DISASTER PREVENTION RESEARCH INSTITUTE

BULLETIN No. 21 MARCH, 1958

THE PROPAGATION OF WAVES NEAR EXPLOSION AND FRACTURE OF ROCK (I)

BY

SŌJI YOSHIKAWA

KYOTO UNIVERSITY, KYOTO, JAPAN

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Abstract

The basic character of fracture and plastic deformation processes that will be operative under extremely high, yet very transitory pressure, imposed on rock by explosion is studied experimentally. The mode of propagation of transient disturbance is measured by seismometric pick up and strain gage especially devised for this purpose put within the fracture zone and neighboring plastic zone which would be formed by explosion. Magnetic tape recoding system is used partially and play back records are obtained with several ranges of filtering.

The strain wave shapes, that is the rise time, the pulse width. etc., are shown to be influenced by applied pressure, the distance from the shot point and free surface; moreover, these pulses are composed by component waves different in propagating velocity. The experimental results are discussed referring to the stress strain relation of each rock determined statically by experiment. In the very neighbourhood of shot point two different kinds of waves are detected. One is the elastic wave of relatively higher frequency, and the other the plastic wave of lower frequency, with the increase of amount of explosive the propagating velocity of the plastic wave is effected and becomes slower.

1. Introduction

When an explosive is detonated in intimate contact with rock, its loading becomes impulsive and its intensity is of sufficient magnitude to produce beyond the elasticity limit and it produces fracturing and permanent distortions in rock upon which it acts. The strains accompaning elastroplastic deformations are frequently so large that the simplified equations of the small-strain theory are invalid. In case of metallic bar or wire, this problem was investigated experimentally by Karman[1] and Duwez with their theoretical study. B.F. Howell[2] and Koukonen discusses the decay of waves near explosion, introducing the plastic deformation due to the fact that the elastic decay equation $E_X = E_0 X^{-P}$ was not profitable, and the new equation $E_X = E_0 X^{-A} e^{-\alpha X}$ had to be used. (where E_X, E_0, denote energy, P, A are constants and X is the distance from the shot point.)

On the other hand, the propagations of waves near explosion were first investigated by Sharpe[3] in 1942 theoretically with empirical field observation within the elasticity limit, since then similar method was adopted by W. I. Duvall[4] and Ito[5] Lately Okawa[6] measured the strain near explosion in concrete block by wire strain gage and reported the strain in his experiment could be interpreted by elastic dynamics. All the experimental results were pretty good agreement with the Sharpe equation. But the strain wave observed in their experimemts was of comparatively high frequency. If the plastic strain and the strain wave of low frequency had existed, these waves would have been overlooked on the account of the lack in low frequency response of instruments. Sakurai[7] measured the shock wave near explosion in metals and referred to the rock and reported the velocities of shock waves and the area which might be able to propagate as the shock wave.

It appears that the wave generated by explosion would propagate as a shock wave, plastic wave and elastic wave when the resultant stress is the function of time and is of sufficient magnitude to produce them. But it is difficult to identify each component wave since these waves are mutually superposed and propagate almost concurrently. However, it will not be at all impossible to discern them when the difference in propagating velocity or frequency exists among these waves, if we analyse the experimental results by some suitable methods. Therefore, the frequency response of the instruments must be taken wide as far as possible and it is necessary to measure from the wave of very low frequency to the higher one. However, in actual case the total response of the instruments will be defined under certain combination of pick up, amplifier and galvanometer. For this reason the experiments are repeated in a definite condition of measured circumstances by use of various pick up and strain gage having each different frequency responses. The field experiments were carried out at the quarry of metal mine, and beside them accurate measurement of strain wave in a granite pillar is carried out. In this case the magnetic recording system is used, and the play back record is obtained with the several ranges of filtering. The results of field experiments are investigated referring to these quantitative measurements.

When the magnitude of the stress generated by explosion becomes to the fracturing stress of rock, fracture may occur by explosion. The mechanisms of fracture are investigated from the experimental results.

As experimented results, two wave groups are detected in the neighbourhood of explosion, that is, the wave of higher frequency in the initial parts of the oscillation and the following lower frequency one. The propagation velocities of initial shock are influenced by the quantity of explosive and in the very neighbourhood of explosion the velocity of propagation of the initial motion is lower than that of elastic wave which is determined by seismic prospection method and ultra sonic wave. The area where the propagating velocity is lower than that of infinitesimal elastic wave is enlarged with the increasing explosive.

The plastic deformation is detected later than the initial shock and is chiefly produced by the tension wave which is formed by the compressional strain reflected from the free surface.

From the frequency analysis of waves, the distribution of maximum amplitude of component waves is not influenced by the quantity of explosive, but the distribution of component waves with regard to time is largely influenced.

2. Experimental Technique

The measuring apparatus must be given special considerations that they

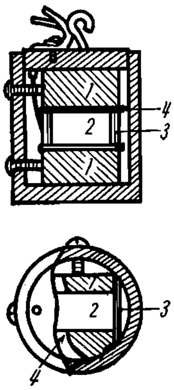


Fig. 1 Schematic representation of pick up.
1. Permanent magnet
2. Coil
3. Frame of coil
4. Rubber plate

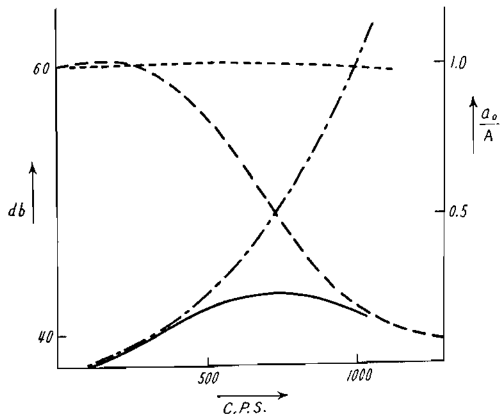


Fig. 2 Frequency response of instruments.
·············· Pick up
—·—·— Amplifier
— — — — Galvanometer
———— Total response

may be free from destruction on account of large pressure caused by explosion; moreover, it must be small as far as possible to be placed at many measure points within a limited area near the explosion. Sassa's I-type pick up is used, and its schematic diagram is given in Fig. 1.

The main parts of the instrument are enclosed by thick brass cylindrical case so that the pick up may not be destroyed by the applied pressure when it jumps out from its set position with the fractured rock. Its frequency of free oscillation is ca. 2000 c.p.s. and the coil with its frame is put between rubber plates and that of galvanometer is 1000 c.p.s.. In actual measurement, pick up is connected with galvanometer through amplifier, their individual and total frequency response is as shown in Fig. 2.

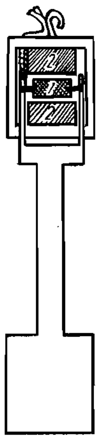


Fig. 3 Schematic representation of strain gage.

Schematic diagram of strain gage is shown in Fig. 3.

In the figures (1) and (2) show coil and magnets, respectively, and the instrument is sensitive longitudinally. Coil and brass mass are connected with the bar 8 cm in length which is made of the same materials. The bar and mass are prevented from rolling by piston type guides and ditches.

Now if the actual direction of strain be x, and the sensitive direction be y, then the strain of y direction becomes

$$y=\int_0^L \cos\beta \frac{\delta\xi}{\delta x}\, dx\ ,$$

where L is the length of strain gage, β the angle between x and y, ξ the displacement of x direction. Actual record is obtained by direct connection with a galvanometer of the free oscillation period 1/1000 sec. and then the deflection of the galvanometer ϕ becomes for the strain wave of enough longer period compared with that of galvanometer approximately.

$$\phi \simeq K\frac{\delta y}{\delta t}=K\frac{\delta}{\delta t}\int_0^L \cos\beta \frac{\delta\xi}{\delta x}\, dx,$$

K is the e.m.f. per unit velocity between bar and magnet. The wave length of strain wave near explosion is long enough compared with the length of bar, so the strain will be constant between integral intervals. Accordingly, the strain and strain rate are given by the following equation,

$$y = L \cos \beta \frac{\delta \xi}{\delta x}$$

$$K \frac{\delta y}{\delta t} = KL \cos \beta \frac{\delta^2 \xi}{\delta x \delta t}.$$

The mine is usually full of moisture and dust, accordingly the image of the galvanometer is apt to be unclear, and so the oscillograph must be sealed from atmosphere. The recorder is devised especially keeping in mind the above point. Time elapse of the measuring phenomena may be very short, and so the velocity of rolling film is made about 1∼1.5 m per second. As seen from the frequency response curve, the measurement by pick up and strain gage may overlook a relatively high frequency wave. An experiment is preferable with wide frequency response and one may be able to analyse by electrical method, since the various frequencies of waves are superposed and the exact aspect of wave propagation is to be obtained. For this reason, the magnetic tape recording system is adopted and the play back record is obtained through filters and analysed electrically. The frequency response of the magnetic recording system used in this case is 50∼7000 c.p.s. as usual tape corder, and the block diagram of this instrument is shown in Fig. 4.

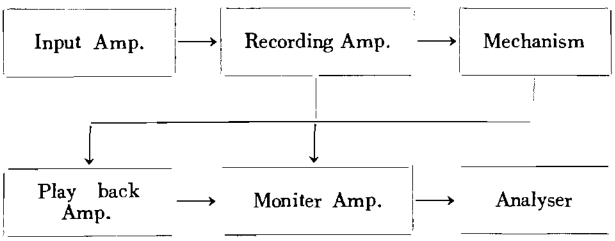


Fig. 4 System block diagram.

The instrument is composed of 7 elements, 5 to record the phenomena, 1 to record time and shot time, 1 to specify the record by voice. The input of time is connected both to the oscillator of 1000 c.p.s. and to the lead wire bound to the detonator as a shunt which will be cut off by explosion. Thus the shot mark of the record is given.

The seismometric pick up and strain gage are connected to the recording amplifer of magnetic recording system. Then the total frequency response of the instrument is determined by the individual response of pick up, strain gage and amplifier of magnetic recording system, for the galvanometer can be exchanged for any suitable one when the play back recording is obtained. Thus the frequency response of this recording system can be taken wider than the direct combination of pick up, amplifier and galvanometer.

The oscillogram by pick up and strain gage is recorded in magnetic type. The gain of recording amplifier is to be controlled in order not to be saturated. And so the saturation limit of the amplifier is determined as the maximum amplitude of the wave to be 30~40% smaller than the fracture strength of the rock which is measured by statical method. When a little explosive is detonated the gain of amplifier is determined by assuming the decay equation and then the amplitude is calculated from the maximum one thus determined. Of course, these operations may be only the rough order estimation which ought to be done as an experimental technique, for the quantitative gain control is impossible in the strict sense.

The electromagnetic wave which is generated with explosion is apt to be superposed with the initial motion of oscillation as a noise. It can be prevented by filter and proper shielding, since its frequency is about 30 kc. p.s. as pointed out by Okawa. Also, referring to the response curve, the total gain is almost zero at this frequency.

Besides the electromagnetic strain gage, wire strain gage is used. In this case the experiment is divided in two, that is, for low frequency wave and higher one. This is only the problem of experimental technique and low frequency strain wave is measured by a bridge system as a carrier of 5000 c.p.s. a.c. current. But for the strain wave more than 1000 c.p.s. the carrier and phenomena can not be separated and is actually difficult to measure. And so the voltage variation of d.c. current which is introduced to the gage directly is connected to the input of recording amplifier and recorded in magnetic tape. The schematic diagram is given in Fig. 5.

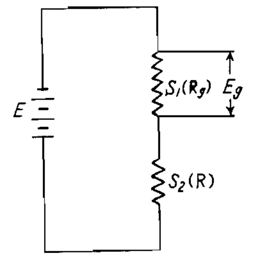


Fig. 5 Measuring system for strain wave of high frequency.

If there is any variation of resistance of the measuring gage, the variation of Eg is equal to dEg, then the actual strain can be calculated as follows,

$$\frac{dL}{L}=\frac{R_g+R}{R_g\cdot R}\frac{dE_g}{I\cdot K}.$$

where I is current, E the voltage of battery, K the gage factor. Because $R \gg R_g$

$$\frac{dL}{L} \simeq \frac{I}{R_g} \cdot \frac{dE_g}{I \cdot K}$$

The strain can be recorded by introducing dEg to the input of the recording amplifier. The gage factor used in this measurement is 2, and the wire with its paper base is fixed to the surface of rock with adhesive cement. The surface of rock where the gage is to be fixed is polished with whetstone and swept and cleaned with cleaner, so that the gage is fixed confirmly to the rock. This preparation for experiment is very easy when the rock is of the shape such as an angular pillar, but is very difficult at the quarry of the mine where the free surface is only one and the measure point is far from the surface and where the drilled hole for insertion of the instrument is very deep. In this case the boring core of the same rock is taken and the gage is fixed to the core and inserted into the deepest position of the hole and is set with fixing apparatus. Thus the compression strain is easily measured as long as the fixing apparatus does not slip, but, as to the tension strain the measurement is very difficult beyond the strain which is given initially to the strain gage. And so the strain measurement at the mine is almost carried out by electromagnetic strain gage.

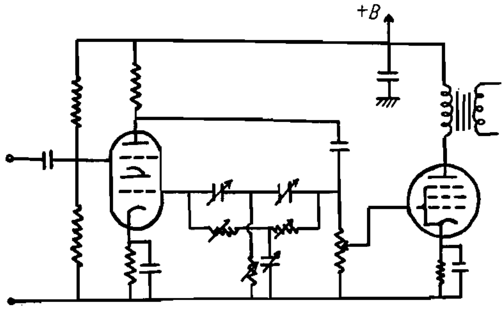


Fig. 6 Schematic diagram of analysis.

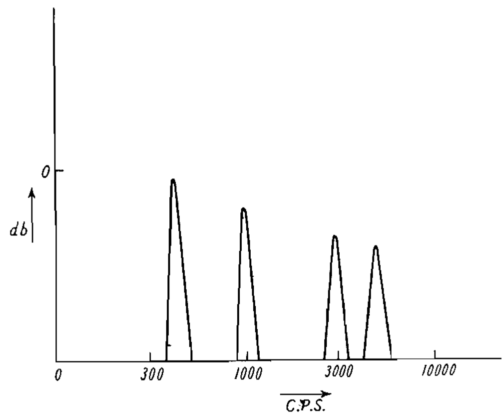


Fig. 7 Frequency respone of analyser for each peak frequency.

The record which has been taken in magnetic tape is analysed by the frequency analyser shown in Fig. 6. The frequency response of the analyser for each frequency is shown in Fig. 7.

3. Experimental Results

(1) Oscillation near explosion.

The oscillation of rock near explosion is measured by Sassa's I-type pick up set in the distance 20～100 cm. from the shot point. The shot hole is drilled perpendicular to the free surface to the depth of ca. lm. and the pick up is set at the deepest position of the hole drilled by similar method according to the distribution plan.

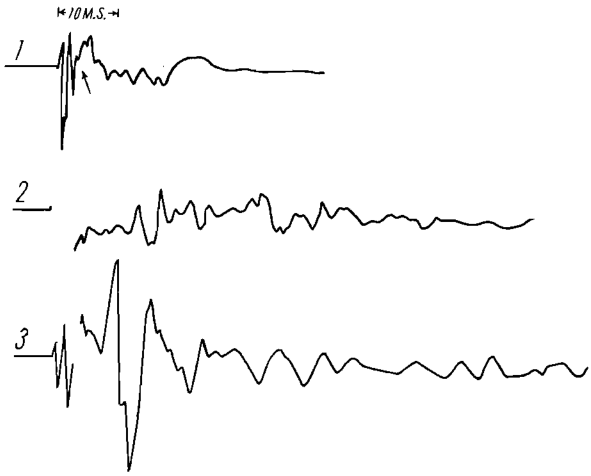


Fig. 8 Oscillogram near explosion. (Explosive, 400 gr).

The explosive used is 30% dynamite and its characteristics per 1 kg. are shown in the following table.

detonation velocity (m/sec)	6000
temperature (C°)	2540
specific volume of gas (l/kg)	875
density	1.5
power (kg/cm²)	9300

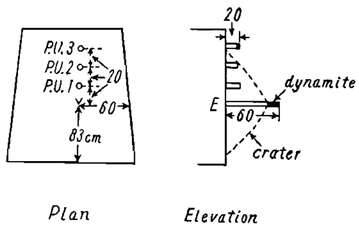


Fig. 9 Distributive positions of pick up and explosive.

a record thus obtained is shown in Fig. 8. And the distribution of pick up and explosive is shown in Fig. 9.

As seen in the Fig. 8, the waves of relatively high frequency (600～1000 c.p.s.) are detected in the initial part of the wave train for 5～10 m.s. and later, waves of low frequency (200～600 c.p.s.) continue for about 10～20 m.s., after that a new oscillation of high cycles reappears. When pick up is put within fracture zone the train of wave is cut off with the phase, which is expected to appear in the later part of waves having relatively longer period. Of course, the frequency and the duration of the wave is largely influenced by the rock property and the amount of the explosive.

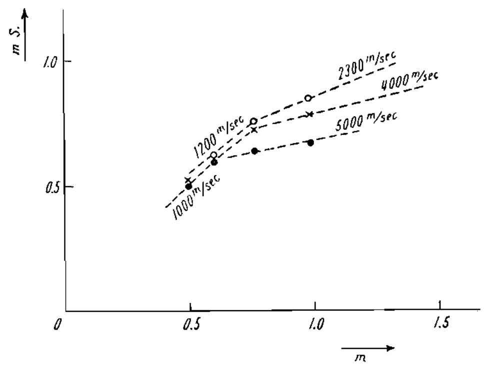


Fig. 10 Travel-time curve of initial shock near explosion, when quantities of dynamite are varied.
● ; 55 gr, × ; 220 gr, ○ ; 450 gr

The time distance curve of initial shocks when the quantities of dynamite are 50gr., 220gr. and 450gr. under the same distributions of seismometric pick up and explosive is shown in Fig. 10.

As can be seen in Fig. 10, the propagating velocity of initial shock becomes lower in accordance with approch to the shot point. The area where the initial shock propagates at low velocity is enlarged with increasing amount of explosive. However, the distances between each pick up are not enough in these experiments to measure accurately the propagating velocity, and so the inaccuracy may exist in calculating the velocity.

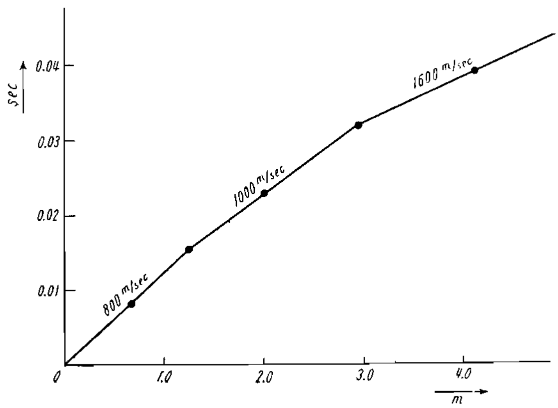


Fig. 11 Travl-time curve near explosion on the occasion of Kamaishi Explosion.

To obtain more accurate value, an experiment is preferable in which the velocity abnomal can be found in wide area, accordingly the magnitude of explosion is large enough. Then the oscillogram is obtained on occasion of Kamaishi Explosion, May I, 1954. In this explosion the amount of dynamite is 0.1 ton and the instrument used in this experiment is Sassa's C-type seismograph and recording apparatus of the same design which is usually used in seismometric prospecting. In this explosion many shot holes for insertion of dynamite are drilled in the lime stone from the surface. Seismographes are set directly on the surface of the lime stone in the neighbourhood of shot hole. The time-distance curve thus obtained is shown in Fig. 11.

The velocity of propagation of elastic wave in lime stone is 4 km/sec which is measured by ultra sonic wave method. On the other hand the propagating velocity near explosion obtained by the Research Group of Explosion Earthquake is 4.5 m/sec, which is determined from travel time of measure point, 1 km. apart from the shot point.

As is shown in Fig. 11, the area of low propagating velocity is enlarged remarkably in this explosion.

The emergency of secondary low frequency wave (F) (shown by arrow in Fig. 8) is fastest at the entrance of shot hole not near the shot point, (E point shown in Fig. 9) and its propagating velocities are 80~200 m/sec in liparite which is far lower than the initial shocks.

When the stress generated by explosion is greater than the fracture stress of the rock, fracturing will naturally take place and the pick up may jump out with the ejected rock by the explosion generated gas pressure. Then at the time of ejection the corresponding phase shown by the thrown out pick up may be able to trace from the oscillogram. From these experimental results this fracturing phase can be found, which is earliest at the entrance of the shot hole, and is shown in Fig. 12. The fracturing phase is good agreement with the above mentioned low frequency wave phase

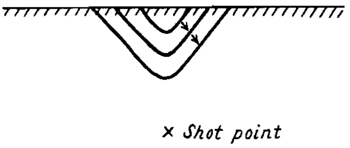


Fig. 12 Equi-wavefront curve of the secondary phase.

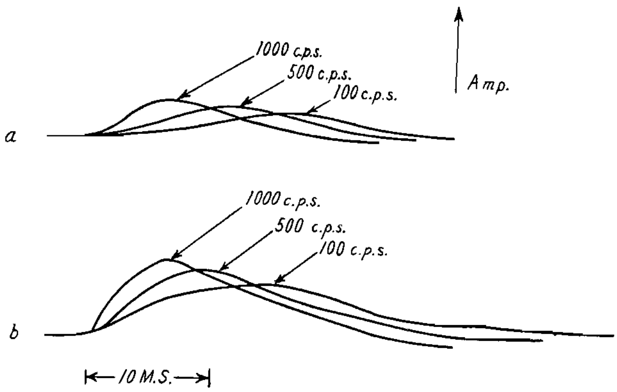


Fig. 13 Distribution of component wave as to time. (a) Explosive, 100 gr. (b) Explosive, 300 gr.

(F). The variations of component waves with the amount of explosive are investigated experimentally. The oscillograms are obtained in magnetic tape through seismometric pick up and recording amplifier and play back records are obtained through filters having each peak frequency of 100 c.p.s., 500 c.p.s. and 1000 c.p.s.. These results are shown in Fig. 13.

The distance between measure point and shot point is 50 cm. in each case, and the quantity of dynamite is 100 gr. in (a) and 300 gr. in (b). Comparing (a) with (b), the high frequency wave dominates in the initial parts of oscillation and the low frequency wave follows. With the increase of explosive the low frequency waves converge to the initial part of oscillation.

The propagating velocity of component wave of 1000 c.p.s. is 4 km/sec., equal to the elastic one, but that of wave of 500 c.p.s. is lower and is 600 m/sec.

As already related, the velocity of propagtion of secondary wave is influenced by the rock property and amount of explosive, these are shown in following table with effect of fracture.

Depth of shot hole	Amount of explosive	Length of axis of cone formed by explosion	Propagating velocity of secondary wave	t_1	t_2
(cm.)	(gr.)	(cm.)	(m/sec)	(M.S.)	(M.S.)
60	400	36	170	5.6	11.0
60	400	28	130	12.0	12.0
80	600	50	130	11.0	9.0
60	400	27	110	10.0	
80	600	19	90	12.5	12.5

where t_1 is the duration time of high frequency wave and t_2 that of low frequency one.

From the above table the propagating velocity of secondary wave is low when the fracture effect is not good, that is, the length of axis of cone formed by explosion is short.

The explosions are superposed at the shot interval of 10~20 M.S. and an example of records is given in Fig. 14.

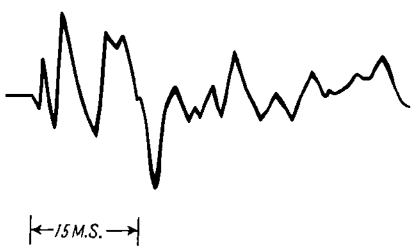


Fig. 14 Superposion of two explosion 60 cm from first explosion and 4 cm from second explosion, time difference is 15 M.S..

As to the first explosion the oscillogram is of no difference compared with the above described results, but regarding to the second explosion the mode of oscillation is different from the usual isolated one. The initial motion of the second explosion begins with the low frequency wave omitting high frequency preliminary phase.

(2) Strain near explosion

(2) Measurement by electromagnetic strain gage.

The strain distribution as to time and space near the origin of explosion is measured with the electromagnetic strain gage by the same method which is used to obtain oscillogram by the seismograph. The distributive positions of instrument and shot point are shown in Fig. 15. The shadowed line denotes the border of rock and free surface.

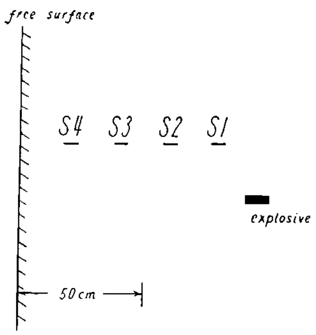


Fig. 15. Distributive positions of strain gage and shot point.

Fig. 16~Fig. 18 are the record obtained the strain gage with the same condition of Fig. 15.

The fracture caused by explosion is seen in traces of S_2, S_3, S_4 of Fig. 18. Among the the strains which are given by explosion the plastic deformation will influence the following experiments when they are repeated at the same place, and so the experiments are carried out from the one of smaller quantity of dynamite. As can be seen from the initial shocks of the record a conspicuous tensional deformation (arrowed in the figures) is recorded at first at S_4 and then S_3, S_2, S_1, from this fact this phase propagates from the free surface. The variations of the propagating velocities of this secondary phase with the amount of explosive are shown in following table with that of the

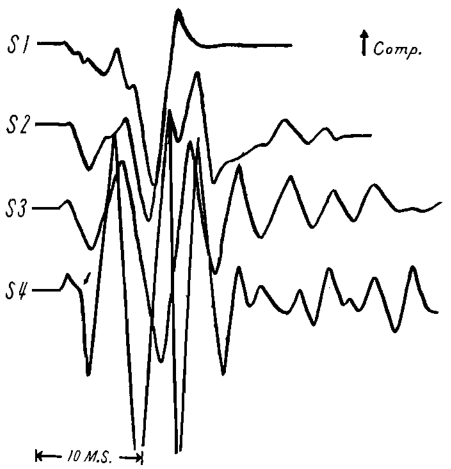


Fig. 16. Oscillogram recorded by the strain gage. (Explosion, 50 gr).

initial shock.

Quantity of dynamite	Propagating velocity of initial shock	Propagating velocity of secondary phase
(gr.)	(m/sec)	(m/sec)
50	1500	270
150	1100	180
300	900	—

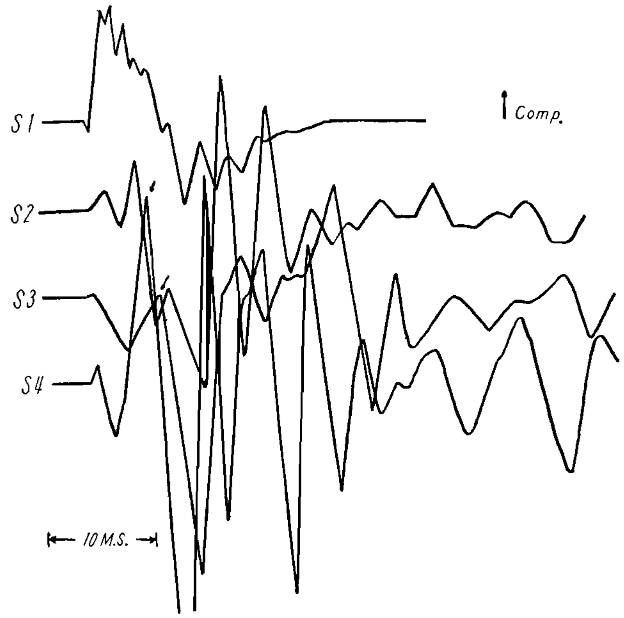
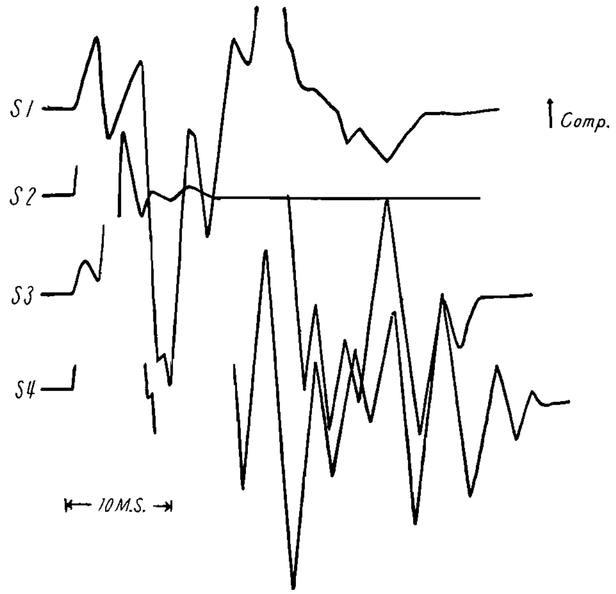


Fig 17 Oscillogram recorded by the strain gage. (Explosive, 150 gr.)

The velocities of propagation of initial shock and secondary phase become lower with increasing explosive. The rock where these experiments are carried out is liparite as in the experiment by seismograph and the propagating velocity of elastic wave measured experimentally by ultra sonic wave method is ca. 4 km/sec.

As can be seen from Fig. 16~18, the oscillatory nature of the wave pulse decreases, as the distance from the shot point decreases. With the increase of quantity of dynamite, the nonoscillatory region is enlarged and the time elapse of strain wave becomes slow.

These results were already obtained partially by W.I. Duvall in his measurement of strain waves near explosion, but his experiment was done in rock having no free surface. Therefore the tensional strain wave of low frequency reflected from the free surface was not detected. Moreover, he interpreted all the observed phenomena within the limit of elasticity. However, in these experiments, the strain wave of lower propagating velocity than the elastic one propagate from the initial part of strain wave and far lower regarding to the secondary phase.



Fig˙ 18 Oscillogram recorded by the strain gage. (Explosive, 300 gr)

The strain generated by two explosions at different shot interval is recorded with the same method in oscilla tion experiments. As can be easily seen from the above described experimental results, the wave trains may be able to be divided into two parts, that is, the high frequency part and relatively low frequency one; accordingly the strain generated by two explosions will be superposed in the follow ing three ways.

(a) Superposition of two high frequency parts.
(b) Superposition of the second high frequency part and first low frequency part.
(c) Superposition of the second high frequency part and the ending part of the first explosion.

In the actual explosion the time of duration of the high frequency part and lower one is largely influenced by the rock property, quantity of explosive and the distance from the free surface. At the quarry where these experiments are carried out the time of duration of high frequency part is about 5 m.s., when the rock is an andesite, the minimum distance from the free surface is 1 m. and the quantity of dynamite is 100 gr.. Then two explosions are superposed at the time interval of 4.2, 15.7, and 40.8 m.s. The distributive positions of instruments and explosive are shown in Fig. 19 and the oscillograms obtained are shown in Fig. 20~22.

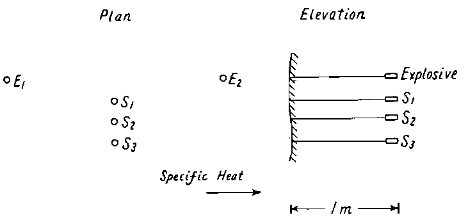


Fig 19 Distributive positions of strain gage and explosive.

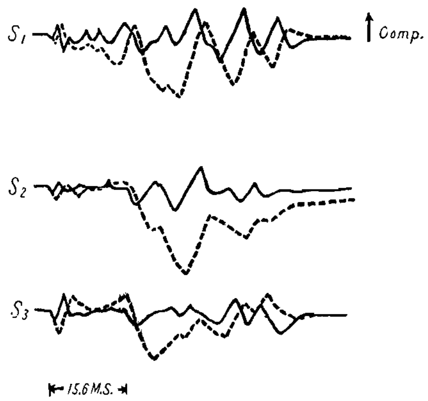


Fig. 20 Superposition of two explosions; time difference, 15.6 M.S..
——— Strain rate ---- Strain

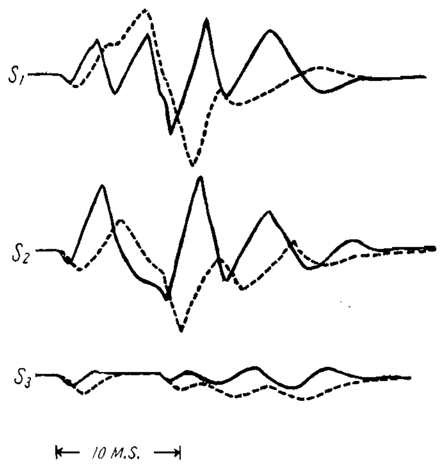


Fig. 21 Time difference, 4.2 M.S..

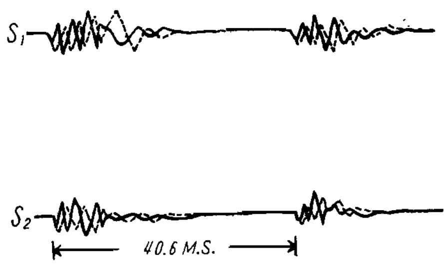


Fig. 22 Time difference, 40.8 M.S..

As can be seen from the figures the effect of superposition cannot be detected when the time difference is 40.8 m.s. and the strains are measured independently in both explosions. The remarkable change can be detected when the time difference is 15.6 m.s., in this case the the strain wave of the second explosion is composed of large tension wave of long period. When the shorter time difference of 4.2 m.s. is taken, the effect of superposition is small. The exact value of the propagating velocity of these waves cannot be determined, for the number of measure point and the distances of each measure point are not enough. But from the rough estimation, the propagating velocity of the initial shock of the first explosion is equivalent to that of elastic one. On the contrary that of the initial shock of the second explosion is effected by the shot time interval of two explosions in other words, by the method of superpositions.

(b) Measurement by wire strain gage.

The strain generated by explosion can be easily measured by the electro-magnetic strain gage, but the results thus obtained are confined by the frequency responses of the strain gage and galvanometer. The plastic strain and strain wave of high frequency must be measured by another method. For this reason wire strain gages are used as already stated.

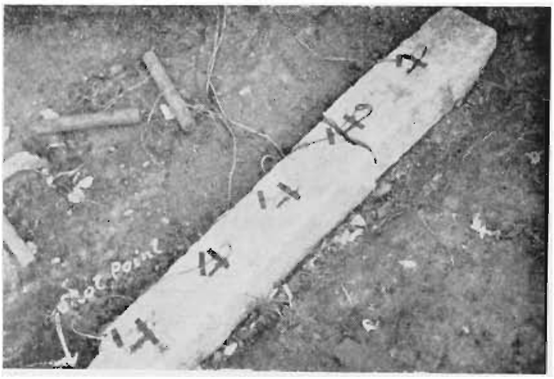


Fig. 23. distributive position of strain gages.

Wire strain gages are fixed on one surface of angular pillar of granite, 180 cm. in length and its section area is 20×25 cm.. The intervals of each gage are 30 cm. and the dynamite is detonated at one end of pillar. The quantity of dynamite is varied from 15 gr. to 60 gr. and the corresponding strains

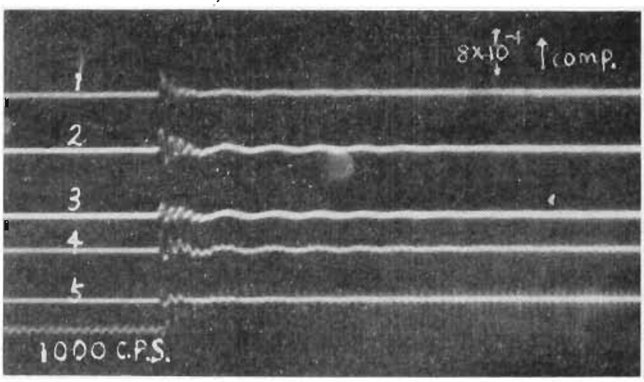


Fig. 24. Strain near explosion measured by wire strain gages. (Explosive, 15 gr).

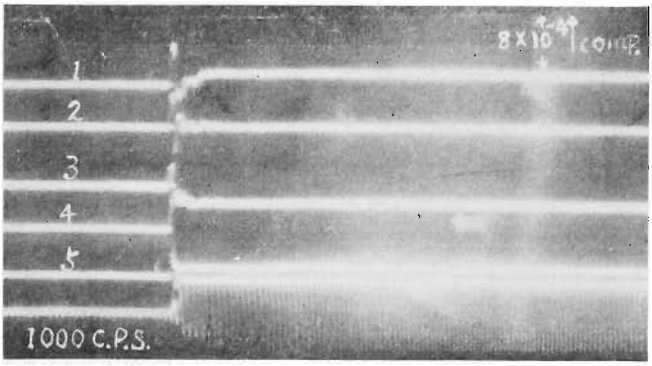


Fig. 25. Strains near explosion measured by wire strain gages. (Explosive 45 gr.).

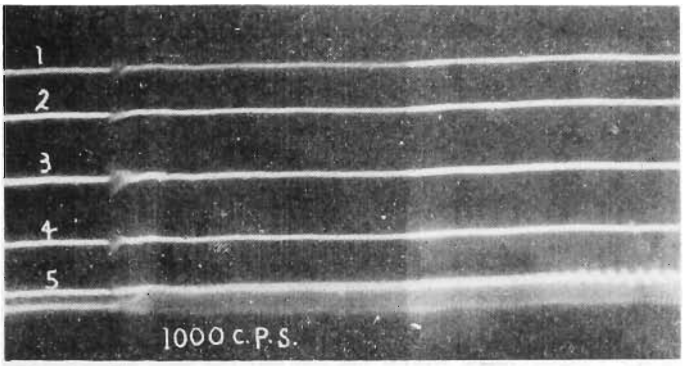


Fig. 26 Strain wave near explosion obtained by magnetic recording system. Distributive positions of pick up and explosive is the same with Fig. 23 and amount of explosive is 30 gr..

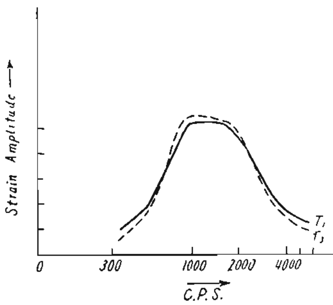


Fig. 27 Distribution of strain amplitude : explosive, 30 gr..

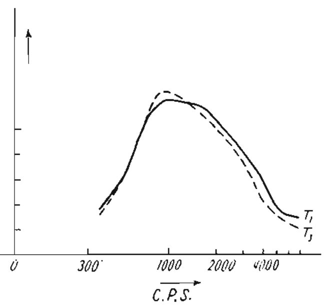


Fig. 28 Distribution of strain amplitude : explosive, 45 gr..

are measured. The strain waves of lower frequency (0~1000 c.p.s.) are measured by bridge system. The strain waves of higher frequency are recorded in magnetic tape and the play back records are analysed shown in Fig. 6. The distributive positions of the strain gages are shown in Fig. 23 and the strain measured by bridge system, accordingly regarding to the lower frequency strain wave and plastic deformation are as shown in Fig. 24 and Fig. 25.

As is shown in Fig. 24, when a little quantity of dynamite is detonated the wave which is caused by multiple reflection is conspicuous, however, with the increase of quantity of dynamite the compressional strain of initial motion naturally increases, and the tensional wave which is reflected from the another end is remarkable and this becomes the plastic strain of low propagating velocity. This plastic strain is of very slow time variation.

The propagating velocity of elastic wave which is obtained from the time distance curve of initial motion when the quantity of dynamite is 15 gr. is 3920 m/sec.. In Fig. 25 the remarkable phase velocity of tensional plastic strain propagated from the other end of cylinder, not the shot point is 120 m/sec., which is far smaller than that of elastic one.

With the increase of quantity of dynamite, fracturing is produced by the strain wave which is shown in Fig. 23. From the results of the experiments, main fracture is produced by the tensional strain wave which is reflected when the initial compressional strain wave reaches another end of the granite pillar. Of course, as can be seen from Fig. 25 at the neighbouring parts of shot point the permanent compressional strains are left and the rock near the shot point is broken into fragments by the direct shock of explosion.

The propagation of high frequency strain wave higher than 1000 c.p.s. is investigated under the same conditions about the rock shape, property and magnitude. In these experiments the strain waves are measured by magnetic recording system and the play back records are obtained through electric filter and analysed. The results are shown in Fig. 26~Fig. 28.

T_1, T_3 show respectively the measure points where those distances from the shot point are 30 cm. and 90 cm.

In Fig. 26~27 the frequency distribution is obtained as to the maximum strain amplitude and not to the time. Comparing Fig. 26 with Fig. 27, the distribution of component waves which give maximum strain amplitude, is the same and in Fig. 27 the increase of strain amplitude due to the increase of amount of explosive can be detected, but the total distribution of component waves is not effected by the quantity by dynamite within the scope of these frequency. Comparing T_1 with, T_3 the decay of strain wave amplitude is small near the frequency which gives maximum amplitude, of distribution curve, but in the lower and higher frequency the decay of the component strain wave is large.

What is meant by these frequency distribution of strain wave cannot be found. We may be able to conceive that the granite used in these experiments behaves as a visco-elastic body[8] The retardation time of granite statically determined by Matsushima[9] are 7~8 sec., and so these cannot be attributed to the effect of viscosity.

(4) Discussion of the results and the mechanism of fracture of rock.

·From the measurement of oscillation and strain near explosion, the wave of high frequency in the initial part of oscillation and following lower frequency wave are detected, and the compressional strain caused by explosion and the tensional strain reflected from the free surface are measured. Shock waves may propagate in the very near place of shot point, but in these experiments these waves cannot be measured.

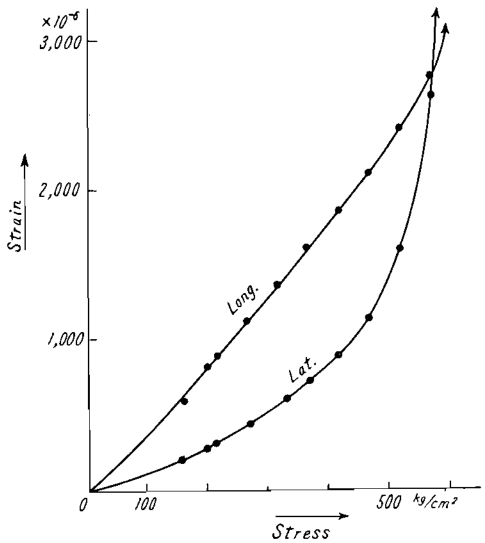


Fig. 29 Stress-strain relation of liparite.

Comparing the oscillation with strain near explosion the higher frequency parts of oscillation correspond to the compressional strain and lower one to the tentional strain. The stress strain relation of the liparite at the place where most experiments are carried out is shown in Fig. 29, which is statically determined.

The stress-strain relations of granite of many different kinds of test pieces were given by Matsushima. For the stress-strain relation above described, the rate of increasing of strain to corresponding stress becomes large when the stress is of sufficient magnitude beyond elastic limits. The velocity of propagation of waves beyond elastic limit is given by $r=\sqrt{\frac{d\sigma}{dE}/g}$, the propagating velocity of stress wave decreases with increasing stress, since $\frac{d\sigma}{dE}$ decreases as is shown in Fig. 28. The slow propagating velocity of plastic waves which are obtained in the experiments is conceived to be above process.

As is seen from frequency distribution curve, the distribution of component waves which compose the higher frequency part of the oscillogram is not effected by the quantity of dynamite, but the distribution of frequency regarding to time is effected. The waves of lower frequency appear in the initial part of oscillation with the increase of the amount of explosive which may be the cause of the low propagating velocity of initial shock. The increases of period of initial motion with the increasing explosive will be thus formed.

The theory of fracture mechanism of rock near explosion has been presented by many investigators, and their applications for practical case are true in certain phase of the fracturing of the rock, but none of them are satisfactory in other phase and comprehensive.

In general the fracture of material can be understood as a stochastic process, since the general principle of fracture may be very difficult. When the applied pressure is of very transitory and large intensity such as explosion, the material will be conceived to be structure insentive, the large stress concentration is produced in the material by the interference between the incident stress wave and reflected one. In practice the shape of the crater which will be formed under the definite conditions regarding to the shape of the free surface, quantity of dynamite and shot point are determined, irrespective of the rock property, of course, the heterogeneity of rock produces the difference more or less in this case.

From the experimental results, most of the fractures of rock are produced by the tensional strain which is reflected from the free surface and the fracture is caused by the Hopkinson's[10] effect.

Generally the compressional fracture strength of rock is far larger than tensional one, for instance, the experimental results given by Ito and Terada is shown in following table.

For this reason, the pressure generated by explosion will produce the fracture from the free surface, while at the same place compressional strain propagates within an elastic limit of the rock. The rock which is in intimate contact with explosion is fractured by direct pressure of the explosion and this

		tensional strength (kg/cm²)	compressional strength (kg/cm²)
granite	1	59	735
	2	60	503
	3	60	588
sand stone	1	71	1350
	2	67	966
	3	101	1350
coarse grained marble	1	46	366
	2	44	222
fine grained marble	1	35	734
	2	36	512
	3	46	690

is proved by experimental results, but the quantity of rock fractured by this process is small compared with that of total fractured rock.

The mode of oscillation near explosion takes a definite form when the rock property and the distance between measure point and shot is defined. The seismogram of the earthquake of definte region is similar one when observed at the same observatory[12] Considering these experimental facts, the elastic wave emitted from the disturbance origin is conceived to be composed of a definite component waves. These are proved by experimental results concerning frequency distribution of strain wave.

In conclusion the auther expresses his hearty thanks to Prof. K. Sassa for his kind advice. He also expresses his gratefulness for financial indebtness to the Fund for the Scientific Research of the Education Department and the Ikuno, Kamioka, Kishu mine that gave convenience for this experiment.

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Bulletin No. 21 Published March, 1958

昭和 33 年 3 月 20 日 印 刷
昭和 33 年 3 月 31 日 発 行
編輯兼発行者 京都大学防災研究所
印刷者 山代多三郎
京都市上京区寺之内通小川西入
印刷所 山代印刷株式会社