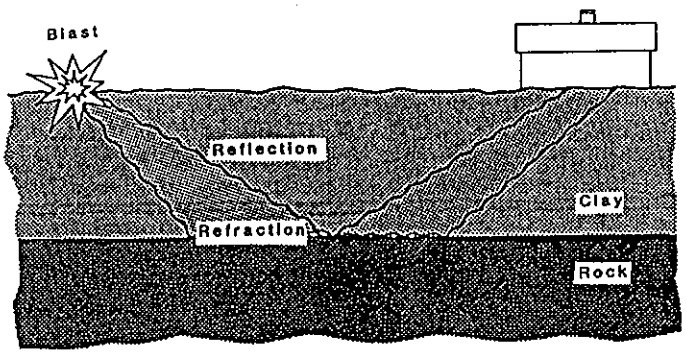


FIGURE 9 - REFLECTION AND REFRACTION

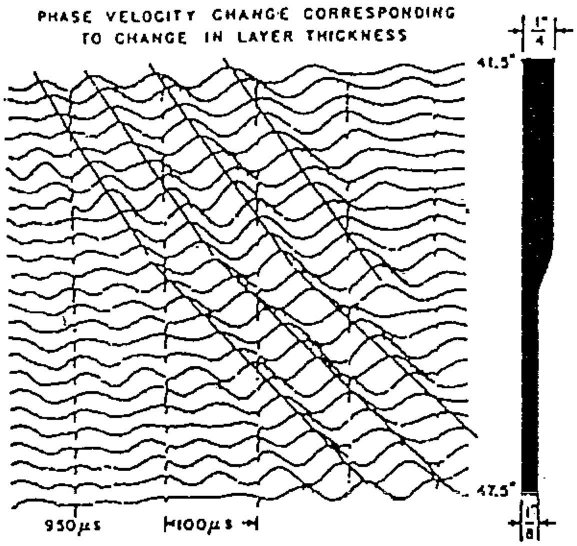
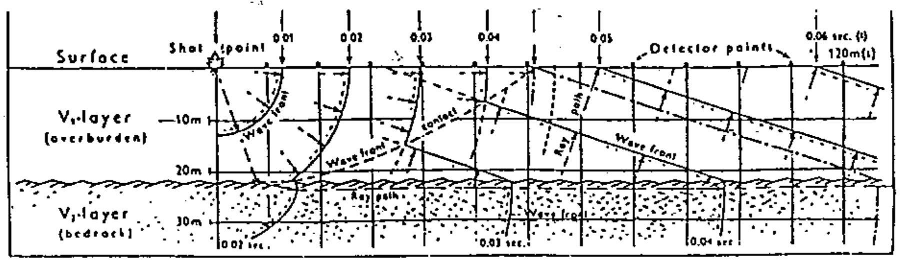


FIGURE 10 - PHASE VELOCITY CHANGE CORRESPONDENCE TO CHANGE IN LAYER THICKNESS



*Time-distance graphs for a theoretical single-layer problem, with parallel interface.*

FIGURE 11 - PARTICLE MOTION DIRECTION WITH DISTANCE

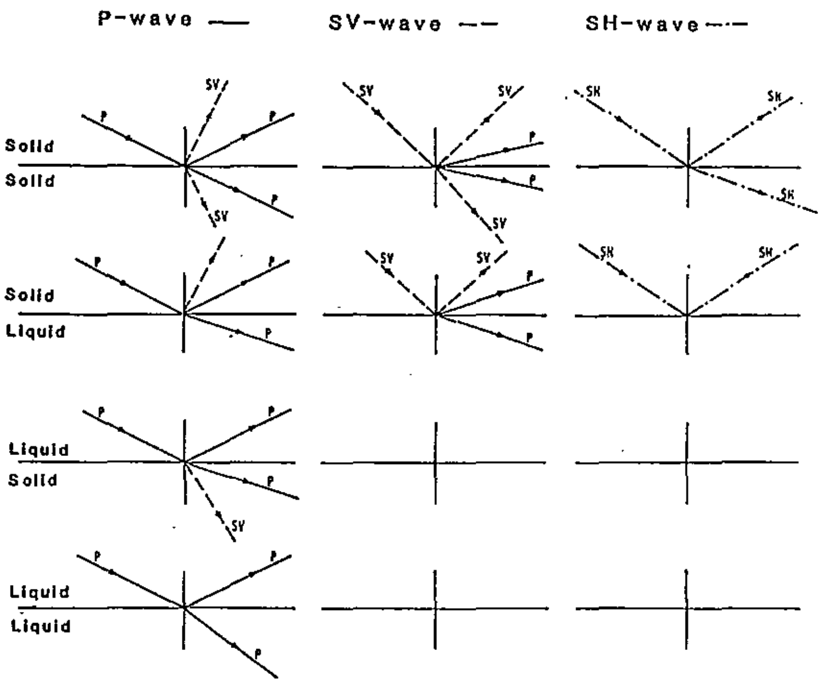


FIGURE 12 - REFLECTION OF A WAVE TYPE WILL RESULT IN REPRODUCTION OF NEW WAVE TYPES.

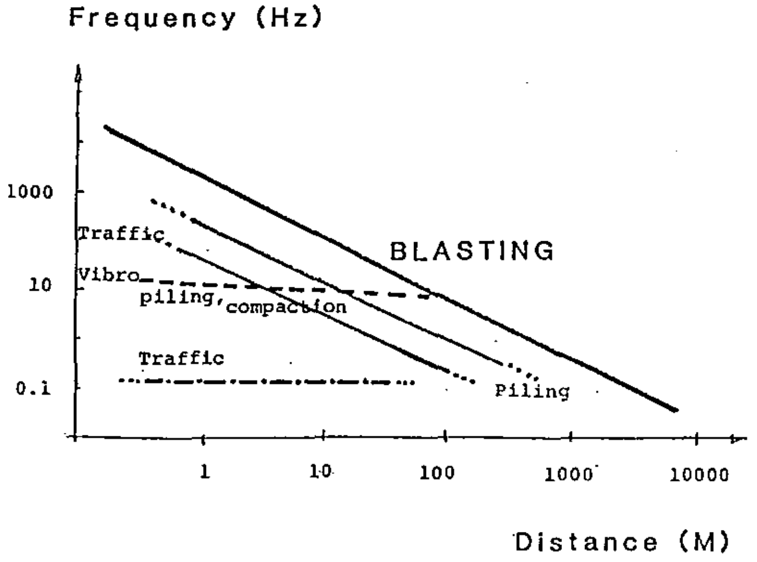


FIGURE 13 - RELATIONSHIP BETWEEN FREQUENCY AND DISTANCE

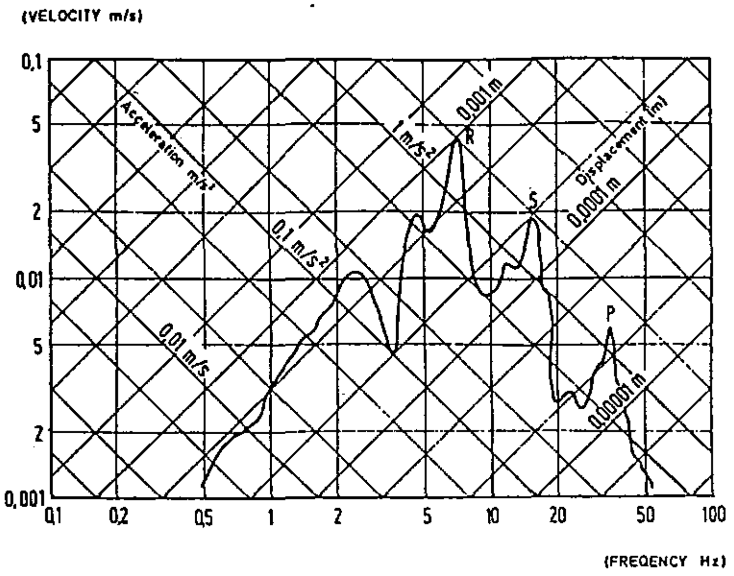
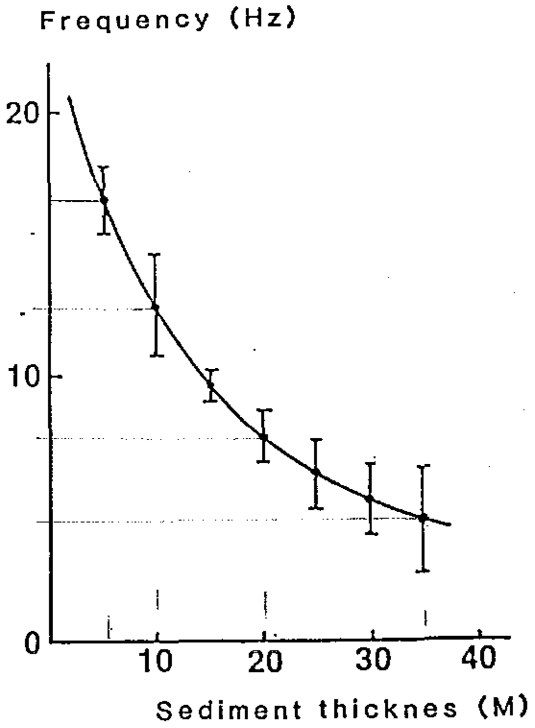


FIGURE 14 - RESPONSE SPECTRUM



RAYLEIGH WAVES ONLY?
FROM TRAFFIC DATA

FIGURE 15 - RELATIONSHIP BETWEEN THE DOMINATING FREQUENCY AND THE SEDIMENT THICKNESS.

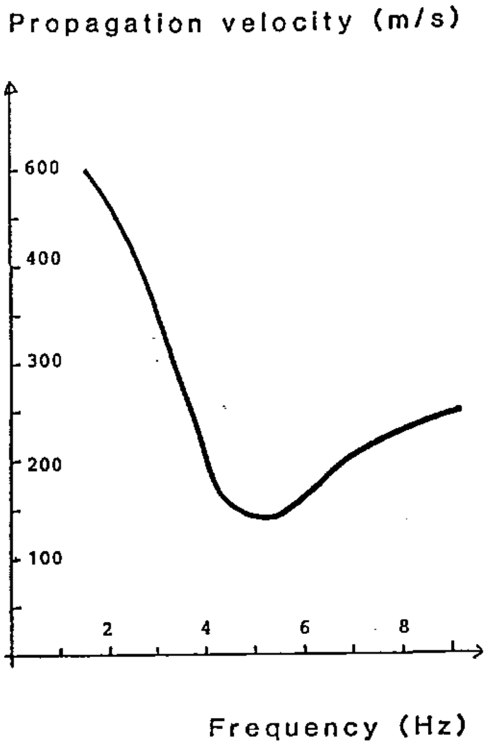


FIGURE 16 - DISPERSION

SCME ?

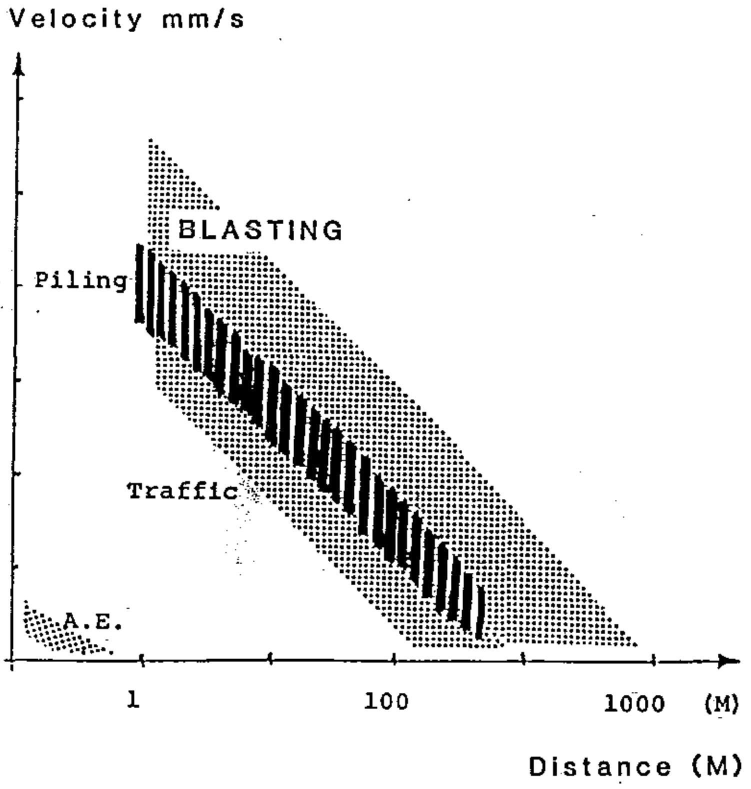


FIGURE 17 - ATTENUATION

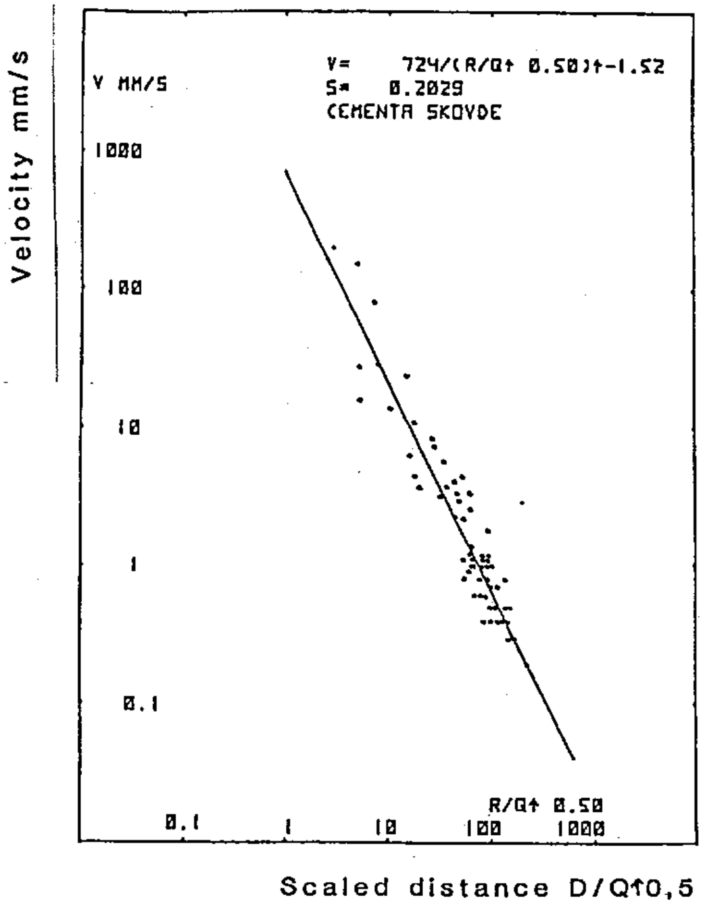
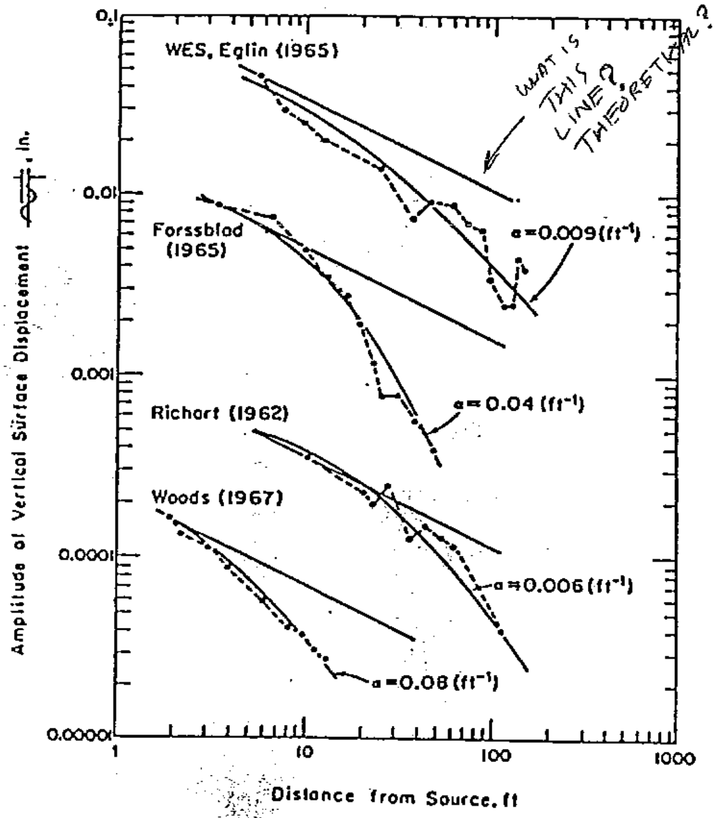


FIGURE 18 - LINEAR REGRESSION



WHAT IS THIS LINE? THEORETICAL?

FIGURE 19 - ABSORPTION

REFS MISSING

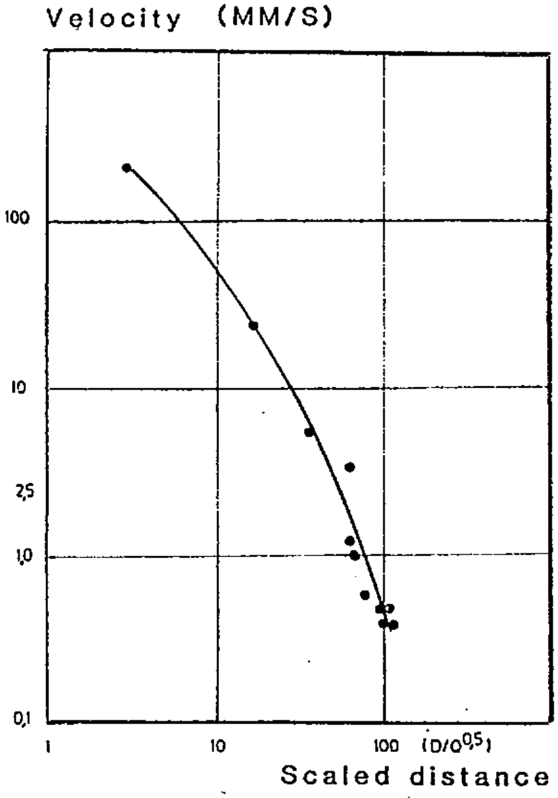


FIGURE 20 - IMPROVED CURVE FITTING

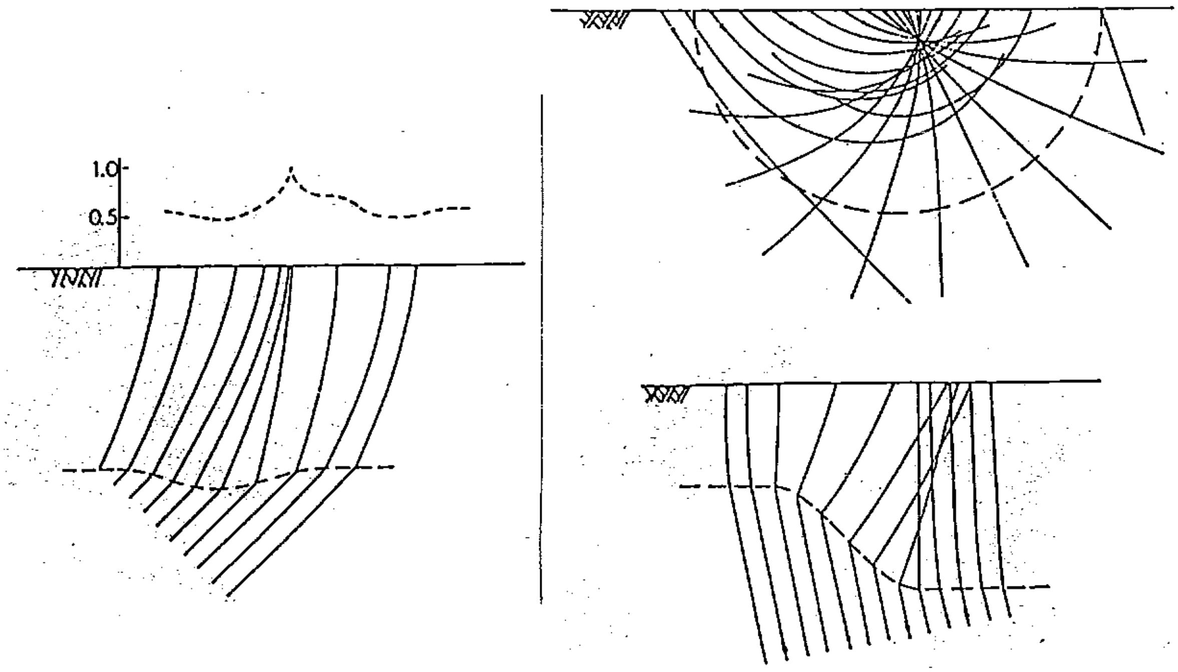
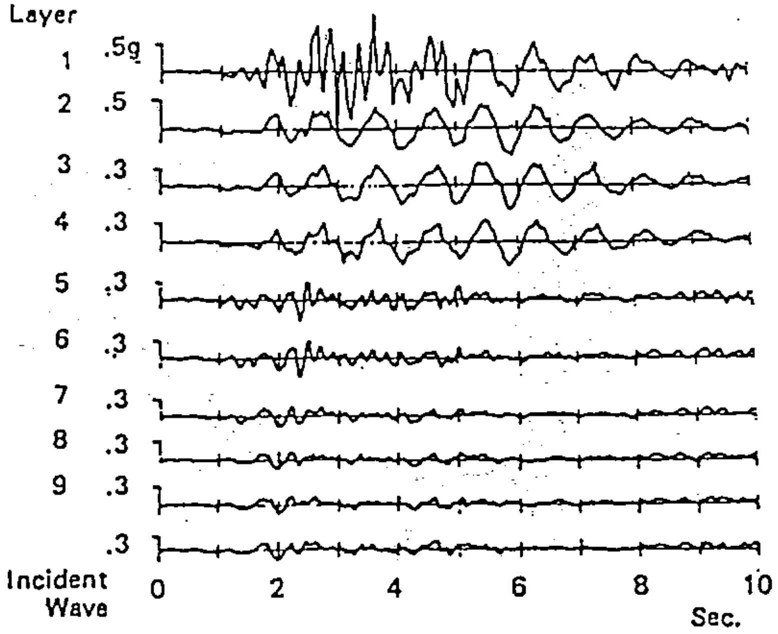
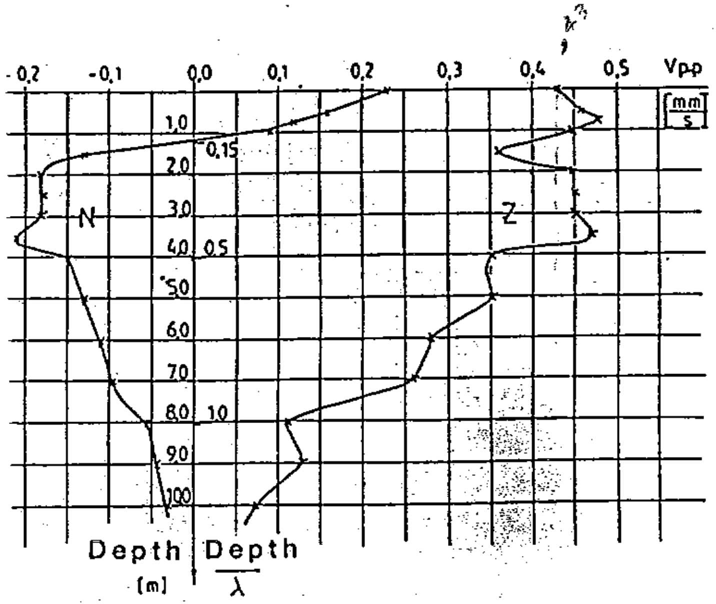


FIGURE 21 - FOCUSING



L R

FIGURE 22 - ACCERELATION OF LAYERED SOIL



15' before
Significant
fall off

FIGURE 23 - RAYLEIGH-WAVE AMPLITUDE PROFILE VERSUS DEPTH

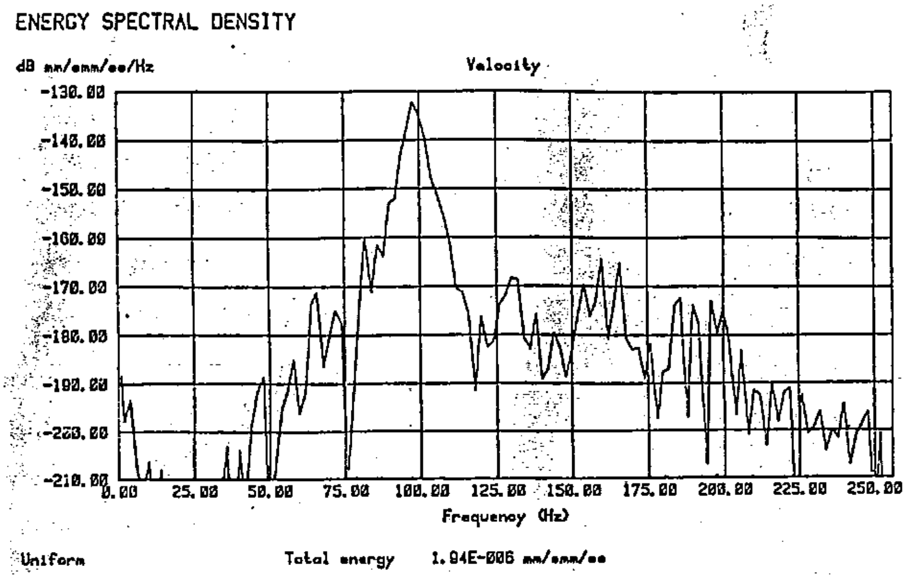


FIGURE 24 - ENERGY SPECTRAL DENSITY REAR OF STRUCTURE

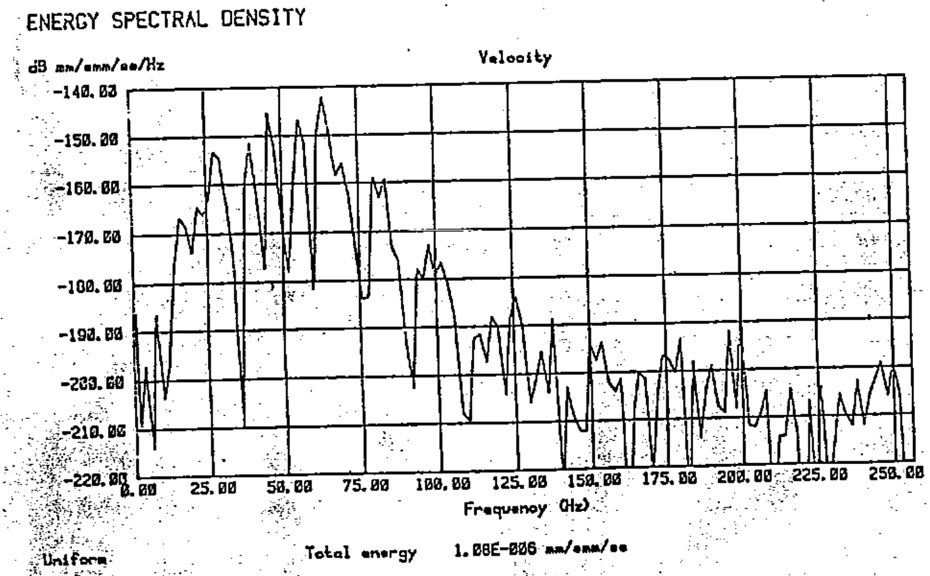


FIGURE 25 - ENERGY SPECTRAL DENSITY FRONT OF STRUCTURE

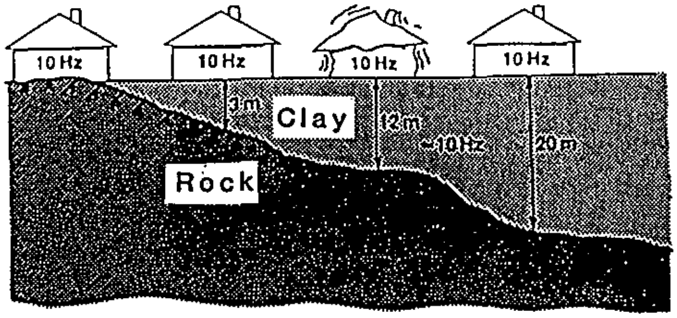


FIGURE 26 - MAGNIFICATION EFFECTS WHEN THE BUILDING NATUAL FREQUENCY IS CLOSE TO THE DOMINATING FREQUENCY IN THE EARTH.

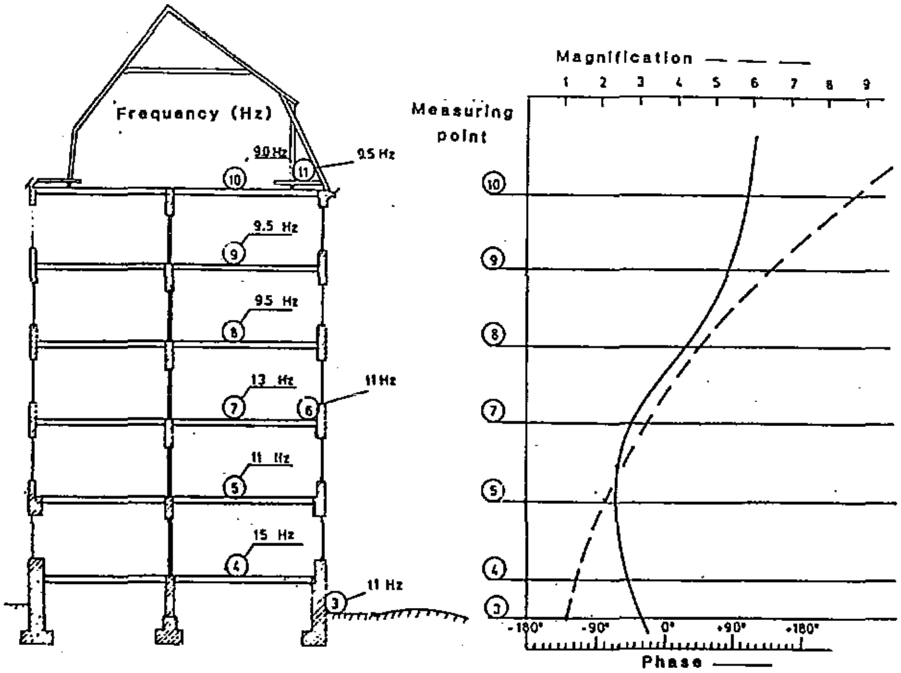


FIGURE 27 - MAGNIFICATION WITHIN A BUILDING

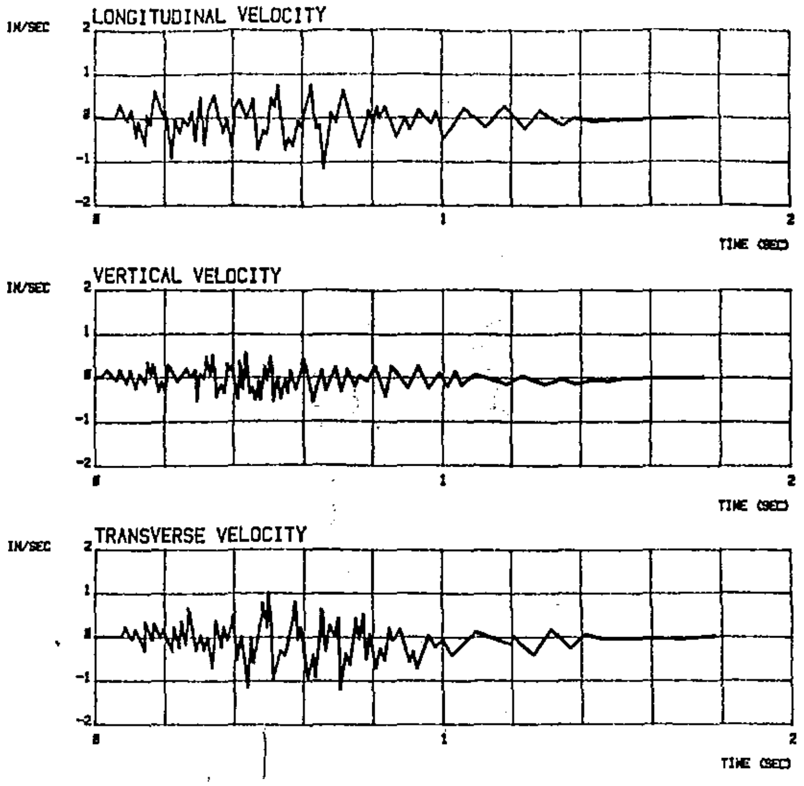


FIGURE 28 - TYPICAL TIME HISTORY

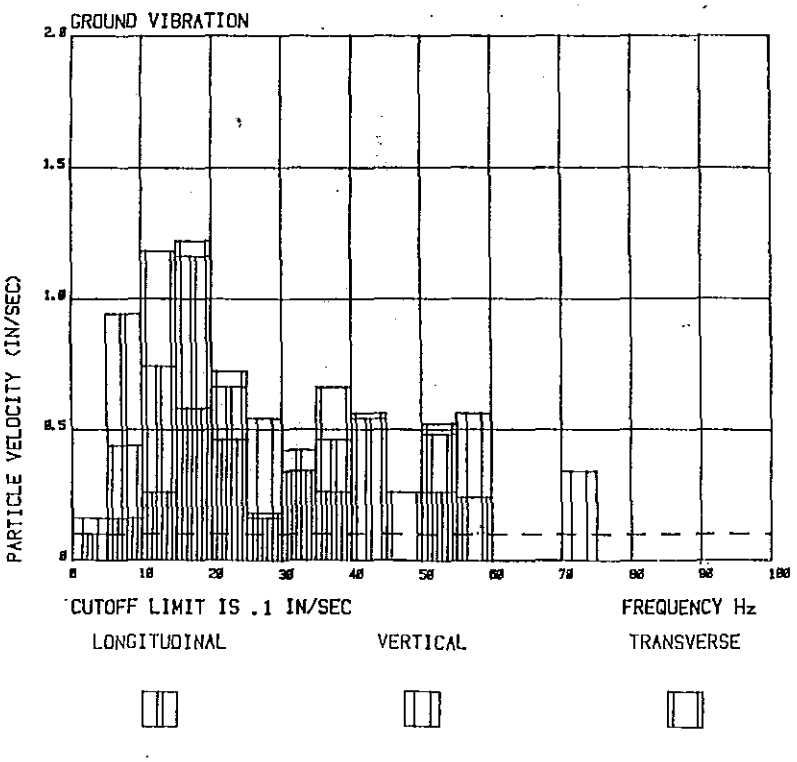


FIGURE 29 - TYPICAL TRACE DIAGRAM

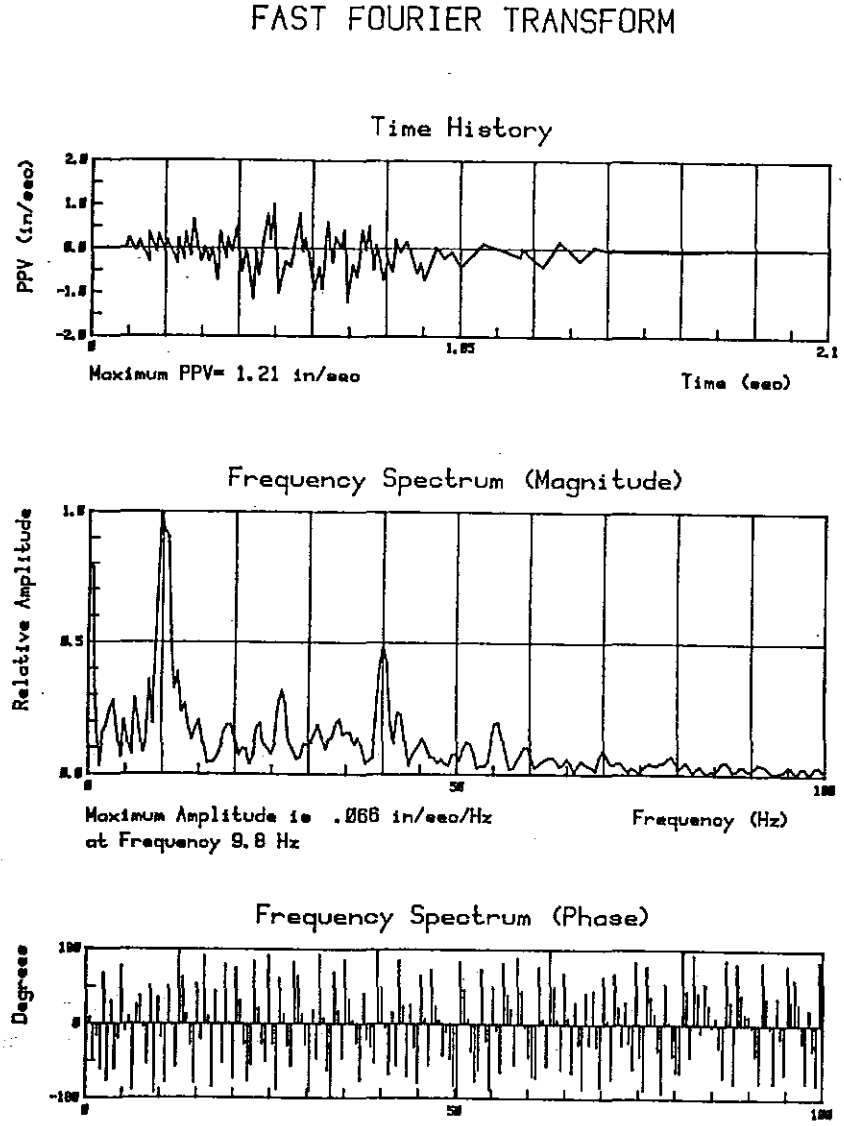
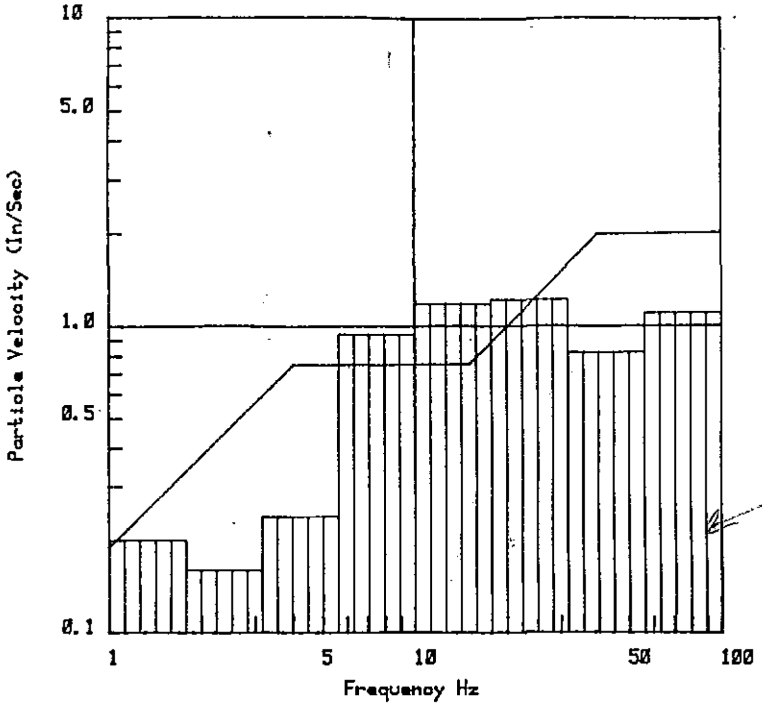


FIGURE 30 - FAST FOURIER TRANSFORM



Cutoff limit is .1 in/sec

WHERE DID THIS COME FROM

FIGURE 31 - MAXIMUM RESPONSE DIAGRAM

PPV=204.4*(SD)^-1.32 (95%)

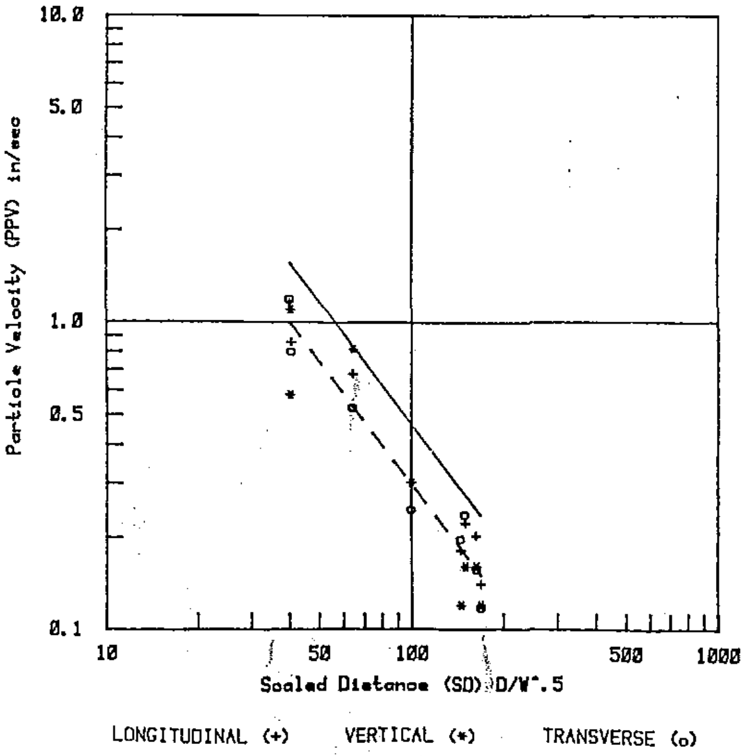


FIGURE 32 - SCALED DISTANCE CURVE

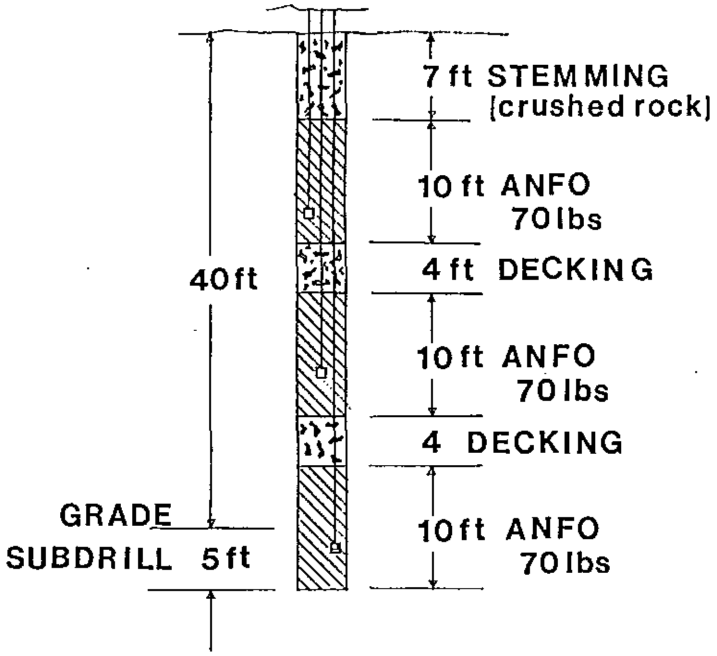


FIGURE 33 - MODIFIED HOLE LOADING

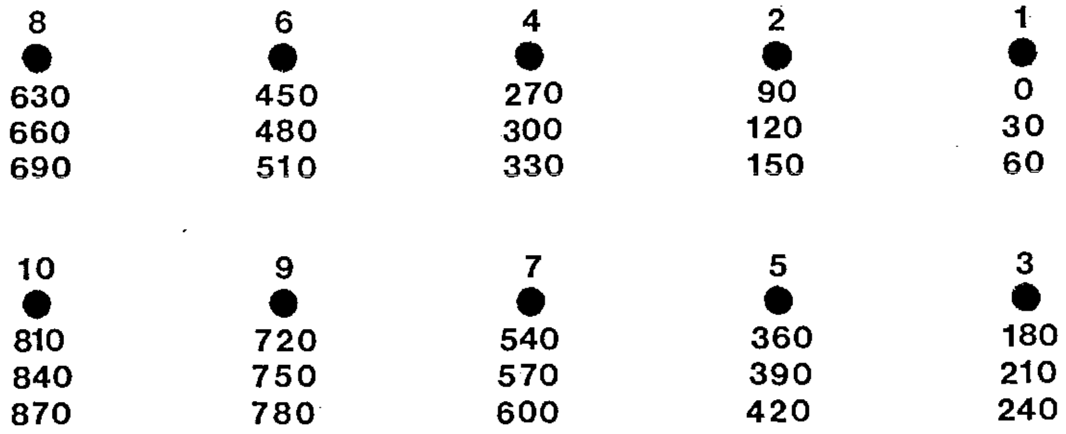


FIGURE 34 - MODIFIED DELAY PATTERN

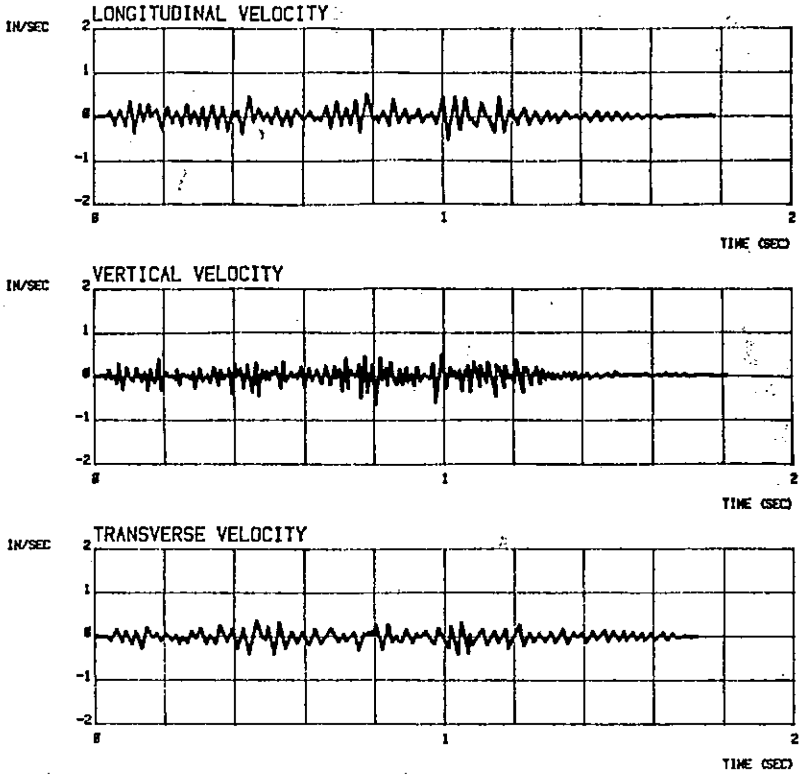


FIGURE 35 - MODIFIED TIME HISTORY

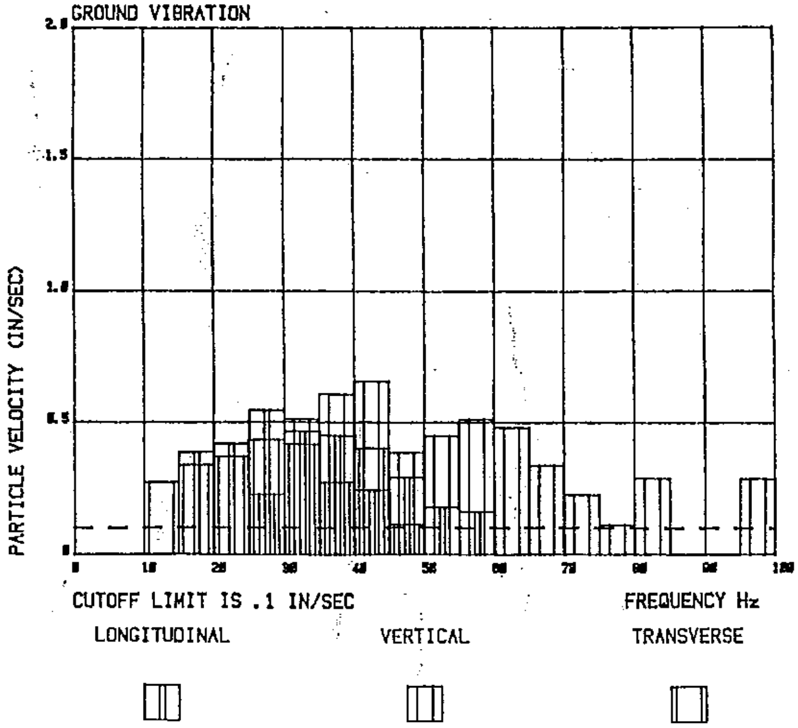


FIGURE 36 - MODIFIED TRACE DIAGRAM

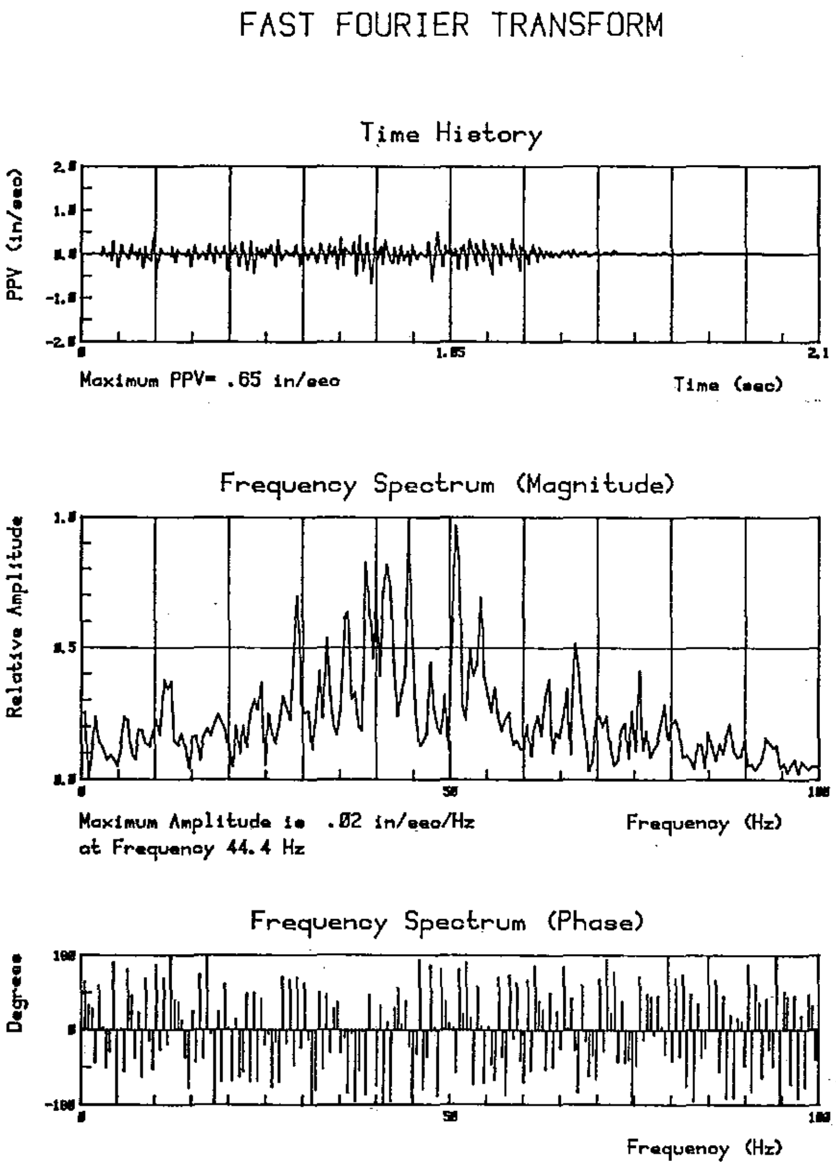


FIGURE 37 - MODIFIED FAST FOURIER TRANSFORM