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RECORD No. 1964/71

LAKE BELLFIELD DAM SITE VIBRATION TESTS, NEAR HALLS GAP, VICTORIA 1963

by

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SUMMARY

Vibration tests were made at Lake Bellfield dam site to determine the size of explosive charge that could be used for spillway blasting without risk of damage to concrete tunnel lining.

The tests show that the detonation of about 1350 lb of explosive in three charges of 450 lb with delays of 0, 98, and 185 msec produced at distances of 400 and 600 ft a ground acceleration approximately equal to that produced by a single charge of 450 lb.

Measurements of the ground accelerations produced by an explosive charge of about 3700 lb fired with fourteen 10-msec delays and a maximum charge of 503 lb per delay showed that the acceleration was greater in a test section of concrete tunnel lining than in sandstone rock. The greater acceleration may be due to a high-frequency mode of vibration of the concrete lining. The tests suggest that ripple firing with 100-msec delays instead of with the 10-msec delays proposed by the Commission for the spillway blasting may produce lower-frequency vibrations and probably lower accelerations.

Parameters such as ground acceleration, charge weight, and distance have been used by different authorities to determine the likelihood of damage to buildings. The same parameters are used to determine the likelihood of damage to the concrete lining of a tunnel. A test section of concrete lining was undamaged in the experiments described in this Record.

An empirical equation can be used to estimate the maximum 'safe' charge at a given distance if an acceptable acceleration is adopted.

1. INTRODUCTION

The construction of the Lake Bellfield dam near Halls Gap, Victoria by the State Rivers and Water Supply Commission of Victoria includes lining a diversion tunnel with concrete and excavating a deep spillway by blasting. The Commission believed that the detonation of heavy charges during the course of excavating the spillway may damage the concrete lining of the tunnel. The bedrock consists of medium to coarse-grained quartzose sandstone or quartzite.

The Commission requested the Bureau of Mineral Resources, Geology and Geophysics to make vibration tests to determine the size of charge that could be used for spillway blasting without risk of damage to the concrete tunnel lining. The vibration tests made on the 23rd and 24th September 1963 by geophysicist P.E. Mann and geophysical assistant A. Radeski of the Bureau were marred by technical faults and consequently the data were incomplete. Further vibration tests were made by P.E. Mann on the 16th and 17th December 1963.

2. METHOD AND EQUIPMENT

Various limiting standards for damaging and non-damaging effects of vibrations have been proposed by different authorities. The US Bureau of Mines (Thoenen and Windes, 1942), using acceleration in units of g (gravity acceleration) as an index of likelihood of damage, proposed the following classification applicable to buildings:

Acceleration	Effect
Greater than 1.0g	damaging
Between 0.1g and 1.0g	may be slightly damaging, caution zone
Less than 0.1g	no damage, safe zone

Assuming that the motion of the ground is simple harmonic, the relation between the maximum acceleration (a), frequency (f), and displacement amplitude (A) is

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

Northwood, Crawford, and Edwards (1963), who have combined their studies with those of Thoenen and Windes (1942) and of Morris and Westwater (1953) on the relation between charge, distance, and the damage to buildings, suggest that a safe limit for blasting is given by the empirical relation:

$$E^{0.98}/d^{1.71} = 0.02 \qquad (1)$$

where E is the allowable explosive charge (lb) and d the distance (ft). Edwards and Northwood (1960) in a similar study at the St Lawrence Power Project, Canada, derived a more-conservative empirical relation:

$$E^{0.67}/d = 0.1 \qquad (2)$$

Equations (1) and (2) refer to the detonation of single charges.

Multi-delay or ripple firing can improve the efficiency and precision of the blast and will alter the vibration amplitude and frequency compared with amplitude and frequency produced by detonating a single charge.

Northwood et al. (1963) state that it is generally safe to assume that the resulting vibration amplitude with delay firing is slightly greater than the value to be expected from the largest individual charge and suggest that a factor of 1.5 would be a safe rule.

In a series of controlled quarry shots, detonated with 17-msec delays to ascertain the effect of ripple firing on the amplitude and frequency of seismic waves, Willis (1963) reports a measurable reduction in the amplitude of compressional and shear waves for frequencies up to about 40 c/s. Generally multiple-hole shots showed larger amplitudes than the single-hole shot with the same total charge for frequencies greater than 40 c/s.

To calculate acceleration, vibrations in three mutually-perpendicular directions are recorded on a seismogram. Amplitude and frequency for each component are scaled from the seismogram. The resultant ground acceleration is computed by taking the square root of the maximum acceleration of each component irrespective of time. Thus the true ground accelerations are equal to, or less than, the computed resultant accelerations, depending on the phase relations.

The following equipment was used in the first vibration-test series in September to record the vibration generated in the tunnel by detonating test charges:

(a) Sprengnether portable blast and vibration seismograph (Serial No.1577) with a magnification factor of 100,

(b) Midwestern shallow reflection-refraction seismograph, with ordinary geophones recording vertical movements and three-component geophones recording movement in three mutually-perpendicular directions,

(c) Leet three-component portable seismograph with a magnification factor of 50. This instrument was damaged during the first test and gave no usable records,

(d) Cambridge universal vibrograph which records the ground motion in either vertical or horizontal direction by means of a stylus on a moving celluloid strip. The magnification can be either 10 or 50.

The Cambridge vibrograph gave no readable records because of (a) its low magnification in the case of smaller charges, and (b) insufficient friction between stylus and celluloid strip in the other cases.

During December 1963 a second vibration-test series was made with two Sprengnether seismographs (Serial No.1577 and 1863). The relative magnification of the two instruments was compared in the laboratory. Adopting the magnification given by the manufacturer as 100 for Sprengnether No.1577, the magnification of Sprengnether No. 1863 was found to be about 160.

In September 1963 about 160 ft of rock had been excavated at the upstream end of the diversion tunnel. The Midwestern seismograph was set up inside the tunnel. The Sprengnether seismograph was placed on the sandstone rock floor, 3 ft from survey peg RD40. The following arrangement of geophones was used for the Midwestern seismograph:

one 3-component geophone at the tunnel entrance about 25 ft from RD40,

six vertical geophones and another 3-component geophone at 20-ft intervals so that the 3-component geophone was about 20 ft from the tunnel face.

Test charges of 10, 20, 40, and 100 lb (Tests 1 to 4 respectively) were detonated in the spillway area at inclined distances ranging from about 335 ft to 465 ft from the recording equipment. For practical reasons a 203-lb test charge (Test 5) was detonated with a 1414-lb charge (Test 6) fired in three phases, viz. 594 lb instantaneous, 575 lb with 98-msec delay, and 245 lb with 185-msec delay. The instant at which the 203-lb charge detonated is not known accurately in relation to the other charges. The delay times should be long enough for the vibrations from each detonation to decay to a small fraction of their maximum amplitude before the arrival of the next wave train. Thus the resulting vibrations should be the equivalent of those produced by a single shot of between roughly 450 and 800 lb.

In the second vibration test series in December 1963 two Sprengnether seismographs (Serial No.1577 and 1863) were used to record vibrations generated in the tunnel by the detonation of test charges. The excavation of the tunnel was complete and an 8-ft test section of unreinforced tunnel lining had been poured. One instrument (No.1577) was set up at RD40 and the other was set up on the concrete lining. Test charges of 444, 1338, and 3664 lb (Tests 7, 8, and 9) at distances ranging from about 420 ft to 715 ft from the recording equipment, were detonated in the spillway area.

3. RESULTS

Plate 1 shows the locality of the survey and the positions of the seismographs, geophones, and shot-points used. Plate 2 shows reproduction of some of the seismograms recorded in December 1963. Table 1 shows the results obtained in the tests completed in September 1963. Columns 1 and 3 of Table 1 show the tests and instruments that gave useful records. Columns 5 and 7 list the maximum displacement and frequency of each component of the ground-motion scaled from the seismograms. The letters L, V, and T refer respectively to horizontal movement in the direction of the explosion, vertical movement, and horizontal movement transverse to the direction of the explosion.

The letters V, H, and H refer to vertical and unoriented horizontal movements.* The resultant amplitude computed by taking the square root of the sum of the squares of the component amplitudes is shown in Column 6. The resultant acceleration of the ground, computed by taking the square root of the sum of the squares of the acceleration of each component of the ground-motion, is shown in Column 9. Column 10 gives the resultant acceleration expressed as a fraction of the acceleration due to gravity.

An approximate calibration for the Midwestern seismograph against the Sprengnether seismograph was obtained from Test 4. This calibration was used to compute the displacements recorded by the Midwestern seismograph in Tests 5 and 6. This calibration could be used because the range of frequencies recorded in Tests 5 and 6 is of the same order of magnitude as in Test 4. The photographic paper jammed in the camera for about 30 to 70 msec while recording ground vibrations from the blast. However, some vibrations were recorded before the paper jammed and after it freed itself. Resultant accelerations computed before and after the jammed strip on the seismogram are given in Column 9.

The seismic velocity of longitudinal waves in the bedrock was found to be about 13,000 ft/sec.

Table 2 shows the results obtained in the tests completed in December 1963. The results of Test 9 show that with the detonation of 3664 lb of explosive fired with fourteen 10-msec delays and a maximum weight of 503 lb per delay the accelerations recorded on sandstone rock and unreinforced concrete equidistant from the shot-point are in the 'safety' and 'caution' zones respectively. In this test the frequency of the ground motion of each component scaled from the seismograms show a distinct division into high (60 to 80 c/s) and low (4 to 8 c/s) frequency ranges at each recording station. No cracks visible to the naked eye were found in the walls of the concrete lining after Tests 7, 8, and 9.

The most reliable results were given by Tests 1, 2, 3, 4, 7, 8, and 9 recorded by Sprengnether seismographs. For each test the resultant acceleration of the ground-motion has been computed for the most unfavourable conditions, viz. the maximum displacement of each component of the ground-motion is assumed to occur simultaneously. However, owing to the phase differences between components, the ground acceleration at any instant is less than the resultant accelerations shown in Tables 1 and 2. The resultant accelerations of the ground calculated for Tests 1, 3, 4, 7, 8, and 9 are close to the figure of 0.1g adopted by Thoenen and Windes (1942) to define 'safe' and 'caution' zones.

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* The Hall-Sears miniature three-component geophones were newly delivered and had not been used prior to these tests. There was no indication on the instrument case as to the orientation of the coil system inside. The geophones were aligned with reference to a common mark on the case and later they were dismantled to discover the relation between this mark and the coil system. Unfortunately it was impossible to remove the system without rotating it and the relative positions could not be established.

Figure 1 shows the curves derived from equations (1) and (2) and the charges and distances used in Tests 1, 3, 4, 5, 6, 7, 8 and 9. All the charges and distances used would be safe according to Northwood et al. (1963) and only Tests 5, 6, 7, and 8 have charge and distance outside the safe limit proposed by Edwards and Northwood (1960).

In Figure 2 the charge E (lb) is plotted on a log-log scale against the product of the resultant acceleration R (g) and the shot distance d (ft), for Tests 1, 3, 4, 7, and 8. The equation of the straight line relating the variables is:

$$E^{0.22}/(R \times d) = 0.07 \qquad (3)$$

Equation (3) has been derived from tests on a single charge or multiple charges detonated with about 100-msec delay at distances ranging from 335 to 715 ft in a sandstone in which the seismic velocity is 13,000 ft/sec.

4. CONCLUSIONS

Large charges are required to blast rock efficiently in the spillway cut. Thus Tests 7, 8, and 9 are representative of the charges that will probably be used to blast rock. Table 2 shows that the ground accelerations produced by the detonation either of 444 lb or of 1338 lb fired in three phases (viz. 447 lb instantaneous, 447 lb with a delay of 98 msec, and 444 lb with a delay of 185 msec) at a distance of about 600 ft are in the 'safe' zone. At a distance of about 400 ft, the same charges give ground accelerations classified in the 'caution' zone. This suggests that the use of delay times of 0, 98, and 185 msec with 450 lb of explosive per delay produces a ground acceleration nearly equal to that produced by the detonation of a single charge of 450 lb. The ground acceleration would probably be in the 'safe' zone at a distance of 500 ft from a 450-lb charge and also from a 1350-lb charge fired with three 100-msec delays.

A comparison between Tests 7, 8, and 9 suggests that the use of 100-msec delays instead of 10 msec delays for large charges may result in vibrations of lower frequency.

In Test 9 the ground accelerations recorded by two Sprengnether instruments, one mounted on sandstone rock and one on concrete about 715 ft from the shot, can be classified in the 'safe' and 'caution' zones respectively. The larger values of acceleration calculated for the concrete base is due to the higher frequencies recorded. This may be due to the concrete lining vibrating in a high-frequency mode.

Tests 7, 8, and 9 show that the charges that gave maximum ground accelerations of about 0.1g did not damage the concrete lining of the tunnel.

The empirical relation (3) can be used to calculate the maximum safe charge for blasting if the shot distance and the fraction of g considered as non-damaging to the concrete lining are known. For practical use, if a value of R equal to 0.1 (Thoenen and Windes, 1942) is adopted the formula becomes:

$$E^{0.22} = 0.007\ d \qquad (4)$$

5. REFERENCES

EDWARDS, A.T. and NORTHWOOD, T.D.	1960	Experimental studies of the effects of blasting on structures. The Engineer 210, 538-546.
MORRIS, G. and WESTWATER, R.,	1953	Damage to structures by ground vibrations due to blasting. Mine Quarry Engng 18, 116-118.
NORTHWOOD, T.D., CRAWFORD, R., and EDWARDS, A.T.,	1963	Blasting vibrations and building damage. The Engineer 215, 973-978.
THOENEN, J.R. and WINDES, S.L.	1942	Seismic effects of quarry blasting. Bull. U.S. Bur. Min. 442
WILLIS, D.E.	1963	A note on the effect of ripple firing on the spectra of quarry shots. Bull. seis. Soc. Amer. 53, 79-86.

TABLE 1

1 TEST	2 TOTAL CHARGE (lb)	3 INSTRUMENT M.W.	SPRENG.	4 INCLINED DISTANCE (ft)	5 MAXIMUM DISPLACEMENT (in)	6 RESULTANT AMPLITUDE (in)	7 FREQUENCY (c/s)	8 ACCELERATION (in/sec^2)	9 RESULTANT ACCELERATION (in/sec^2)	10 RESULTANT ACCELERATION (g)	11 REMARKS
1	10	x	x	335	L 0.00015		40	19.5			Gain setting of
					V 0.00015	0.00023	66	25.9	28.7	0.07	Midwestern amplifier
					T 0.00008		50	7.9			very low.
3(a)	40		x	345	L 0.0003		40	18.9			
					V 0.0002	0.0004	50	19.8	33.8	0.09	
					T 0.0002		50	19.8			
4	100	x	x	430	L 0.0011		20	17.4			
					V 0.0007	0.0014	30	25.0	35.0	0.09	
					T 0.0004		33	17.2			
5&6	203 +	x		470	V 0			0			
(b)	1414				H 0.0013	0.0013	25	32	32	0.08	
					H 0			0			)Before paper jammed
											)in Midwestern
		x			V 0.0007		35	34			)camera.
					H 0.0009	0.0011	25	22	41	0.11	
					H 0		0	0			
		x			V 0		0	0			
					H 0.0020	0.0024	20	32	45	0.12	
					H 0.0013		25	32			)After paper jammed
											)in Midwestern
		x			V 0.0009		40	57			)camera.
					H 0.0013	0.0020	25	32	73	0.28	
					H 0.0013		25	32			

(a) Although a 50-lb charge was loaded, the backbreak from the 20-lb shot left one hole in broken ground. A 10-lb charge was removed and 40 lb detonated.

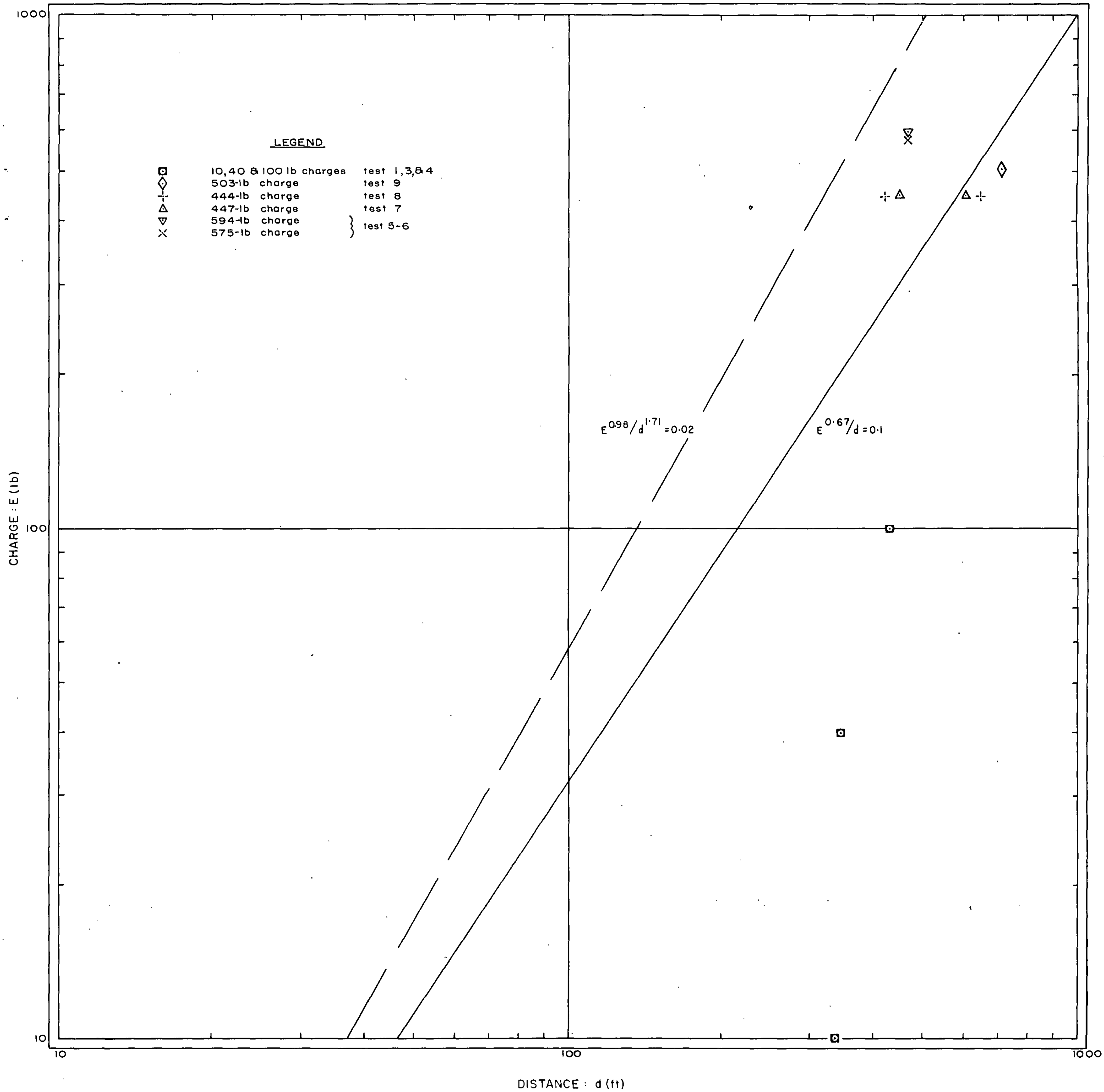
(b) Based on the experience gained from (a) it was thought that the 203-lb shot could cause backbreak into the 1414-lb charge. It was decided to detonate the 203 and 1414-lb charges together, viz. 203 and 594 lb instantaneously, 575 lb with 98-msec delay and 245 lb with 185-msec delay.

TABLE 2

1 TEST	2 TOTAL CHARGE (lb)	3 CHARGE AND DELAY (lb)	(msec)	4 INCLINED DISTANCE (ft) 1577	1863	5 MAXIMUM DISPLACEMENT (in) 1577	1863	6 RESULTANT AMPLITUDE (in) 1577	1863	7 FREQUENCY (c/s) 1577	1863	8 ACCELERATION (in/sec²) 1577	1863	9 RESULTANT ACCELERATION (in/sec²) 1577	1863	10 RESULTANT ACCELERATION (g) 1577	1863
7	1338	447	0	450	610	L 0.0015	0.0009			20	25	23.7	22.2) 24.7				
													10.8)				
		447	98			V 0.0008	0.0006	0.0024	0.0013	22	8	1.5) 14.3	15.2) 16.3				
												14.2)	5.9)				
		444	185			0.0001	0.00006			60	50			37.4	32.9	0.10	0.08
						T 0.0022	0.00002			17	10	25.2	4.1) 14.5				
							0.00003				50		13.9)				
8	444	444	0	420	650	L 0.0018	0.0006			25	25	44.4	14.8				
						V 0.0005	0.0002			25	14	12.4	1.9) 25.8	47.1	30.5	0.12	0.08
							0.0002	0.0020	0.0007		60		25.7)				
						T 0.0006	0.0003			20	25	9.5	6.9				
9	3664	32	0	715	715	L 0.0001	0.00005			50	66	9.9) 9.9	8.6) 8.6				
		32	10			0.0003	0.0005			6	6	0.4)	0.7)				
						V 0.0002	0.0002			66	77	34.6) 34.6	47.0) 47.0	36.2	55.6	0.09	0.14
		88	20			0.0006	0.0005	0.0009	0.0009	4	4	0.3)	0.4)				
		137	30			T 0.0001	0.0002			30	60	3.5) 3.7	28.5) 28.5				
		183	40			0.0005	0.0002			8	8	1.3)	0.5)				
		273	50														
		380	60														
		394	70														
		503	80														
		485	90														
		396	100														
		317	110														
		243	120														
		155	130														
		46	140														

NOTE: Sprengnether 1577 in tunnel entrance near RD40
Sprengnether 1863 on concrete lining in tunnel

FIGURE I

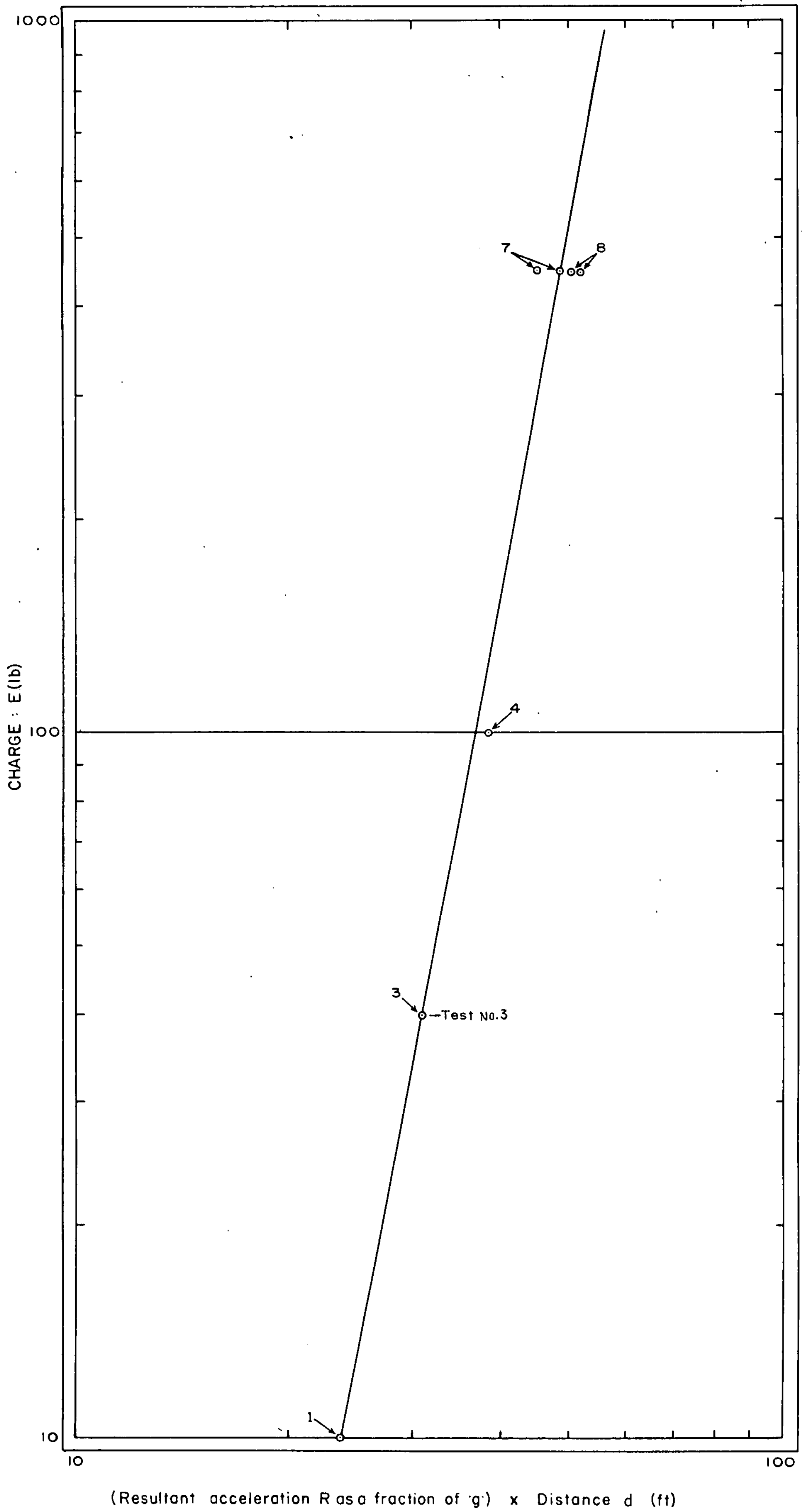


CHARGE, DISTANCE, AND SAFE LIMIT FOR BLASTING

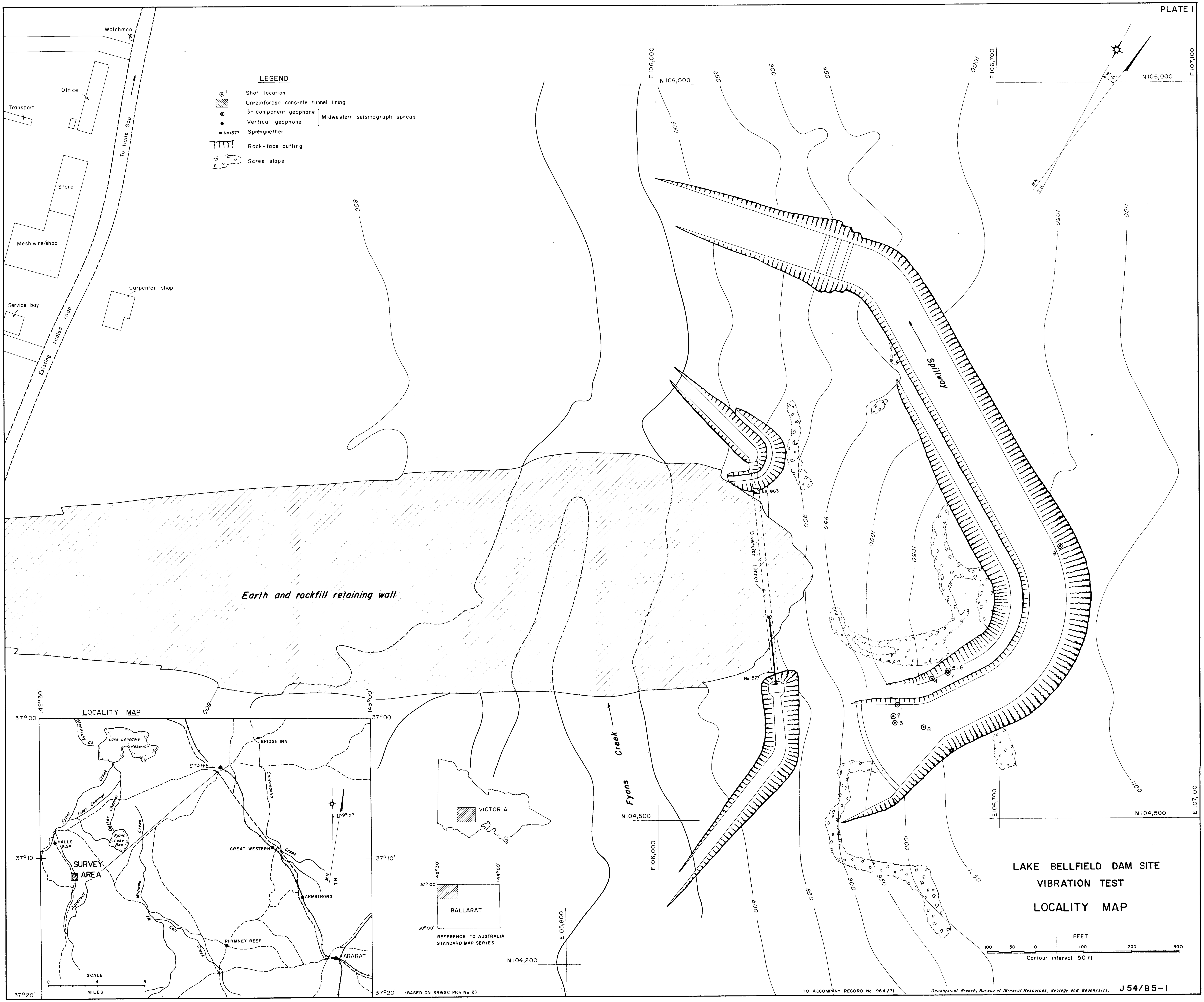
J54/B5-4

TO ACCOMPANY RECORD No. 1964/71

FIGURE 2

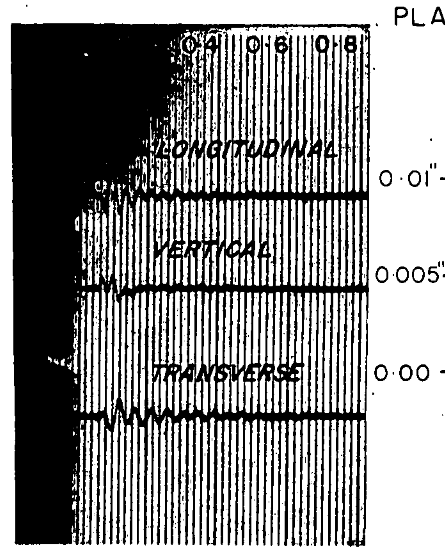


GRAPH OF THE EMPIRICAL EQUATION $\frac{E^{0\cdot22}}{(R \times d)} = 0\cdot07$

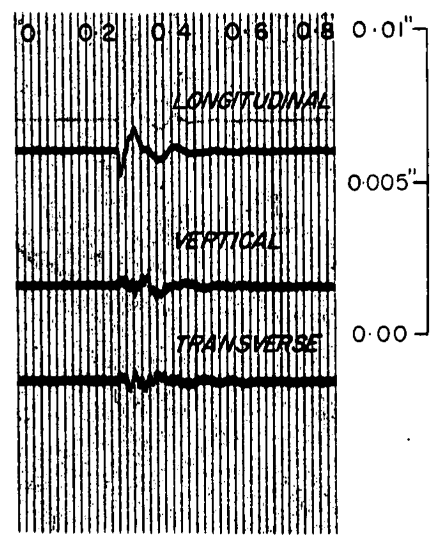


LAKE BELLFIELD DAM SITE
VIBRATION TEST
LOCALITY MAP

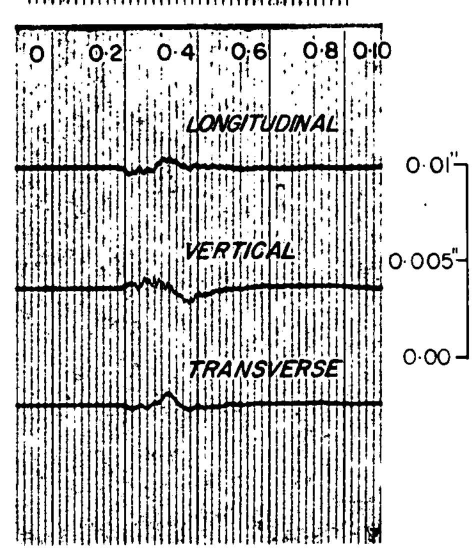
SITE : *Diversion Tunnel Survey Peg R.D. 40*
DATE : *16/12/63*
INSTRUMENT : *Sprengnether Seismograph No 1577*
TEST CHARGE : *444 lb A.N. "60" Gelignite and Nitrolite A.N.F.O.*
DISTANCE : *420 feet*



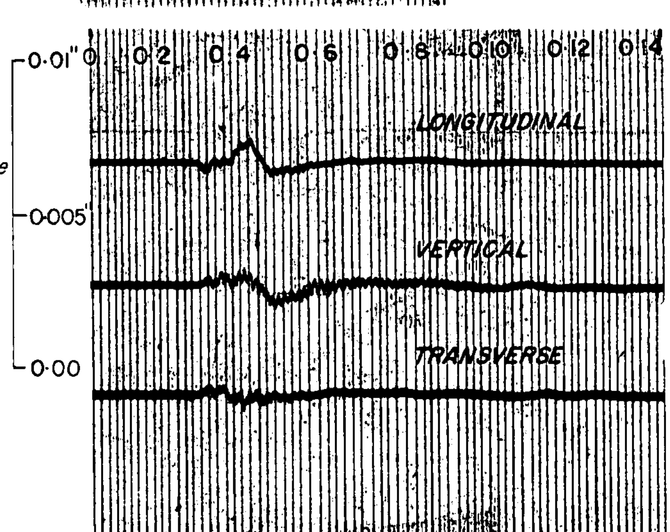
SITE : *Diversion Tunnel Unreinforced Concrete Tunnel Lining R.D. 410 to 418*
DATE : *16/12/63*
INSTRUMENT : *Sprengnether Seismograph No 1863*
TEST CHARGE : *444 lb A.N. "60" Gelignite and Nitrolite A.N.F.O.*
DISTANCE : *650 feet*



SITE : *Diversion Tunnel Survey Peg R.D. 40*
DATE : *17/12/63*
INSTRUMENT : *Sprengnether Seismograph No 1577*
TEST CHARGE : *3664 lb fired with 14 delays 10-millisecond interval "Quarigel" and A.N.F.O. Nitrolite*
DISTANCE : *715 feet*



SITE : *Diversion Tunnel Unreinforced Concrete Tunnel Lining R.D. 410 to R.D. 418*
DATE : *17/12/63*
INSTRUMENT : *Sprengnether Seismograph No 1863*
TEST CHARGE : *3664 lb fired with 14 delays 10-millisecond interval. "Quarigel" and A.N.F.O. Nitrolite*
DISTANCE : *715 feet*



LAKE BELLFIELD DAM SITE, HALLS GAP, VICTORIA
VIBRATION TESTS FOR TUNNEL
VIBRATION RECORDS

GEOPHYSICAL BRANCH, BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS J54/B5-2
TO ACCOMPANY RECORD No 1964/71