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DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD No. 1962/23

ALLIANCE CHAMBERS VIBRATION TESTS, MELBOURNE 1961

by

E.J. Polak and J.T.G. Andrew

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ILLUSTRATIONS

SUMMARY

Tests were made of vibrations in the building of the Alliance Assurance Company Ltd in Melbourne. The object was to find the cause of breakage of windows in the curtain wall of the building. None of the vibrations recorded in various parts of the building exceeded the safe limits for damage as specified by various authorities; however, it is possible that continuous vibrations of certain frequencies may cause damage to parts of the building if resonances occur.

1. INTRODUCTION

This Record describes a vibration investigation made by the Bureau of Mineral Resources, Geology and Geophysics at the request of the Alliance Assurance Company Ltd.

It was believed that breakage of a number of windows in the curtain walls of the Company's building, Alliance Chambers, at 408 Collins Street, Melbourne, might be caused by vibrations. The purpose of this investigation was to measure the amplitude and frequency of vibrations on different floors, and to trace the source of the vibrations. To achieve the latter objective, measurements were made near suspected sources of vibrations so that their frequencies could be compared with those measured elsewhere in the building. Further, measurements were made at the same location with a suspected source of vibrations both operating and not operating.

Possible sources investigated included two compressors in the air-conditioning plant on the roof, the ventilating fans, lavatory flushing, teleprinters, lift motors, and trams.

The investigation was made on 15th and 20th December 1961, by E.J. Polak and J.T.G. Andrew, Geophysicists of the Bureau.

2. INSTRUMENT AND METHOD

The instrument used in recording the vibrations was a Sprengnether Portable Blast and Vibration Seismograph, Serial No. 1577. This instrument records three mutually perpendicular components of the ground vibration on a moving strip of photographic paper. In the third and fourth columns of Table 2, the letter L indicates vibration along the long axis of the instrument, the letter V indicates vertical vibration, and the letter T the horizontal vibration across the axis of the instrument. In Plates 3 and 4 the top trace is the L component, the centre trace the V component, and the bottom trace the T component. A record shows the ground motion magnified 100 times, with timing lines at intervals of 0.02 seconds.

Details of the records taken during the tests are listed in Table 1.

3. RESULTS

Plates 1 and 2 in conjunction with Table 1 show the location of the instrument for all measurements. Table 2 shows the results of the measurements.

Plates 3 and 4 show some of the records obtained. In each test the record was run for several seconds, but only part of the record, showing the greatest displacement of each component, is reproduced here. The amplitude and frequencies of the three components of the displacement were scaled from the records.

Several records (2, 34, 42, and their subdivisions) were taken with the instrument alongside the two compressors. The compressors are both Carrier units. No. 1 is of 40 h.p. and has a speed of 550 rev/min.; No. 2 is of 50 h.p. and has a speed of 600 rev/min. The amplitudes recorded on the 20th December (record 42), were considerably larger than those recorded on the 15th December (records 2 and 34). As one of the compressors was not operating properly on 15th December, the results from record 42 will be considered more reliable. With both compressors running at full load there are two frequencies on the record, one of 11 c/s, and the other of 1.2 c/s. The vertical component varies in amplitude, with a period of 2.2 sec. The 11-c/s vibration is close to the speeds of the compressor unit as measured, 10 rev/sec and 9.2 rev/sec respectively. The lower frequencies are due to beats produced in the structure by the simultaneous running of the two compressors.

On the 11th floor, directly beneath the roof where the compressors are situated, the beat frequency of about 1 sec was again observed in one position. This was on record 44, which was taken with the instrument on the sill of one of the windows that has had to be replaced. In the building there were two main groups of vibrations, one with frequency between 1 and 3 c/s with a mean value of 2 c/s, and one between 10 and 17 c/s with a mean value of about 13 c/s. There was no obvious relation between the frequency observed and the floor on which the vibrations were measured. Some 10th floor records (32, 31, and 30) show a vibration of about 20 c/s, and a 3rd floor record (13) shows a vibration of about the same frequency.

The group around 2 c/s probably represents the natural frequency of the building, which should be of this order. A relation $T = 0.006H$, where H is the height of the building in feet, and T the period in seconds, was deduced by Ulrich and Carder (1952) from records of vibrations in 3000 cases investigated by the United States Coast and Geodetic Survey. Other empirical relations, given by Kawasumi and Kanai (1956), are:

$$T = (0.08 \pm 0.01)\,N \text{ sec, where N is the number of storeys}$$

$$T = 0.05\,H/\sqrt{D} \text{ sec,}$$

$$\text{or } T = 0.06\,H/\sqrt{D} \text{ sec, where D = depth of structure below surface}$$

The height of Alliance Chambers is 132 ft. From these relations the natural frequency would be expected to be of the order of 1 c/s. The second mode for the Alliance Building appears to be of the order of 14 c/s from observed vibration records. This is consistent with values obtained on other buildings for secondary modes of vibration (Blume, 1956).

Table 2 shows the magnitude of the three components of ground displacement (taken as half the peak-to-trough amplitude) corresponding to the various positions of the seismograph. On the assumption that the vibrations are sinusoidal, the accelerations can be calculated from the relation :-

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

Where a = maximum acceleration

f = frequency

A = ground displacement

The resultant maximum acceleration is the vector sum of the accelerations for the three components. The 6th column shows the resultant acceleration as a fraction of g, the acceleration due to gravity (= 386 in./sec^2).

Various limiting standards for damaging and non-damaging effect of vibration have been proposed by different authorities (see Appendix). The U.S. Bureau of Mines (Thoenen and Windes, 1942), using acceleration as an index of likelihood of damage, proposed the following classification, applicable to buildings:

Acceleration greater than 1.0g - Damaging

Acceleration between 0.1g and 1.0g - Slightly damaging (caution zone)

Acceleration less than 0.1g - No damage (safe zone)

All the accelerations measured at Alliance Chambers are in the safe zone; however, the figures above were obtained for transient vibrations, and it is likely that for continuous vibrations the accelerations liable to produce damage are somewhat smaller.

The effect of vibrations whose frequency is close to the natural resonance frequency of a part of the building, such as a window pane, could of course be more damaging than the limits imply. However, it should be noted that the maximum acceleration recorded, on top of the extractor fan housing, is less than one-tenth of that caused by a man making a small jump, and is therefore considerably less than the accelerations which could be caused by normal activities in the building.

Some authorities cite different criteria for the effect of vibrations on human beings. The following results of English and German work are quoted by Steffens (1952):

Authority	Minimum displacement that will cause annoyance (in.)		
	5 c/s	10 c/s	20 c/s
Matlock	0.0196	0.0049	0.00122
Melville	0.0370	0.0046	0.00058
Digby & Sankey	0.0039	0.00197	0.00098
Reiher & Meister	0.0032-0.0160	0.0016-.005	0.0008-0.0018

Matlock also suggested that perceptibility of vibrations depends on the magnitude of the maximum ground acceleration, accelerations greater than .01g being perceptible. None of the amplitudes measured were great enough to be considered annoying by any of the authorities quoted, although in one or two cases they were above the minimum perceptible limit.

All the vibrations were recorded with the instrument standing on some rigid surface that was a part of the structure of the building. Some of the vertical structures in the building, such as partitions and windows, are less damped than the structure as a whole. This means that the vibrations may build up to a greater amplitude in the windows and partitions than was measured on the instrument, particularly if resonance of some of these parts occurs.

4. CONCLUSIONS

All the vibrations recorded (except those caused by a man jumping) were in the 'safe zone' according to the criterion of Thoenen and Windes (1942) for transient vibrations. However, as these criteria are probably not applicable to continuous vibrations, it is possible that some of the vibrations, particularly those on the 10th floor and above, could be damaging. The vibrations due to the two compressors could be accentuated for two reasons: (1) The beat frequency of the two compressors running together is of the same order as the primary mode of vibration of the building. (2) It is believed that the frequency of each of the compressors is of the same order as the secondary mode of vibration of the building. A suitable alteration of the frequency of the compressors could decrease the amplitude of the observed vibrations.

All readings were taken when there was little wind blowing. It is possible that a strong wind could cause vibrations with amplitudes considerably greater than those recorded.

5. REFERENCES

BLUME, J.A.	1956	Period determinations and other earthquake studies on a fifteen storey building. Proc. World Confer. earthq. Engrg., California, Paper No. 11.
KAWASUMI, H and KANAI, K.	1956	Vibrations of buildings in Japan. ibid. Paper No. 7
STEFFENS, R.J.	1952	The assessment of vibration intensity and its application to the study of building vibrations. Nat. build. Stud. spec. Rep. 19.
THOENEN, J.R. and WINDES, S.L.	1942	Seismic effects of quarry blasting. Bull. U.S. Bur. Min. 442.
ULRICH, F.P. and CARDER, D.S.	1952	On vibrations of structures, properties of structures and materials. Proc. symposium on the earthquake and blast effects on structures, Los Angeles. p 135.

TABLE 1

Record	Floor	Seismograph Position (see Plate 1)		Remarks
1	1	B		
2a	Roof	By compressor	(1)	Compressor No. 1 at $\frac{1}{2}$ load, No.2 off.
2b	"	"		Compressor No. 1 at full load, No.2 at $\frac{1}{2}$ load.
2c	"	"		Both off and settling down
3a	"	C		Normal running by compressors
3b	"	"		Full load on both compressors
3c	"	"		Compressors off, blower fan on
3d	"	"		Compressors off, blower fan off
3e	"	"		Normal running
4a	11	C	(2)	Both lifts running
4b	"	"		Both lifts stopped
5a	11	A		Without tram below
5b	"	"		With tram below
6a	11	B		Without tram below
6b	"	"		With tram below
7a	11	H		Lifts running
7b	"	"		Lifts running, 2 toilet flushes operated
8a	11	J		1 compressor running
8b	"	"		Both compressors running
9a	1	C		Both lifts going
9b	"	"		Both lifts stopped
10	1	H		Both flushes operated
11a	1	D		Local air conditioning on
11b	"	"		Local air conditioning off and 1 ft. jump
12	3	B		No tram
13a	3	K		With tram passing
13b	"	"		No tram

TABLE 1 (Contd.)

Record	Floor	Seismograph Position (see Plate 1)		Remarks
14	3	D		
15	3	C		Both lifts going
15b	"	"		Both lifts stopped
16a	5	"		Both lifts stopped
16b	"	"		Both lifts going
17	5	D		
18	5	B		
19	5	A		
20	7	B		
21	7	A		
22	7	D		
23a	7	C		Both lifts going
23b	"	C		1 lift going
23c	"	"		Both lifts stopped
24a	9	C		1 lift going
24b	"	"		Both lifts stopped
24c	"	"		1 lift going
25	9	D		
27	9	K	(3)	Nearest window fogged
28	9	A	(3)	Nearest window fogged
29a	10	C		Both lifts going
29b	"	"		Both lifts stopped
30	10	D		
31	10	A		
32	10	B	(3)	Nearest window fogged
33	Roof	By extractor fan housing		
34a	"	Beside compressor		Normally running compressors
34b	"	" "	(4)	Cylinder pairs cut out
34c	"	" "	(4)	" " " "
34d	"	" "		Compressor No. 1 on full load

TABLE 1 (contd.)

Record	Floor	Seismograph Position (see Plate 1)	Remarks
34e	Roof	Beside compressor	Nos. 1 and 2 on full load
35a	Ground	C	1 lift going
35b	"	"	Both lifts stopped
35c	"	"	1 lift going
35d	"	"	Both lifts going
36	"	D	
37a	"	A	Without tram
37b	"	"	With tram
38	"	In porch	With tram
39	Basement	A	
40	"	D	
41	"	(5)	Under typical floor air conditioner unit
42	Roof	By compressor	No. 1 on, No. 2 off
42b	"	"	No. 1 on, No. 2 on ½ load
42c	"	"	Both full on
42d	"	"	Normal running
43	"	On extractor fan housing	Sounding board effect?
44	11	B	Latest window to break
45	10	E	
46	10	F	
47	10	G	
48	9	D	
49	8	B	
50	6	E	
51	6	I	
52	6	D	
53	7	Next to teleprinter	Teleprinter operating

TABLE 1 (contd.)

NOTES:

(1) Roof locations shown on Plate 2.

(2) Unless otherwise stated the compressors were operating normally. This means that compressor No. 1 was running continuously, and compressor No. 2 occasionally.

(3) Windows are fogged when sealing of glass becomes porous. This often precedes breakage.

(4) On the 4-cylinder compressors, 2 cylinders were cut out.

(5) As well as the main compressor each floor has a small auxiliary unit.

TABLE 2

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible acceleration (in/sec^2)	a/g	Remarks
		L 0.00025	2 + 13			
2a	Roof	V 0.0001	12 + 150	1.8	0.005	High frequency has very small amplitude
		T 0.00015	2			
		L 0.0001	2			
2b	Roof	V 0.0001 (x)	1 + 150	0.1 (y)	0.0005±	High frequency has very small amplitude
		T 0.00015				
		L 0.00015	2			
2c	Roof	V 0.0001 (x)	150	0.4	0.001	High frequency has very small amplitude
		T 0.0001	2 + 10			
		L 0.00025	1.5			
3a	Roof	V 0.0001 (x)	12	0.6 (y)	0.002	
		T 0.0002	2.5			
3b	Roof	Negligible (z)				
3c	Roof	Negligible				
		L 0.0002	2			
3d	Roof	V 0.0001 (x)	12	0.7 (y)	0.002	
		T 0.0001	11			
		L 0.0002	2			
3e	Roof	V 0.0001 (x)	12	0.7 (y)	0.002	
		T 0.0001	10			
		L 0.0002	11			
34a	Roof	V 0.00015	12	1.6	0.004	
		T 0.0001	14			
		L 0.00015	11			
34b	Roof	V 0.00012	12	1.3	0.004	
		T 0.0001	14			

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible acceleration (in/sec^2)	a/g	Remarks
		L 0.0002	11			
34c	Roof	V 0.00015	12	1.6	0.004	
		T 0.0001	14			
		L 0.00015	11			
34d	Roof	V 0.00015	12	1.4	0.004	
		T 0.0001	14			
		L 0.0001	11			
34e	Roof	V 0.0001	12	1.1	0.003	
		T 0.0001	14			
		L 0.00025	13			
42a	Roof	V 0.0002	15	2.8	0.007	
		T 0.00015	15			
		L 0.0003	13$\pm$			
42b	Roof	V 0.00025	15$\pm$	3.8$\pm$	0.010$\pm$	No timing lines on record
		T 0.0002	16$\pm$			
		L 0.00025	12			
42c	Roof	V 0.0005	13	4.4	0.011	2½ second beat present
		T 0.0002	14			
		L 0.00025	12			
42d	Roof	V {0.0003 {0.00015	11 15	2.5	0.007	
		T 0.00025	1			
		L 0.0004	17			
43	Roof	V 0.0004	20	12.3	0.033	On top of extractor fan housing
		T 0.0003	28			

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible acceleration (in/sec^2)	a/g	Remarks
		L 0.00015	13			
5a	11	V -	-	2.0	0.005	
		T 0.00025	13			
		L 0.00018	11			
5b	11	V -	-	1.3	0.003	
		T 0.0002	11			
		L 0.0002	11			
6a	11	V 0.0004	12	2.6	0.007	
		T 0.0002	11			
		L 0.0001	11			
6b	11	V 0.00015	11	1.3	0.003	
		T 0.0002	11			
		L 0.0001	2			
4a	11	V -	-	0.1 (y)	0.0003±	
		T 0.0001	2.5			
		L 0.0002	2			
4b	11	V -	-	0.1 (y)	0.0003±	
		T 0.0001	2.5			
		L 0.00025	2±			
8a	11	V 0.0002	13±	1.3±	0.003	No timing lines on record
		T 0.00015	1±			
		L (0.0001	20			
		L (0.0002	1.75			
8b	11	V 0.00015	11	2.4	0.006	
		T 0.0002	13			

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible acceleration (in/sec^2)	a/g	Remarks
7	11	Negligible				
		L 0.00025	12			
44	11	V 0.00015	13	2.2	0.006	Beat frequency of 1.2 second period present
		T 0.00025	12			
		L (0.00012	14			
		L (0.00025	15			
45	10	V (0.0001	15	1.3	0.003	
		V (0.00015	1			
		T 0.00015	0.7			
		L 0.00025	2±			
46	10	V 0.0001	1.5±	1.8±	0.005±	No timing lines on record
		T 0.0002	15±			
		L 0.0002	1			
47	10	V 0.00012	12	0.9	0.002	
		T 0.0001	12			
		L (0.0001	22			
		L (0.00015	2			
30	10	V (0.0001	2	2.2	0.006	
		V (0.0001	1			
		T 0.00015	13			
		L 0.0001	10			
29	10	V -	-	0.6	0.002	
		T 0.0001	10			
		L -	-			
31	10	V 0.0004	20±	7±	0.018±	No timing lines on record.
		T 0.0002	20±			

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible acceleration (in/sec²)	a/g	Remarks
		L 0.0001	18±			
32	10	V 0.00015	18±	2.8±	0.007±	No timing lines on record.
		T 0.00012	18±			
		L 0.00015	10			
28	9	V -	-	1.2±	0.003±	No timing lines on record
		T 0.00025	10			
		L 0.0001(x)	15			
27	9	V 0.0001(x)	14	1.8 (y)	0.005	
		T 0.0002	13			
		L 0.0001	17			
24	9	V -	-	1.6	0.004	
		T 0.0001	17			
		L 0.0002	12			
25	9	V 0.00015	13	2.3	0.006	
		T 0.0002	14			
		L (0.0001(x)	40			
		L (0.0001	2			
48	9	V 0.00012	15	6.5 (y)	0.017	High frequency on L has very small amplitude.
		T 0.0001	15			
		L (0.00015	12			
		L (0.0002	2			
49	8	V 0.00012	12	1.3	0.003	
		T 0.00012	13			
21	7	Negligible				
20	7	Negligible				
		L 0.0001	17			
23	7	V -	-	1.2	0.003	
		T -	-			

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible acceleration (in/sec^2)	a/g	Remarks
		L (0.0001	13			
		L (0.00015	3			
22	7	V 0.00015	15	1.5	0.004	
		T 0.0002	2			
		L 0.0001	2			
53	7	V -		.1 (y)	0.0003±	
		T 0.00015	2			
		L 0.0001	2			
50	6	V 0.0001 (x)	12	0.6 (y)	0.002	
		T 0.0001	1			
		L 0.00025	2			
51	6	V 0.0001	12	0.6	0.002	
		T 0.00015	5			
		L 0.0007	2			
52	6	V 0.0001 (x)	10	0.4 (y)	0.001	
		T 0.0001	5			
		L -	-			
19	5	V -	-	1.1	0.003	
		T 0.00012	15			
18		Negligible				
		L 0.0001	12±			No timing lines on record
17	5	V 0.0001	12±	1.0±	0.003±	
		T 0.0001	12±			
16	5	Negligible				

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible Acceleration (in/sec^2)	a/g	Remarks
12	3	L 0.0001(x) V 0.0001(x) T 0.0001	13 13 13	1.2 (y)	0.003	
13a	3	L - V 0.00015 T 0.00015	 26 26	5.7	0.015	Vibration intermittent
13b	3	L - V 0.0001 T 0.0001	 26 26	3.8	0.01	Vibration intermittent
16	3	Negligible				
1	1	Negligible				
9	1	Negligible				
11	1	Negligible				
37	Ground	Negligible				
38	Ground	Negligible				
35	Ground	Negligible				
36	Ground	Negligible				
10	1	Negligible	No significant vibration from flush in toilet			
39	Basement	Negligible				
40	Basement	Negligible				
41	Basement	Negligible				

Record	Floor	Maximum Amplitude (in)	Main Frequency (c/s)	Maximum (w) possible acceleration (in/sec^2)	a/g	Remarks
		L 0.00025	70±			154-lb man
11	1	V 0.0003	100±	220±	0.57±	jumping 1 foot.
(with jump)		T 0.0002	150±			

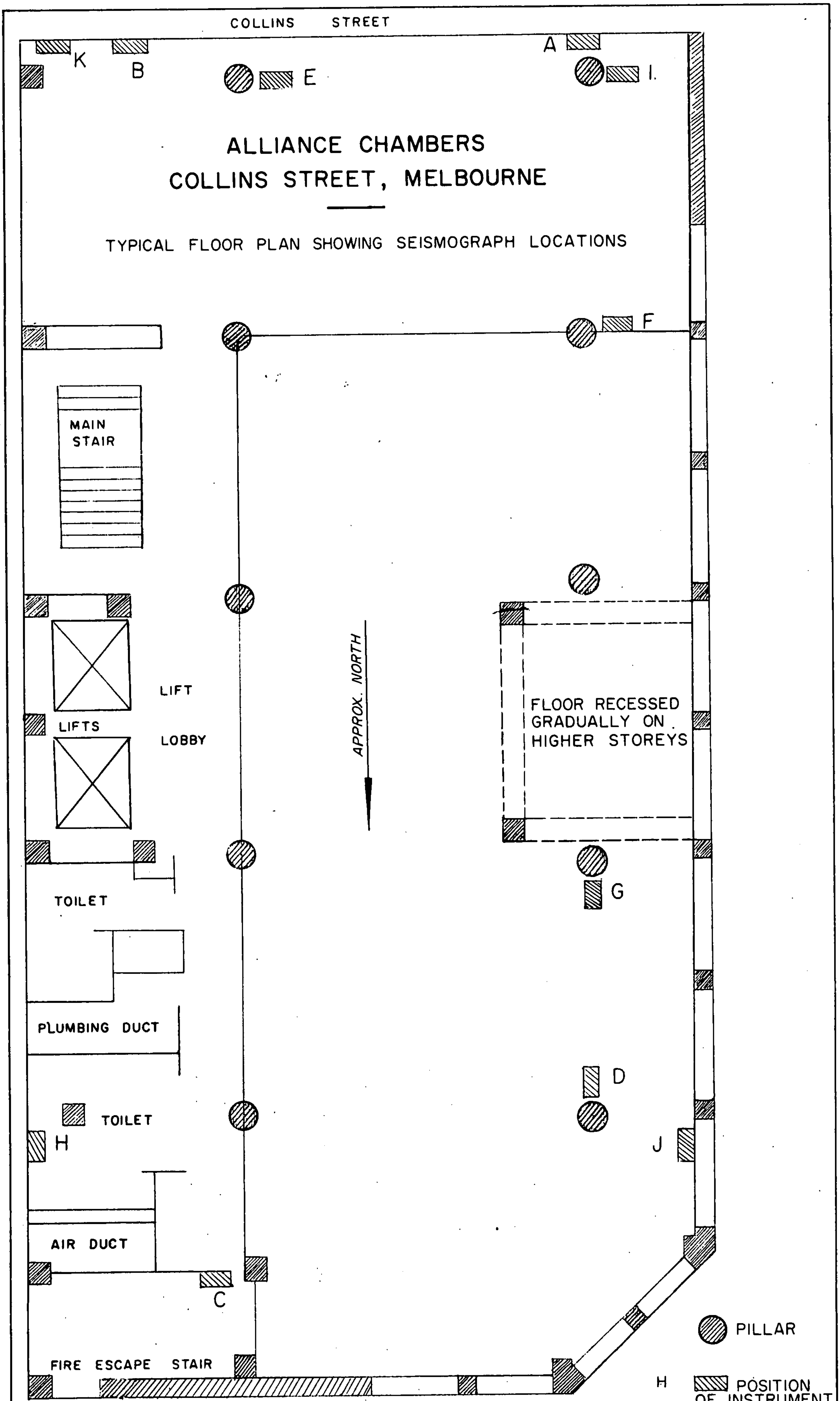
Notes on Table 2

(w) If it is assumed that, under the most unfavourable circumstances, the frequencies on all three traces are not the same, there must come a time when all three components will reach their maximum simultaneously. The acceleration given is the maximum that can be expected under the conditions at the time of observation, assuming that the three frequencies differ.

(x) Owing to the limitations of the experimental method it is not possible to measure accurately displacements of less than 0.0001 of an inch. Readings 0.0001" (x) lie between 0.00002" and 0.0001".

(y) Accelerations marked (y) are calculated on the assumption that 0.0001" (x) has its maximum possible value of 0.0001". They will all be greater than the true value, but of the same order of magnitude.

(z) Those readings marked as negligible all have accelerations of less than 0.1 in/sec^2.



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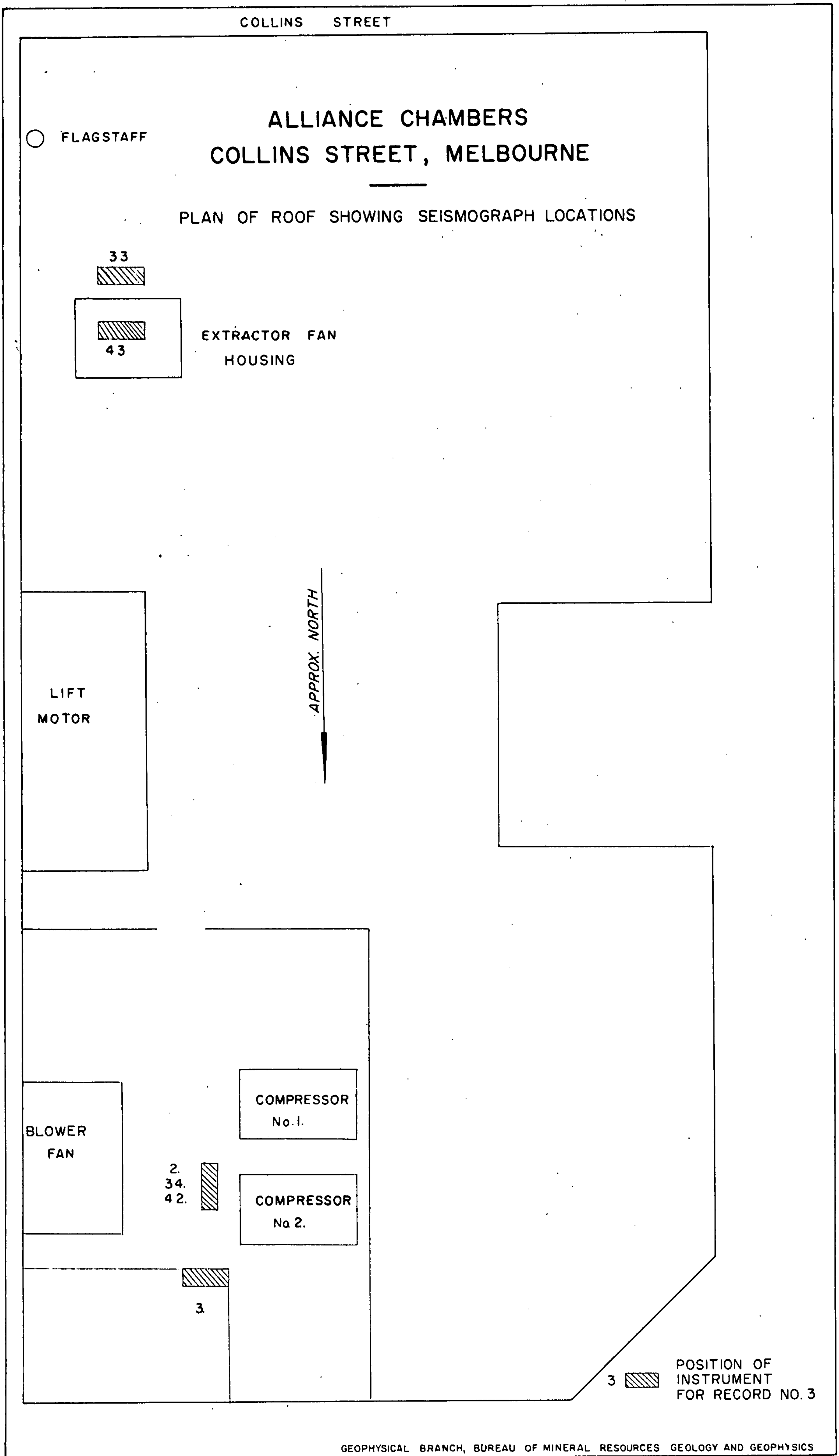
G 344-95

To Accompany Record No. 1962/23

PLATE 2



To Accompany Record No. 1962/23

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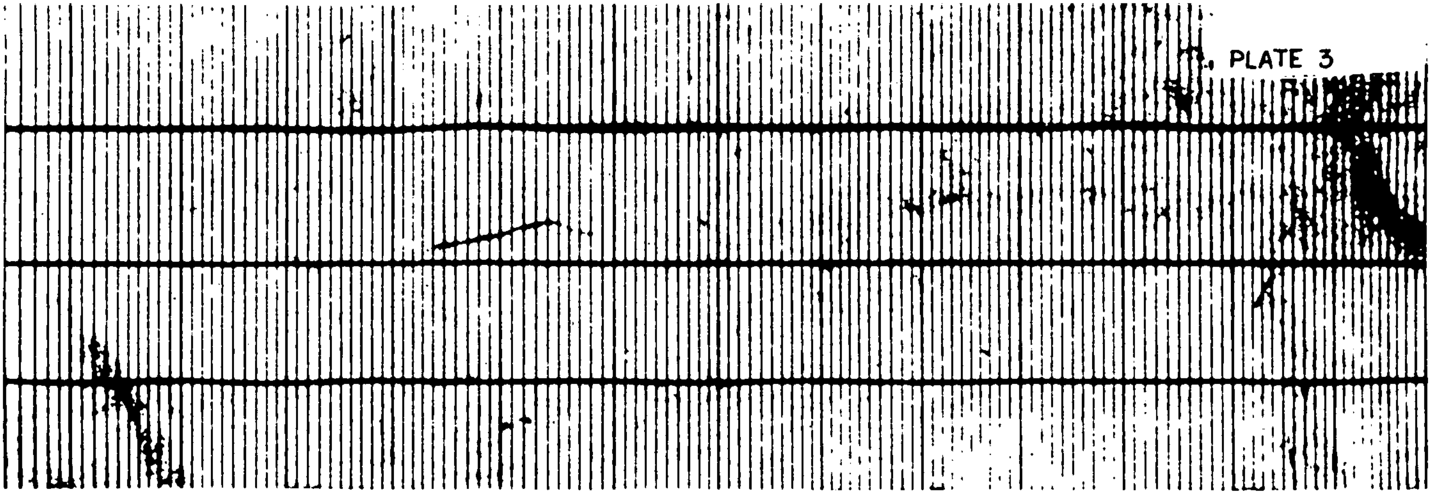
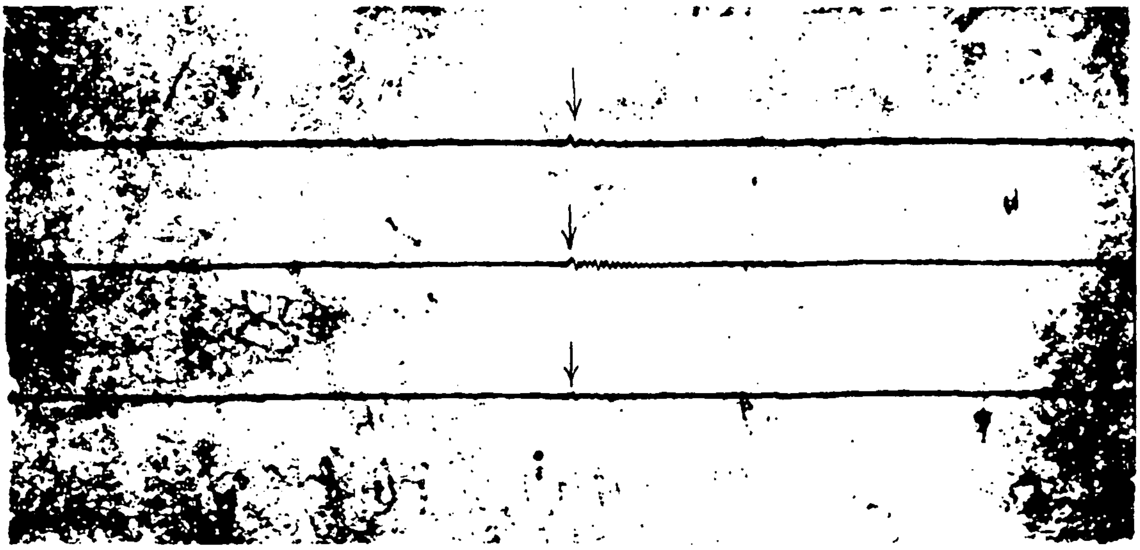
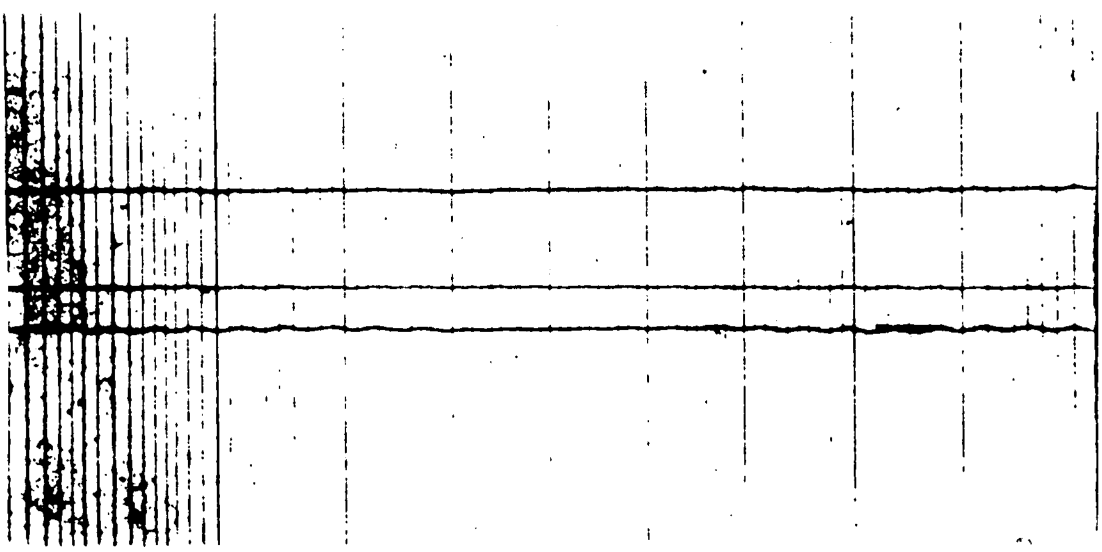
PLATE 3



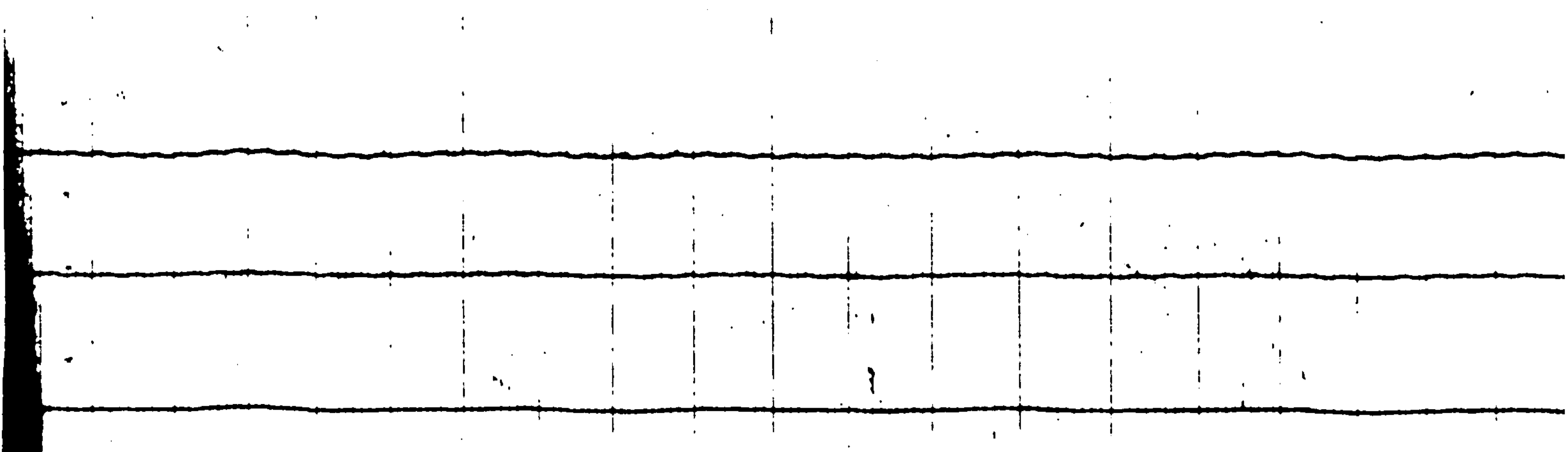
RECORD N°4 a 11th FLOOR POSITION C BOTH LIFTS RUNNING C



RECORD 11b 1st FLOOR POSITION D. 154-lb MAN JUMPING 1 ft



RECORD No 27 POSITION K 9th FLOOR NEAREST WINDOW FOGGED

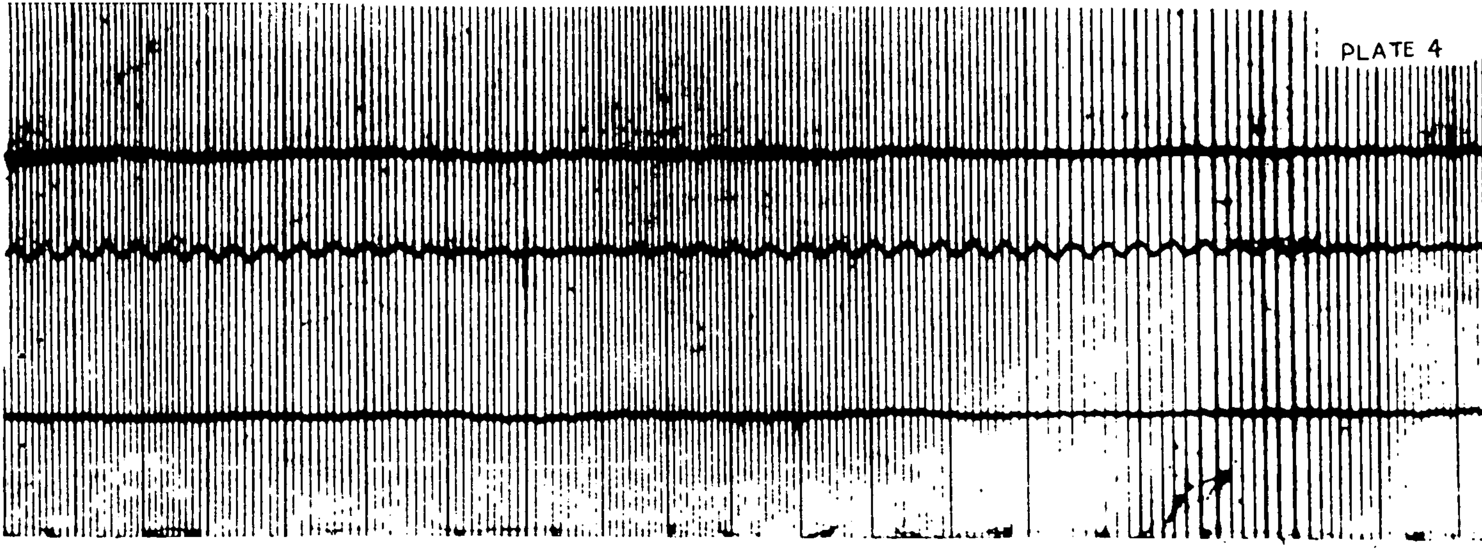


VIBRATION RECORDS
ALLIANCE CHAMBERS

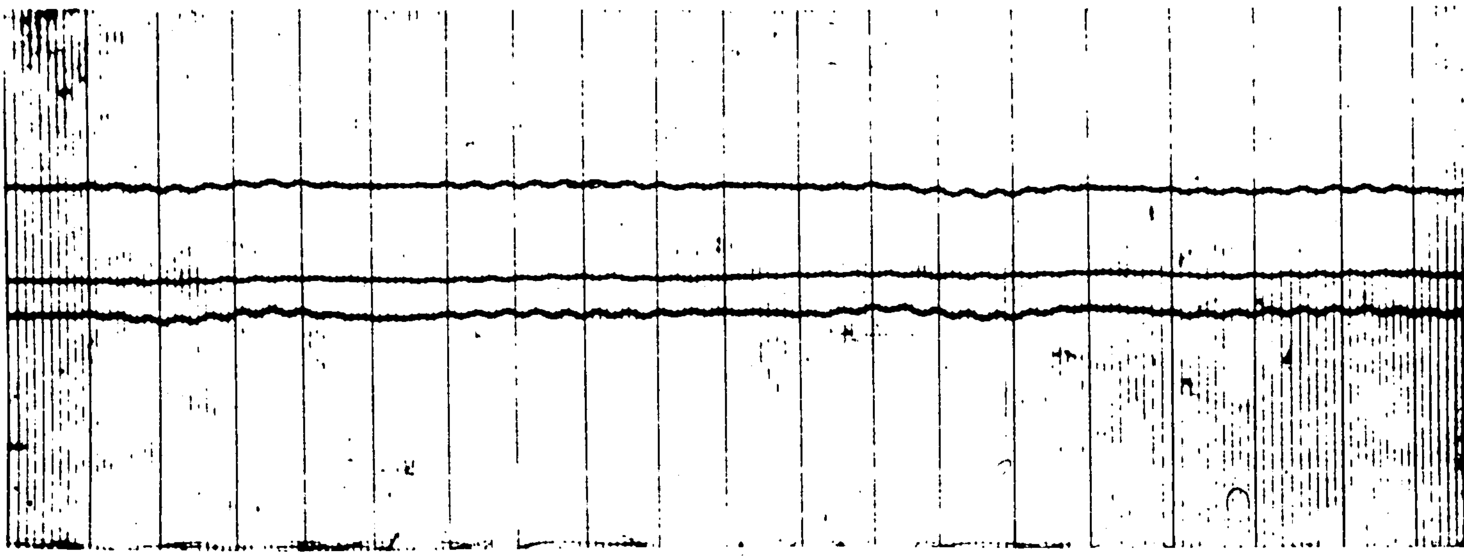
RECORD No 45 10th FLOOR POSITION E

TO ACCOMPANY RECORDS No. 1962/23

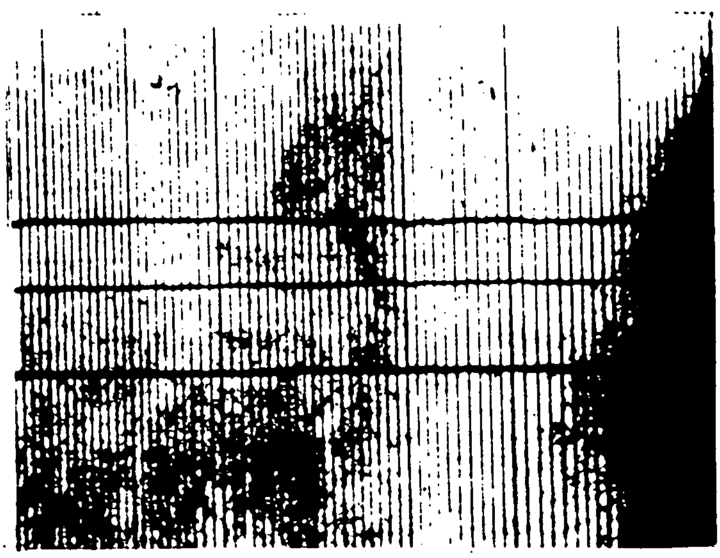
G 344-97



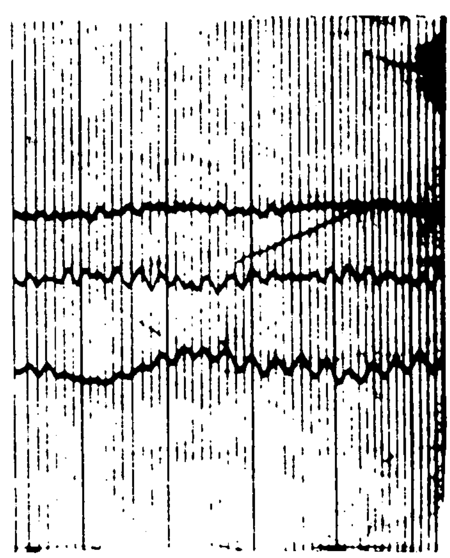
RECORD No 42 c BY COMPRESSORS ON ROOF BOTH FULL ON BEAT PRESENT.



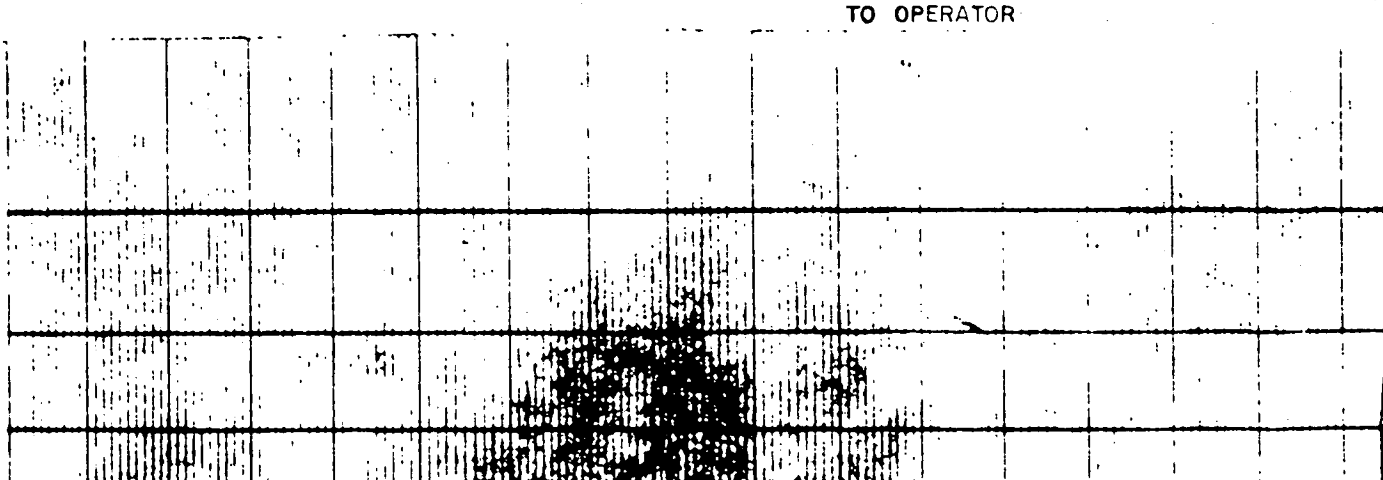
RECORD No. 44 ON WINDOWSILL (POSITION B) 11th FLOOR.



RECORD Nº18 5th FLOOR. POSITION B



RECORD No 43 ON EXTRACTOR FAN HOUSING ROOF IRREGULARITY DUE TO OPERATOR



VIBRATION RECORDS
ALLIANCE CHAMBERS

BASEMENT RECORD Nº 3[illegible] BASEMENT POSITION A [illegible]

G 344-98

APPENDIX

The following are references to and extracts from regulations and authoritative publications in the United States and Great Britain covering or recommending safe amplitudes of vibrations that may be applicable to buildings:

(Note: f = frequency in cycles per second.
A = $\frac{1}{2}$ peak to trough amplitude, inches).

Reference 1

State of New Jersey, U.S.A. Extract from rules and regulations governing Quarry Blasting and Related Operations. 26th March 1954.

'6.1 Allowable Limits. Allowable Limits of ground motion and sound pressure contained in this section shall be considered neither to produce structural damage in any structure that has been reasonably well constructed according to accepted engineering practice nor to constitute a nuisance to persons.'

'6.3 Frequency - amplitude relations. When ground frequency and displacement characteristics in relation to known quantities of detonated explosives in primary blasts have been determined by approved means of instrumentation to the satisfaction of the Commissioner, the allowable limits of the maximum amplitude of ground vibrations related to frequencies of vibration shall be as indicated in the following table:

Frequency of ground motion in cycles per second.	Maximum amplitude of ground movement, in inches.
up to 10	not more than 0.0305
20	0.0153
30	0.0102
40	0.0076
50	0.0061
60	0.0051'

Reference 2

Rules Concerning Blasting in Strip Mine Operations in the Anthracite Region, Pennsylvania, Act No. 472, 27th June 1947.

'Section 20

... in no case shall the ground displacement be in excess of 0.03 inches at any dwelling house, public building, school, church, commercial or institutional building.'

Reference 3

Teichman, G.A. & Westwater, R. 1955 Blasting and associated vibration. Engineering 460-465, 12th April.

'Because of the variation in the types of structure it has been recommended that they should be broadly classified into four groups:

(a) structures of great value and frailty. This will include certain ancient monuments, such as churches and certain badly designed properties.

(b) Property, houses etc. closely congested.

(c) Isolated property.

(d) Civil engineering structures.

Taking suitable safety factors and after the site has been investigated by a vibrograph caution limits are applied. These limits usually are 0.004, 0.008, 0.016, 0.030 inches, respectively.'

Reference 4

Crandell, working on behalf of a United States Insurance Co., suggests fA as a suitable relationship and quotes:

'fA = 0.745 as the damaging level

fA 0.527 as safe level.'

Reference 5

Morris, C. 1950 Vibrations due to blasting and their effect on building structures. The Engineer 394-395 & 414-418, 3rd November.

'the limiting amplitude of 8.2×10^{-3} (0.0082) inches gives a conservative estimate of the limiting amplitude for conventional structures. The state of repair of the building does not seriously affect this estimate, as an old building technically less strong than a new one will have benefitted by a process of "bedding in" due to long-continued small movement.'

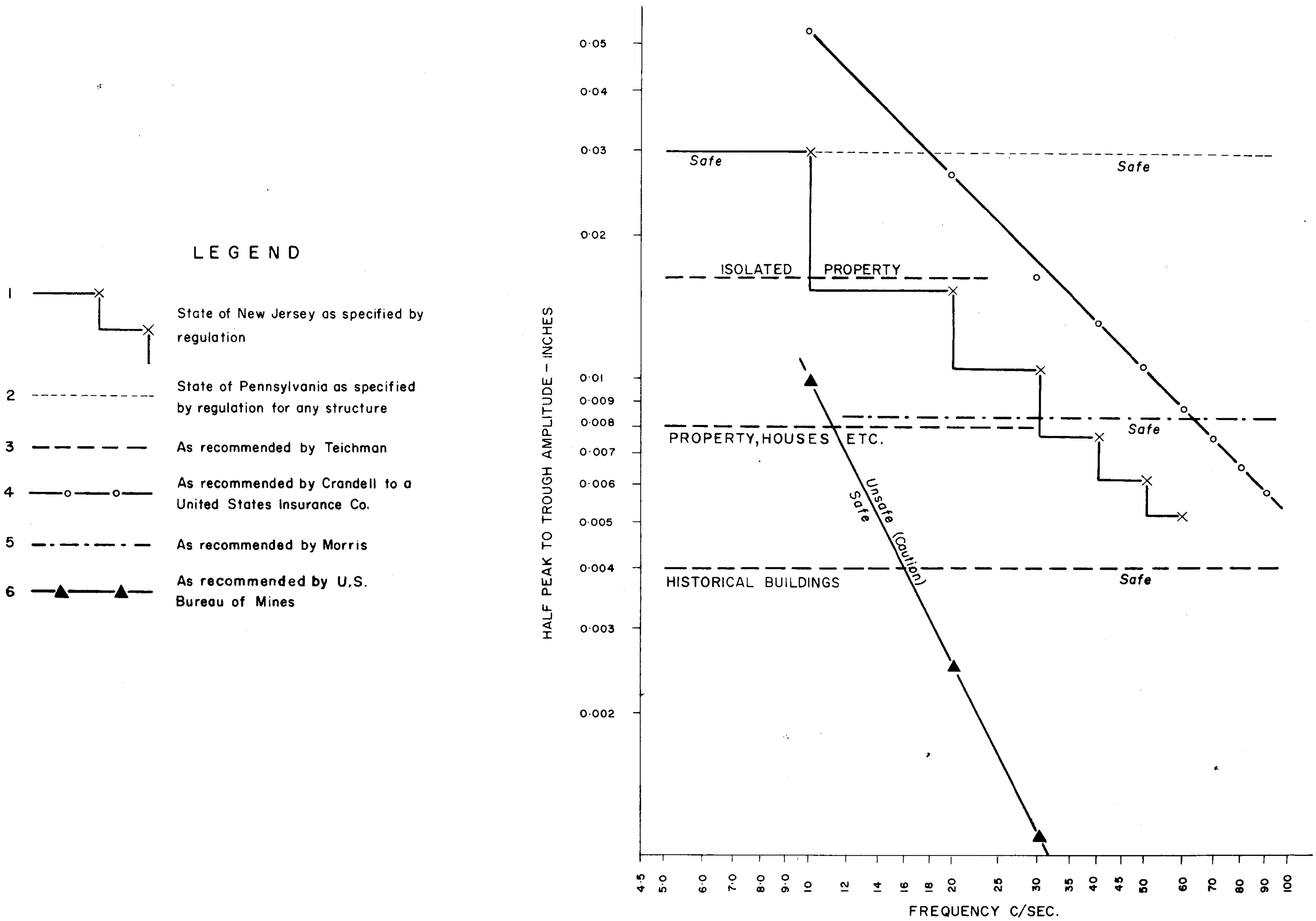
Reference 6

Thoenen, F.R. and Windes, S.L. 1942 Seismic effects of quarry blasting. Bull. U.S. Bur. Min. 442.

' $f^2A > 10$ Damage

$f^2A < 1$ Safe

'Vibrations of very low amplitude and short duration were neglected, even though the accelerations may have been high, because these conditions were noticeable in the records of many tests that did not cause damage'.



MAXIMUM SAFE HALF PEAK TO TROUGH AMPLITUDE OF VIBRATION PLOTTED AGAINST FREQUENCY AS SPECIFIED AND RECOMMENDED BY VARIOUS U.S. GOVERMENT AUTHORITIES AND BY INDIVIDUALS