BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 46 (1968), pp. 687-696

31. *Evaluation of Seismic Safety during Blasting Operations in Mines.**

By S. V. MEDVEDEV,

Institute of Physics of the Earth, Academy of Sciences of U. S. S. R.

(Read March 26, 1968.—Received March 30, 1968.)

Introduction

The present article deals with the basic regularities of seismic effects of explosions upon buildings. The characteristics of the seismic effect of explosions are described in a number of M. A. Sadovskij's important works. The present article deals with a scale of the intensity of seismic oscillations during the explosions in the Mining Industry and a practical method for evaluating the safety distances from the explosion center to structures. The empirical data used as a base for creating this method, mainly, are given in Medvedev (1963, 1964), as well as in Karapetyan (1963), Leet (1963), Lyakhov (1962) and in other works.

1. Application of Blasting

The blasting is widely used in mine work. When mining the minerals, the blasting operations are usually conducted with the use of great-weight explosive charges. Sometimes, an explosive charge weighs some ten or hundred tons. These explosions cause considerable seismic oscillations in the surrounding ground. The seismic effect can be harmful for the buildings located near the blasting centre. The seismic danger for the buildings is usually evaluated in the following cases:

a) The explosion is the first one in the given area. For example, it is necessary to change the course of the river in order to prevent the mine from flooding.

b) A charge used for blasting is of much more weight than it was before.

c) A new quarry for mining the minerals is established.

d) A mine is extended and comes nearer to the existent buildings.

e) The strength of the existent buildings decreased, for instance,

* Communicated by E. Shima.

because of landslides.

f) Construction of new buildings is planned near the mining enterprise.

g) The method of blasting is changed. For example, a delayed-action explosion is used instead of instantaneous blasting. In order to decide how to conduct such blasting the results of theoretical and experimental investigations of the seismic effect should be used.

2. Ground Oscillation Velocity

The seismic oscillations during blasting were measured at many mining enterprises. On the grounds of experimental data it is reasonable that the velocity of oscillation of a ground particle in the radial direction should be evaluated according to the following formula (Medvedev, 1963, 1964) :

$$V_p = k_B \sqrt{\frac{g}{jB_1\tau}} (R_{red.})^{-1.5} \qquad (1)$$

$$R_{red.} = \frac{r}{c^{1/3}} \qquad (2)$$

where : V_p—the greatest velocity along the radial component, cm/sec.

k_B—7.5.10[4] cm—empirical coefficient.

j—the specific weight of the ground at the observation point, kg/m^3.

g—acceleration of the force of gravity, m/sec^2.

τ—period of ground oscillation, sec.

B_1—wave spreading velocity, m/sec.

r—distance from the explosion center, m.

c—charge weight, kg.

$R_{red.}$—distance reduced to the charge weight.

Dependence of V_p upon $R_{red.}$ is shown in Fig. 1. This Figure is drawn on a double logarithmic scale and relates to one of the Urals' quarries.

When conducting a short delayed-action explosion, the oscillation velocity vector V_k is of smaller value in comparison with the instantaneous explosion velocity vector $V_{inst.}$.

3. Seismic Effect of Explosion upon Structures

A structure is a complex mechanical system. As a result of an explosion, space oscillations occur in it. Three components of an oscillation

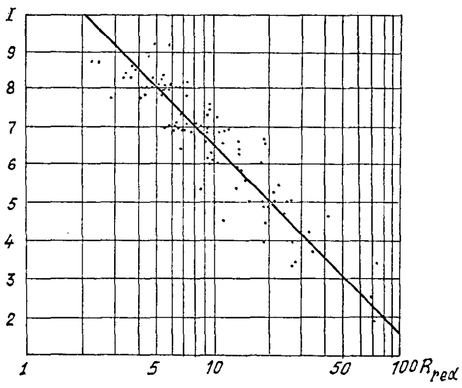

Fig. 1.

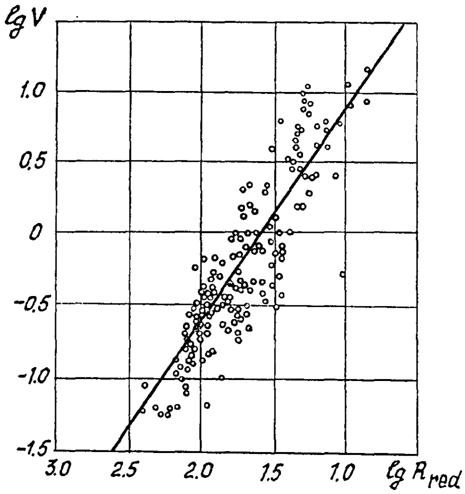

Fig. 2.

in the direction of the three main axes of inertia of the structure are considered. In every direction the structure is of several forms of oscillation with corresponding periods T.

In the final analysis, the oscillation of the structure is the superposition of oscillations of all forms in three directions. Each form of the oscillation is described by the following equation:

$$\frac{d^2x}{dt^2}+\frac{2\lambda}{T}\frac{dx}{dt}+\frac{4\pi^2}{T^2}x=\frac{d^2u}{dt^2} \tag{3}$$

where: x—shift of the system center relative to the ground.
u—ground displacement.
λ—logarithmic decrement of an oscillation damping.
T—proper oscillation period of the system.

Solving equation (3), we can obtain the oscillation velocity of the system in the following way:

$$v_n(t)=\frac{dx}{dt}=-A\frac{2\pi}{T}\exp\left(-\frac{\lambda t}{T}\right)\sin\left(t\sqrt{\frac{4\pi^2-\lambda^2}{T^2}}-\varphi+\Psi\right)$$
$$+\frac{1}{\sqrt{1+\left(\frac{\lambda}{2}\right)^2}}\int_0^t \exp\left[-\lambda(t-\xi)/T\right]\frac{d^2u}{dt^2}(\xi)$$
$$\times\sin\left[(t-\xi)\frac{4\pi^2-\lambda^2}{T^2}+\frac{\pi}{2}+\Psi\right]d\xi \tag{4}$$

where : A—initial amplitude of oscillation.

φ—initial phase.

$\Psi=\arctan\dfrac{1}{\sqrt{\left(\frac{2\pi}{T}\right)^2-1}}$ —phase angle.

ξ—time as variable quantity of integration.

The maximum value of deformations and stresses in the material will correspond to that of velocity $v_n(t)$. Thus, the maximum velocity, which in consequence will be simply designated as v_m, is intended for the evaluation of the seismic resistance of the structure.

The maximum velocity $v_m=(v_n(t))_{max}$ will be different for different values of period T, decrement of damping λ and ground acceleration $\frac{d^2u}{dt^2}$, i.e.

$$v_m=v_m\left(T,\ \lambda,\ \frac{d^2u}{dt^2}\right) \tag{5}$$

For the same explosion a spectrum of different values of maximum velocities v_m for different periods T can be evaluated. This spectrum is called an action spectrum. In practice, a range of periods from $T_1=0.15$ sec. to $T_2=0.8$ sec. is of great importance. Within this range for all periods T the logarithmic decrement of oscillation damping of the structures is assumed to be constant, and on the grounds of the experimental data it is assumed that $\lambda=0.5$. It corresponds to the damping which is equal to 8 per cent of a critical damping. Hence, the effect of an explosion upon the structure can be characterized by a mean value of maximum velocities v_m ranging from 0.15 to 0.8 sec. If we designate this mean value as "S", then we obtain :

$$S=\frac{1}{T_2-T_1}\int_{T_1}^{T_2}v_m dt \tag{6}$$

4. Scale of Intensity of Seismic Oscillations during Explosions

In order to evaluate the intensity of ground oscillations during earthquakes the Institute of Physics of the Earth, Academy of Sciences of the U. S. S. R. developed a seismic scale (Medvedev, 1965). The latter is of twelve points. The part of this scale from the 6-th to 9-th point (this part is the most important for practical application) is adopted as standard (USSR State Std-ГОСТ 6249-52).

The lesser points from the 1-st to the 5-th are not harmful for the structures, and the greater points, i.e. from the 10-th to the 12-th number, very rarely happen. The scale is provided with a descriptive part which characterizes the subsequences of an earthquake (called the macroseismic data), and, in addition, the values of standard pendulum displacements corresponding to the scale descriptive part.

The study of the subsequences of explosions resulted in the author's creation of a scale for the determination of the seismic oscillation intensity during explosions (Table 1). The macroseismic effect according to the readings of this scale corresponds to the effect according to the points of the earthquake intensity scale. The most important task is the evaluation of a dependence between the macroseismic effect and the quantitative characteristics, such as $R_{red.}$, V and S.

From the results of the data concerning the subsequences of the seismic explosions, which were obtained for several hundred cases (Medvedev, 1964), an empirical dependence between intensity I of structures (in points) and reduced distance $R_{red.}$ can be evaluated. In addition, it is necessary to take into consideration that the intensity of seismic oscillations increases on weak waterlogged grounds, and usually is lesser on rocks. The experimental data are given in Fig. 2. They are averaged with the help of an inclined straight line which expresses a relation between I and $R_{red.}$ shown in Table 1.

The formula which relates intensity I (in points) to reduced distance $R_{red.}$ is the following:

$$11-5\,lg\ R_{red.}\leq I\leq 12-5\,lg\ R_{red.} \tag{7}$$

On the results of interpretation the instrumental data (Medvedev, 1967) dependence of the mean velocity on the spectrum of oscillation effect on a structure was obtained in the following form:

$$S=315R_{red.}^{-1.5} \tag{8}$$

where: S—velocity according to one component, cm/sec;
$R_{red.}$—reduced distance, m. $kg^{-1/3}$.

This ratio (8) between S and $R_{red.}$ is shown in Table 1.

The ratio of ground oscillation velocities V and $R_{red.}$ for different sections of blasting operations in quarries indicates that the diversity of values of oscillation velocities is great. It should be taken into account when estimating the seismic effects. It is also reasonable to indicate in the seismic intensity scale mean values of the maximum velocity of ground oscillation V like to one component similar to the oscillation velocity in the action spectrum S. According to instrumental data, the dependence of V upon $R_{red.}$ is expressed by the following formula:

$$V = 190\ R_{red.}^{-1.5} \tag{9}$$

According to formulas (7), (8) and (9), in the scale of intensity of seismic oscillations during explosions (Table 1), the greatest velocities of ground oscillations V, the mean values of the action spectrum S in a range of periods from 0.15 to 0.8 sec., as well as reduced distances $R_{red.}$ are given. They correspond to the descriptions of the subsequences and apply to those cases when the distance from an explosion centre to a structure exceeds the dimensions of the structure.

The data of Table 1, which define the intensity of seismic oscillations during explosions, apply to medium ground conditions, as well as to the explosions conducted at open-cast workings.

5. Behaviour of Buildings which are of Different Safety and Different Ground Conditions during Different Methods of Blasting Operations

In deformed buildings and, in particular, in ramshackle ones, the damage is caused with a lesser intensity of oscillations than in the buildings which are in a satisfactory state. In the ramshackle buildings, deformed buildings and in the buildings which are in a satisfactory state the damage may occur at 5, 6, and 7 points respectively.

Consequently, in order to ensure the safety of structures it is forbidden to allow the appearance of the abovementioned quakes.

The allowed intensity of quakes for the structures of different safety is shown in Table 2.

K_3 coefficient, which is indicated in Table 2, shows how many times the radius of the seismically dangerous zone for deformed and ramshackle buildings exceeds the radius of the seismically dangerous zone for the buildings which are in a satisfactory state.

Table 3 shows the values of the transitional coefficient of explosion conditions K_y which determines the ratio between the reduced distance under different conditions of blasting operations and an instantaneous explosion at open-cast workings. Coefficients K_y (Table 3), which correspond to short delayed-action explosions, are taken into account only

Table 1. Scale of Intensity I of Seismic Oscillations during Explosions.

I, Points	Characteristics of quakes	V, cm/sec	S, cm/sec	$R_{red.}$ m. kg$^{-1/3}$
1	Oscillations are noted only with the use of instruments	$V<0.2$	$S\leqslant 0.2$	$R_{red.}>100$
2	Oscillations are sometimes felt during quiet conditions	0.2- 0.4	0.3- 0.6	63-100
3	Oscillations are felt by some people or by the people who know about the explosion	0.4- 0.8	0.6- 1.2	40- 63
4	Oscillations are noted by many people; there is a rattle of window-panes	0.8- 1.5	1.2- 2.5	25- 40
5	There is a fall of whitewashing; damage to ramshackle buildings	1.5- 3.0	2.5- 5.0	16- 25
6	There are thin cracks in plaster; damage to deformed buildings	3.0- 6.0	5.0-10.0	10- 16
7	There is damage to the buildings which are in a satisfactory state, such as: cracks in plaster, fall of plaster pieces, thin cracks in walls, cracks in stoves and chimneys	6.0-12.0	10.0-20.0	6.3- 10
8	There is considerable damage to buildings, such as: cracks in bearing structures and walls, big cracks in partitions, fall of chimneys and plaster	12.0-24.0	20.0-40.0	4.0-6.3
9	There is destruction of buildings, i.e. big cracks in walls, exfolliation of masonry, fall of some sections of walls	24.0-48.0	40.0-80.0	2.5-4.0
10-12	Great destruction and collapse of buildings	$V>48.0$	$S>80.0$	$R_{red.}<2.5$

Table 2.

State of building	I, points	K_3
Satisfactory	6	1
Deformed buildings	5	1.6
Ramshackle buildings	4	2.5

in those cases when the instrumental seismic investigations were not carried out at the site.

The ground conditions also affect the intensity of quakes. With a set intensity the reduced distance $R_{red.}$ increases by 40 per cent for weak ground, and for rocks it decreases by 30 per cent.

Depending upon the reduced distance $R_{red.}$, coefficients $K_{gr.}$, which

Table 3.

Method of blasting	Conditions of blasting operations	K_y
Instantaneous blasting	Open-cast workings	1
	Underground workings	0.72
	Outburst explosions (momentaneous)	0.91
Short delayed-action blasting	Open-cast workings	0.80
	Underground workings	0.63
	Outburst explosions (momentaneous)	0.83

Table 4.

Ground conditions	$K_{gr.}$
Compact rocks	0.5
Fissured rocks	0.7
Semirocks (marls, sandstones, gyps)	0.8
Compact pebble rock	0.9
Sandy and clayey grounds with ground waters flowing at a depth of 10 m and more	1.0
Sandy and clayey grounds with ground waters flowing at 5 to 10 m depth	1.2
Sandy and clayey grounds with ground waters at the depth of less than 5 m	1.4
Swampy grounds and peat-bogs	1.8

define the effect of ground conditions upon the seismic vibrations during explosions, are given as follows.

The coefficients listed in Tables 2, 3 and 4 were obtained macroseismic data of the explosions indicated in Table 3.

6. Seismic Safety Distances

Using coefficients K_3, K_y, $K_{gr.}$, we can obtain a ratio between reduced distance $R_{red.}$ (which is indicated in Table 1) and the value $R^1_{red.}$ for other conditions:

$$R^1_{red.} = K_3 K_y K_{gr.} R_{red.} \tag{10}$$

The ratio beween reduced distance $R^1_{red.}$ and actual distance r is usually determinated by the following dependence:

$$R^1_{red.} = \frac{r}{\sqrt[3]{c}} \tag{11}$$

Consequently, distances r (for which seismic danger of explosions is determined) can be calculated according to the following formula:

$$r = K_3 K_y K_{gr.} \cdot R_{red.} \sqrt[3]{c} \tag{12}$$

where: c-weight of blasting explosive charge, kg.

$R_{red.}$-reduced distance (from Table 1)

Usually, the value of $R_{red.}$ should be taken as the limit between the intensity zones of 6 and 7 points.

When explosions are fired repeatedly, because of the great diversity of the observed points it is necessary to ignore the mean values of distances or velocities, but their maximum, least probable values should be taken into account. These radii of dangerous zones are used for designing the buildings.

7. Ratio of Seismic Oscillations during Explosions and Earthquakes

The intensity of seismic oscillations during explosions (in points) corresponds to the same scale, to the intensity of earthquakes. This is due to the fact that the seismic oscillations of the ground during explosions are similar to the oscillations which occur during the earthquakes. When the distances to the sources of explosion and earthquake, as well as the energy of these sources are the same, this similarity is very great. In reality, distances are different. The radii of the seismically dangerous zones are equal to several tens or hundred meters. Distances from the earthquake center to the line limiting the zone of destruction effect are equal to a few or some ten kilometers. At various distances a spectral composition of oscillations during the explosions differs from a spectral composition of vibrations during earthquakes. In this connection some peculiarities of an explosion effect in comparison with that of an earthquake are described below.

The spectral composition of seismic oscillations during explosions is narrower than that of earthquakes. Usually, during the explosions there are no long-period oscillations; therefore, the effect of the explosions upon high and flexible structures is not so dangerous when compared to earthquakes. Falls of stone structures of buildings or other massive elements during earthquakes are often caused by the effect of a long-period component of the spectrum of seismic oscillations. Therefore, during blasting operations the fall of buildings almost never occurs.

A lesser duration of oscillations during the explosions usually results in a lesser swinging of buildings. During the explosions the ratio of the amplitudes of oscillations of the top of a building to its base is less than it is during the earthquakes. During the explosion the building can withstand more considerable oscillations of the ground.

A predominance of high frequencies during the explosions can sometimes increase the danger for building structures. In particular, it is dangerous for rigid joints, e.g. anchor fastenings of girders and supporting structures of frames.

The fact that the distances from the explosion center are commensurable with the dimensions of a structure is also of substantial importance. Therefore, the seismic effect along the entire base of a building is usually uneven.

References

KARAPETYAN, B. K., 1963. Many-pendulum Seismometers and Results of their Application in Engineering Seismology. Aipetrat, Erevan.

LEET, L. D., 1963 Seismic Effect of Explosion. Gosgortechizdat, Moscow. (Russian translation of Vibration From Blasting Rock published in 1960)

LYAKHOV, G. M. and G. I. POKROVSKII, 1962. Explosion Waves in Grounds. Gosgortechizdat, Moscow.

MEDVEDEV, S. V. 1963. Problems of Engineering Seismology. Consultants Bureau, New York.

MEDVEDEV, S. V., 1964. Seismics of Blasting Operations in Mines. Nedra, Moscow.

MEDVEDEV, S. V., 1965. Engineering Seismology. Israel Program for Scientific Translations. Published Pursuant to an Agreement with the National Science Foundation. Washington D. C..

SADOVSKY, M. A., 1964. The Most Simple Methods of Evaluation of Danger of Mass Explosions. Izv. AN SSSR, Moscow.

---

31. 鉱山発破の地震動によっておこされる震害からの安全性の評価

Institute of Physics of the Earth, U.S.S.R. S. V. MEDVEDEV

鉱山における大量の火薬爆破作業により発生した地震動を各種地盤上で観測し，その結果についてすでに報告した.(例えば，Problems of Engineering Seismology, 1963 参照)

本論文では，まずこのような地震動と震度との関係についてのべてある．次に，安全距離，すなわち，爆破地震動により建築物に被害を与えない震央距離を推定する方法についてのべてある．安全距離は，建物の丈夫さ K_3，爆破の条件 K_y，地盤のよしあし $K_{gr.}$ によってかえなければならない．このための補正量 K_3, K_y, $K_{gr.}$ はそれぞれ Tables 2, 3, 4 にまとめられてある.

さいごに，人工地震動と天然の地震動とのちがいについてふれた.