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THE GROUND MOTION NEAR EXPLOTION

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Abstract

The generation of waves from explosive origin and related problem are studied in continuation of the previous paper[1]. The spherical origin generally assumed in this case is applicable for a deep seated blast in which surface fracture is negligible. A method of estimating the effect of blast on the ground motion from the experimental results of minor blasts is also discussed. It is found that the wave generation is dependent on loading conditions, geological structure and types of blasts. Therefore, the effect of blasts on the ground motion should be correlated to these dominating factors.

1. Introduction

The blast is generally used for fracturing rock and sometimes for generating elastic waves in the medium. The mechanism of wave generation is different in each case. In former case the energy will be planned to be dissipated for fracture, whereas in latter case the main purpose of blast is the generation of elastic waves in the medium. These two blasts are usually carried out under different blasting conditions, i.e., distribution of shot hole and charge, minimum distance of shot point to the free surface, time delay between each shot point. The behaviour of waves in each case have to be discussed separately. For the explosive origin in which the main purpose is the generation of elastic waves, many investigations have been published so far and got fairly good agreement with experimental results. However, when explosive is used for fracture no definite theory has been developed so far and especially when time delay exists between each shot point the resultant effect is very difficult to presume. In this paper the behaviour of waves generated from different explosive origin is discussed along with the dominating factors for blasts.

The effect of blast on the structure is highly indeterminate problem.

In this case the relationship between ground motion on which the structure stands and the distance from the shot point and amount of charge is obtained under minor blasts. This relationship is generally extrapolated for the big blasts and sometimes the resistant characteristic of structure for vibration caused by blast is estimated from this result. In this case the validity of extrapolation is rather doubtful because the period of the wave is dependent on the amount of explosive. A method is proposed for the estimation of ground motion caused by the blast.

2. Waves Generated by Explosion

The wave generation from spherical origin was studied by H. Kawasumi and R. Yoshiyama[2] in which the wave form was given as a function of the radius of the surface on which the stress change occured. This theory was applied for explosive origin by J. A. Sharpe[3]. Later W. I. Duvall[4] studied the wave form generated by explosion applying Sharpe's displacement potential to practical cases and got fairly good agreement with the experimental results. It means that the spherical origin assumed in above cases seems to be valid as long as the fracture near the surface is negligible when compared with that of directly crushed rock by high detonative pressure. And the behaviour of waves regarded as perfectly elastic in this case is likely to be applicable even to the pretty vicinity of the shot point.

When the explosive is used for the purpose of generating elastic waves such as in the case of seismic prospecting the shot hole is made deep from the free surface and blasting will be carried out with a sufficient tamping and hence the waves generated from such an origin can be regarded more or less as spherical as a first approximation. The behaviour of the waves also will be reasonably considered as elastic, since the area in which the abnormal phenomina such as shock waves and plastic waves propagates will be restricted only in the vicinity of the origin. However, when the explosive is used for fracturing rocks this is not always the case because the main purpose of blast is to cause fracture in the rock and hence the energy of explosion will be distributed into elastic deformation, plastic deformation and fracturing the rock. The rate of distribution will be different according to the circumstances of the blasts. In the case of theory mentioned above, these differences of circumstances were not considered and hence are not applicable in this case. Therefore, these two cases should be discriminated in each blasting and the corresponding behaviours of waves have to be obtained. However, the theoretical treatment in the latter case has not yet been developed so far. As has been discussed in the previous paper the main factor which influences the wave form generated by the explosion in this case appears to be the free surface because the secondary wave caused by the incidence of high compressive waves from the origin has a pretty large amplitude and it is sometimes very difficult to separate these waves due to superposition of the waves. When the amount of explosive is taken suitably according to the strength of the rock along with the distance between the shot point and the free surface it will cause the fractures by tensional waves reflected at free surface and thus energy of explosion will be dissipated for the fracture of rock. Subsequently the resultant amplitude near the explosion will be decreased.

In general the following factors can be mentioned which affect the wave form generated by explosion.

(a) Characteristics of explosive,

(b) Loading condition,

(c) Material in which the explosive is put and the wave propagates.

(a) Characteristics of explosive. The detonation velocity of explosives will change the rise-time to the maximum amplitude and hence the stress rate to the cavity in which the explosive is put. And according to the specific volume of gas of explosive, the gas pressure will be determined. The power of explosive will affect the stress amount which is applied to the cavity. Therefore, when the specifications of an explosive together with its amount are given we shall be able to draw a qualitative effect of explosive to the wave form generated by explosion.

(b) Loading condition. As has been mentioned previously the fracture of rock by tensional wave is mainly concerned with the distance from the blasting point to nearest surface when the depth of a hole is shallow enough to cause the fracture. And hence this fracture will affect the wave. The tamping of the explosive is closely connected with the stress rate applied to the rock. For example, when the explosives are attached to the material directly in the free air, the impact shock will be given to the rock, however, due to the sudden dispersion of gas pressure formed by explosion, the total duration time of the stress wave will be less. This duration time of the stress is conceived to be closely connected with the deformation of the rock, since the stress rate is one of the main factors which determine the stress-strain relation of the material. This has been verified experimentally as well, i.e., in the experimental results obtained by Ito and Sakurai[5] in which the disturbance origin of the plastic deformation was observed in only restricted area, whereas in the author's experiment[6] it was pretty in wide range.

(c) **Material in which the explosive is put and the wave propagates.** The visco-elastic characteristics of the material influences the wave form to a great extent. In this connection so many investigations[7,8,9] have been done. The strength of rock especially the compressive strength in the deep hole blast should also be taken into consideration, since the total amount of fractured rock is dependent on its strength. In the equation which was given by Kawasumi as the rock characteristics affecting the wave form v, V, a_0 and ρ are mentioned, where v, V denoted the velocity of dilatation and rotation, a_0 : equivalent radius (Kasahara)[10], ρ : the density.

However, a_0 should depend on the strength or the brittleness of the material as well. Because the type of fracture of rock will depend on the rock characteristics.

Moreover, there are many factors which have to be taken into consideration in the case of fracture of rock and these factors are sometimes independent from the above mentioned quantities V, ρ, v an a_0. For example, the process of fracture which appears to be effective for the wave form near explosion brittleness of rock should be taken into consideration. When the material is of the brittle character the transition from fracture zone to elastic zone is very sudden and plastic zone will be very less. In Okawa's experiment[11] he could observe only elastic wave in the brittle concrete block even in the very vicinity of the explosive origin. M. P. Volarovich and E. I. Parkomemk[12] studied the break-down of the rock under unilateral pressures. They found plastic deformation before break-down in the case of marble and dolomite, whereas rapture type break-down in the case of synite quartz, gabbro, basalt and diabase. Ito and Terada[13] reported the characteristic affecting on the effect of blasting. According to their results, the fracture of rock has no relation with density and stiffness. However, some relation between propagating velocity of elastic waves and strength and more closely connected with grain size of rock and cohesive force.

The experimental results[14] reported in the previous paper, i.e., the wide abnormal range of wave propagation at Kamaishi can be reasonably understood when considering the rock in the field was limestone.

In any case, when the secondary effect at free surface are neglected the stress waves may be expressed by the following equations as given by Sharpe[15].

1. $P_t = P_0 (1 - e^{\sqrt{2}\,\omega t})$
2. $P_t = P_0 N (e^{\frac{-\omega t}{\sqrt{2}}} - e^{\sqrt{2}\,\omega t})$
3. $P_t = P_0 e^{\frac{-\omega t}{\sqrt{2}}}$

These equations can be used in each case according to the circumstances. For instance, when the material is of visco-elastic material and explosive is loaded at deep shot hole with sufficient tamping, equation (1) will be applicable. This was verified by Iida[16] both experimentally and theoretically. Similarly, in the case of the free air explosion the stress decay is supposed to be very sudden and hence equation (3) or (1) with large ω can be applied. After specifying these explosive conditions by above mentioned equations, it is possible to work out displacement, velocity, strain and acceleration with Sharpe's displacement potential beyond the abnormal region. Also, from the same equation we shall be able to get indication which type of deformation will occur near explosive origin. Because the types of fracture of rock is closely connected with the stress rate which is given in the equation.

3. The Ground Motion Near Explosion

The study of dynamic effect on the ground motion by blast is very important problem since blast is to be carried out sometimes in the vicinity of structures. Some empirical relations had been obtained between the ground acceleration and displacement on which the structure stands, the distance of the blast from the point of measurement and the amount of charges. The relationships are generally not applicable under different local conditions since the constants involved vary with the geology of the region and the type of blast. Because the attenuation of waves is related to the geological structure of the ground through which the wave propagates and the blasted energy of explosives are dissipated in various ways according to the condition of the blast. These two points are discussed in the following :

a) Attenuation of the waves generated by explosion.

The attenuation of waves generated by explosion has been investigated both theoretically and experimentally by many investigators. When the sine wave motion is assumed the decay of the amplitude of displacement, velocity and acceleration does not make much difference because each equation can be obtained by simple differentiation or integration from another equation.

As a first approximation the amplitude of displacement may be given as follows, where the amount of charge is same

$$a=\frac{a_0}{r^n},$$

in which a is the amplitude at the distance r from the shot point and a_0 and n are both constants. Some more detailed expressions are given by visco-elastic theory. For instance, Iida and Aoki reported that the decrease in amplitude with distance r is intermediate between $\frac{1}{r}e^{-ar}$ and r^{-n}. Ricker[18] has given the following expression,

$$X_1=e^{-(\omega/\omega_0)qkx}\sin\frac{2\pi\omega}{v}(x-vt)$$

where X_1 : plane wave (longitudinal) of single frequency ω, q and k are constants, ω_0 : cut off frequency which characterise the absorption in the medium. In any case the expression is given both experimentally and theoretically as long as the wave decay depends on the visco-elastic characteristics of the medium.

In the very vicinity of the shot point the equation is very difficult to obtain due to the plastic deformation which is caused by high compressive force exceeding the elastic limit of the material. In this connection the decay equations have been obtained only from the empirical results.

b) Effect of blasting condition.

As has been described in the previous chapter the wave forms are dependent on the blasting condition. The design of shot hole and distribution of charge are also different in each case. For example, in generating elastic waves, the charges are preferably to be placed in one deep hole with sufficient tamping. On the contrary, for the fracture of rock shot holes are taken to suitable depth according to the strength and characteristics of rocks and amount of charges. Also, many shot holes are made and these kinds of origin are regarded as less than that of single blast of the same amount of charge. The main reason is conceived to be the superposition of the wave. In the case of deep hole blasting with sufficient tamping the wave form is given by Sharpe's displacement potential and hence it will not be impossible to work out the effect of superposition provided the time and other specifications of the blast are given. However, when the blast is used for fracturing rock, the individual corresponding wave form is very difficult to presume as has been described previously and hence it is almost impossible to estimate the effect of superposition. Therefore, the acceleration and displacement from a certain explosion can not be estimated because the amplitude will be variable under different superposition of the wave and energy dissipation for elastic, plastic waves and fracture of rock are also variable in this case. From experience it is known that maximum ground motion corresponds to that associated with charge size of the individual fractions.

Empirical Formulas

A number of empirical formulas are available giving expected displacement and acceleration as a fraction of the weight of the explosive and distance. Some of these are given as follows :

I) Theonen J. R. & Windes S. L.[19]

$$A\,(\text{inches}) = \frac{C^{2/3}}{100}\,(0.07e^{-0.00143d}+0.001)$$

where A is displacement,

C amount of explosive in lbs.

d distance between place of observation and shot hole in ft.

II) Carder & Cloud[20]

$$A\,(\text{cms}) = 3.6\frac{W^{0.75}}{d^2}\times 10^4\ \text{cms},$$

where A is displacement

W is amount of explosive in lbs.

d is distance between shot hole and place of obseevation in ft.

III) Carder & Cloud[21]

$$a = 0.95 \frac{W^{3/4}}{d^2} \times 10^4 \text{ g},$$

where a is acceleration

W is charge in short tons

d is distance from short hole in ft.

Regarding the strain amplitude in the vicinity of the shot point Okawa[22] obtained the experimental formulae as follows :

$$\varepsilon_r = \varepsilon_0 \frac{1}{r^n}$$

where ε_r is radial strain,

r is the distance,

ε_0, n are constants.

	Rectangular bar	Plate	Cube, Cylinder
n	0.5～0.6	0.8～1.0	1.5～1.7

In this case the medium was concrete block and strain was measured by a strain gauge. Kaukonen and Howell[23] obtained the empirical equation of attenuation of wave energy as follows :

$$E_x = E_0 X^{-A} e^{-ax},$$

where E_x, E_0 are energy,

A, a are constants,

X is the distance.

In this case the above equation is applicable even in the plastic area.

Generally the ground motion may be given by the following equation :

$$a = \frac{K W^{\beta} e^{-ar}}{r^{\gamma}} f(t),$$

in which a is amplitude of the ground motion, r : distance and K, a, β and γ are the constants. In extrapolating the relation which is obtained for a minor blast to larger one the change of the period caused by the increase of amount of charge becomes problem.

The spectral intensity is maximum for the predominant period which is given by[10]

$$T_p = \frac{2\pi}{n} = \frac{\pi a_0}{v} ,$$

where n is natural frequency of vibration, v is velocity of shear waves, a_0 is critical radius and is given by $a_0 \propto \sqrt[3]{W}$, where W is weight of charge. Therefore $T_p \propto \sqrt[3]{W}$, thus the variation of a predominant period with amount of charge is not so remarkable and hence the equation which is obtained experimentally from the minor blast can be extrapolated for a larger blast so far as time period is concerned. In actual case the observed variation of the time period with the charge is not so remarkable and can be regarded within experimental error as will be seen in Table 1.

Table 1.

Bhakra Dam No.	Charge (lbs.)	Distance (feet)	Acceleration (g)	Time Period (sec.)
1	10	356	0.0015	0.0334
2	10	189	0.006	0.0274
3	10	332	0.0026	0.0470
4	20	351	0.0032	0.0445
5	30	211	0.0200	0.0267
6	30	331	0.00595	0.0287
7	60	347	0.012	0.0385
8	100	536	0.00725	0.0338
9	100	390	0.0115	0.0303
10	150	447	0.0177	0.0788
11	150	320	0.033	0.0655

The factor $e^{-\alpha r}$ can be considered as a constant in particular of small variation of distance with which we are concerned. Finally we get the empirical equation as follows :

$$a = \frac{K' W^{\beta}}{r^{\gamma}} ,$$

where a is amplitude of the ground motion,

K' β, γ are constants,

W is weight of explosive,

r is the distance between shot point and observed point.

A number of observations were made to determine the constants involved in the above equation. Two Miller Accelerographs with Brush Recorders were used for the measurements of acceleration. The experiments were carried out at Bhakra and Ram Ganga dam site in India.

The geological structure in both places can be regarded more or less as uniform respectively and the accelerographs were fixed rigidly to the rods which were introduced in the hole and grouted with cement concrete so as to ensure rigid fixing.

The details as regard to the charge used, distances from the charge, acceleration and their periods measured are given in Table 1. In this case the maximum amplitude in the initial part of the record was taken as acceleration reading which is shown in fig. 1. Firstly, it is assumed that the constant γ is 2 in order to obtain the relation between a and W and the value of β was obtain. For this purpose accelerations at a fixed distance 350 ft. from the blast were worked out and a graph plotted between log a and log W to determine β in the relation $a \propto W^{\beta}$. (fig. 2)
The value of β thus determined was 0.93.

The values in Table 1. were used to draw another graph to find K' in the relation $a = K' \frac{W^{\beta}}{\gamma^2}$. Using $\beta = 0.93$ obtained in the above, we get fig. 3.

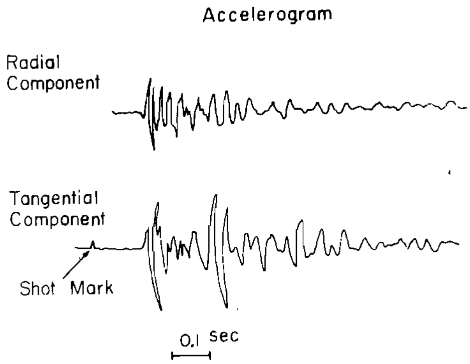

Fig. 1. An example of accelerogram, the distance from shot 500 ft. and charge 50 lbs.

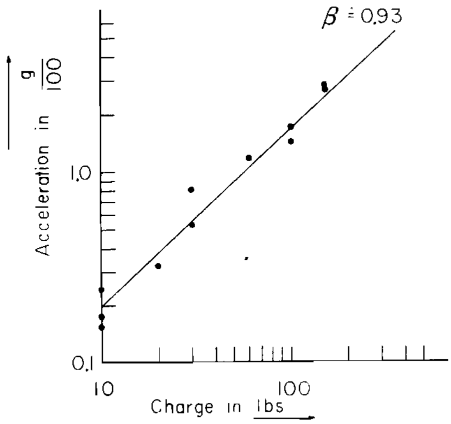

Fig. 2. Relation between log a and log W to obtain β. In this case $\beta = 0.93$.

From the above graph the value of K' was obtained as 30.6 g. Also, the assumption of $\gamma = 2$ seems to be valid since the scattering of observed points from the linearity are not so remarkable.

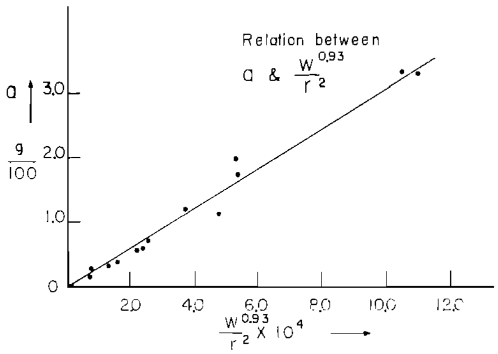

Fig. 3. Relation between a and $\frac{W^{0.93}}{r^2}$ to obtain K′. $K'=30.6\,g$ in this case.

Finally we get the relation as follows.

$$a=30.6\frac{W^{0.93}}{r^2}g,$$

where a : acceleration in g

W : charge in lbs.

r : distance in feet.

Similarly, we get the relation from Table 2. obtained at Ram Ganga dam site as follows.

$$a=161.1\frac{W^{0.94}}{r^2}g,$$

The differences of the constants involved in the equation may be attributed to that of the geological structures. Because the shot holes are made similarly in both cases, i.e., perpendicularly to the ground surface in a single hole and their depths are designed so as to have a clearance of same height after loading which will be filled with water for tamping. Moreover, the range of charge were of the same order and hence the total depth of the shot hole were not so different in each case of similar charges.

At Bhakra Dam the rock is soft sand stone in the place of experiment, whereas at Ram Ganga is sand stone of middle hardness (the propagating velocities of P and S wave are 2500 m/sec. and 1114 m/sec. respectively.)

Table 2.

No.	Charge (lbs.)	Distance (feet)	Acceleration (g)
1	10	500	0.00403
2	10	500	0.00482
3	20	500	0.0136
4	50	500	0.0204
5	25	1050	0.0061
6	50	1050	0.0090
7	20	1050	0.0010
8	100	3000	0.00233

Therefore, it appears that the constants involved in the equation are variable under different geology of the shot point and medium through which the elastic wave propagates. And hence the relation between the ground motion caused by the explosion and the charge shold be obtained at each local condition when the ground motion is required comparatively near the explosion.

Summary

The propagation of waves near explosion and related problems are discussed along with other dominating factors of blasting. Since the phenomena near the disturbance origin are very complicated, the unified interpretation is very difficult to get.

However, the classification of many factors affecting the blast such as the loading conditions, the geological structure, etc., of the shot point enable us to approach more correct aspect of the problem.

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