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DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES
JOHN W. FINCH, DIRECTOR

REPORT OF INVESTIGATIONS

EARTH VIBRATIONS CAUSED BY QUARRY BLASTING

BY

F. W. LEE, J. R. THOENEN, AND STEPHEN L. WINDES

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By F. W. Lee,[2] J. R. Thoenen,[3] and Stephen L. Windes[4]

INTRODUCTION

This paper purposes to outline briefly results of seismic measurements made in the vicinity of blasts in a mine and in open-quarry operations. It endeavors to examine the amplitude and frequency of such vibrations as influenced by the loading, geology, and distance from the source and includes comments on factors that may index the destructiveness of a vibration and a method for measuring the stresses produced. There seems to be no simple mathematical analysis of the transmission of seismic energy through the ground, and experimental observations are at present most feasible.

SEISMOLOGIC INSTRUMENTS

Instruments developed by the Bureau of Mines for recording ground vibrations from quarry blasting comprise a new type of seismometer, oscillators, and a recording oscillograph. The seismometers respond to vibrations reaching them through the earth and transmit their characteristics by electric current to the oscillograph, where they are recorded by a beam of light on a moving strip of sensitized photographic paper. The seismometers are so constructed that their sensitivity to earth vibration can be controlled, thus keeping the amplitude of the recorded wave within bounds on the paper. Each instrument has been calibrated against vibrations of known intensity and frequency so that correction factors are known for the idiosyncracies of each unit. Moreover, each seismometer is calibrated in the field for its particular sensitivity setting at each blast. By these controls the actual movement of the earth due to vibrations of one ten-thousandth of an inch can be accurately measured.

Three seismometers, each with its vacuum-tube circuit for sensitivity calibration, are used at each recording point. One measures the earth movement vertically, one horizontally in the line between the blast and the seismometer, and one horizontally but at right angles. Thus the actual earth movement is measured in each of three dimensions.

The oscillograph is equipped with a firing recorder so that the instant of actual firing of the explosive is made a part of the record. This is accomplished by running a wire circuit from the oscillograph to and around the detonator. As the detonator explodes the circuit is broken, and the exact time is recorded on the sensitized photographic paper.

The oscillograph is also equipped with a recording timing device which, by means of a light beam, marks the moving paper with a vertical line at each one-hundredth of a second. By varying the rate of movement of the paper the spacing of these timing lines can be controlled. Thus the spacing of the timing lines will always record time accurately.

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[1] The Bureau of Mines will welcome reprinting of this paper provided the following footnote acknowledgment is used: "Reprinted from U.S. Bureau of Mines Report of Investigations 3319."

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The firing and timing circuits are tied in solidly with the nine elements that record the vibration wave from each of nine seismometers, so that the exact time that elapses between the blast and the receipt of the vibration wave at each seismometer, as well as the amplitude and frequency of the vibrations, can be read from the record.

Technical detail is not attempted in this description, as the apparatus has been described by Dr. George A. Irland in an earlier Bureau publication.[5]

FIELD TECHNIQUE

In order that the quarry operator may know the arrangements necessary to record a blast, the field technique so far developed is described below.

The recording oscillograph is carried in a specially built truck, which is taken to the quarry and placed in a central location. This truck is the control station for all instruments and has an operator in it during the blast.

In the truck is a locked switch which actuates a relay placed in the firing circuit. The operator of the oscillograph fires the shot by closing the relay switch. This is necessary to assure accurate records without waste of expensive photographic paper.

When the location for the truck has been selected, the points at which the seismometers are to be set up to record vibrations are determined. These may be placed at any desired points, limited only by the amount of wire available. At present, three stations 2,000 feet apart can be accommodated. If the first is placed 1,000 feet from the blast, the third can be 4,000 feet away. The distances can be varied to fit local requirements.

After the recording points have been selected, three seismometers are placed at each point. To insure accurate records steel pins are driven into the ground, and the seismometers are set up on them and leveled much as a surveyor levels a transit. Each instrument is connected to its oscillator-box circuit, and the necessary wires are run from each to the oscillograph in the truck.

The next step is to run telephone wires from the truck to each recording point and to the quarry firing switch. These are necessary for constant contact between the control operator at the truck and the seismometer operators. The quarry connection is necessary for communication between the control truck and the quarry operator.

When wires are strung and telephone sets ready, the next step is to calibrate the instruments with the oscillograph. This usually requires 2 to 5 hours, depending upon the sensitivity used. The greater the sensitivity, the longer the time necessary for calibration. When calibrated and unclamped, the apparatus is ready for the blast.

Several blasts can be shot at predetermined intervals without calibration between, but calibration between shots prevents certain inaccuracies caused by a possible change in sensitivity. Calibration requires 30 minutes to 1 hour.

It will be noted that a separate blast-timing line must be run from the detonator in each blast for accurate timing on the record.

Preliminary experiments indicate that the apparatus should reach the site of the blast at least 2 days ahead of the time scheduled for the shot.

EXPERIMENTAL OBJECTIVES

The ultimate objective of these experiments is to determine the effect of ground vibrations from quarry blasting on nearby buildings.

Before final results can be obtained, it is necessary to know:

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[5] Irland, George A., A Study of Some Seismometers: Tech. Paper 556, Bureau of Mines, 1934, 48 pp.

1. The speed at which the vibration wave travels.
2. The intensities, or amplitudes, of the component waves.
3. The actual movement of the ground or resultant of the three components.
4. The ratio of decrease of amplitude to distance from the blast.
5. The frequency of vibration of each component.
6. The amount and kind of explosive used.
7. The distribution of the explosive in the hole.
8. The detonating speed of the explosive.
9. The kind of detonator used (cordeau or electric cap).
10. The position of the detonator in the charge.
11. The relative elevation, direction, and distance of each recording station with respect to the blast.
12. The geology of the subsurface strata, including the physical characteristics, the strike and dip of the bedding, and the location of intervening major faults or seams, if any.

The first five points will be determined by the instruments. The rest must be obtained from the conditions of the test in each instance.

Inasmuch as the path of the vibration wave through the strata cannot be definitely forecast and as field instruments show definitely that reflected waves are present, it is necessary to have all possible knowledge of the transmitting media (the subsurface strata) in order that the results can be interpreted properly.

After a series of tests has been made at one quarry with different kinds and quantities of explosives and possibly different methods of charging holes, from different recording positions, the characteristics of the vibration waves and the actual earth movement can be mathematically determined. The tests are repeated at a number of quarry sites under various differing conditions to determine what, if any, fundamental laws can be discovered.

The problem then enters its second phase - determination of the effect of ground vibrations on buildings. It is not felt that a detailed field plan for this phase is practicable at this time, since the problem is not imminent. However, it is hoped that simple structures may be set up at various distances from a blast and the effect noted from vibrations of a measured amplitude and frequency or actual ground movement.

The following questionnaire lists the essential data needed at each blast.

Essential information at each blast

1. Company name and address ______ Alabama Limestone Quarry, Blake, Ala. ______
2. Quarry address ______ Blake, Ala. ______
3. Official in charge of blast ______ John Blank, Pres. ______
4. Characteristics of stone blasted ______ Dolomite ______
5. a. Massive ______ Faults ______ Joints ______
   b. Bedded __X__ Thickness __900'__ Dip __21°SE__ Strike __NE__
   c. Hardness __Coefficient 15.7__ Crushing strength __14.4 tons per sq.in.__
   d. Overburden removed __Yes__ Kind __Clay__ Thickness __20'__
5. Type of hole ______
   a. Coyote ______ Size of tunnel ______ Height burden ______
   b. Well drill holes __X__ Number shot __17__ Diameter __6"__
   Elevation collar __608__ Elevation bottom __478__
   Elevation quarry floor __481__ Spacing __18'__ Burden __19'__
   c. Hammer drill holes ______ Number shot ______ Diameter ______
   Depth of holes ______ Hole angle ______ Spacing ______
   Burden ______

6. Type of blast. Chambered ____________ Unchambered ____X____
a. Explosive. Type __Gelatin__ Strength __60-80%__ Amount __15,400 lb.__
How distributed in holes __Deck Loaded__ Length of charge __110'__
Weight per stick __25 lb.__ Rate of detonation __15,000__ Sensitivity ____
b. Detonator. Cap __EB__ Strength __No. 8__ Position in charge __Top__
Fuse ____________ Type ____________ Burning rate ________
Cordeau __Yes__ Arrangement ____________
c. Stemming. Kind __Screenings__ Method of tamping __Wood block__
Amount ____________ Position in holes __Deck loaded__
7. Position of seismometers. Rough sketch showing position in relation to blast ________
____
Seismometer station A. Direction __S87°45'W__ Distance __630'__
Elevation __611__
Seismometer station B. Direction __Same__ Distance __1,375'__
Elevation __652__
Seismometer station C. Direction __S86°15'W__ Distance __2,090'__
Elevation __757__
8. Position of oscillograph relative to blast and seismometer stations ____________
__30' S. of station A.__
9. Date __1/7/36__ Time of blast __4 p.m.__ Temperature __50°F.__ Humidity __95__

There should also be a plan of the quarry showing topography; bench arrangement; location of holes; location of any geological features, such as faults, seams, etc.; location of seismometer stations; elevations of principal points; and all other pertinent data.

In order that all possible facts may be ascertained from these observations the cooperation of quarry operators is requested, so far as is possible, in arranging for duplicate shots in which one set of conditions remains unchanged while others are varied. For example, the transmitting medium at any one quarry will remain constant for one setting of seismometers. For this setting, it is desirable that the quarry shot should be made in two or more blasts, in which the kind, amount, or distribution of the explosive may be varied. For example, assume it is desired to shoot 12 holes in a quarry face and to obtain information on the effect of more than one kind of explosive or method of loading holes. One or more holes may be loaded with one kind of explosive and an equal number with the same weight of another kind. One group is fired, and the second group is fired 20 or 30 minutes later. Both shots are recorded on identical seismometer settings.

If only one kind of explosive is used the blast may be divided into two shots in which the quantity of explosive is varied.

If information is desired on the effect of different explosive distribution in the hole, two or more shots may be made.

Various other combinations will be apparent and applicable to different quarry conditions. For instance, it may be that determination of the vibration effect in different compass directions is important. In this event, it will be necessary for 2 days to elapse between shots to enable a change of seismometer setting and calibration, and the shots must be as nearly identical as possible.

The writers realize fully that splitting a quarry blast into more than one shot is difficult and that it is not always possible to do so. However, in some operations multiple shots may be possible.

SEISMOLOGICAL OBSERVATIONS IN MINES

Considerable interest is shown by mine operators at present in the degree of loading rock pillars and arches in mine headings and stopes. Owing to irregular settling and the

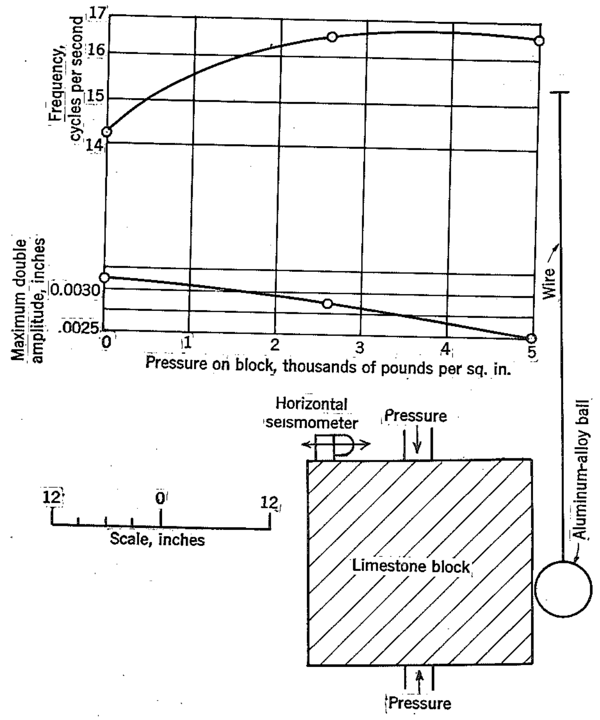

Figure 1.- Limestone-block vibration tests, U. S. Bureau of Mines, Experimental mine. Impact given to 22- by 25- by 15-inch block by 6-inch diameter, 11.75-pound sphere. Frequency and amplitude measured by a horizontal seismometer as pressure increased.

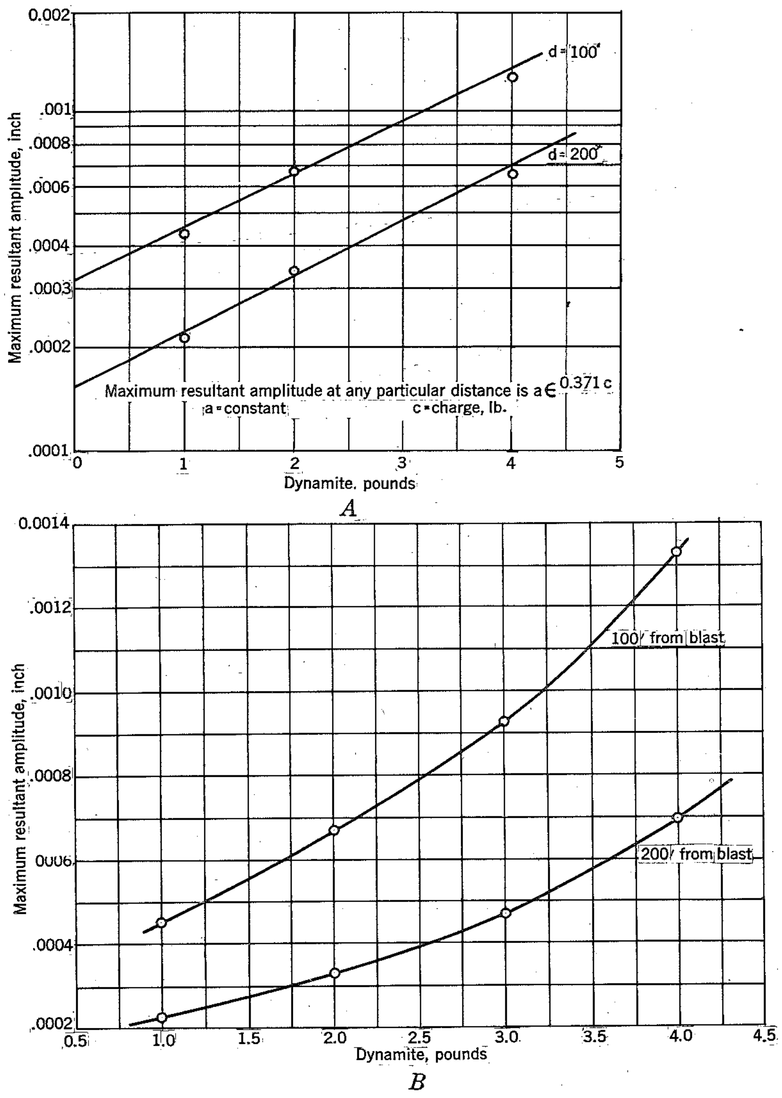

Figure 2.- Coal-mine shots, U. S. Bureau of Mines, Experimental mine. Vibration measurements made on earth surface 60 to 350 feet from point of shot.

gradual application of load by the superincumbent strata or "pressure block," the degree of loading is always uncertain and there is danger of sudden collapse or failure.

Studies are now being made upon the behavior of rock in the transmission of seismic vibrations under various degrees of stress. It can be generally assumed that when a body under load is given the same energy as an applied impulse, it will transmit this energy with different degrees of displacement, depending upon the stress.

A limestone block approximately 2 feet by 2 feet by 1 foot was put in a hydraulic press, as shown in figure 1. An impulse of definite magnitude was applied at one end of the block, and the vibrations were recorded by seismometers at the other end. The magnitude of the impulses was varied, and the amplitude of recorded vibrations increased with the magnitude of the impulse. On the other hand, the frequency of the recorded vibrations was found to be independent of the force of the impulse.

The block was then subjected to pressure, and impulses of constant magnitude were applied; the amplitude of the vibrations decreased with an increase of pressure, while the frequency increased as pressure increased.

It is too early to give a complete report on this work, but indications are that further research is warranted.

SUPERSONIC VIBRATIONS

It is of utmost importance to seismologists to know the degree of stress in geological structures undergoing deformation. To what degree these phenomena may be used as an index of impending disturbances is yet to be determined.

Since there is some slipping and yielding of a structure under strain before final collapse, the vibrations that accompany this preliminary motion are being investigated. There is ample evidence that this yielding sets up vibrations which are perceived by birds, fish, and other animals sensitive to very high frequencies of vibration, before earthquakes occur. Such high frequencies would have their source in the natural periods of vibrations of small pieces of rock and sand grains. These vibrations would be in the supersonic range and would require very delicate instruments for detecting them. Perceptible increases in the frequency of occurrences of such vibrations and the intensity may precede failure either in mine workings or in earthquake areas. The problem is also being approached from this angle.

MODIFIED MERCALLI INTENSITY SCALE OF 1931

Harry O. Wood and Frank Neumann have devised a modified scale of measuring ground vibrations. This work was done in connection with earthquake recording. It has become necessary to assign numbers to various intensities of earthquakes. These numbers bear a certain relation to physiological effects and to damage done. As earth vibrations caused by earthquakes differ only in degree from those caused by blasting, it may be desirable to use a similar system for differentiating their intensities. Because of the general interest and specific lack of information concerning these phenomena, the following table by Wood and Neumann is reproduced.

Intensity	Description	Acceleration, mm per sec.^{2}
1	Not felt – detectable by instruments only.	0.0– 2.5
2	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended object may swing	2.5– 5.0
3	Felt quite noticeably indoors, especially in upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations like passing of truck. Duration can be estimated.	5.0– 10.0
4	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, and doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.	10– 25
5	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.	25– 50
6	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.	50– 100
7	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving a motor car.	100– 250
8	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving cars.	250– 500
9	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.	500– 1,000
10	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent, landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.	1,000– 2,500
11	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps, and land slips in soft ground. Rails bent greatly.	2,500– 5,000
12	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown upward into the air.	5,000–10,000

As most displacements of ground caused by blasting are of a vibratory nature, it has become customary to think of them as purely sinusoidal vibrations. These have very simple mathematical expressions. Thus if the displacement is represented by

$$s = A \sin p\, t \tag{1}$$

where s is the displacement, A the amplitude or displacement from the rest position, and p the angular velocity which equals $2\pi f$ where f is the frequency of vibration, then the velocity, v, is found by differentiation.

$$v = ds/dt = Ap \cos p\, t \tag{2}$$

This means that the velocity has the same frequency but the amplitude is Ap.

Differentiating again with respect to time to secure the acceleration a,

$$a = dv/dt = d^2s/dt^2 = -Ap^2 \sin pt = Ap^2 \sin(pt \pm 180°) \tag{3}$$

This means that the acceleration has the same frequency as the displacement, but the maximum value is proportional to the square of the frequency. Moreover the maximum amplitude is in the opposite direction to the displacement. For convenience, the unit of acceleration is the gal (derived from Galileo); it is equivalent to an acceleration of 1 cm per second per second.

As the damage to any building or object is not from a finite continuous stress or constant acceleration that does not change with time but rather from a change of force or shaking effect, it might be better to introduce a new factor proportional to the change of acceleration. Then

$$w = da/dt = -Ap^3 \cos p\, t \tag{4}$$

The product of this value and the mass is offered as the index of destructiveness.

This shaking factor would have the same frequency but would be proportional to the cube of the frequency and to the amplitude of the displacement.

At present small structures are being placed upon a mechanical oscillator and tested for failure. The results of this investigation will be published later. Instruments that actually measure this change of acceleration have been constructed by Kato and Nakamura in designing an accelerometer (28).[6]

There is still considerable discussion as to what function can best be used to measure seismic destructiveness (29).

Special formulas for determining destructiveness of earthquakes have been proposed by Hugo Benioff (27).

Fundamentally, the problem of destructiveness or failure of material is simple. If two points on a structure are a definite geometric distance apart and if there is any simultaneous relative displacement between these two points, it is possible to evaluate the stresses that the frame must support because of this displacement. If these stresses go beyond the elastic limit, yield point, etc., then the structure has been damaged. It matters little what produced the relative displacement, whether actual settling of a building, reversal of impulses, or passage of short vibrational waves of high intensity through the structure. Actually, most damage is probably done when the natural period of the structure

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[6] Figures in parentheses refer to bibliography at end of this report.

coincides with the period of applied forces. Few such resonant vibrations will transmit enough energy from the ground to the structure to damage it.

Because of these complicated functions it was thought best to measure actual physical displacements as accurately as possible and not to use velocity meters or accelerometers. If such instruments had been used it would have been necessary to compute the relative displacements, and in so doing errors of more than 100 percent would be introduced. This was also experimentally demonstrated by K. Dyk (9) and by T. Hagiwara (10).

Sources of different types of vibrations were examined with seismometers. The results of the investigation are shown in table A. It is well known that the earth is always in a continuous quiver caused by various forces. For example, very small vibrations of the order of 1/100,000 inch are produced by the wind blowing through the grass or trees. Such vibrations, of course, cannot be felt and do no damage. Then vibrations of the ground that are perceptible but cause no concern are produced by passenger automobiles and trucks or a train of cars. Measurements showed that such displacements were of the order of 1/10,000 inch, heavier trucks of the order of 1/1,000 inch. The latter values were in some instances of the same order of magnitude as vibrations produced by blasting.

Further examination shows that the frequency of these vibrations was not the same but ranged from 20 to 40 cycles per second. Since the frequency enters into the acceleration as the square, the corresponding maximum forces are greatly modified by this frequency. Small vibration accelerations are of the order of 100 centimeters per second per second or less. These values are generally less than one-tenth of the acceleration of gravity, which is about 1,000 centimeters per second per second. If they are compared with the modified Mercalli scale such vibrations are classed as severe, although of course they are not.

TABLE A.- Table for frequency, maximum displacement, maximum velocity, maximum acceleration, and maximum rate of change of acceleration

Source of vibration	Distance from source, feet	Frequency, cycles per sec.	Displacement		Velocity, cm/sec.	Acceleration, cm/sec.^{2} or gals	Rate of change of acceleration, cm/sec.^{2}/sec. or gals./sec.
			Inch	Cm			
Passenger sedan, 40 m.p.h.	30	36	0.000066	0.00017	0.036	10.4	2,000
Passenger train - 5 cars, 35 m.p.h., bldg. vibration	110	22	.000125	.00032	.044	6.20	865
Passenger train - 5 cars, 35 m.p.h., ground vibration	110	35	.00025	.00063	.139	31.0	6,750
Truck, medium speed	30	22	.00026	.00066	.093	12.8	1,780
1-lb. surface shot	180	26	.000265	.00067	.110	18.1	1,180
Coal truck, fast	30	20	.00033	.00084	.105	13.4	1,680
Large 10-ton truck, 25 m.p.h.	30	22	.004	.0010	.138	19.4	2,700
140-lb. man jumping from 2-foot keg in building	15	31	.00075	.00190	.370	73.0	14,200
1-lb. test shot	80	40	.0017	.0043	1.080	275.0	69,000

Even with a 1-pound test shot, which caused a displacement of 0.0017 inch at the relatively high frequency of 40 cycles per second, the force associated with it was equivalent only to that produced by an acceleration of 275 centimeters per second per second or about one-fourth that of gravity.

All of these measurements and values indicate clearly that at present there is no definite index number to define the safe vibration limit of various types of construction. It can only be said that a vibration was greater or less than that caused by another agent.

As the time of detonation is generally very brief the effect is that of a sharp blow or impulse which is imparted to the ground. The frequency arising from such an impulse depends upon the natural frequency of the ground or geologic structure in question, which is controlled by the mass and elastic forces in question. Setting in motion large masses with low elastic forces will produce low frequencies and vice versa.

In addition to the acceleration applied to a structure other important considerations bear directly upon the damage that a building may sustain. These are the degree of coupling which the actuating mass has to the building and the natural frequency of the building. Under resonant conditions such vibrations may become severe after only a few vibrations.

Therefore a careful survey around a quarry should not only determine the natural frequency of vibration in the quarry but should also test the natural frequency of vibration of the structures affected.

RELATION BETWEEN MAXIMUM AMPLITUDE OF VIBRATION AND EXPLOSIVE CHARGE

It can be assumed generally that a larger vibration will be produced by increasing the quantity of explosive set off in a blast. But just what this relation is, whether the effect is proportional to the quantity of explosive or obeys some other more complicated law is under investigation. Results of coal-mine shots at the Bureau's Experimental mine at Bruceton indicate that it seems possible to analyze the results on semilog paper where the relation between pounds of dynamite plotted on one axis and the amplitude plotted on the other indicates a straight-line function; the relation observed on this geologic structure was

$$\underline{A}\ \text{max.} = \underline{K}\epsilon^{0.371C} \qquad (5)$$

where $\underline{A}$ max. = maximum resultant amplitude, $\underline{K}$ = constant depending upon the distance from the shot, $\underline{C}$ = charge of explosive in pounds,

$$\epsilon = \text{base of napierian log} = 2.73.$$

Figure 2,A, shows the results plotted on semilog paper and figure 2,B, the results plotted on ordinary paper. Of course the factor 0.371 is wholly local and would be different in a quarry.

One would therefore expect that the same quantity of explosive would cause greater or less vibrations in other localities. It is desirable to know the relation between the amplitude of vibration, the amount of explosive, and the distance from the shot, as it would indicate the maximum charge that should be fired for a certain maximum amplitude of vibration at a given distance.

WIRING AND LOADING HOLES

Usually each quarry operator has a system best adapted to his particular quarry structure for loading holes.

Figure 3 shows a typical loading scheme and the circuit connections for firing and timing the blast. In general, there are two methods of observing the exact time of detonation. In one the instant is observed at which the dynamite or cordeau detonates and in the other the instant at which the detonating circuit is closed. There is usually a difference of one- to two-hundredths of a second between these readings. Great precaution must be taken to insure safety and reliability in this part of the operation.

DESCRIPTION OF EXPERIMENTAL MINE SHOWING PLAN OF OPERATION

Special facilities were available for making preliminary tests of vibrations caused by blasting at the Bureau's Experimental mine at Bruceton. Figure 4 shows a plan and sections of the seismometer stations and their elevations as well as their relation to underground operations.

Here three instruments were used at each station, and three stations were observed for each shot. The three instruments at each station recorded the three components of motion on an oscillographic record at a single recording station located about 600 feet from the shot. The records of all the instruments in the three stations and the blast time were on the same strip of film.

The practice followed was to shoot successively 1, 4, and 2 pounds of explosive in each butt face. Two kinds of explosive were used. For a complete picture in the four cardinal directions, four separate orientations were necessary.

The two cross-sections show each seismometer station and the maximum resultant amplitude measured at that station. The geological structure is fairly simple and comprises about 20 feet of overburden and horizontal beds of clay, sandstone, shale, coal and shale, and coal. At the north end of the structure, near the 150-foot station, the sandstone outcropped. In addition, an ill-defined clay seam penetrated the structure. It passed through the 150 west station, and its course was approximately north and south.

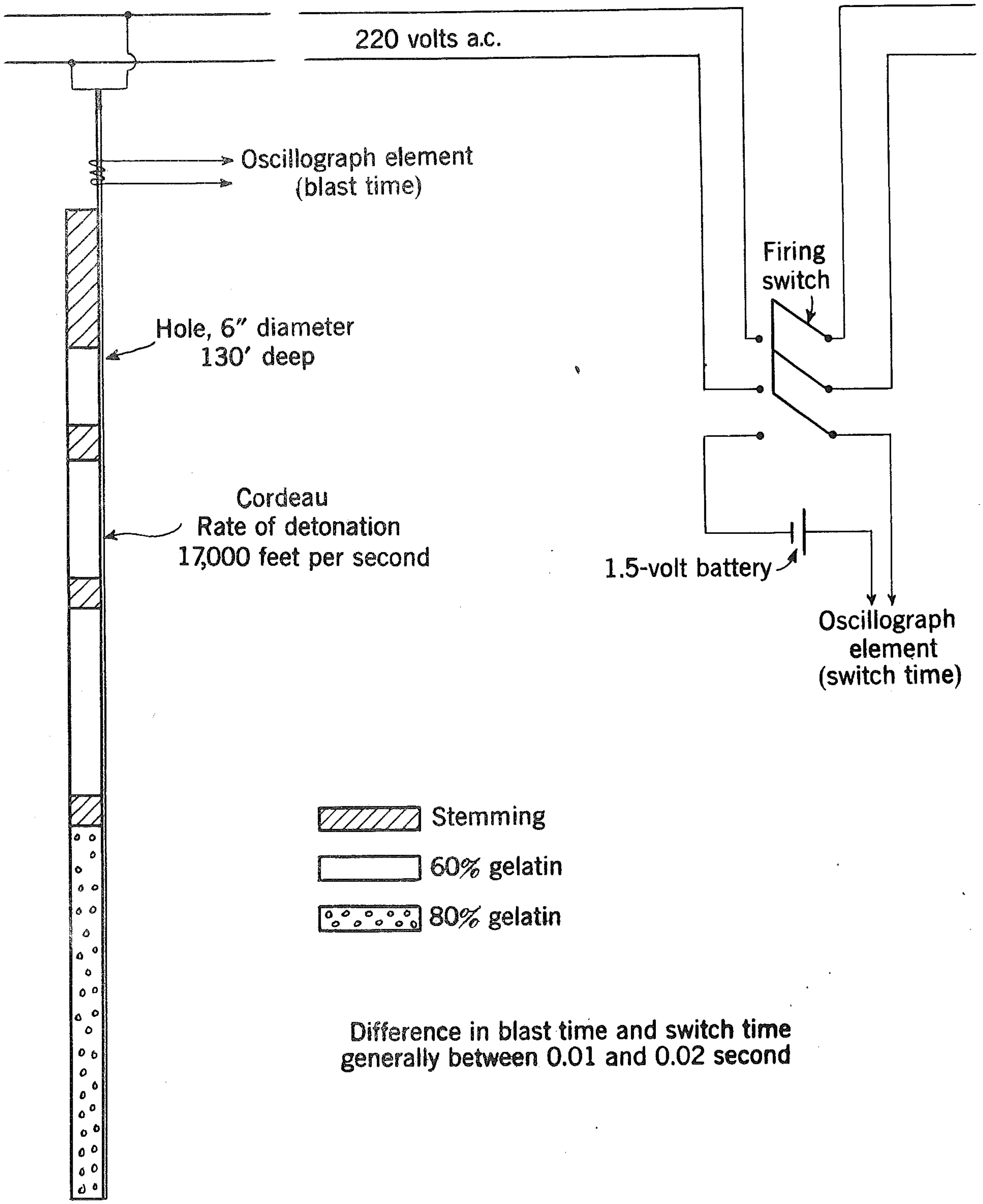
PROCEDURE OF MEASUREMENTS AND EVALUATIONS

After the seismic record was developed, the respective curves (fig. 5) were transposed from a standard oscillographic sheet. In this transfer a pantograph is used and adjusted so as to correct for calibration of the respective seismometers. The deflection constants of the seismometer are obtained from a static field calibration made before and after the shot. In addition to this correction a further instrument conversion constant was obtained from the master mechanical oscillator. The curves so obtained represent the actual displacement of the ground at different times, and are the fundamental point from which all other curves are derived.

An example of the vertical component of displacement at the station 300 feet to the north for a 4-pound shot in B butt is shown in figure 6, curve a. When this displacement is differentiated, the velocity curve, b, is obtained. A further differentiation of the velocity curve yields the acceleration curve, c. The resultant displacement curves are obtained at each station by combining the three separate components vectorially. Figure 7 shows these curves for 1-, 2-, and 4-pound shots at the station 150 feet north in B butt. Of course this procedure does not indicate the direction of the resultant displacement.

Other information, such as frequency and time-distance curves, were also obtained directly from the displacement curves.

Investigations were also made at a limestone quarry in Alabama. Figure 8 shows a cross-section and surface plan of the seismometer stations. A 17-hole shot of 15,000 pounds was taken for observation. Fundamentally, the geologic structure here is relatively simple and comprises Ketona dolomite changing into Knox dolomite with about 20 feet of overburden.



Difference in blast time and switch time generally between 0.01 and 0.02 second

Figure 3.—Wiring and loading diagram, typical hole.

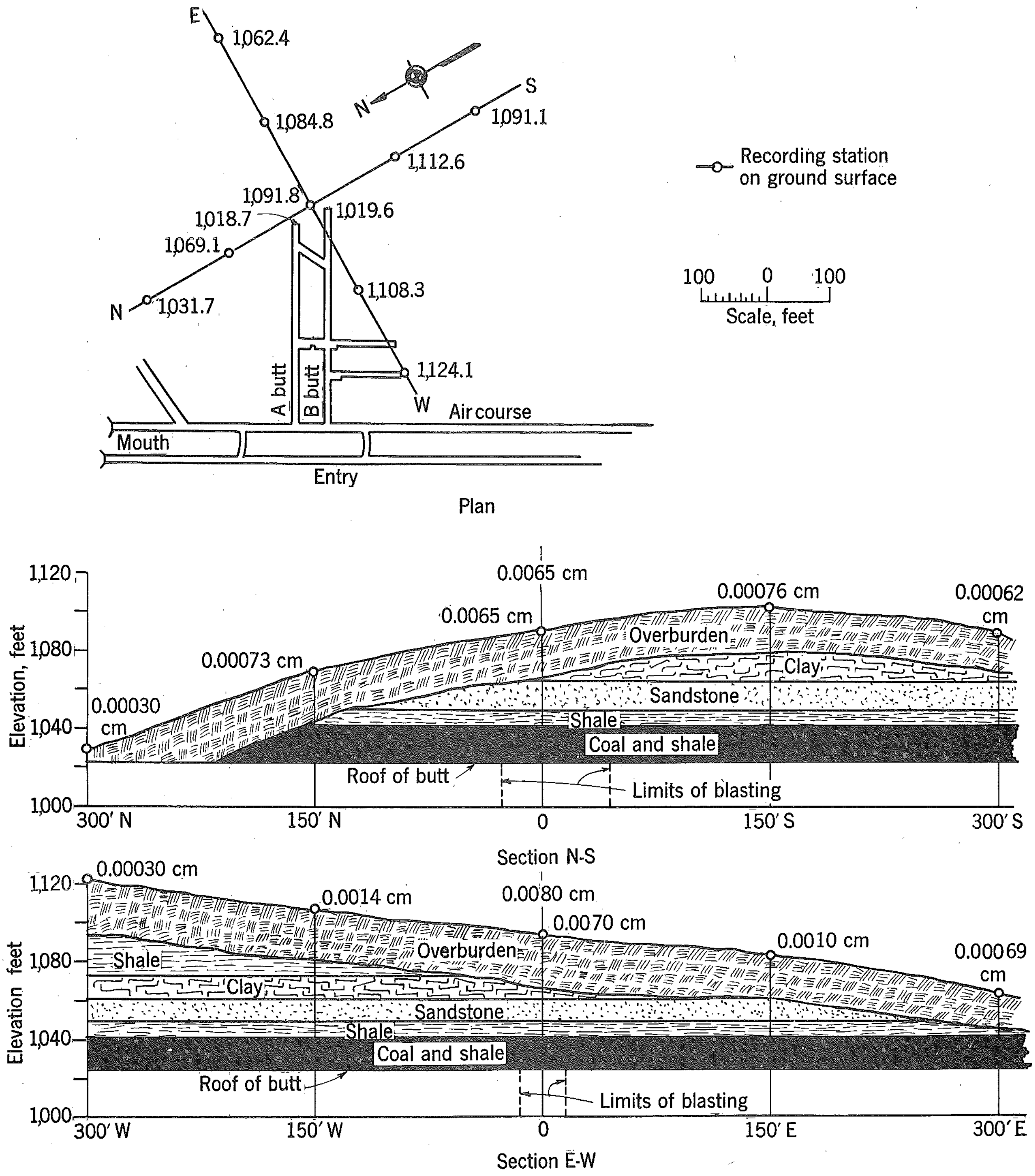


Figure 4.- Plan and sections of U. S. Bureau of Mines Experimental mine, showing location of recording stations and geologic formation with maximum resultant indicated for 2-pound ammonia-dynamite shots.

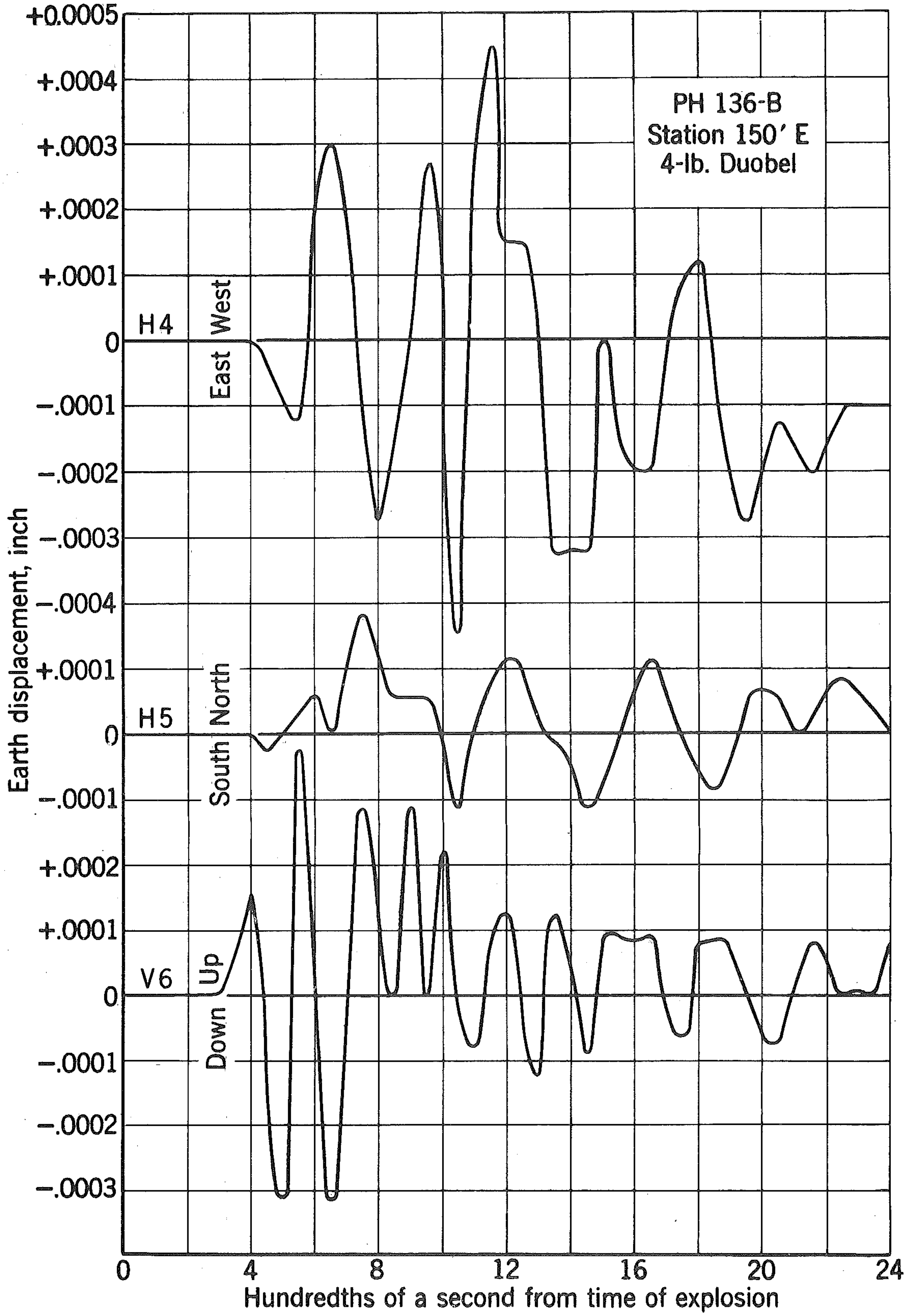


Figure 5.— Pantagraph reproduction of oscillographic record.

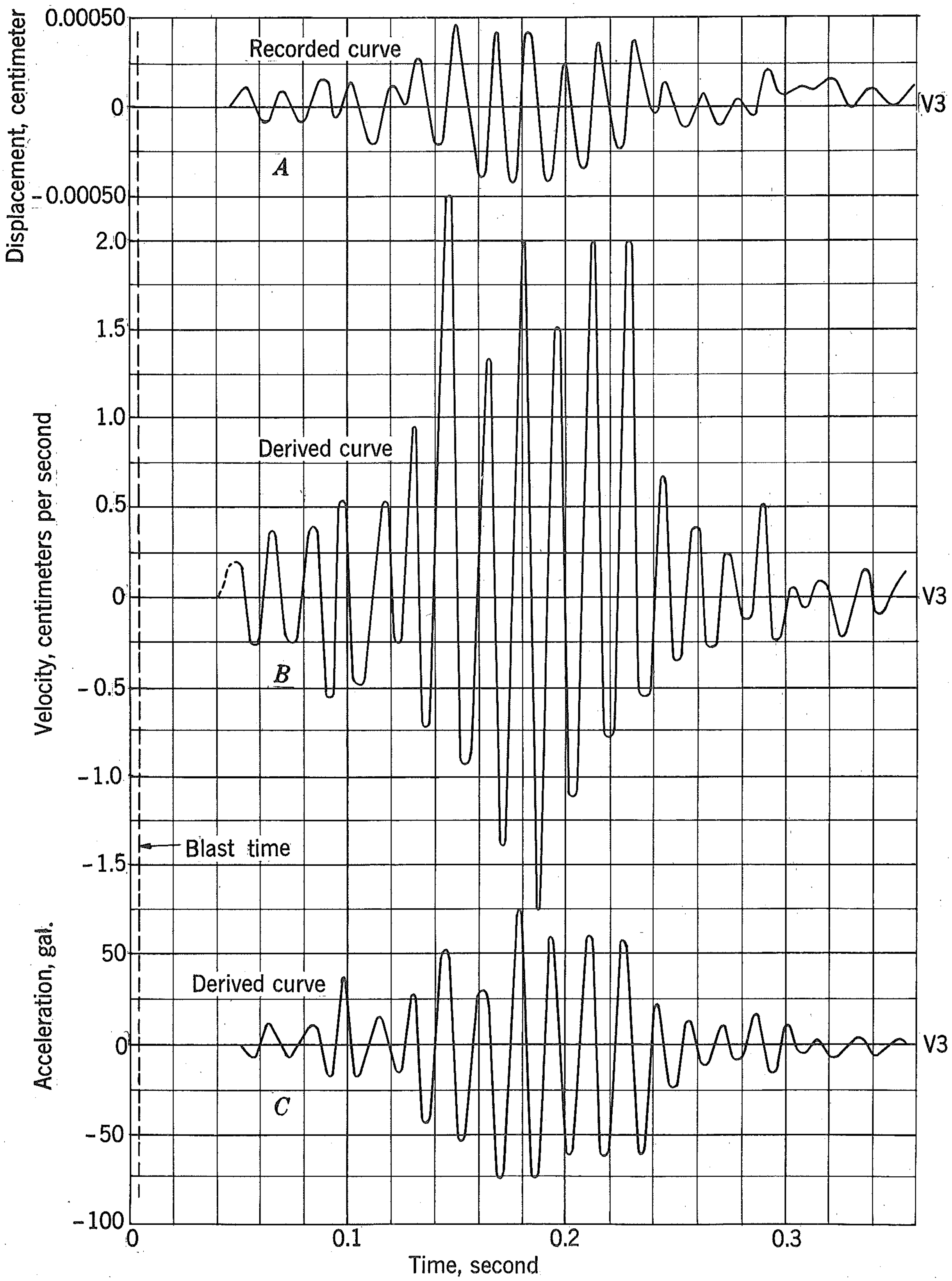


Figure 6.- U. S. Bureau of Mines Experimental mine. Ammonia dynamite, 4-pound shot in B butt. Vertical seismometer V3 at station 300 feet north.

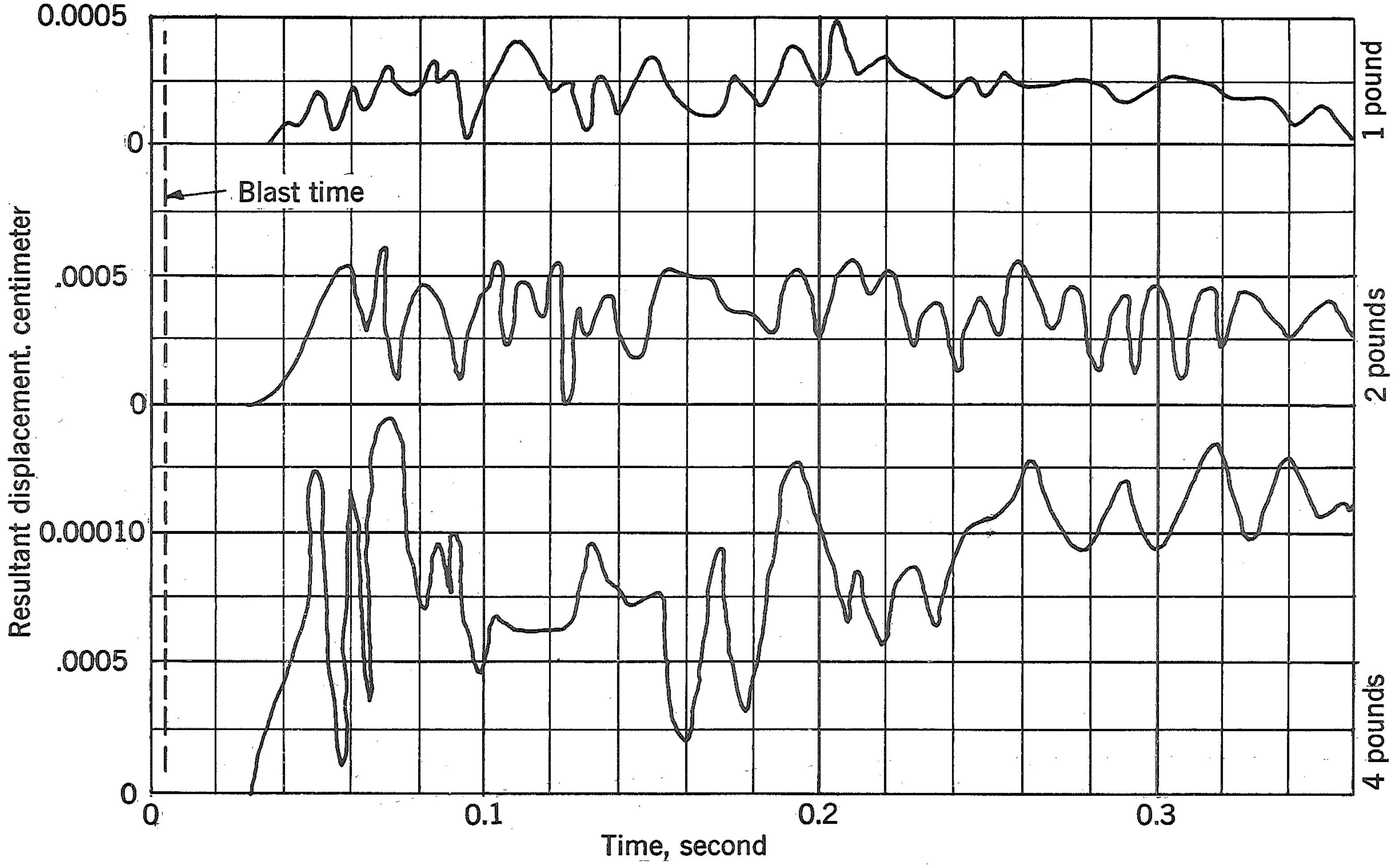


Figure 7.– U. S. Bureau of Mines Experimental mine. Ammonia dynamite in B butt; station 150 feet north.

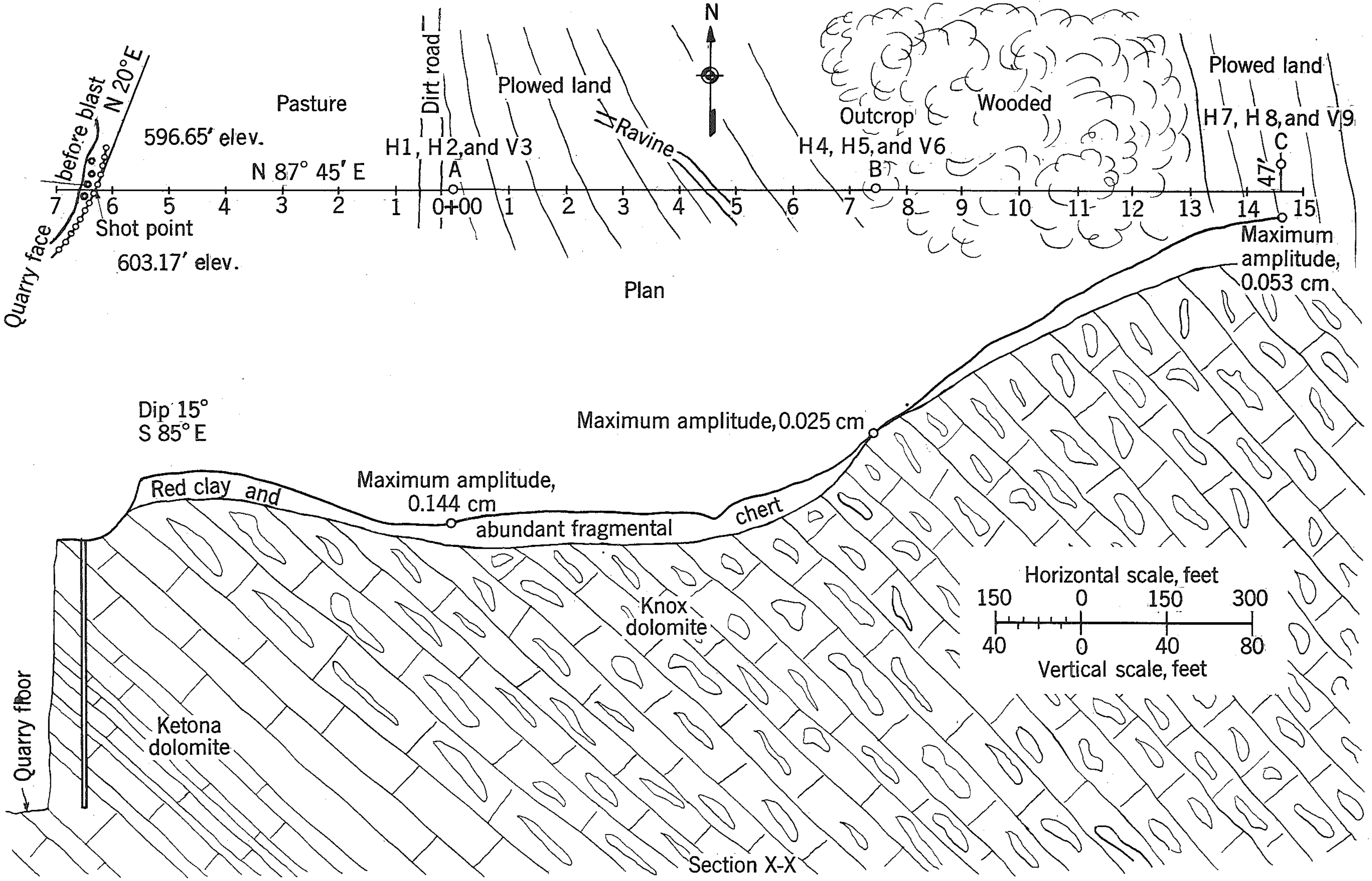


Figure 8.- Seismologic set-up, Alabama limestone quarry.

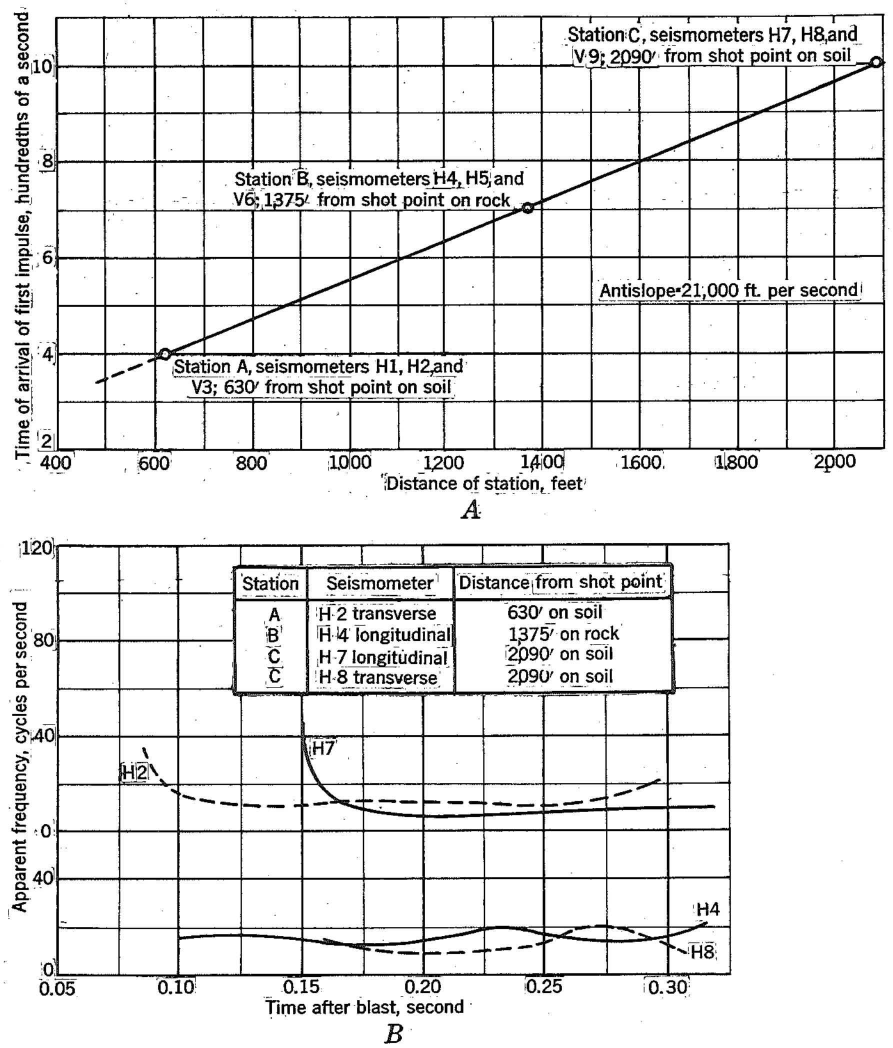


Figure 9.- Alabama limestone quarry, 15,400-pound well drill shot. A, Time-distance curve; B, frequency curve.

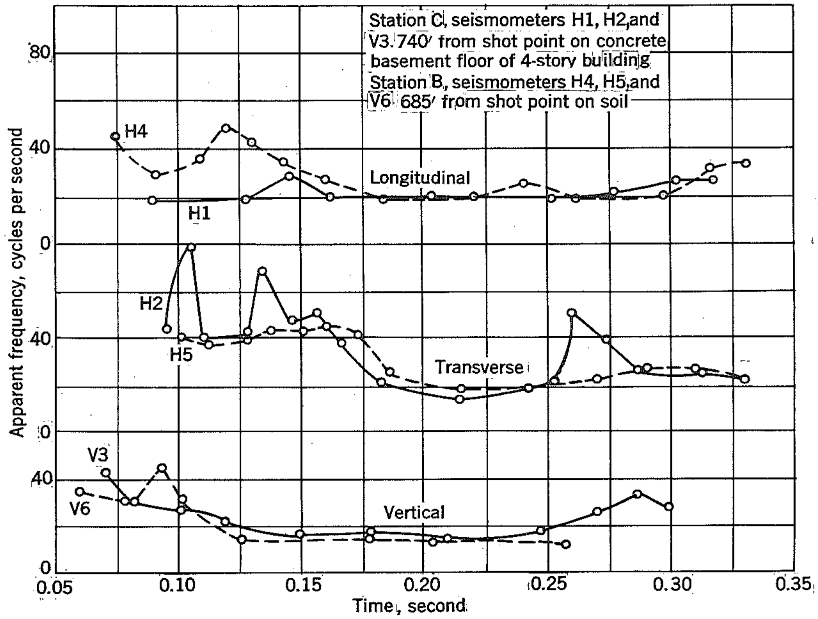


Figure 10.- South Carolina limestone quarry, well drill shot. One hole, 250 pounds nitrostarch, 50 percent dynamite.

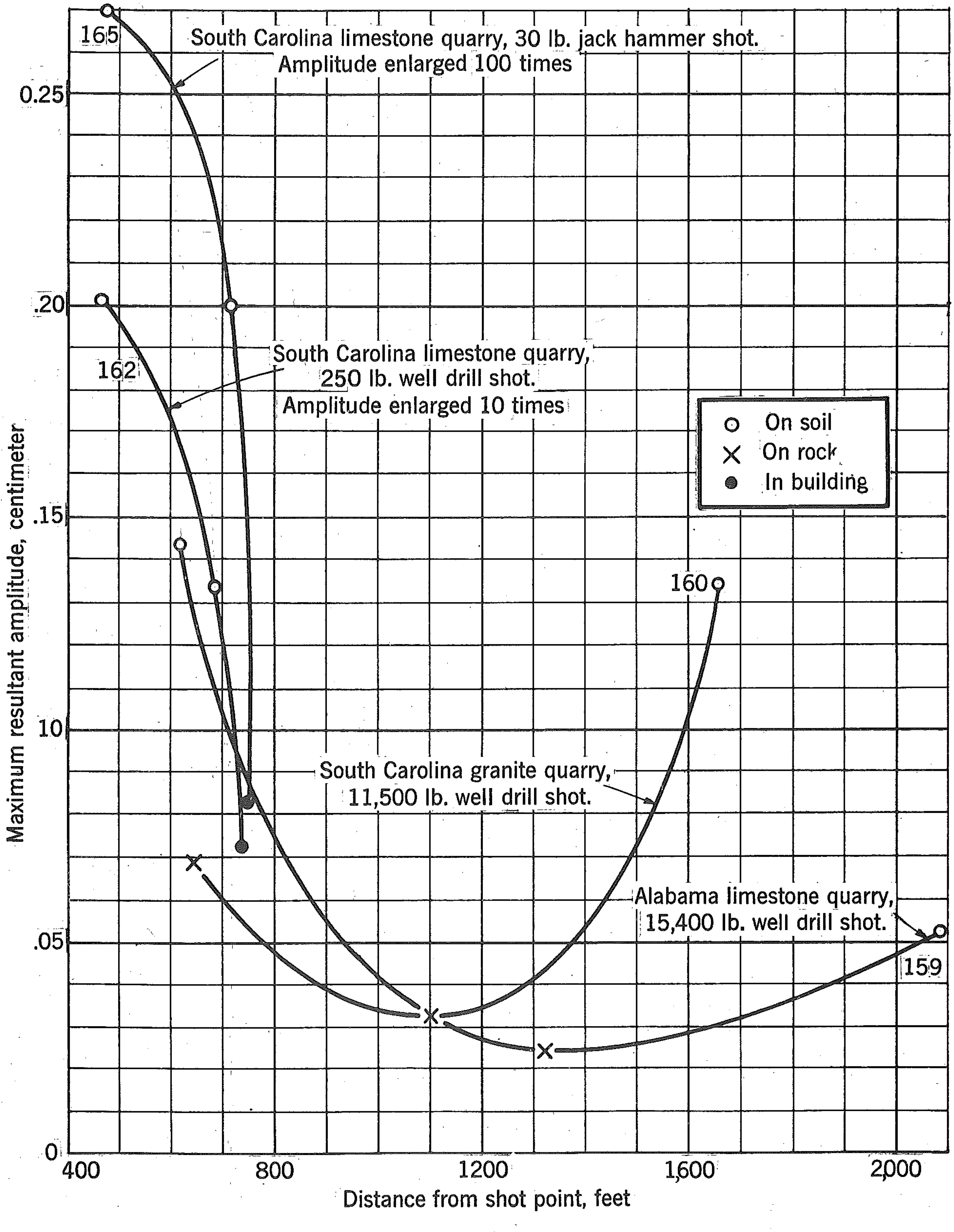
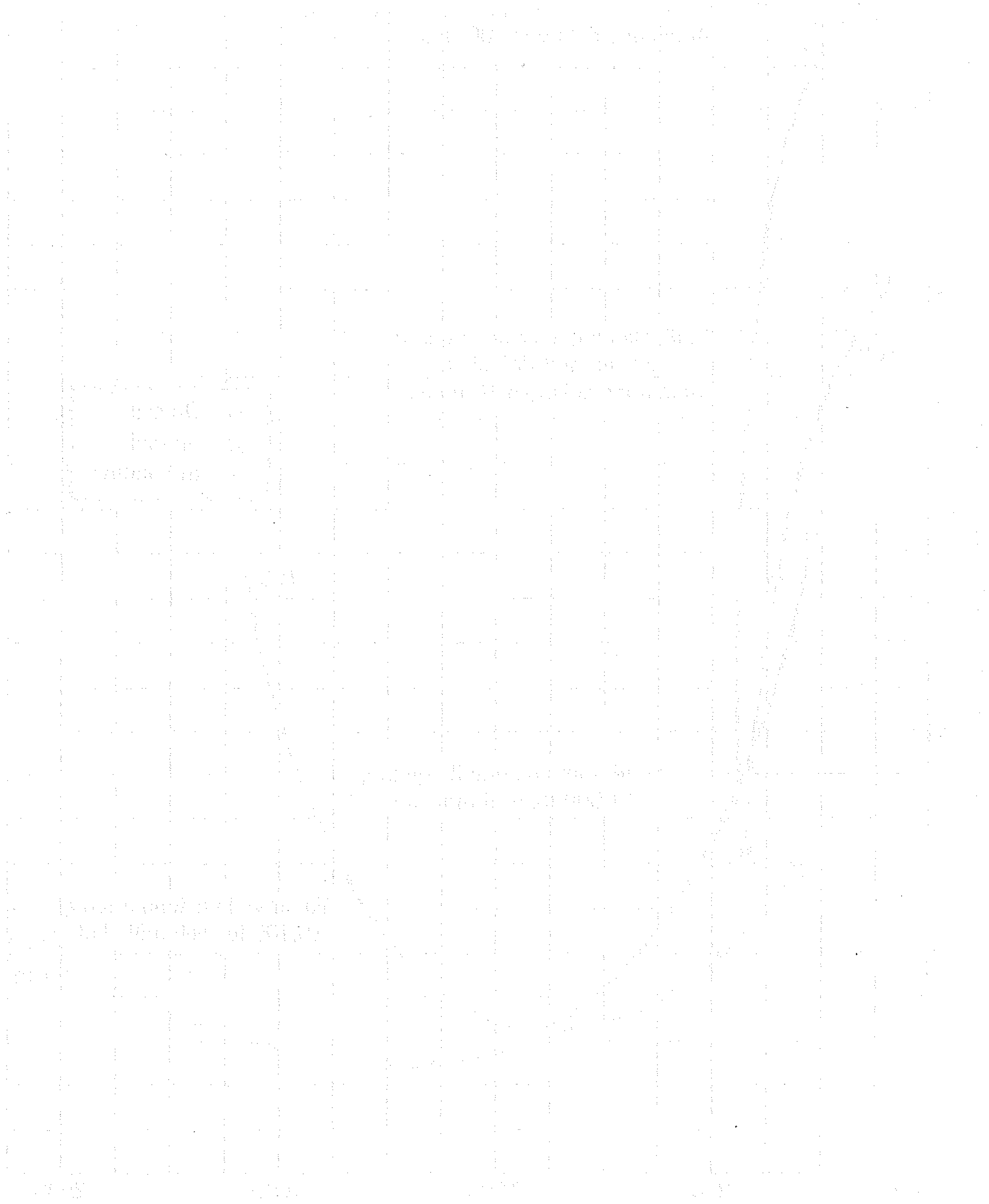


Figure 11.– Amplitude–distance curves for different quarries.



Seismometer stations were placed 630 feet, 1,375 feet, and 2,090 feet from the center of the line of holes, as shown in figure 8. Figure 8 also shows the maximum displacement of the ground at each station.

Station B was on an outcrop of Knox dolomite. The tops and bottoms of the charged holes were connected by cordeau, and electric detonators were placed at both top and bottom. There were 17 holes so placed, as shown in figure 8.

The time-distance curve (fig. 9) shows that the structure is very homogeneous and that there is some refraction, as the curve does not go through the origin but is a straight line. Between the high-speed dolomite and the instruments is a slow-speed layer comprising 15 to 20 feet of clay overburden. The speed in the dolomite was 21,000 feet per second.

The frequency curves in figure 10 indicate that at first the frequencies were high (of the order of 40 cycles per second) but later dropped to 10 cycles per second. The slow frequency appears to be the natural period of the ground. It is interesting to note that the plane of vibration shifts 90° in space in a distance of about 700 feet, as shown in figure 10. The frequency pattern for this shot was relatively simple, and the displacements, 0.144 cm nearest the shot (630 feet), 0.025 cm (1,375 feet) on the outcrop, and 0.053 cm (2,075 feet), indicate either a reflection phenomenon or a loose surface mantle in this vicinity. The waves passed through the geologic structure in the direction of, as well as across, the bedding and through the overburden.

In a granite quarry in South Carolina a 11,500-pound shot was observed. Here the frequencies were of a higher order and of a different character than those in limestone. (See fig. 11.) The normal ground vibrations were of the order of 20 cycles per second. The initial frequency was 14 to 80 cycles per second. It is noteworthy that the frequencies in separate components were different. Thus a complex pattern of polarized vibrations was indicated.

As before, the tendency is toward high frequencies at the beginning, which later decrease and remain nearly constant. This substantiates the theory that after a certain time the ground near quarries vibrates at its natural frequency.

Owing to the more complex nature of the geology the vibrations here are not so simple as in the dolomite of Alabama.

DISCUSSION OF MAXIMUM RESULTANT AMPLITUDES

Experiments have shown that in uniform media extending indefinitely or a great distance the vibration spreads out very much the same as the light from a candle. However, such media are rarely encountered around quarries. Bedded formations carry vibrations much farther than a uniform material would. In addition there often are geological discontinuities in the form of faults. Under such conditions a vibrational wave is reflected and refracted. This would tend to build the amplitude at selected points to a higher value than the normal spreading of the wave.

Observations made at a South Carolina limestone quarry with 250- and 30-pound shots show a general decrease of amplitude with distance. (See fig. 11.) On the other hand, at the South Carolina granite quarry the vibration at the farthest station was greater than that at the nearest station. This would indicate a "Ferranti effect;" that is, the succeeding waves gradually built up the vibration of part of the ground which had more or less the same period as the oncoming waves.

In these curves strata of different characteristics such as limestone and overburden were coupled together, and the points of low vibration were on outcrops of the same medium without coupling.

Figure 11, curve 159, shows this effect in Alabama limestone, but not to the same degree.

Owing to the complex geologic nature of the ground theoretical deduction at present could give little information. On the other hand, a careful mapping of the geology around a quarry and judicious placing of vibration-measuring apparatus will permit enough information to be secured for proper determination and control of undue vibrations.

CONCLUSION

A definite limit for vibrations and their effects on buildings is still to be determined from the results of the experimental investigations. The factors that cause damage are at present too indefinite, and there is no definite criterion of seismic destructiveness.

Each quarry differs from all others in its vibration characteristics, and these can be found only by experiment on the ground.

A careful study of the natural vibrations of buildings around a quarry and the natural ground vibrations will give information as to possible resonance between them. A vibration that may not harm one building may harm another.

There are indications that the observation of ground vibrations artificially produced and those occurring spontaneously may bear a relation to the degree of loading or stress in columns, arches, faults, etc., and may offer a means for predicting dangerous conditions in the ground.

PRECAUTIONS IN STUDYING VIBRATIONS

1. Ordinary vibrographs generally combine their own inertial motion with the applied motion of the ground so that it is impossible to separate them. Seismometers should be calibrated on standard calibrating machines at frequent intervals to test their accuracy.
2. In many types of vibration-measuring apparatus the amplifying mechanism, filter circuits, etc., may introduce very complicated functions into the record of a vibration so that it bears little or no relation to the actual ground movements.
3. Vibration-measuring instruments must have a very wide range of sensitivity and be capable of field calibration bfore and after each shot.
4. Conclusions on the vibrations around a quarry cannot be hastily drawn but require much detailed study and observation of methods of blasting, geological structure, locations of buildings, etc.

In order to study vibrations, the whole subject matter can be approached through the idea of coupling; that is, every vibrating element is attached to another vibrating element by more or less rigid mechanical connections or coupling. Such coupling may be very rigid or very loose and may transmit longitudinal vibrations, torsional vibrations, or combinations of the two.

In a very rigid coupling much energy is quickly transmitted, and the damaging resonant period need exist only a short time. If the coupling is loose, a resonant vibration would require a longer time to produce large amplitude.

Vibration of nonresonant frequencies would produce comparatively little effect, in either case.

After a seismic wave has passed and has set a building in vibration the building will return most of the energy to the ground through the coupling between ground and building. This has been discussed by K. Sezawa and K. Kanai (21).

Ramspach (19) has endeavored to compute the vibrations of buildings from the vibrations of the ground and a coupling factor, which he calls a magnification factor.

The ability of the ground to dissipate the energy returned to it by a vibrating building has been studied by S. K. Banerji and M. D. Manohar (15). They dropped a metal ball on the ground and measured the amplitude of vibration at different distances to determine the damping function of the ground. The results can be expressed by the relation:

$$A = a_o/d^{1/2}, \tag{6}$$

where $\underline{A}$ = amplitude at a given distance from source $\underline{d}$ and a = a constant.

In one location it was found that the results with the author's instruments could be expressed as

$$A = a_o/d^{2.2}, \tag{7}$$

At other locations different functions were obtained. The various results indicate that

$$A = a_o/d^x, \tag{8}$$

where x depends upon the terrain.

The decay constants of surface layers have been discussed mathematically by K. Sezawa and K. Kanai (22). Because of the singular properties attributed to the medium, mathematical work alone cannot generally be relied upon to give accurate knowledge of the dissipation of energy of vibration.

An interesting experiment was conducted by D. Kirnos (17) which showed that the resonant effects of the ground are very important in absorbing and transmitting ground vibrations. A sawmill running at 345 r.p.m. caused considerable ground vibration, whereas the same mill running at 275 to 290 r.p.m. caused little vibration of the ground. This shows that different parts of the ground have their own periods which depend upon their density and elastic properties and the degrees of coupling between parts.

In questions involving many elements, each having its own natural frequency and all coupled together in a very complicated manner which does not permit simple mathematical solution, it is suggested that such systems be simulated by electrical circuits interconnected to correspond to the mechanical interconnections. Vibrations of different frequencies, durations, and wave forms may be applied to such an equivalent system, from which all vibration factors can be observed experimentally.

MECHANICS OF DEFORMABLE BODIES

From a purely physical point of view, elastic waves and their associated phenomena have received much practical and theoretical consideration. It can be said generally that no intrinsically new theoretical analyses are needed. Enough mathematical machinery already exists to correlate such observations properly.

On the other hand, there is a definite lack of technique owing largely to the complicated occurrence of such phenomena, which does not permit them to be reduced to their simplest elements. The ground is a heterogeneous mass composed of diverse materials, all of which obey different laws relating to possible movement and elastic constants. The laws of deformation relating to stress and strain cannot always be expressed by simple functions of directions and magnitudes. For example, the simplest relation between the two, as expressed by the linear vector function, is as follows:

$$\begin{gathered}\text{Strain} = \text{W stress, or}\\ S = W\,p\end{gathered} \tag{9}$$

which, considering the components of motion, is

$$S_1 = W_{11}p_1 + W_{12}p_2 + W_{13}p_3 \qquad (10)$$
$$S_2 = W_{21}p_1 + W_{22}p_2 + W_{23}p_3$$
$$S_3 = W_{31}p_1 + W_{32}p_2 + W_{33}p_3.$$

Here S_1, S_2, and S_3 are the three components of motion due to stresses, p_1, p_2, and p_3. The formula simply states that the S_1 component depends upon the three stresses or pressures p_1, p_2 and p_3 and bears a simple scalar coefficient W_{11}, W_{12} and W_{13} to p_1, p_2 and p_3, rerespectively.

In elementary mechanics such a stress can be resolved into a configuration that would change, for example, a small sphere into an ellipsoid, turn the axis of the original sphere, and give it a movement or displacement. If this is done to very small elements in the mathematical developments described as limiting ratios, then the cubic dilation would be expressed as

$$\theta = \text{div } S \qquad (11)$$

and the rotation of the element as

$$\phi = 1/2 \text{ curl } S. \qquad (12)$$

If the element of volume was d$\underline{T}$, it would also be displaced an amount equal to $\underline{S}$.

These equations are very convenient, as

$$\int S\theta dT = \text{dilation of whole volume, and} \qquad (13)$$

$$\int S\phi dT = \text{distribution of rotation or torsional strains of volume.} \qquad (14)$$

Unfortunately, these simple analyses do not apply in blasting operations and can be used only as a guide for certain approximations. Nevertheless, they form the basis of the simple relation expressed in equations 1 and 2. The coefficients W_{11}, W_{12}, W_{13}, etc., instead of being scalar constants become functions of p_1, p_2, and p_3, so that instead of only nine scalar constants each term also introduces a large number of functional constants, and separate functions are necessary to describe the whole phenomena. This immediately introduces group determinants and group velocities, variable frequency parameters, and similar factors under various assumed functional strains.

ACKNOWLEDGMENTS

The seismometers used in this study were developed in Bureau of Mines laboratories during a 5-year program of experimentation. This development was started and continued as a cooperative problem between the Bureau and a group of quarry companies, who generously offered the use of their quarries in field tests and supplied part of the funds used in preliminary development of the seismometers.

The authors wish to acknowledge the cooperation and assistance of the General Crushed Stone Co., Easton, Pa.; New Haven Trap Rock Co., New Haven, Conn.; Lynn Sand & Stone Co., Swampscott, Mass.; Rowe Contracting Co., Malden, Mass.; Massachusetts Broken Stone Co., Waltham, Mass.; West Roxbury Trap Rock Co., West Roxbury, Mass.; and J. S. Lane & Son, Inc., Meriden, Conn.

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   The author gives the form of the law of propagation of seismic waves as $T = T_0 2+0D$; although this law shows that the period should increase with the distance, D, from the source, we have found that our results obey no such law. The frequency of the vertical component usually was higher than the longitudinal or transverse and remained quite constant. The transverse and longitudinal waves had very random frequency variations showing that the frequency depended considerably upon the terrain.

2. LEET, L. DON. The Provincetown, Mass., Earthquake of April 23, 1935, and Data for Investigating New England's Seismicity. Proc. Nat. Acad. Sci., Washington, vol. 21, no. 6, 1935, pp. 305 - 313. Bureau of Mines Geophys. Abst. 2718.

   Used blasts to determine seismicity. Periods of vibrations about 1 second. Leet used three large New England blasts to find the velocity of seismic waves through the typical New England terrain. He used the results to locate the epicenter of the quake.

3. RIXMANN, F. Untersuchungen über die abhangigheit der Bodenbewegung bei Sprengungen von der Ladung. Ztschr. Geophysik, Braunschweig, vol. 11, no. 4/5, 1935, pp. 197 - 207. Bureau of Mines Geophys. Abs. 2598.

   As the authors found the frequency to be independent of charge, their assumption that the frequency depends only on the density of the mass set in vibration is substantiated to a certain degree.

B. Velocity

4. LEET, L. DON, and EWING, W. MAURICE. Velocity of Elastic Waves in Granite. Physics, Menasha, Wis., vol. 2, no. 3, 1932, pp. 160 - 173. Bureau of Mines Geophys. Abs. 809.

   This is a seismic study of travel-time curves. Gives seismograms from which periods can be calculated.

5. NORLUND, N. E., and BROCKAMP, B. Seismische Feldarbeiten in Danemark (Part I). Institut Géodisque de Danemark, Copenhagen, Memoirs, ser. 3, vol. 2, 1934, 48 pp. U.S. Bureau of Mines Geophys. Abs. 2588.

   A table of velocity of propagation of seismic waves through various media is given. This table illustrates the wide variation in the speed of seismic waves through various rocks.

6. WIECHERT, E. Seismische Beobachtungen von Steinbruchsprengungen. Ztschr. Geophysik, vol. 5, no. 3-4, 1929, pp. 159 - 162.

7. BROCKAMP, B. and WOLKEN, K. Bemerkungen zu den Beobachtungen bei Steinbruchsprengungen. Ztschr. Geophysik, vol. 5, no. 3-4, 1929, pp. 163 - 171.

   Although these men have treated seismic ray paths rather elaborately the ordinary principles of optics can readily be applied to this work. In general, the rays follow straight-line paths if the medium is homogeneous, changing direction only on changing medium. If the medium has mechanical elastic coefficients varying with depth, the path of the rays is curved.

C. Instruments

8. AMERICAN ASKANIA CORPORATION. Two-Component Vibrograph. Instruments, Pittsburgh, Pa., vol. 5, no. 1, 1932, p. 21. Bureau of Mines Geophys. Abs. 993.

Visible, not recording. Simply an indicator.

9. DYK, KARL. On the Reductions of Seismograms Obtained in Shaking-Table Experiments. Bull. Seis. Soc. America, Stanford Univ., Calif., vol. 25, no. 2, 1935, pp. 119 - 137. Bureau of Mines Geophys. Abs. 2703.

This paper states that on integrating an acceleration curve there exists a possibility of 100 percent error. It therefore illustrates that the most accurate way to do seismic research, where extreme sensitivity is not necessary, is to measure the amplitude and find the velocity and acceleration by differentiating the amplitude curves.

10. HAGIWARA, T. Comparison of Displacement, Velocity, and Acceleration Seismograms. Bull. Earthquake Research Inst., Tokyo, vol. 13, March 1935, pp. 138 - 145. Bureau of Mines Geophys. Abs. 2771.

Used (a) displacement seismograph, (b) velocity seismograph, and (c) acceleration seismograph. Integrated curves of three instruments to compare results for accuracy. They come to the conclusion that integrated acceleration curves and velocity curves were in error because of the deviation in the zero line of original curves. This conclusion seems doubtful for anything but sinusoidal curves. In general, for a general form of wave, there must be added a constant of integration for each harmonic wave if the wave is resolved into a Fourier's series.

11. GENIE CIVIL. Seismographe enregistreur Askania a trois composantes destine a la mesure des vibrations des constructions. Paris, vol. 100, no. 8, 1932, pp. 193 - 195. Bureau of Mines Geophys. Abs. 867.

Description of three-component building vibration recorder. Vibrograph type of instrument. It is rather doubtful what these instruments are measuring - amplitude, velocity, acceleration, a combination of two, or all three.

12. SHRADER, J. E. A Three-Dimensional Vibrograph. Phys. Review, Minneapolis, vol. 38, no. 10, 1931, p. 1923. Bureau of Mines Geophys. Abs. 926.

Moving element damped by felt. Criticism same as above. In addition, the damping of this instrument is accomplished by felt rubbing against moving element.

13. _____ The Tri-Dimensional Vibrograph. Jour. Franklin Inst., Lancaster, Pa., vol. 215, no. 4, 1933, pp. 455 - 469. Bureau of Mines Geophys. Abs. 1465.

Felt damped; cannot be trusted to reproduce readings or to record amplitudes faithfully.

14. TRI-DIMENSIONAL VIBROGRAPH. Instruments, Pittsburg, Pa., vol. 5, no. 5, 1932, p. 136. Bureau of Mines Geophys. Abs. 994.

Indicating and recording. Same as all vibrographs.

D. Building and Ground Vibration

15. BANERJI, S. K., and MANOHAR, M. D. On the Artificial Vibrations of the Ground. Indian Jour. Phys., Calcutta, vol. 8, pt. 2, 1933, pp. 95 - 121. U.S. Bureau of Mines Geophys. Abs. 1851.

Deduce $A = a_0 d^{-1/2}$, where d = distance, A = amplitude of ground vibration at distance d, and a_0 = a constant. Artificial vibrations set up by dropping metal sphere onto ground. The exponent to which d is raised varies with the type of ground. In Bureau of Mines work we obtained value -2.2. Atlas Powder Co. obtained -0.7.

16. BLUME, J. A. A Machine for Setting Structures and Ground into Forced Vibrations. Bull. Seis. Soc. America, Stanford Univ., Calif., vol. 25, no. 4, 1935, pp. 361 - 379. Bureau of Mines Geophys. Abs. 3018.

This machine consists of a rotating unbalanced flywheel. In operation the machine is set up in a building and then speeded to about 600 r.p.m. and then allowed to slow down. As the flywheel slows, the building is subjected to a changing frequency, and when a resonant frequency is reached, the vibrograph records the vibrations indicating the resonant peaks.

17. KIRNOS, D. Seismometrical Investigation of Sawmills "26" and "A" in the Region of Arkhangelsk (Russian). Academie des Sciences de l'U.S.S.R., Pub. Seis. Inst., Leningrad, no. 36, 1933, 18 pp. U.S. Bureau of Mines Geophys. Abs. 1649.

    Sawmill running at 345 r.p.m. vibrated ground pronouncedly; 275 to 290 r.p.m. caused very little vibration of ground. Vertical and horizontal seismographs were used.

18. KOHLER, R. Formen der Bodenschwingung bei sinusförmiger Anregung. Ztschr. Geophysik, Braunschweig, vol. 10, no. 8, 1934, pp. 386 - 387. Bureau of Mines Geophys. Abs. 2405.

    10 to 50 cycles per second used: 1. Elliptic form of ground motion for low frequency. Artificially applied vibration. 2. Plane of oscillation is vertical through source and receiver for long waves. 3. Plane of oscillation changes position with frequency for high frequencies.

    In our work we found that this conclusion was verified. We found that the maximum amplitude shifted from the vertical to longitudinal with time and distance.

19. RAMSPECK, A. Versuche über Boden und Gebaude-Schwingungen. Ztschr. Geophysik, Braunschweig, vol. 9, no. 1/2, 1933, pp. 44 - 59. Bureau of Mines Geophys. Abs. 1418.

    Calculation of vibration of building from known ground vibrations if function of magnification of building is known. This research again shows that by far the most efficient way of studying effect of vibrations on buildings is by resonance studies of ground and building vibrations.

20. _____ Zusammenhang zwischen Boden und Gebaudeschwingungen. Ztschr. Geophysik, Braunschweig, vol. 8, no. 8, 1932, pp. 467 - 469. Bureau of Mines Geophys. Abs. 1277.

    Studied only the influence of horizontal vibration of building.

21. SEZAWA, K., and KANAI, K. Decay in the Seismic Vibrations of a Structure by Dissipation of their Energy into the Ground: Proc. Imp. Acad., Tokyo, vol. 11, no. 5, 1935, pp. 174 - 176. Bureau of Mines Geophys. Abs. 2716.

    Studies dissipation of energy in air and materials with relation to its dissipation when transmitted to the ground. The authors claimed that a structure first receives the vibrational energy from the ground and then transmits the vibration back to the ground to be dissipated.

22. _____ Decay Constants of Seismic Vibrations of a Surface Layer. Bull. Earthquake Research Inst., Tokyo, vol. 13, no. 2, 1935, pp. 251 - 262. Bureau of Mines Geophys. Abs. 2772.

    Mathematical discussion of the damping of a surface layer excited by seismic waves.

23. _____ Some New Problems of Free Vibrations of a Structure. Bull. Earthquake Res. Inst., Tokyo, vol. 12, no. 4, 1934, pp. 804 - 822. Bureau of Mines Geophys. Abs. 2579.

24. _____ Some New Problems of Forced Vibrations of a Structure. Bull. Earthquake Research, Inst., Tokyo, vol. 12, no. 4, 1934. Bureau of Mines Geophys. Abs. 2580.

    In the forced vibrations studied authors used horizontal sinusoidal driving forces and give methods for reducing effect of vibration. In general, the problem resolves itself simply into a determination of the period of the building and finding how close this period is to the period of the earth vibration. Greatest damage is, of course, done when the two frequencies are resonant.

25. TSSHOKHER, V. Investigation of Equilibrium Conditions of Earthen Masses under the Action of Seismic Forces. Academie des Sciences de l'U.S.S.R., Pub. Seis. Inst., Leningrad, no. 5, 1930, p. 1 - 11. Bureau of Mines Geophys. Abs. 36, p. 424.

    Author studied angle of repose of various materials (soil, sand, loess, etc.) before and after they were subjected to shaking table vibration.

26. VESHNIAKOV, N. V. Seismometric Investigations of Several Bridges in Leningrad. Academie des Sciences de l'U.S.S.R., Pub. Seis., Inst., Leningrad, no. 4, 1930, pp. 1 - 20. Geophys. Abs. 36, p. 424.

    Large-scale study of bridges.

E. Earth Vibration Intensity Scale

27. BENIOFF, HUGO. The Physical Evaluation of Seismic Destructiveness. Bull. Seismic Soc. America, Stanford Univ., Calif., vol. 24, no. 4, 1934, pp. 398 - 403. Bureau of Mines Geophys. Abs. 2445.

    Determines new type of instrument for evaluating seismic destruction. Geophysical abstract gave no result of research. Makes no mention of time-rate change of acceleration as criterion.

28. KATO, Y, and NAKAMURA, S. On the Piezo-Electric Accelerometer and its Application to the Measurement of the Velocity of the Elastic Waves Produced by Artificial Disturbances. Proc. Imp. Acad., Tokyo, vol. 6, no. 7, pp. 272 - 274. Bureau of Mines Geophys. Abs. 18, p. 12.

    Before perfecting this instrument, the authors found that it was measuring time rate of change of acceleration. This simply gives one an idea for designing an instrument to measure what we think to be the true criterion for seismic destructiveness.

29. McADIE, A. A Serviceable Scale for Earthquake Intensity. Proc. 1930 Meeting, Eastern Sec. Seis. Soc. America, Washington, D.C., pp. 54 - 56. Bureau of Mines Geophys. Abs. 19, p. 8.

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30. WOOD, H. O., and NEUMANN, F. Modified Mercalli Intensity Scale of 1931. Bull. Seis. Soc. America, Stanford Univ., Calif., vol. 21, no. 4, 1932, pp. 277 - 283. U.S. Bureau of Mines Geophys. Abs. 860.

F. Blasting Measurement

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    Gives a description of seismic work done on the Manistique, Mich., quarry shot.

32. ROCKWELL, E. H. Vibrations Caused by Blasting and Their Effect on Structures. Hercules Powder Co., Wilmington, Del., 1934, 69 pp. Bureau of Mines Geophys. Abs. 2449.

    Rockwell uses vibrographs and pin test for scientific measurement of the amplitude of blasting vibrations.

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34. WOOD, H. O., and RICHTER, CHAS. F. A Second Study of Blasting Recorded in Southern California. Bull. Seismic. Soc. America, Stanford Univ., Calif., vol. 23, no. 3, 1933, pp. 95 - 110. Bureau of Mines Geophys. Abs. 1592.

    Study made from teleseismic standpoint. Used travel-time curves to do geophysical prospecting. Made no measurements of amplitudes.

G. Physiological Effect of Vibrations

35. ISHIMOTO, M. and OOTUKA, M. Determination de la limite perceptible des secousses. Bull. Earthquake Research Inst., Tokyo, vol. 11, no. 1, 1933, pp. 113 - 120. Bureau of Mines Geophys. Abs. 1470.

Claimed impossible to get pure sine wave. Gave no results of research in Geophysical Abstract. Studied physiological and psychological effect of sinusoidal waves on human beings.

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