Paper No. 95, Bulletin of the Indian Society of Earthquake Technology, Vol. VII, No. 3, pp. 137–146, Sept. 1970

EFFECT OF VIBRATION ON BUILDINGS AND PERSONS

P. Srinivasulu*, Member

INTRODUCTION

It is well known that vibration produces additional stresses in structural members of a building and moreover, reduces with frequent repetitions the resistance of the building to damage. The question is therefore often asked whether the vibrations arising from a certain source are dangerous to a building in the vicinity and if so, how they influence the resistance of the building. It is also known that vibration has a physiological effect on human beings. The second question naturally arises as to how dangerous the vibrations are on persons working at the site and to what extent they influence their efficiency.

It is hard to answer precisely such questions in practice as it involves several factors. An exact mathematical treatment of the problem is sometimes so complex that it is worthwhile only in a few practical cases. Among the many uncertainities in the approach to the calculation for building vibrations are the participation of various constructional elements such as partition-walls etc......., the choice of material constants, the degree of fixity of structural components, the fatigue strength of materials and so on.

It is from this standpoint that vibration measurements on buildings and other structures assume great importance. The aim of this paper is to discuss the important practical criteria in vogue for the evaluation of the effect of man-made vibrations on buildings and persons based on vibration measurements. The various criteria are first explained and they are later illustrated with certain examples taken from practice.

CRITERIA FOR THE ASSESSMENT OF VIBRATION EFFECT ON BUILDINGS

The physical quantities commonly taken as the basis for the various criteria for the evaluation of vibration are : (i) Maximum amplitude (A), (ii) frequency (f), (iii) maximum velocity (v) and (iv) maximum acceleration (a).

Assuming sinusoidal type of vibration,

$$a = 4\pi^2 A f^2$$

$$V = 2\pi . A f$$

Expressed in terms of these physical quantities, various units of vibration intensity have come into vogue although, however, no single unit has been universally recognized. Almost all these units are functions of either displacement, velocity or acceleration and frequency of vibration. These physical quantities can easily be measured on site with a simple set of equipment comprising of a vibration pick-up and a vibration meter, an oscilloscope or a recorder. The standard units are : (a) Zeller's power or intensity of vibration, (b) the Vibrar and (c) the Pal Units.

(a) Zelles's[12] 'Power' of vibration which takes into account acceleration and frequency is given by

$$Z = \frac{a^2}{f} = 16\pi^4 A^2 f^3 \ (cm^2/sec^3)$$

* Scientist, Structural Engineering Research Centre, Roorkee (U.P.).

According to Zeller's scale of danger the first damage to buildings can be observed from Z=25 to 100. His scale is divided into 12 degrees depending on value of Z. Koch[6] has suggested another table relating the intensity as given by Zeller's Power of vibration and its corresponding effect on buildings (Table 1).

TABLE 1

Intensity of vibration	Nature of vibration	Effect on building
1-10	Light	No damage to building
10-100	Medium	No damage to building
100-1000	Strong	Small damage likely. Plaster may crack. Weaker walls may split.
1000-10,000	Stronger	Bigger damage on building-cracks on load bearing walls.
10,000-100,000	Very strong	Total damage expected.

Zeller's scale essentially tallies with the table given by Koch.

(b) The strength of vibration in Vibrar units associated with Zeller's value (Z) is as follows :

Strength in Vibrars = $10 \text{ Log}_{10} (10 Z)$.

The scale of damage associated with Vibrar is given in Table 2.

TABLE 2

Range in Vibrars	Effect	Possible damage to buildings
10–20	Light	None
20—30	Medium	None
30—40	Strong	Light damage
40–50	Heavy	Severe damage damage to main-walls.
50–60	Very heavy	Destruction

(c) The 'Pal' unit has two versions—one suggested by Zeller himself and the other as adopted by DIN 4150 [5] "protection against vibration in Building Construction". The former may be called 'Zeller Pal' unit and the latter 'DIN PAL' unit. They are defined as below :

Strength in 'Zeller Pal' units = $10 \log_{10} (2Z)$.

This is not bassically different from the Vibrar unit already described. Hence it may not be considered here further.

Strength in 'DIN Pal's = $20 \text{ Log}_{10} \left(\frac{V_e}{V_o}\right)$. Where V_o is the threshold value of velocity viz. 0.0316 cm/sec and V_e is the root mean square value of velocity of vibration

$$\left(V_e = \frac{V}{\sqrt{2}} = \frac{2\pi A f}{\sqrt{2}} \right),$$

Strength in DIN Pals is therefore further expressed as :

$$= 20 \log \left(\frac{V}{\sqrt{2} \times 0.0316} \right)$$
$$= 20 \log (22.4\ V)$$
$$= 20 \log (140\ A\ f)$$

Where A is in cm and f in cm/sec.

According to DIN 4150[5], the criteria for permissible vibration intensity is decided by the following :

(i) 35 Pal (DIN) corresponding to 2.54 cm/sec.

(i i) A f = 0.4 cm/sec.

(iii) Constant acceleration of 0.5 g

(iv) $A f^2 = 12.4$

For any given frequency the least of the above four criteria should be followed.

Soliman[10] suggests the following criteria for determining the so called "threshold of damage" to buildings.

(a) In the frequency range 5 – 16 c/sec,
Constant acceleration $A w^2 = 762$ cm/sec²

(b) In the frequency range 16–150 c/sec,
Constant velocity (A w) = 7.62 cm/sec.

The 'threshold of damage' is that limiting value of vibration intensity at which damage would start to occur. For design purpose, one-tenth of these values may be taken as permissible limits of vibration.

Soliman[10] gave a nomogram (Fig. 1) by means of which the so called "degree of safety" for buildings can be predicted, once the measured values of frequency and amplitude are known. The "degree of safety" is defined by the values of a/75, and V/0.75 for the frequency range 5–16 c/sec. and 16–150 c/sec. respectively where a is in cm/sec² and V in cm/sec.

In U. S. A. the practice has been to take a constant acceleration of 1 g as 'threshold of damage' and 0.1 g as limit for permissible vibrations.

The permissible limits of vibration as suggested by DIN 4150, Soliman and the practice in U.S.A. are shown in Figure 3 which is plotted on a log-log scale.

For harmonic vibrations, Dawance and Seguin[2] presented a log-log plot (fig. 4) which shows the relation between frequency and acceleration for different ranges of

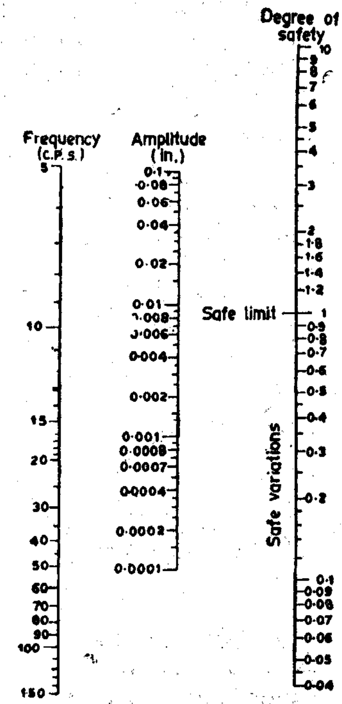

Fig. 1. Soliman's Nomogram for 'Degree of Safety' For Buildings.

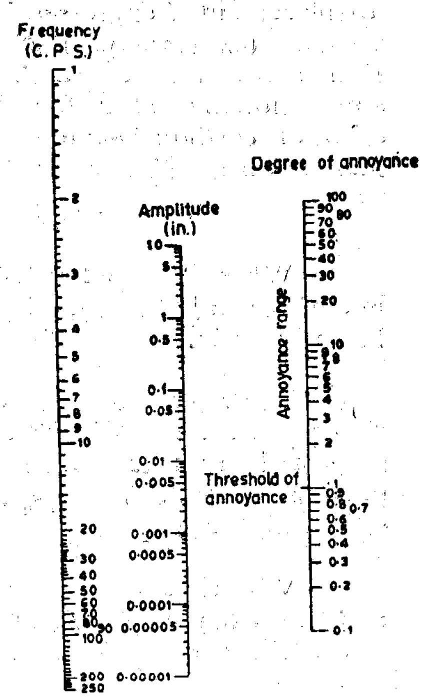

Fig. 2. Soliman's Nomogram for 'Degree of annoyance'

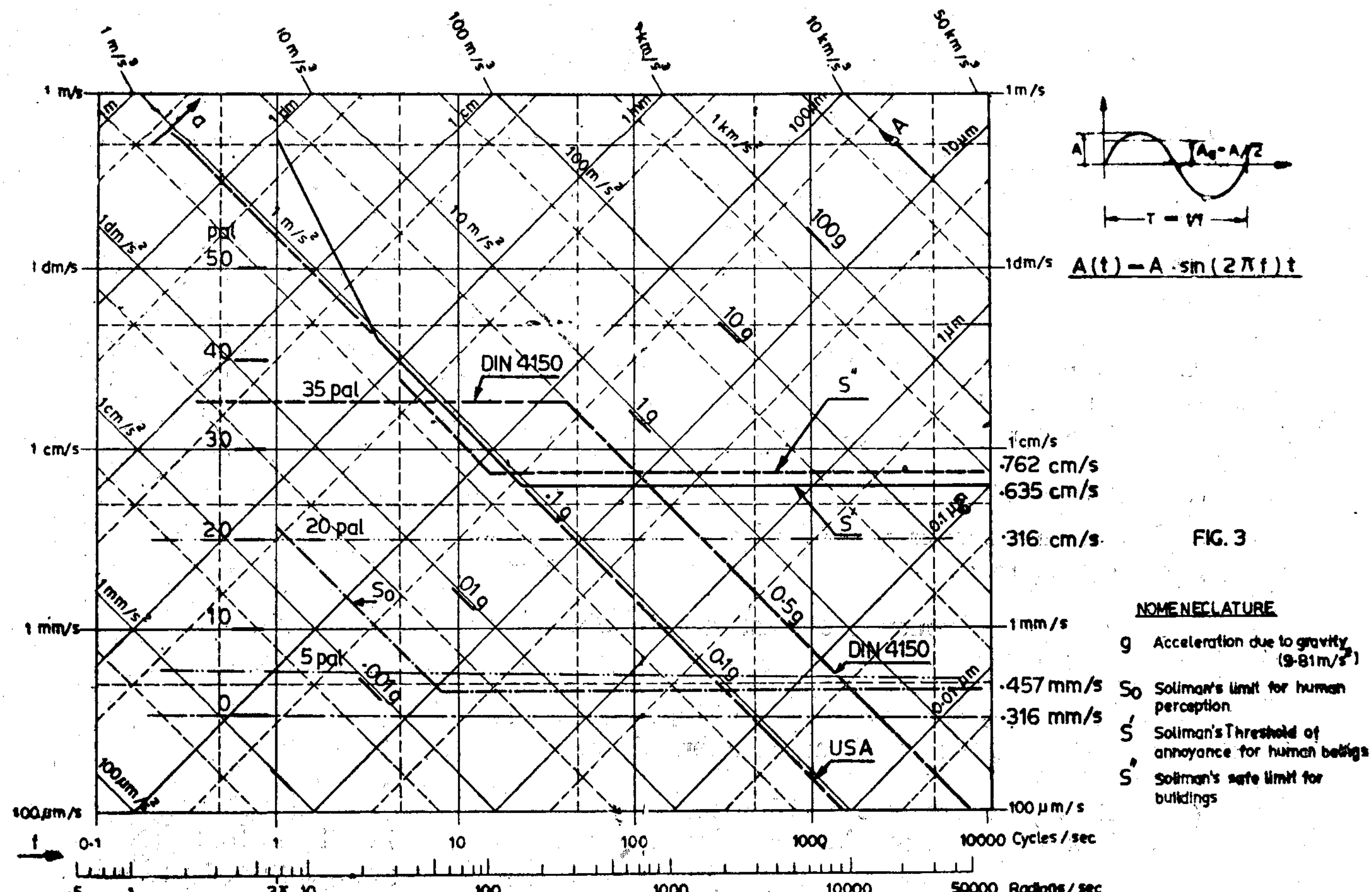

FIG. 3

displacement (expressed in microns) and velocity (expressed in DIN Pals). The relation between Modified Mercalli Intensity conventionally used for representing the effect of earthquakes and accelerations also marked on the plot is given by

$$\log a = N/3 - 1$$

Where a is peak value of acceleration in cm/sec² and N is intensity rating used in Mercalli scale.

The vibration effect on buildings is also given for the different zones. It was suggested that acceleration was the important factor at low frequencies and velocity at higher frequencies.

Vibrations caused by an earthquake is perhaps the most severe to which a building is likely to be exposed. Under such conditions, large horizontal forces and movements may be involved and there is also possibility of resonance in taller structures. The intensity of earthquake at a place is generally represented by its damaging effects on building and persons. The Modi-

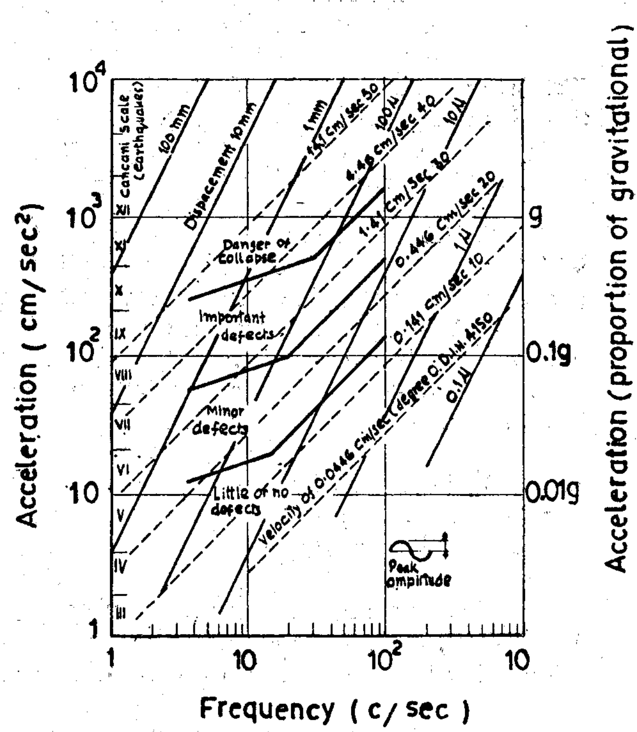

Fig. 4. Effect of Vibrations on Buildings. Relation Between Various Means of Measuring Vibrations (Sinusoidal Vibrations).

fied Mercalli scale of intensity has been proposed on this basis. The extreme limits of the seale are – Class I, which represents practically no effect and class XII which represents total damage and destruction. The intermediate classes correspond to different degrees of damage.

CRITERIA FOR VIBRATION EFFECT ON PERSONS

On the question of human sensitivity to vibrations, many criteria have been suggested. Significant of these are given below.

An important investigation was carried out in Germany in 1931 when a selected group of people were subjected to vibrations of known amplitudes and frequencies and their sensations noted. The results obtained[9] are summarized in Figure 5. The curves shown relate frequency and amplitude of vibration for different degrees of human perception.

Soliman[10] gave separate criteria for obtaining in dimensionless units the so called 'degree of perceptibility' and 'degree of annoyance' the two terms representing the extreme limits of human sensitivity. Fig. 2 shows the nomogram for obtaining the 'degree of annoyanee' as suggested by Soliman, its value being given by 1/2250, da/dt, a/90 and V/0.625 respectively for the frequency ranges 1–4 c/sec., 4–22 c/sec. and more than 22 c/sec da/dt means rate of change of acceleration in cm/sec which governs the annoyance limit in the specified frequency range a and f are expressed in cm/sec² and c/sec. respectively.

Dieckmann[3] suggests a value K given by Table 4, separately for vertical and horizontal vibration. The level of vibration based on value of K is given in Table 5.

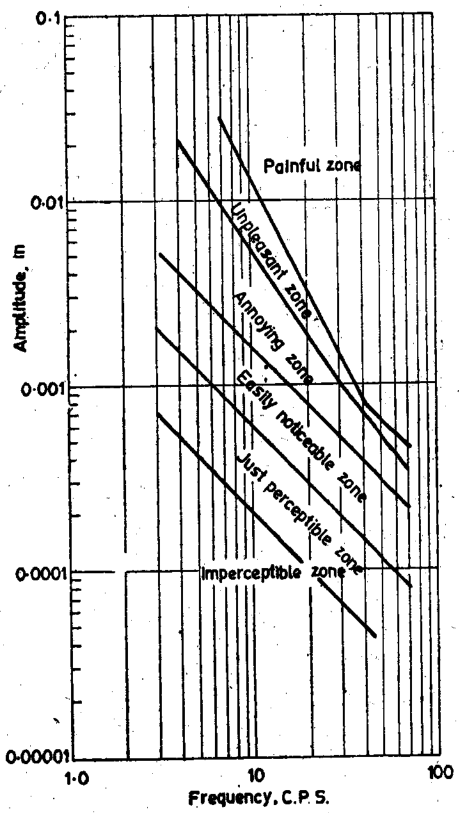

Fig. 5 Reiter and Melster Scale of human Suceptibility to Vibrations

TABLE 4

Frequeney (c/sec)	Horizontal vibrations	Vertical vibrations
5	10 Af^2	20 Af^2
5 – 40	50 Af	40 Af
< 40	2000 A	1000 A

(A is amplitude in cm and f requency in cycles/sec.)

TABLE 5

Value of K as per Table 4	Level of vibration
0.1	Lower limit for human perception
1	Tolerance even for long periods
10	Tolerance only for short periods
100	Upper limit for tolerance

Postlethwaite[8] suggests the following formula for the permissible amplitude from the point of view human of discomfort.

$$\text{Amplitude (cm)} = 0.0076\left(1 + \frac{194}{f^2}\right)$$

As seen from Figure 3, the so called 'threshold limit' of human annoyance is almost same as the threshold limit for safety of buildings which means that the upper limits of tolerance for buildings and human beings are nearly the same in the frequency range of 5-150 c/sec.

According DIN 4150, the effect of vibration on human beings can be obtained from Table 6 below :

TABLE 6

DIN (Pal)	Effect on present persons
0–5	Vibration just perceptible
5–10	Vibration well perceptible
10–20	Vibration strongly perceptible
20–40	Vibration unpleasant

The DIN Code rightly differentiates between the effects of continuous and intermittent vibrations. The tolerance limit for continuous vibration is given as 5 pals and for non-continuous vibration as 20 pals.

EFFECT OF VIBRATION DUE TO BLASTING

A variety of damage criteria have been proposed for vibrations due to blasting. Of these the best known are those due to Thoenen and Windes[11], Crandell[1], Morris[7] and Edwards and Northwood[4].

The U.S. Bureau of mines carried out comprehensive series of tests in which they deliberately attempted to cause damage to houses by blasting operations. The results of these tests[11] showed that the threshold of damage to buildings (cracking of plaster) corresponds to an amplitude of 0.1 in (0.25 cm). Crandell[1] used a criterion based on peak energy in the disturbance, which leads finally to a velocity criterion. He specified a velocity of 3 2 in per second (8 13 cm/sec) as the beginning of a 'Caution zone'. A velocity of 4 5 in/sec (11 45 cm/sec.) is defined as the beginning of the 'danger zone'. Crandell further suggests that the vibration form due to blasting may be approximated as sinusoidal. Morris[7] on the basis of a few observations of damage to buildings due to blasting vibrations estimated the actual damage threshold of about 4.5 in/sec. (11.45 cm/sec.). This is valid for a variety of foundations and a variety of damage machanisms involving predominant frequencies from 2.5 to 400 cycles/sec.

According to the observations of Edwards and Northwood[4], the damage is likely to occur at a velocity of 4 to 5 in/sec. (10 to 12.5 cm/sec.). A safe limit of 2 in/sec. (5cm/sec) is however recommended. They consider that velocity is the quantity which is generally applicable to all types of soils and as the vibration records are generally complex, it is desirable to measure directly velocity rather than inferring it from displacement or acceleration records. Relating the weight of explosive (E) in lbs. and the distance (d) in ft., Edwards and Northwood recommended the formula $E^{2/3} \leqslant 0.1\ d$ as a safe limit for normal blasting operations with a single charge. This formula is believed to have general application for the most soils and for wide range of charges and distances.

SUMMARY AND CONCLUSIONS

Practical criteria for the assessment of vibration effect on buildings and human beings based on vibration measurements have been discussed. Cases of industrial and blasting vibrations have been covered. The examples given in the Appendix show that there is general agreement between the various criteria although some of them are empirical and based on numerous observations. They are therefore quite suitable for application to many of the practical cases.

It appears more appropriate, however, to distinguish between continuous and non-continuous vibrations to judge their effect on human sensitivity. For considering the effect on buildings it may be more rational to classify the criteria, depending on the type of construction whether monolithic or prefabricated and also the material of construction whether brick, stone, or concrete etc. The latter takes into account the fatigue of the material concerned.

It is natural to attribute any formation of cracks particularly in industrial buildings to the vibration caused by the operating machinery within Observations have shown that in numerous cases (as in example 1 illustrated in Appendix) the cracks were not initiated by vibration although it cannot be denied that vibration would have accentuated formation of of cracks, caused primarily by other causes like shrinkage, differential temperatures etc. Such practical criteria as those explained above, afford a quick and a reasonably correct assessment of vibration effect.

ACKNOWLEDGEMENTS

Thanks are due to Mr. Joseph Illessy, Senior Engineer of the Institute of Quality Control, Budapest for his useful suggestions. This paper is published with the kind permission of Director, Structural Engineering Research Centre, Roorkee, U.P. (India).

APPENDIX

Two practical examples based on actual measurements are given below to illustrate the application of the various criteria explained in the main text.

(1) *Example for Industrial Vibrations*

Vibration measurements were taken on the ceiling of the ground floor of a prefabricated building where some textile machines were running at the operating frequency of 1500 r. p. m. (25 H_z). The aim of the investigation was to assess the vibration intensity and consequently derive its effect on the safety of the building and the working of the people in the first floor. The maximum amplitude measured at the middle of ceiling of the ground floor was 12μ. The measured natural frequency of ceiling was 1800/min.

(i) The vibration intensity according to Zeller

$$= 16\pi^4 A^2 f^3$$

$$= 16\pi^4 \left(\frac{12}{10^4}\right)^2 \left(\frac{1500}{60}\right)^3$$

$$= 35 \text{ cm}^2 / \text{sec}^3$$

According to the Table 1, the vibration is of 'medium' intensity and no damage to the building is possible.

(ii) Strength in Vibrar units $= 10 \log_{10} 350$
$= 25.44$

From Table 2, we arrive at the same conclusion that the vibration is medium and no damage is likely.

(iii) According to DIN 4150, for 25 H_z exciting frequency, the permissible amplitude of vibration is the least of the following four criteria.

(a) Constant velocity of 2.54 cm/sec corresponding to a displacement amplitude of 0.016 cm.

(b) $A = \frac{0.4}{25} = 0.016$ cms.

(c) Constant acceleration of 0 5 g corresponding to a displacement amplitude of $\frac{0.5 \times 981}{(50\pi)^2}$ i.e. 0.02 cm.

(iv) Dispacement $= \frac{12.4}{25^2} = 0.02$ cm.

The governing value of permissible amplitude is therefore 0.016 cm which is more than the actual amplitude recorded viz. 12 μ_m (0.0012 cm)

(d) According to Soliman's criteria.

'Safe Limit' amplitude $= \frac{0.75}{50\pi} = 0.005$ cm greater than 0.0012 cm recorded.

(e) The permissible limit for displacement amplitude according to the practice in U. S. A. is 0.004 cm (corresponding to 0.1 g).

From all these criteria it is judged that no damage is likely to the building as a result of vibration. In fact, there were some minor cracks in the ceiling plaster which were however not attributed to vibration.

Effect on human beings

(a) Soliman's Nomogram gives a degree of annoyance of 0.29.

(b) Reiher-Meister's Curves show that the vibration falls in the clearly perceptible zone.

(e) Dieckman's table gives a K value of 3.75 which can be considered to be tolerable.

(d) Postlethwaite's formula gives a permissible amplitude of $0.0076\left(1 + \frac{194}{25^2}\right)$ i. e. 0.01 cm which is more than the recorded amplitude.

(e) Vibration intensity in DIN Pals = 12.26.

According to Table 6, the vibration is strongly perceptible. However as the machines were not working continuously, the limit of 20 Pals as allowed by DIN 4150 may be taken here. For continuous working, however, the machines have to be mounted on elastic under-layers like springs.

(2) *Example for Vibration due to blasting*

Vibration measurements were taken on a building about 50 m from the Centre of a source of blasting. The blasting was intended to demolish an existing adjoining structure. The weight of blasting material used was 18 kg. Both for horizontal and vertical positions of the vibration pick-up, nearly regular sine-waves were registered. The maximum vertical amplitude recorded was 10 μ_m (0.001 cm) and the corresponding frequency was 12.5 H_z. The maximum horizontal amplitude was 15 μ_m (00015 cm) but the frequency was smaller, viz. 10 H_z.

Applying the formula for safe distance as suggested by Edwards and Northwood,[12]

the expression
$$\frac{E^{2/3}}{d} = \left(\frac{18 \times 2.2}{50 \times 3.28}\right)^{2/3}$$
$$= 0.0708$$
$$< 0.1 \text{ the safe limit suggested.}$$

Peak velocity of vibration :

(i) Vertical $= 2\pi \times 12.5 \times 0.001$
$= 0.08 \times$ cm/sec.

(ii) Horizontal $= 2\,\pi \times 10 \times 0.0015$
$= 0.095$ cm/sec.

Either of the two values is less than the value of 2 in/sec. (5 cm/sec) which is the lowest among the limits suggested by the various investigators.

From the various criteria suggested, therefore, the vibrations are considered to be not dangerous to the adjoining building on which measurements are taken. In fact, no damage occured except falling of a pair windows on the facing side; This, besides being minor in nature, was not attributed to ground vibrations but to the associated air blast.

REFERENCES

1. Crandell, F. J., 'Ground Vibrations due to Blasting and its Effect upon Structures', J, Boston, Soc. Civil Engineers, April, 1949, p. 222–245.
2. Dewance, G and Seguin, M , 'Effect of Vibrations on Buildings' Proceedings of Symposium on 'Vibration in Civil Engineering', London, April 1965, pp. 31–33.
3. Dieckman, D., 'A Study of the Influence of Vibration on Man' 'Ergonomics', Vol. 3, Nov. 4, August, 1958 pp. 347–355.
4. Edwards, A.T and Northwood, T.D., 'Experimental Studies of Effects on blasting on Structures', 'The Engineer' Sept.30, 1960 pp. 538–546.
5. German Standards Institute,, 'Protection against Vibration in Building Construction'. DIN 4150

6. Koch, H. W., 'Determining the Effects of Vibration in Buildings', (Zeitschrift des Vereines Deusscher Ingenieure) Vol. 95, No. 21, 1954, pp. 744–747.

7. Morris, G. 'Vibrations due to Blastlng and their Effect on Building Structures', 'The Engineer', Vol. 190 (October 27 & Nov. 3, 1950), pp. 394-395, 414–518.

8. Postlethwiate, F., 'Human Suceptibility to Vibration' 'Engineering', London, Vol. 157, Jan. 28, 1944, pp. 61–63.

9. Reither, H. J. and Meister, F. J., 'Human Sensitivity to Vibration', Forschung auf dem Gebiet. des Ingenieure, Vol. 2, No. 11, Nov. 1931, pp. 381–386.

10. Soliman, J. I., 'Criteria for Permissible Levels of Industrial Vibrations, with Regard to their Effect on Humna Beings and Buildings' Proc. of RILEM Symposium' Budapest 1963, Vol. 1, pp. 111–147.

11. Thoenen, J.R. and Windnes, S.L., 'Seismic Effects of Quarry Blasting', U S. Bureau of Mines, Bulletin 442.

12. Zeller, W., 'Proposal for a Measure of the Strength of Vibration (German), (Zeitschrift des Vereines Deutscher Ingeuieure) 1933, Vol. 77, No. 12, pp. 323.

NOTATIONS

a	Maximum acceleration of vibration
A	Maximum displacement of vibration (half peak-to-peak)
A_e	R. M. S. value of displacement amplitude ($=A\sqrt{2}$)
d	Distance from the blasting source
E	Weight of explosive
f	Frequency of vibration
g	Aceeleration due to gravity
K	Dieckmann's expression (Table 4)
t	Time parameter
N	Modified Mercalli Intensity
T	Period of vibration
V	Velocity of vibration
V_e	R. M. S. value of V ($= V/\sqrt{2}$)
V_0	Threshold value of velocity (= 0.0316 cm/sec.)
Z	Zeller's intensity of vibration
w	Angular velocity of vibration