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ATTENUATION LAWS FOR THE GROUND MOTIONS DUE TO UNDERGROUND EXPLOSIONS IN ROCKS AND THE DAMAGE CRITERIA FOR STRUCTURES

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INTRODUCTION

The ground motion, which is an integral part of any underground explosion, travels through the medium in which the explosion is made to large distances with magnitudes depending upon the amount of charge in the explosion, distance from the explosion and the characteristics of the intervening medium. It is of great importance to know the magnitude of ground motion near a structure and its possible effect on the structure. This would help in designing an explosion in a better way in terms of the safety of the structures. This requires the knowledge of attenuation laws for the ground motions and the damage criterion for the safety of structures in terms of the maximum permissible vibration.

ATTENUATION LAWS FOR THE GROUND MOTION

As pointed out above, it is necessary to have an estimate of the ground motion for assessing the possible damage to any structure during underground explosions. Attempts have been made to study the attenuation laws for the ground particle velocity as well as ground particle acceleration. Though, ground particle velocity or ground particle acceleration can be computed from the displacement records, assuming the recorded motion as simple harmonic, the ground motion due to underground explosion is never a perfect simple harmonic motion as such, it was decided to have instrumentation directly recording either particle velocity or particle acceleration, as desired.

PARTICLE VELOCITY—DISTANCE AND CHARGE DATA STUDY

About 250 underground explosions of varying charges 0.5 kg to 100 kg of 60% Gelatine (1 kg of 60% Gelatine $=3.6\times10^{13}$ ergs) were made at about twenty experimental sites in India having different types of rocks. All the experimental sites have been grouped under three main groups viz. Hard rock—Basalt, Medium rock—Soil or weathered rock cover of small thickness underlain by basalt and loose and weathered rock—Rock formations (Sedimentary) in the Himalayan region. Ground particle velocities in two components viz longitudinal (L) along the line joining explosion and the station of observation and vertical (V) were directly recorded at different distances (3 metres to 100 metres) with the help of Philips Electrodynamic pick-ups connected to an oscillograph through an amplifier. These pick-ups can be mounted in any direction to enable to take measurements in any desired component. The complete assembly of the individual units like pick-up, amplifier and oscillograph had flat frequency response in the frequency range 20 cps to 1000 cps—a band of frequency range normally associated with the ground particle velocities during underground explosions. Fig. 1 shows some typical ground particle velocity records as obtained at different experimental sites.

Peak ground particle velocities v (mm/sec) were measured from each record and have been utilised here for study of attenuation laws along with the other details of the explosion such as, the amount of charge and the distance between the explosion and station of observation. The general form widely accepted for the attenuation law for blast energy is,

$$v=KQ^{m}R^{-n} \qquad \ldots (1)$$

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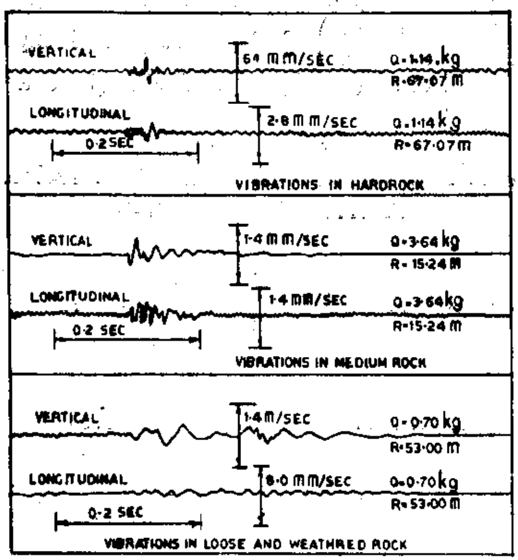

Fig. 1. Oscillograms of Philips Electrodynamic Pick-ups Showing Vib: ations (Particle Velocity) in Different Types of Rocks.

where

v=peak ground particle velocity
K,m,n=constants
Q=amount of charge
R=distance between the explosion and station of observation.

The factor R^{-n} in the eqn. (1) is the contribution in the attenuation of blast energy due to geometrical spreading. As mentioned by Duvall and Petkof (1959) the value of 'n' should be 0, 0.5 and 1.0 for plane, cylindrical and spherical waves respectively. The value of K depends to large extent on the physical properties of the rock Medvedev (1968) such as, density, seismic wave velocity of the propagating medium and the frequency of seismic waves. The values of these physical properties of the rocks at different sites for a particular group of rock were almost similar and are given in Table I, The value of '*m*' mainly depends on the seismic energy efficiency :

TABLE I

SHOWS THE PHYSICAL PROPERTIES OF ROCKS

Type of Rock	Density gm/cc	Wave velocity (compressional m/sec	Young's Modulus Kg/cm²	Compressive strength Kg/cm²	Tensile strength Kg/cm²
Hard rock-Basalt	2.4—2.8	4000—6000	5.9×10^5	800—1200	100—200
Medium rock—Thin soil cover under—lain by basalt.	1.8—2.0	600—1000	$0.1—0.5\times10^5$	—	—
Loose and weathered rock—Rock formation (sedimentary) in the Himalayan region.	2.0—2.2	1000—2000	$0.7—0.8\times10^5$	400—600	100—150

The value of 'm' mainly depends on the seismic energy efficiency $\left(\frac{\text{Energy converted into seismic waves}}{\text{Total energy liberated in explosion}}\right)$ of the underground explosion. Values of K, m and n as obtained by Duvall et al. (1963) and Medvedev (1968) are given in Table II.

TABLE II

SHOWS THE VALUES OF K, m AND n AS OBTAINED BY OTHERS (PARTICLE VELOCITY)

Author	Form of Law	Type of Rock	Component of Vibration	K	m	n
Duvall et al. (1963)	$v=KQ^mR^{-n}$	Lime Stone	L	0.37	0.84	1.63
			V	0.41	0.73	1.74
			T	0.33	0.67	1.28
Medvedev (1968)	$v=KQ^mR^{-n}$	—	L	—	0.50	1.50

The explosion data thus obtained for all the sites have been analysed statistically for the two components separately and the values of K, m and n thus obtained for three types of rocks are given in Table III. Substituting the above obtained values of K, m and n in eqn.

TABLE III

SHOWS THE RESULTS AS OBTAINED FROM THE STATISTICAL ANALYSIS OF EXPLOSION DATA (PARTICLE VELOCITY)

Type of Rock	Component of Vibration	K	m	n
Hard rock-Basalt	L	57	0·87	1·00
	V	38	0·86	1·00
Medium rock—Thin soil or weathered rock cover underlain by basalt	L	28	—	1·00
	V	35	0·91	1·00
Loose and weathered rock—Rock formations (Sedimentary) in the Himalayan region.	L	16	0·87	1·00
	V	9	0·65	1·00

(1) the ground particle velocities were again computed for the above explosion data and these values are designated as expected value of ground particle velocity. A good agreement was obtained between the observed and expected values of the ground particle velocity in two components for three types of rocks. The ratio of the expected value of ground particle velocity and observed value of ground particle velocity with the number of observations have been plotted and are shown in Fig. 2.

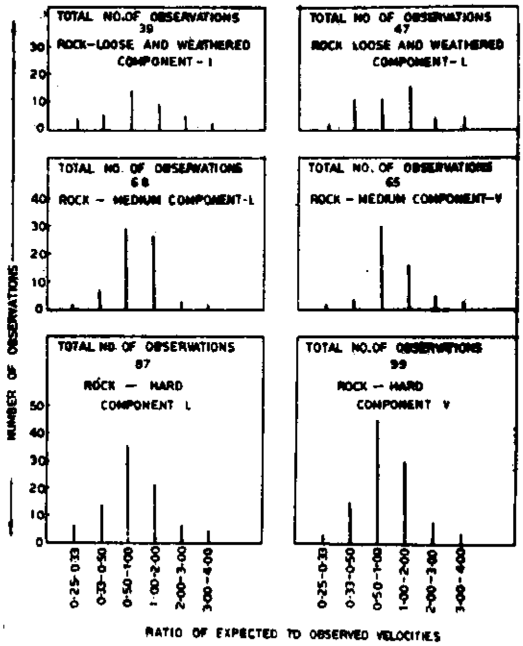

Fig. 2. Number of Observations in Different Groups of the Ratios of Expected to Observed Particle Velocities

PARTICLE-ACCELERATION—DISTANCE AND CHARGE DATA STUDY

About 150 underground explosions of varying charges 0.5 kg to 100 kg of 60% Gelatine were made at about 15 experimental sites in india in Hard rock and Medium rock. The ground particle accelerations in longitudinal (L) component were directly recorded at different distances (3 metres to 100 metres from the explosion) with the help of Philips Electro-dynamic pick-ups connected to an oscillograph through an amplifier and differentiator. The complete assembly had flat frequency response in the frequency range 20 cps to 1000 cps Fig. 3 shows some typical ground particle acceleration records as obtained at different experimental sites.

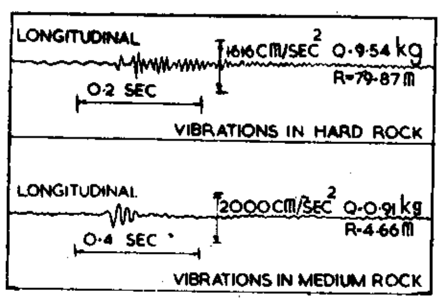

Fig. 3. Oscillograms of Philips Electrodynamic Pick-ups Showing Vibrations (Particle Acceleration) in Different Types of Rocks

The peak ground particle acceleration a (cm/sec^2) were measured for each record and have been utilised here for the study of attenuation laws alongwith other details of the explosion. The form of the attenuation laws fitted in this case is similar to eqation (1) and is,

$$a = K_1 Q^{m_1} R^{-n_1} \quad \ldots(2)$$

Some of the values of K_1, m_1 and n_1 as obtained by Carder and Cloud (1959) and Yoshikawa (1961) are given in Table IV. It is seen that value of n is about two and m is less than one.

TABLE IV

SHOWS THE VALUES OF K_1, m_1, AND n_1 AS OBTAINED BY OTHERS (PARTICLE ACCELERATION)

Author	Forms of Low	Type of Rock	K_1	m_1	n_1
Carder and Cloud (1959)	$a = K_1 Q^{m_1} R^{-n_1}$	Tuff	4865	0·75	2.00
Yoshikawa (1961)	$a = K_1 Q^{m_1} R^{-n_1}$	Soft sand stone	5801	0.93	2.00
Yoshikawa (1961)	$a = K_1 Q^{m_1} R^{-n_1}$	Sand stone of Middle Hardness	30790	0.94	2.00

The explosion data thus obtained for all the sites have been analysed statistically and the values of K_1, m_1 and n_1 thus obtained for two types of rocks are given in Table V. A

TABLE V

SHOWS RESULTS AS OBTAINED FROM THE STATISTICAL ANALYSIS OF EXPLOSION DATA (PARTICLE ACCELERATION)

Type of Rock	Component of Vibration	K_1	m_1	n_1
Hard Rock-Basalt	L	18198	0.45	1.00
Medium rock—Thin soil or weathered rock-cover underlain by basalt.	L	14845	0.22	1.00

good agreement was again obtained between the observed and expected particle accelerations. Fig. 4 shows the plot of the ratio between the observed and expected value of the ground particle acceleration and the number of observations.

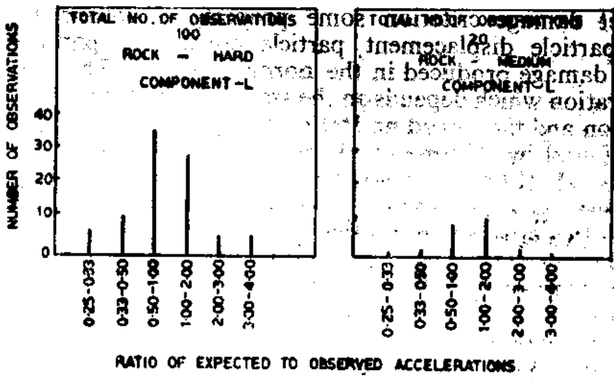

Fig. 4. Number of Observations in Different Groups of the Ratios of Expected to Observed Particle Accelerations

DAMAGE CRITERIA FOR STRUCTURES

In the recent past, there have been many attempts by different workers Crandell (1949), Teichmann and Westwater (1957), Langefore et al. (1958) and Edwards and Northwood (1960) to determine the damage criteria for the safety of structures during underground explosions. These criteria can be grouped under two main groups, such as, direct criterion and indirect criterion. The direct criterion was based on the study of damage produced in the normal houses and its correlation with the amount of charge and the distance between the explosion and the structure. No account was taken of the characteristic of the intervening medium and of the structure, which resulted in lack of agreement in the criteria found by different workers as is evident from the Fig. 5 Alford (1960).

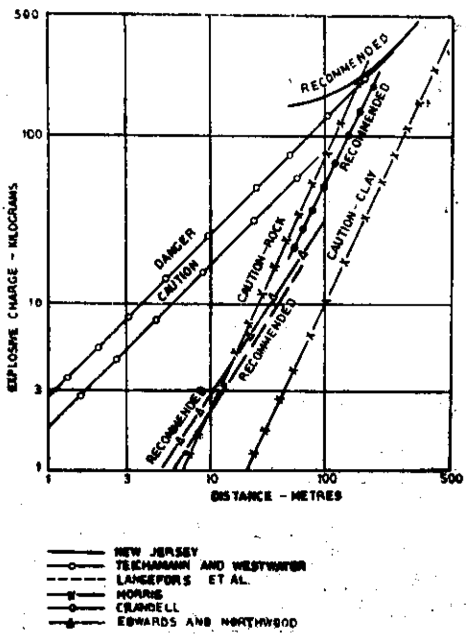

Fig. 5. Damage Versus Charge and Distance Comparison of Various Criteria

In the indirect damage criterion some property of ground motion produced by explosion such as particle displacement, particle velocity or particle acceleration was correlated with the damage produced in the normal houses. This involved the measurement of ground vibration which depends on the amount of charge in the explosion, distance between the explosion and the recording station and the characteristics of the intervening medium. It was found by Thoenen and Windles (1942), Teichmann and Westwater (1957), Langefors et al. (1958) and Edwards and Northwood (1960) that the damage criterion based on the measurement of ground particle displacement and ground particle acceleration depends to a large extent on the associated frequency. The studies carried out by Duvall and Fogelson (1962) have proved that the damge criterion based on the assessment of ground particle velocity gives the best damage criterion and is less dependent on the associated frequency. As such, it has been accepted that while assessing the effect of ground motions on structures ground particle velocities should be measured. It is quite interesting to note that the damage level in terms of ground particle velocity is almost same for the different criteria suggested by different workers (based on the measurement of different quantities) such as Crandell (1949) (energy ratio), Edwards and Northwood (1969) (particle velocity), Langefors et al. (1958) (particle velocity). Fig. 6 shows the plot of the damage criteria as suggested by different workers.

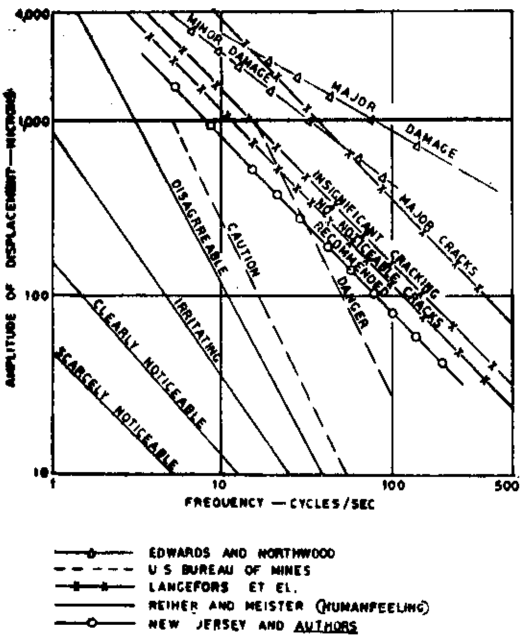

Fig. 6. Damage Criteria by Different Workers and as Recommended by Authors

In the criterion discussed above also, no account was taken of the dynamic characteristics of the structure such as its natural frequency and damping coefficient. It is well known that a structure having natural frequency very close to the ground motion frequency and a small damping coefficient is liable for damage at much lower value of ground particle velocity than another structure having natural frequency much away from the ground motion frequency and higher damping coefficient due to the effect of resonance. This led to the development of response spectrum technique Hudson (1956). Here the response of number idealised structures subjected to the ground accelerations recorded during the explosion is plotted. From these curves the response or the vibration level of any structure to be safeguarded against vibrations can be assessed if its natural period and damping coefficient is known.

The spectrum analysis normally requires ground acceleration records due to explosion. However, as the process of finding the response of a structure for a given accelerogram is too cumbersome and requires analyses by Digital computer, it was agreed that for assessing the safety of any structure due to ground motion, it would be better if damage criterion based on the particle velocity is taken into consideration, provided the ratio of the natural frequency of the structure and the ground motion frequency is somewhat different.

The studies carried out by Devine (1956), Langefors et al. (1958). Edward and Northwood (1960) have led to the conclusion that the ground particle velocity equal to 50 mm/sec is quite safe for normal houses. The numerous explosion experiments carried out by the authors near different types of structures are well in agreement with this. No damage was noticed when the ground particle velocities were about 50 mm/sec (frequency 30-100 cycles/sec). This limit of 50 mm/sec seems to be a reasonable value also from the consideration of stresses in the structures. As is well known that the dynamic stress (Sa) can be calculated for any value of particle velocity (v) with the help of equation 3.

$$Sa = \rho c v \qquad \ldots (3)$$

where ρ = density of the medium

c = wave velocity in the medium

For a normal concrete house, the value of Sa for particle velocity = 50 mm/sec comes out to be about 50 psi, either in tension or compression, assuming the value of density (ρ) = 2.4 gm/cc and wave velocity (c) as 3×10^5 cm/sec.

This value of dynamic stress in concrete is quite low in comparison with the compressive and tensile strengths of normal concrete during vibration. As such, it is considered to be quite safe from any damage point of view to the concrete.

CONCLUSIONS

1. Value of K and K_1 among other things, depend to some extent on the component of vibration.
2. Values of m and m_1 are less than one in all cases.
3. Values of n and n_1 are about one and do not seem to depend on the component of vibration or type of rock which indicates that the explosion waves propagate in the form of spherical waves and the attenuation of the ground motion is mainly due to geometrical spreading of the waves.
4. From Fig. 2 it is seen that ratios of expected values of the ground particle velocities are within a factor of three for 85% of the observed values. This is considered to be a good correlation.
5. From Fig. 4 it is seen that ratios of expected values of the ground particle accelerations are within a factor of one for 100% of the observed values.
6. 50 mm/sec of ground particle velocity seems to be a safe limit for normal houses and can be termed as safe level provided the ratio of natural frequency of the structure to be safe guarded against the vibrations and the ground motion frequency are somewhat different. However, the response spectrum technique may give a better damage criterion for assessing the safety of structures.

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APPENDIX—I

NOTATIONS

a	=peak ground particle acceleration (cm/sec^2)
c	=wave velocity in the medium
K, K_1, m, m_1, n, n_1	=constants
Q	=amount of charge in explosion (Kilogram)
R	=distance beetween the explosion and station of observation (Metres)
Sa	=dynamic stress
v	=peak ground particle velocity (mm/sec)
ρ	=density of the medium