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AWRE, Aldermaston

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A Comparison of the Seismic Effects Produced by a Falling Weight and Detonations of Small, Buried, Explosive Charges

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SUMMARY

An experiment is described in which the seismic effects produced by dropping a standard steel ball used by demolition contractors on to a concrete foundation block were compared with those from small explosive charges detonated in shot holes drilled in the block. Estimates are given for the relative demolition efficiencies of the two methods when the seismic effects are equal and for the effects on seismic amplitude of varying the ball weight and height of fall.

1. INTRODUCTION

During the initial stages of demolition work at Risley ROF, contractors to the Warrington New Town Development Corporation (WNTDC) used a 762 kg (15 cwt) steel ball suspended from a crane jib for both side-ways impact and falling weight applications. While this method was adequate for demolishing structures above ground level, it seemed less likely to be effective in dealing with the massive concrete foundations of some buildings on the site.

The possibility of explosives being used in the later stages of the work, as an alternative to the falling weight, was of concern to the Reactor Group at UKAEA Risley because of the proximity of laboratories to certain parts of the proposed demolition area. In reply to a query from the Chief Engineer (C and A) UKAEA Risley about ground vibration levels which might be expected from nearby explosions, the Superintendent of UKAEA Seismic Detection Group (SSD Blacknest) pointed out that a falling weight may be a more efficient generator of seismic waves than an explosion of equivalent total energy content, the precise relationship being dependent on the surface geology of the site of operations.

In the absence of a body of quantitative information on the subject, it was thought worthwhile to obtain some specific empirical data by making comparative measurements of the seismic effects of weight drops and small explosions at the Risley ROF site. These measurements were carried out by SSD Acoustics Section on 18 April 1972. Because of the necessity for stopping demolition operations during the tests and the involvement of individuals from several different organisations (UKAEA Risley, Blacknest, ICI Nobel Division, WNTDC staff and contractors), the tests were limited by the time available to a small scale programme of weight drops and shot firing in pre-prepared holes. Some additional measurements of the effects of dropping a range of smaller weights from various heights were subsequently made at AWRE.

2. EXPERIMENTAL ARRANGEMENTS

2.1 Test site

The site of the tests was on the unreinforced concrete foundations of a disused water pumping station, the superstructure of which had previously been demolished and removed down to ground level by WNTDC before the test date. This test area (figure 1) imposed some restrictions on the emplacement of seismometers, being partly surrounded by soft ground and adjacent to a large empty walled reservoir and a smaller, semi-underground reservoir containing some water, but it was not untypical of the ROF site as a whole. An earlier survey had shown that the underlying geological structure of the ROF was a 10 m clay layer, containing gravel in the lower 1.5 m, overlaying red sandstone layers down to at least the 120 m depth of the survey borehole.

The pumping station foundation (figure 2) provided an area of concrete of about 84 m^2 varying from 0.91 to 1.53 m depth, giving a sufficient volume of material in which each of a sequence of small charges could be detonated in a fresh zone of the block, unfractured by the previous explosions.

A row of 13 shot firing holes each 32 mm in diameter was bored along a section of the thicker part of the foundation block, with hole spacings of 0.46 or 0.61 m as shown in figure 2. A hole depth of about half the block thickness was chosen to give optimum demolition rather than seismic effect, but practical difficulties encountered in boring gave a spread of hole depths between 0.46 and 0.76 m (as indicated). The weight-drop impact area was on another similarly thick part of the concrete at the opposite side of the foundation.

2.2 Instrumentation

Vertical and radial components of ground motion were recorded at two positions for each of the shots and weight drops by 4 Willmore Mk II seismometers which gave outputs directly proportional to the parameter ground velocity. The instruments were located on the only hard-standings available at ground level near to the test area using, initially, positions 1 and 2 (figure 1) at about 50 and 30 m respectively from the explosion/impact source point and, later, positions 1 and 3, at about 50 and 20 m distance from the source. The signal outputs from the seismometers were recorded on magnetic tape and paper charts.

2.3 Weight drops and shot firing

Only one demolition ball, weighing 762 kg, was available for the weight drop tests which were restricted by certain on-site operational difficulties and time available to a number of drops sufficient to set up recording levels and establish the reproducibility of results from drop to drop. Records from each of the three seismometer positions were obtained from a total of four drops from a height of 9.14 m (30 ft).

Four 57 g (2 oz) charges were detonated initially to determine signal levels at the recording positions and to provide a preliminary basis for comparison with the weight drop seismic effects. The charge weights were then increased by 57 g steps to a maximum of 171 g to straddle the amplitude range of the measured vertical and horizontal seismic components from weight drops. The shot-hole positions used in this firing programme were as follows:-

Explosion	Hole Used	Charge, g
1	No. 1	57
2	No. 3	57
3	No. 2	57
4	No. 5	57
5	No. 7	114
6	No. 10	114
7	No. 13	171

3. RESULTS, CALCULATIONS AND DISCUSSION

3.1 Results from the experiment at ROF Risley

Representative waveforms of vibrations from weight drops and explosions are illustrated in figures 3 to 7.

In the weight drop waveforms of figures 3 and 4 it can be seen that a high frequency train of waves, which appears at the beginning of each vertical component record trace, was recorded as a rather lower frequency wave-train of shorter duration when the near-in instrument pair was transferred from position 2 to position 3, nearer to the source. This implied that the high frequency was more associated with characteristics of the seismometer hard-standings and resonances induced in nearby structures, such as the roofed underground reservoir, than with the source.

Similar sets of results were also obtained at positions 2 and 3 when the 57 g initial proving shots were fired. The seismometers were left at position 3 for recording the sequence of shots from 57 to 171 g weight; the more distant seismometer pair remained at position 1 throughout the experiment. Seismograms from this shot sequence are shown in figures 5, 6 and 7.

The overall similarity between waveforms of the weight drop and shot effects at each recording position made it possible to treat both the high and low frequency components of the observed signals as valid parts of the total induced seismic disturbance caused by each event for the purpose of a comparative analysis. The results of this analysis are shown in graphical form in figures 8 and 9.

In the graphs the amplitudes of vertical and horizontal components of ground motion are plotted as functions of distance from source for both weight drops and shots. Maximum peak particle velocity values from the ball weight drops are indicated by shaded and unshaded circles for low and high frequency components respectively. Low and high frequency amplitude maxima from the shots are similarly represented by shaded and unshaded triangles linked by vertical bars. Because of the similarity of weight drop and shot induced waveforms, like frequencies could be used for these comparative amplitude measurements of the low and high frequency components of signals observed at each recording point, although the values of the frequency components measured were relatively lower at the more distant position as high frequencies are attenuated more rapidly with distance.

It can be seen from figures 5, 6 and 7 that the ratio of the high-to-low frequency waves recorded by the near-in vertical seismometer at position 3 increases with shot size (but note that figures 3 to 7 illustrate wave-shapes only and do not have equivalent vertical scales. For exact amplitude relationships, see figure 8 and 9). The equivalent trace from the weight drop waveforms of figure 4 show that, in this respect, the ball drop result most closely resembles that of detonating the 171 g charge.

Also from figures 8 and 9 it can be seen that the ball drop effects were about equal in amplitude to those of the 171 g charge, although one of the two 114 g charges used, which was fired in a slightly deeper hole (No. 10), produced about the same amplitude at low frequency as the larger charge. For the purpose of the following argument, based on our results, we shall therefore assume, arbitrarily, that the ball drop effects were seismically equivalent to those of a 142 g (5 oz) charge.

3.2 Estimation of demolition efficiency for equivalent seismic effects

From data recorded in a series of experiments in which the effects of buried charges were measured, O'Brien [1] tabulated percentages of total available chemical energy appearing as radiated seismic energy for several weights of explosives fired at 2 depths in 2 different media. This table indicates that larger, shallower shots are appreciably more efficient generators of seismic energy than smaller, deeper ones and that a rather higher fraction of the total energy available appears as seismic waves for shots in sandstone compared to those in clay. The tabled percentages range from 0.75% from a 0.4 kg shot fired at 60 m depth in clay to 7% from 10.0 kg at 15 m depth in sandstone; the smallest shallowest shot in sandstone (0.4 kg at 15 m depth) produced 2.6% of radiated energy.

We have assumed an equivalence for the Risley weight drops to the seismic effects from 0.142 kg of explosive fired at about 0.6 m in a concrete block set in a clay medium. The explosive used, Special Gelatine 80, has a specific energy content at 4.2 kJ g^{-1} giving a total energy of 596 kJ from a 0.142 kg charge. Using O'Brien's data as a basis, we now make a second arbitrary assumption that perhaps 5% of the total energy from the explosion may appear as seismic radiation. Thus, the seismic fraction of the total energy is

$$0.05 \times 596 = 29.8 \text{ kJ}.$$

Now the kinetic energy of a ball of weight 762 kg dropped from a height of 9.14 m

$$= \tfrac{1}{2}\, mv^2$$
$$= \tfrac{1}{2} \times 762 \times 179.2$$
$$= \underline{68300\ \text{J}},$$

where $v^2 = u^2 + 2as$, initial velocity $u = 0$, acceleration $a = 9.8$ m s^{-2} and distance $s = 9.14$ m.

Thus, 29.8/68.3 × 100 = <u>44%</u> of the ball energy appears as seismic waves. The energy available for useful work in breaking up the concrete is therefore 68.3 - 29.8 = 38.5 kJ in the case of the ball drop and 596 - 29.8 = 566.2 kJ for the explosive, ie, there is a factor of 566.2/38.5 = 14.8 in energy available for demolition in favour of the explosive. This is amply demonstrated by the photographs in figure 10 which show the effects of weight drops and explosions on the concrete foundation block.

It should be noted, however, that a demolition efficiency ratio for the seismically equivalent explosive charge and falling weight calculated simply on a basis of available energy will be very conservative. This is because the calculations take no account of the inherently more favourable site of application of forces from a demolition charge inside an unreinforced concrete mass where it can exert large tensile stresses on the material (which is weak in tension) compared to the mainly compressional forces of a weight drop.

The extrapolations from other data and necessary assumptions made in the preceding argument might have been avoided if the experiment had been on a larger scale, so that demolition effects of weight drops and explosions could have been equalized on a suitable test area and the ratio of the seismic effects then found by direct measurement for equivalent demolishing capabilities of the ball and some weight of explosive established by trial and error. In a small scale experiment, however, it is easier to equalize the seismic effects by observation and estimate instead, as we have done, the ratio of energies available.

In making this estimate we note that there are differences of opinion about the proportion of total energy appearing as seismic radiation in an explosion and that this fraction is dependent on the charge shape, density and coupling to the surrounding medium. Thus, for example, Nicholls [2] describes measurements which indicate a transfer to the surrounding medium of 1.8 - 3.7% of the total energy, but quotes earlier work where estimates of 10 - 18% have been given. ICI [3] state that a seismic energy transmission of 40 - 50% of the total is possible. O'Brien's data seem more in accordance with our own observations and we have some knowledge [4] of the circumstances in which it was acquired. Clearly, from a consideration of the data from the Risley tests, the proportion of energy appearing as seismic radiation from the total of 596 kJ available in a 142 g charge would be only 11½% in the extreme case where it is assumed that 100% rather than 44% of the energy from a seismically equivalent 68.3 kJ ball drop is transferred to the ground as seismic waves.

3.3 Results from additional weight drop experiments

As the WNTDC contractors were unable to obtain an additional, larger demolition ball (of weight around 2000 kg) for the Risley tests, some further small scale experiments were carried out at AWRE to determine a relationship between seismic amplitude and size of weight. The effects of varying height of fall was also investigated in these later tests. In the first test, steel balls ranging in weight from 0.7 to 14 kg were dropped on (a) concrete, and (b) soft ground from a height of 7 m and the seismic effects at 30 m distance were recorded by vertically and radially oriented Willmore Mk II seismometers emplaced on a concrete slab.

The results of this test are illustrated by the graphs of figure 11 in which peak particle velocity is plotted against ball weight for both vertical and horizontal components of ground motion and hard and soft ground impacts. It can be seen that, with the partial exception of the radial component produced by soft ground weight drops (where the true maxima from the heavier weight drops were masked by distortion of the main pulses due to the presence of mutually interferring waves of different frequencies), the seismic amplitude was a linear function of the weight dropped in each case.

In the second tests, in which the ball weight was kept constant and the height of ball varied, the results were of the form shown in figure 12. Here the relationship between the amplitude, A, of particle velocity and the height of fall, H, is of the kind

$$A = K \times H^n.$$

In this case, n has an initial value of around 0.5 for very low heights of fall but is evidently becoming asymptotic as the height of fall increases. In the range of more practical heights of drop, say 3 - 10 m, with which we were concerned in these various tests, a value for n of 0.25 seems most appropriate for amplitude versus height of fall extrapolations. (Data for these results were obtained at two test sites. The absolute values of seismic amplitude differed at the two sites, particularly for soft ground drops, but the relationships governing amplitude dependency on weight and height of fall variations were similar at each site.)

The energy, E, of a weight of mass, m, falling from height, H, is given by

$$E = mgH,$$

where $m \times g$ = force in newtons, and H = height in metres. Hence, the total energy available is directly proportional to both weight and height of fall and the experimental observations of near-in seismic amplitudes indicate therefore, how that fraction of the total energy which is transferred to the ground as elastic wave motion varies in relation to alterations in the values of these two parameters. Because of the non-linearity of this transfer function in the case of increasing height of fall, we can see that a larger change in seismic amplitude is obtained when the total energy is increased by increasing the weight, than when it is increased by raising the height of fall. Specifically, a doubling of the energy level by increasing the weight from 7 to 14 kg in our experiments doubled the seismic amplitude, whereas doubling the energy level by increasing the height from 3.5 to 7 m increased the amplitude by 16%.

Conversely therefore, for demolition purposes it should be rather more useful to increase the total energy available for breaking the surface material by increasing the ball height rather than weight.

Finally we consider the attenuation of seismic amplitude (ie, the maximum peak particle velocity at any frequency) which occurs as the radial distance, r, from the source increases. From the data recorded at Risley and AWRE the amplitude distance relationship at distances in the range 10 - 70 m was seen to be of the order $A = Kr^{-2}$. Within this distance range, it should therefore be possible to state a scaling law from which approximate estimates of the seismic amplitude from weight drops of various weight and height of fall values may be derived. Thus, since we have previously established linear and 0.25 power law amplitude relationships with weight and height of fall, the amplitude of ground motion from a weight drop can be predicted from

$$A_2 = A_1 \times \frac{W_2}{W_1} \times \left(\frac{H_2}{H_1}\right)^{0.25} \times \left(\frac{r_2}{r_1}\right)^{-2},$$

where A_1 is the peak particle velocity recorded at distance r_1 from a weight W_1 falling through height H_1, and A_2 is the unknown amplitude from weight W_2 falling through height H_2 at radial distance r_2.

Using the above expression, peak particle velocity data recorded in the tests at the AWRE sites can be used to predict the amplitude for the Risley tests for comparison with the actual results recorded. At the first site at AWRE, a vertical component amplitude of 28.7 $\mu m\ s^{-1}$ was recorded at 30 m from a weight of 14 kg falling on to concrete from a height of 7 m. At the second site the amplitude was 49 $\mu m\ s^{-1}$ at 17.5 m from 8.8 kg falling 3.5 m on to concrete. From Data Set 1

$$A_2 = 28.7 \times \frac{762}{14} \times \left(\frac{9.14}{7}\right)^{0.25} \times \left(\frac{30}{19.5}\right)^2$$

$$= \underline{3940\ \mu m\ s^{-1}}$$

where the distance of the near seismometer at Risley was 19.5 m, and from Data Set 2

$$A_2 = 49 \times \frac{762}{8.8} \times \left(\frac{9.14}{3.5}\right)^{0.25} \times \left(\frac{17.5}{19.5}\right)^2$$

$$= \underline{4710\ \mu m\ s^{-1}}.$$

The ground motion amplitude maxima actually recorded at Risley by the vertical seismometer at 19.5 m were 3600 and 2400 $\mu m\ s^{-1}$ for the high and low frequency components respectively. This is an extrapolation of 54 times on the weight and takes no account of differences in the characteristics of the sites. Nevertheless, from this example, it seems not unreasonable to conclude that, for sites not too dissimilar to the ones used in these tests, this expression could be used to obtain an approximate estimate, say within a factor of 2 up or down, for ground motion at distances of a few tens of metres from weight drops with heights of fall in the range 3 - 10 m.

3.4 Effect of seismic vibration on buildings

A peak particle velocity level of around 50000 $\mu m\ s^{-1}$ has for many years been accepted as the threshold of minor "architectural" (ie, non-structural) damage in ordinary buildings. More recent investigations [5-8] have shown that particle velocities as low as 1000 - 2000 $\mu m\ s^{-1}$ can in some circumstances accelerate the rate of deterioration (minor cracking, brittle fracture, etc) which occurs naturally in buildings. A rounded-up estimate based on our experimental results is that (for concrete impact and recording positions at a site with clay-gravel overburden) a peak particle velocity of 1000 $\mu m\ s^{-1}$ would be experienced at a point 30 m from the fall of a 1000 kg weight from 10 m height. Also, from the results, there is a correspondence for this level of ground motion to the detonation of a near-surface explosive charge of weight in the range 113.5 - 227 g (4 - 8 oz). At distances greater than 30 m, the ground motion resulting from either of these seismically equivalent events would therefore be less than the lowest levels now believed to be of significance to ordinary buildings. The relatively weak ground motion which would occur at rather greater ranges might, however, be considered still significant in the special case of buildings such as laboratories containing delicate apparatus (although this motion would in fact be less in amplitude than the vertical vibrations normally arising from nearby road traffic). Approximate estimates for ranges greater than those involved in the present tests (10 - 70 m) could be obtained by using a 1/r relationship towards which amplitude tends at the higher end of our measurement range.

4. CONCLUSIONS

(1) The peak particle velocity of ground motion produced by a falling weight has been shown by experiment to be of the order of 1000 $\mu m\ s^{-1}$ at 30 m distance from a weight of 1000 kg falling from a height of 10 m on to concrete. This ground motion is directly proportional to the size of weight and proportional to the 4th root of the height of fall.

(2) An equivalent seismic effect would be produced by the detonation of an explosive charge of about 0.2 kg but the demolition capability of the buried explosive for breaking up a solid concrete mass is estimated to be at least fifteen times greater than that of a falling weight.

(3) At distances greater than 30 m the ground motion resulting from either of these events would be less than the lowest levels now believed to initiate damage to ordinary buildings.

(4) Within reasonable limits, simple extrapolations to compare the seismic effects of small buried demolition explosions with ball weight drops can be made from (1) and (2) above by using a linear law for the relationship between seismic amplitude and both ball weight and charge size and assuming a simple inverse law to apply for distances in excess of 30 m. The effect of variation in ball drop height can be assumed to be negligible for heights of the order of 10 m as far as the seismic amplitude is concerned.

5. ACKNOWLEDGMENTS

We would like to record our appreciation of the helpful collaboration of all concerned in the experiment at Risley, in particular from Mr F N Shimmin, CE (C and A), Mr W Fraser, Project Engineer and Mr J R James, ICI Nobel Division.

Thanks are due to Mr P W Burton of SSD, Blacknest for making a critical reading of the draft report.

REFERENCES

1. P N S O'Brien: "Some Experiments Concerning the Primary Seismic Pulse". Geophysical Prospecting, 17, 511-547 (1969)

2. H R Nicholls: "Coupling Explosive Energy to Rock". Geophysics, 27, 3, 305-316 (1962)

3. ICI Nobel's Explosives Company Ltd. Private Communication (15 May 1972)

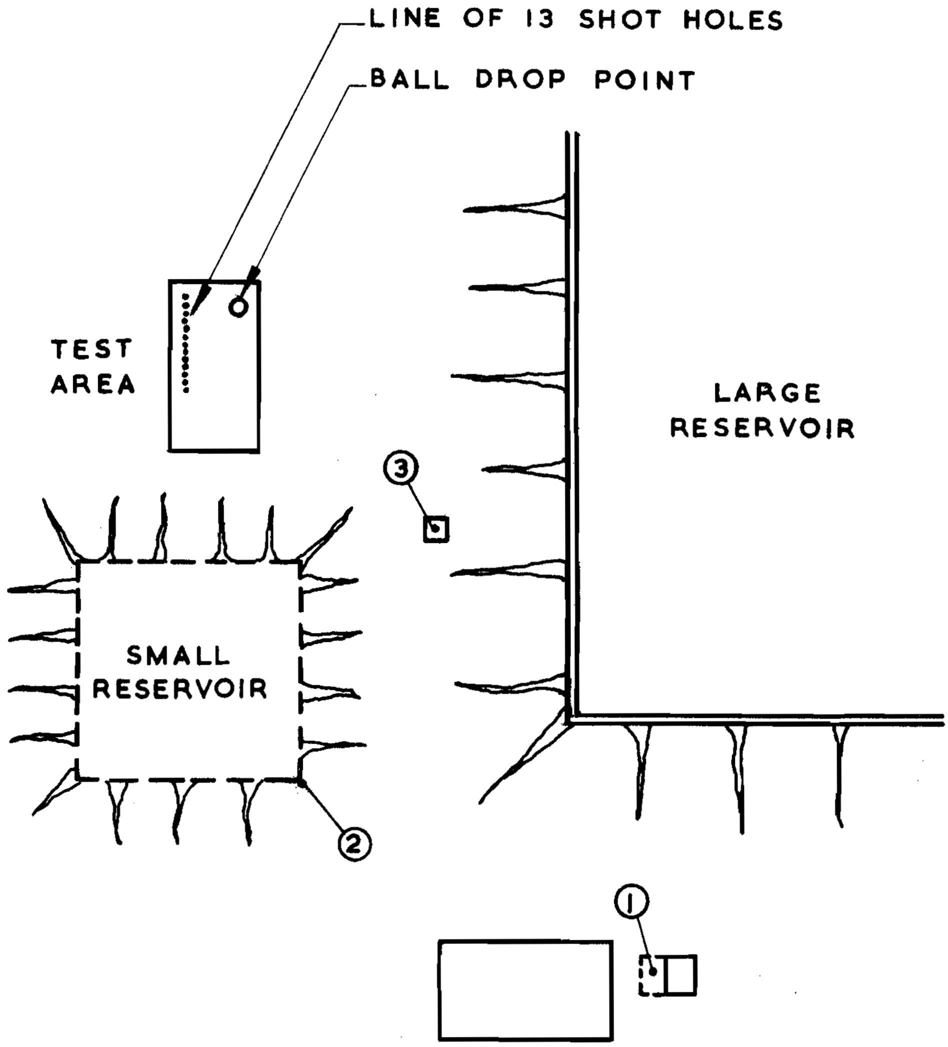
4. R W Allen et al.: "The Primary Seismic Signals from Charges Exploded Underground". AWRE Report T5/65 (1965)

5. J F Wall Jr: "Seismic Induced Architectural Damage to Masonry Structures at Mercury Nevada". Bull Seism Soc Amer, 57, 5, 991-1007 (1967)

6. M E Nadolski: "Architectural Damage to Residential Structures from Seismic Disturbances". Bull Seism Soc Amer, 59, 2, 487-502 (1969)

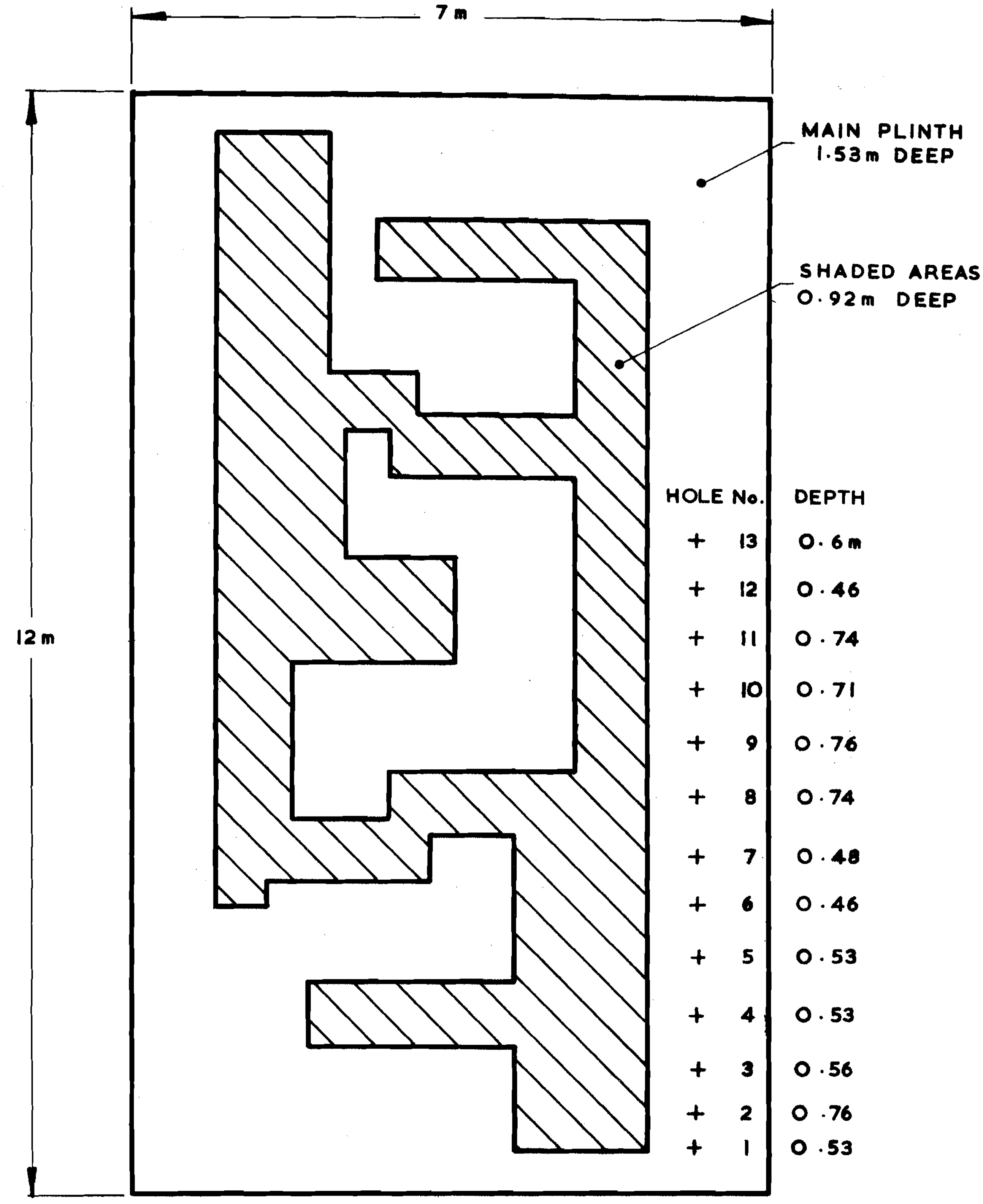
7. F H Grover: "Vibro-Seismic Measurements". Proc Conf Dynamic Waves in Civil Eng, Swansea, July, pp 315-340 (1970)

8. F Holzer: "Ground Motion Effects from Nuclear Explosions. A Review of Damage and Prediction Methods". UCRL 51062 (1971)



1, 2 & 3 ARE SEISMOMETER RECORDING POSITIONS

FIGURE I. LOCATION PLAN FOR TEST EXPLOSIONS AT RISLEY



ALL HOLES 32 mm DIA.
SPACING BETWEEN HOLES
O·6m EXCEPT Nos. 1–4
WHICH WERE AT O·46m
CENTRES.

FIGURE 2. DETAILS OF CONCRETE FOUNDATION

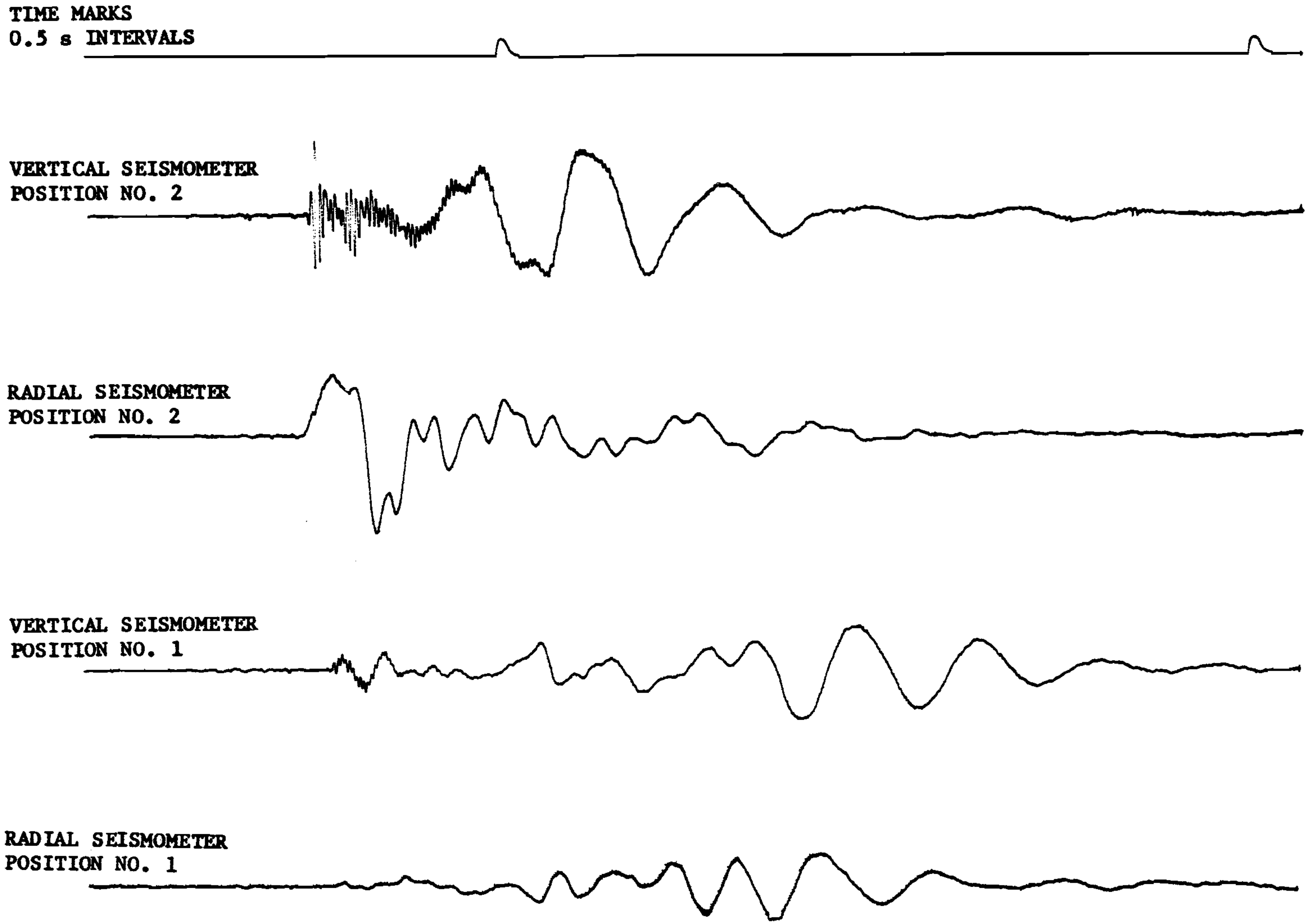


FIGURE 3. BALL WEIGHT DROP NO. 2

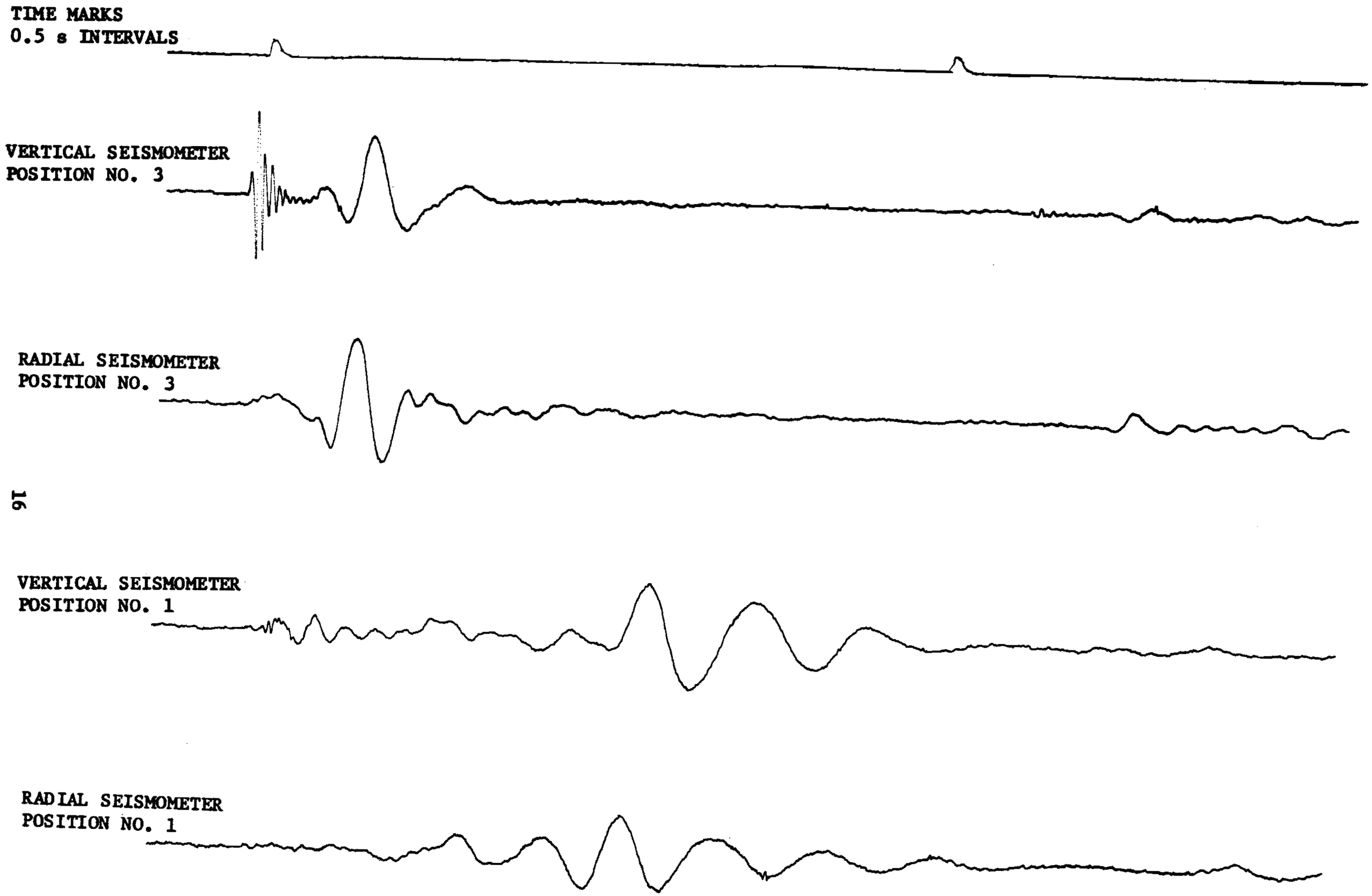


FIGURE 4. BALL WEIGHT DROP NO. 4

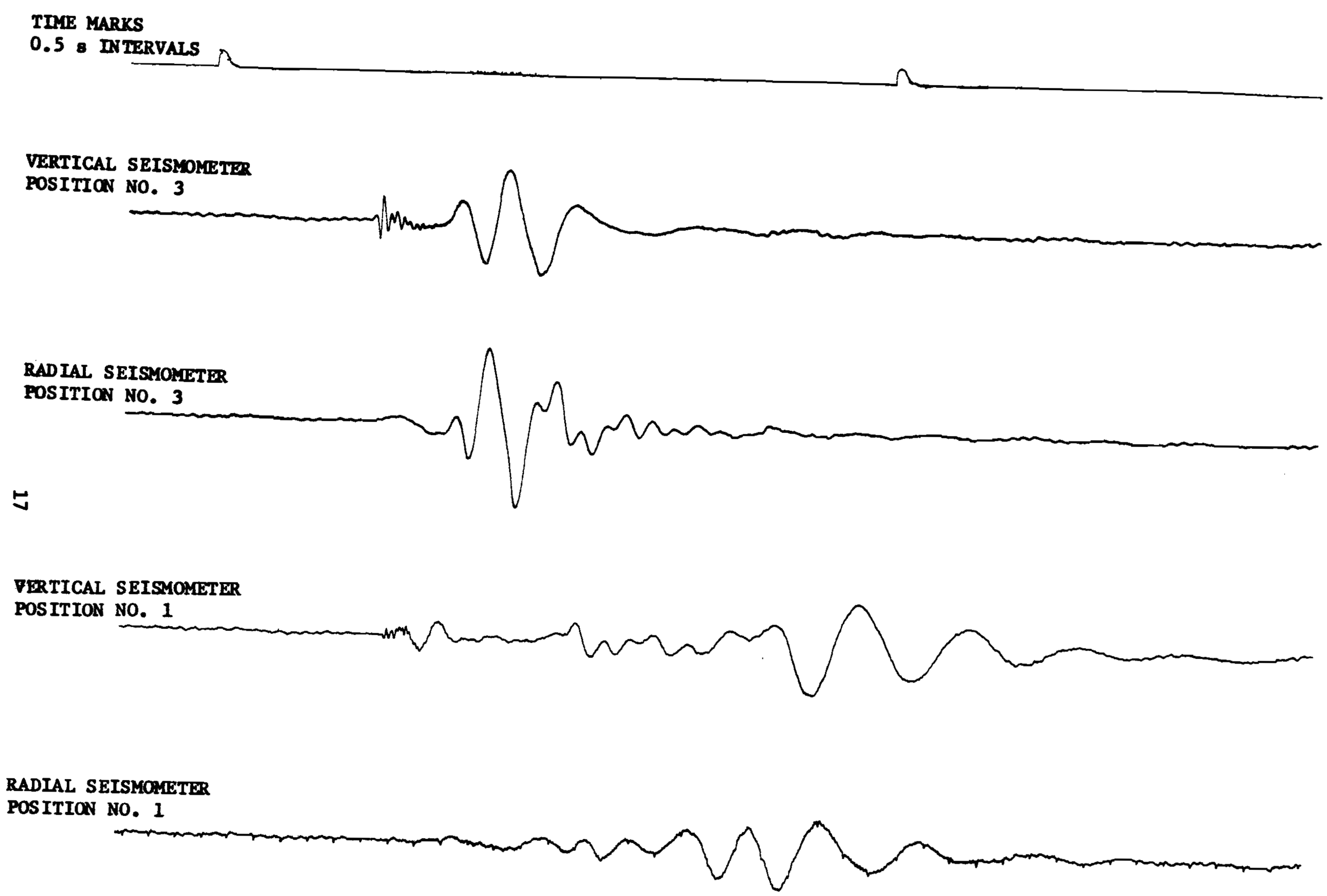
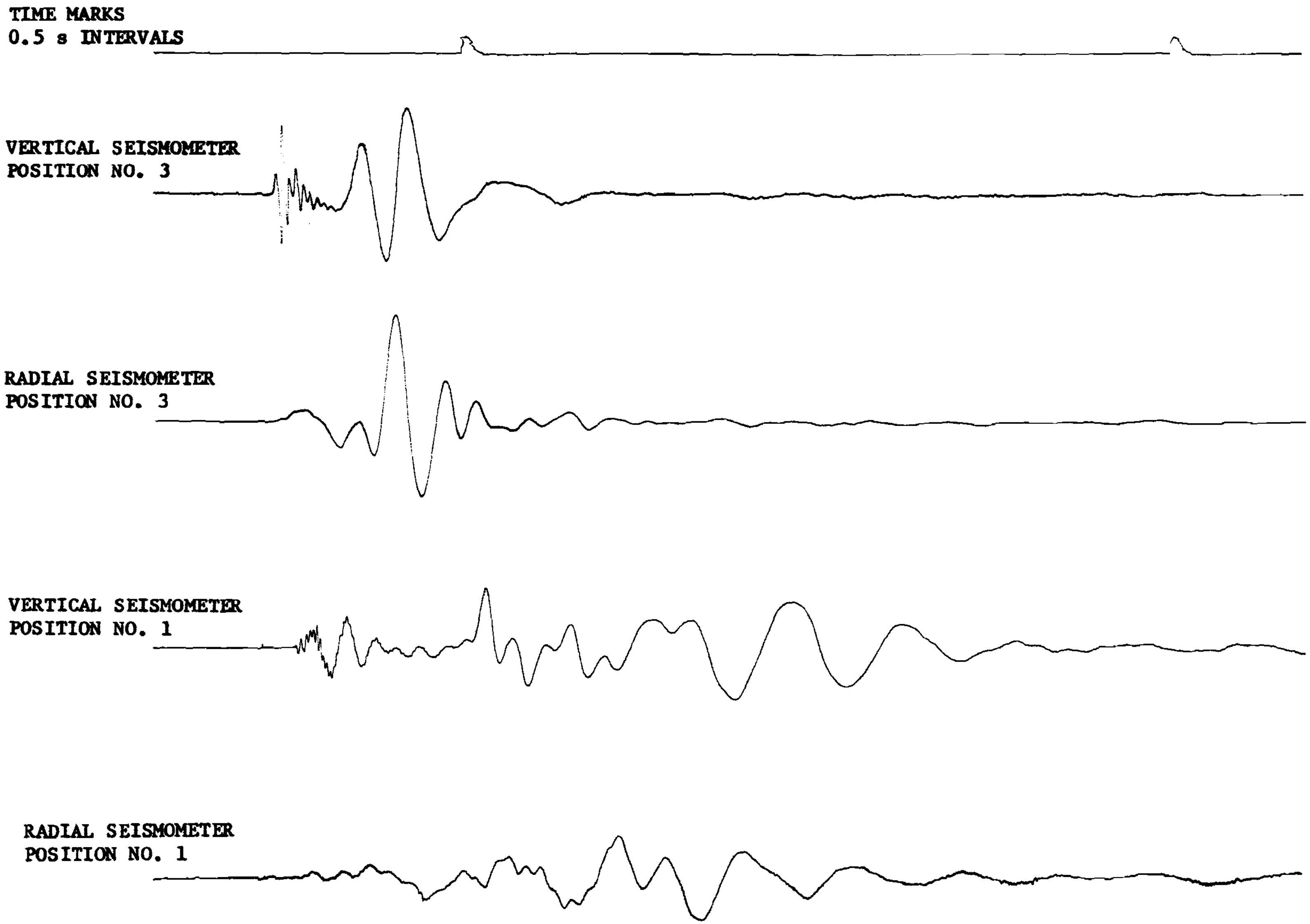


FIGURE 5. SHOT NO. 4, 57 g



<u>FIGURE 6. SHOT NO. 6, 114 g</u>

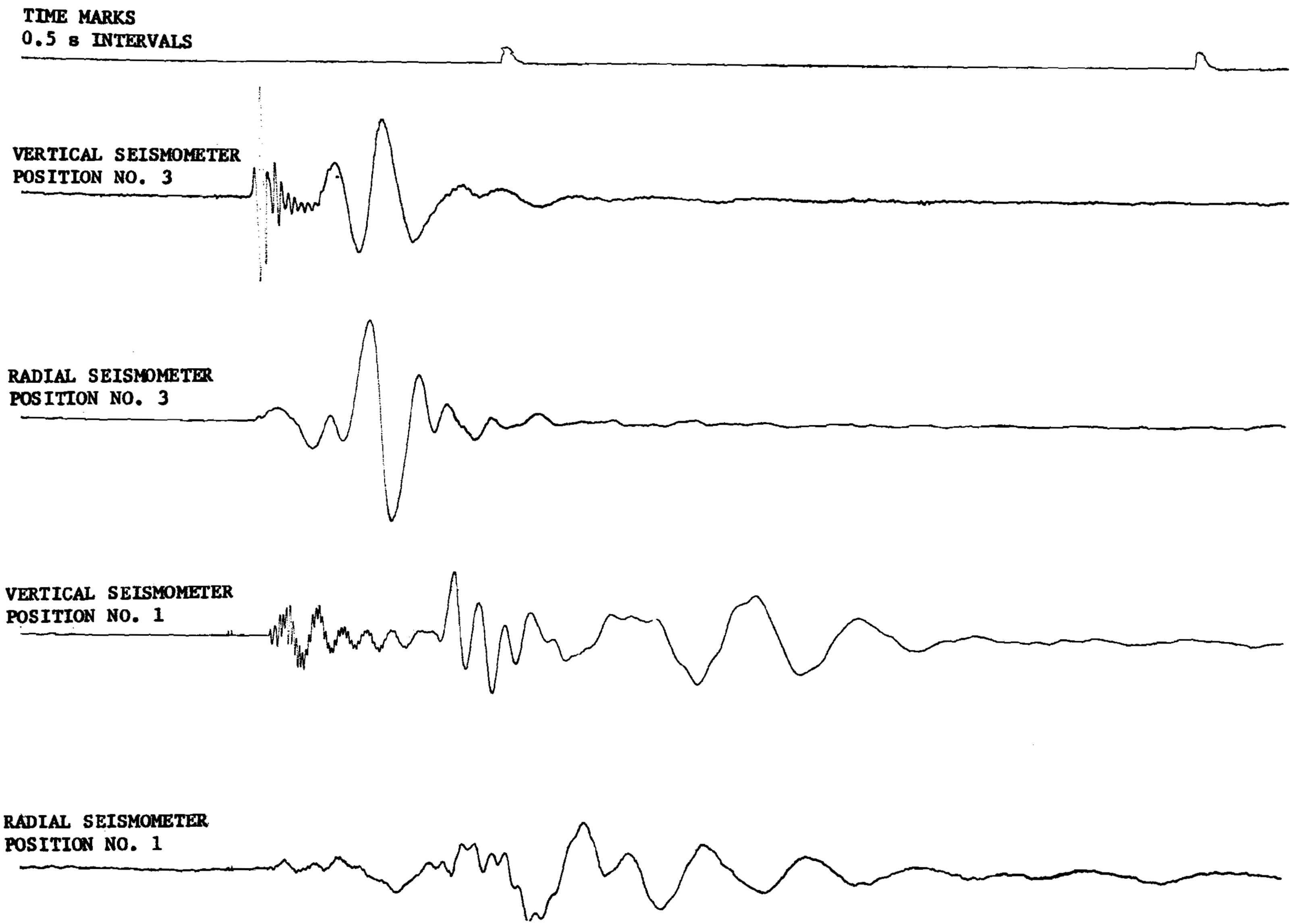


FIGURE 7. SHOT NO. 7, 171 g

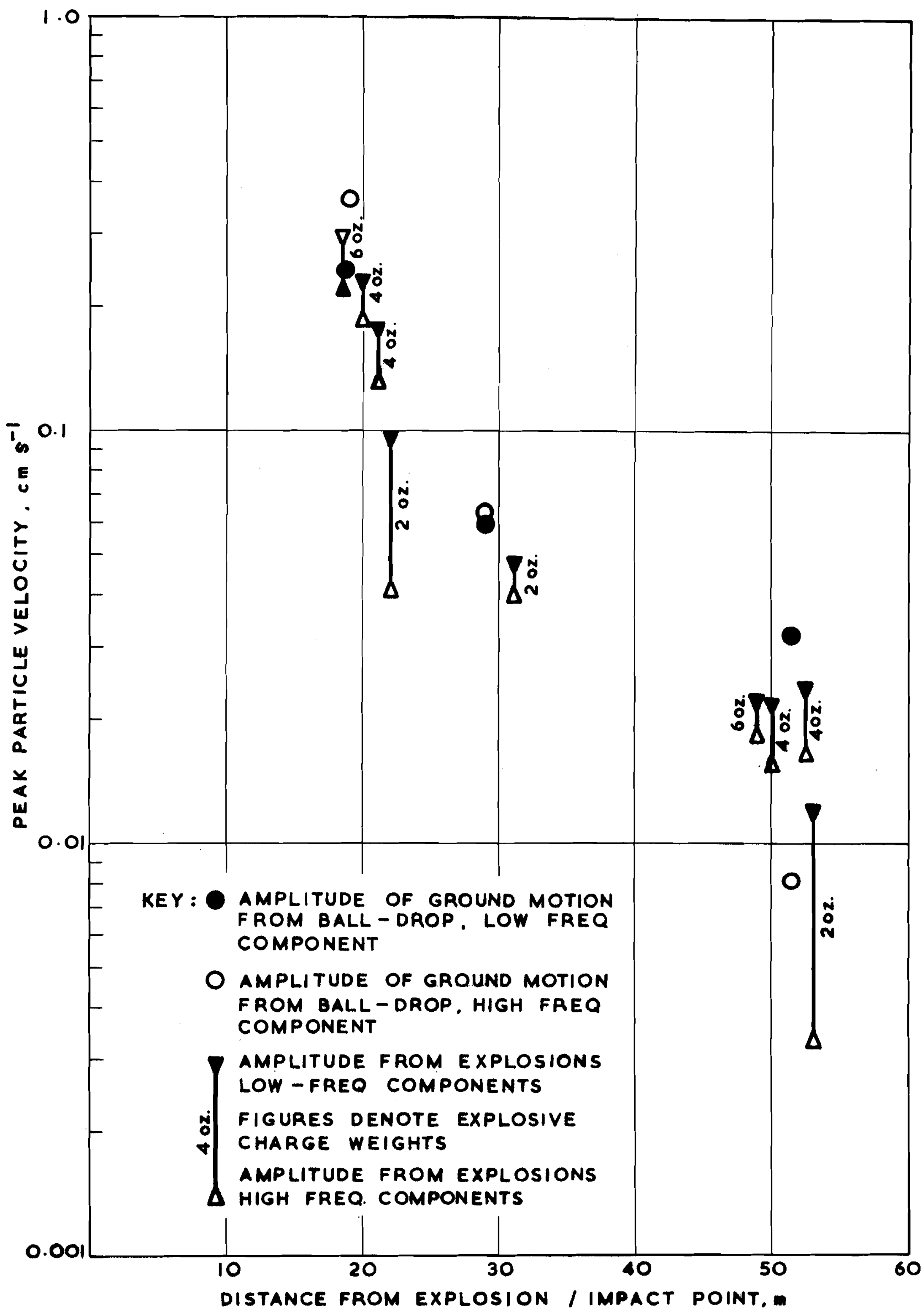


FIGURE 8. AMPLITUDE DISTANCE RELATIONSHIPS FOR VERTICAL COMPONENTS OF GROUND MOTION FROM BALL-DROPS AND EXPLOSIONS

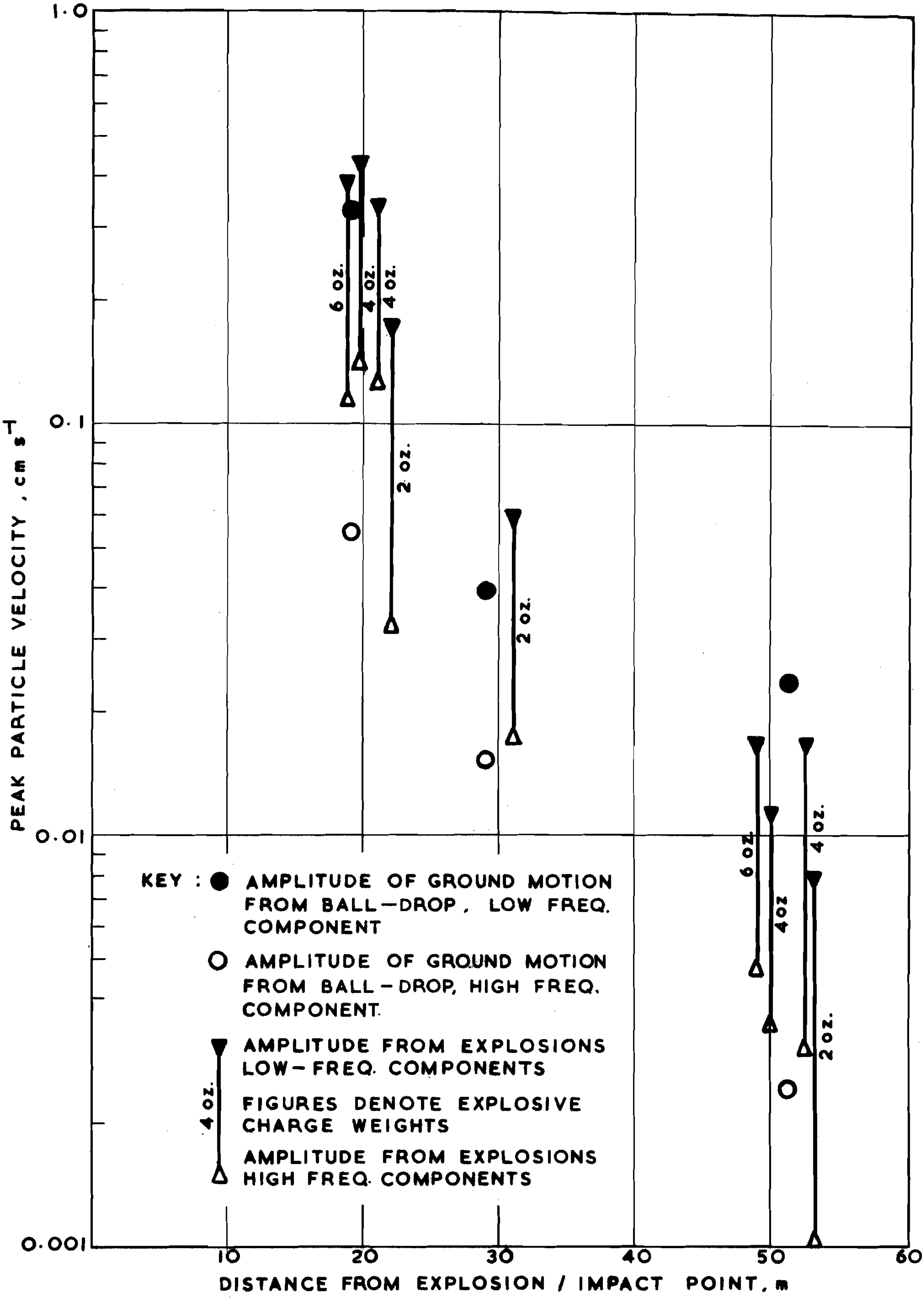
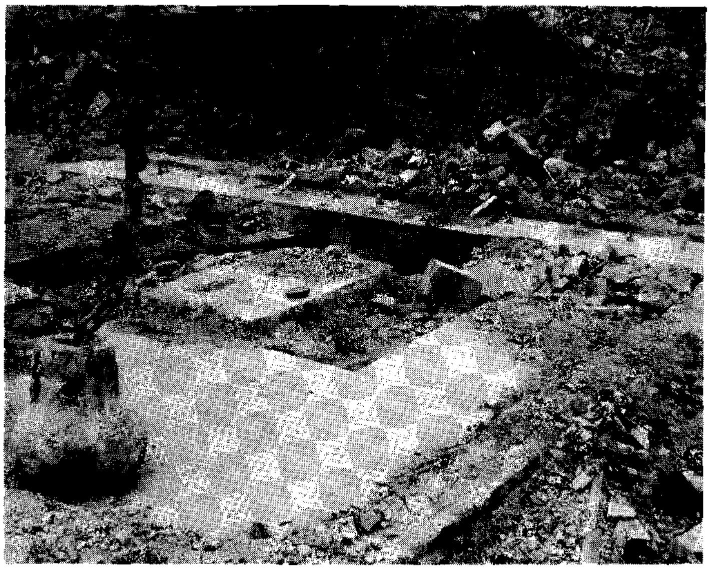


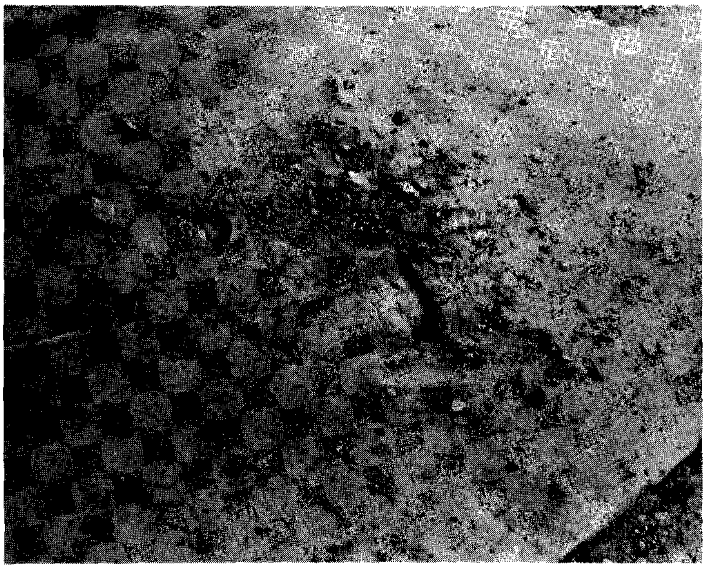
FIGURE 9. AMPLITUDE DISTANCE RELATIONSHIPS FOR HORIZONTAL COMPONENTS OF GROUND MOTION FROM BALL-DROPS AND EXPLOSIONS



DEMOLITION SITE BEFORE TESTS

← LINE OF SHOT HOLES

← BALL IMPACT AREA



EFFECT OF WEIGHT DROP SEQUENCE

EFFECT OF SHOT FIRING SEQUENCE

FIGURE 10. EFFECTS OF BALL WEIGHT DROPS AND EXPLOSIONS ON CONCRETE FOUNDATION BLOCK

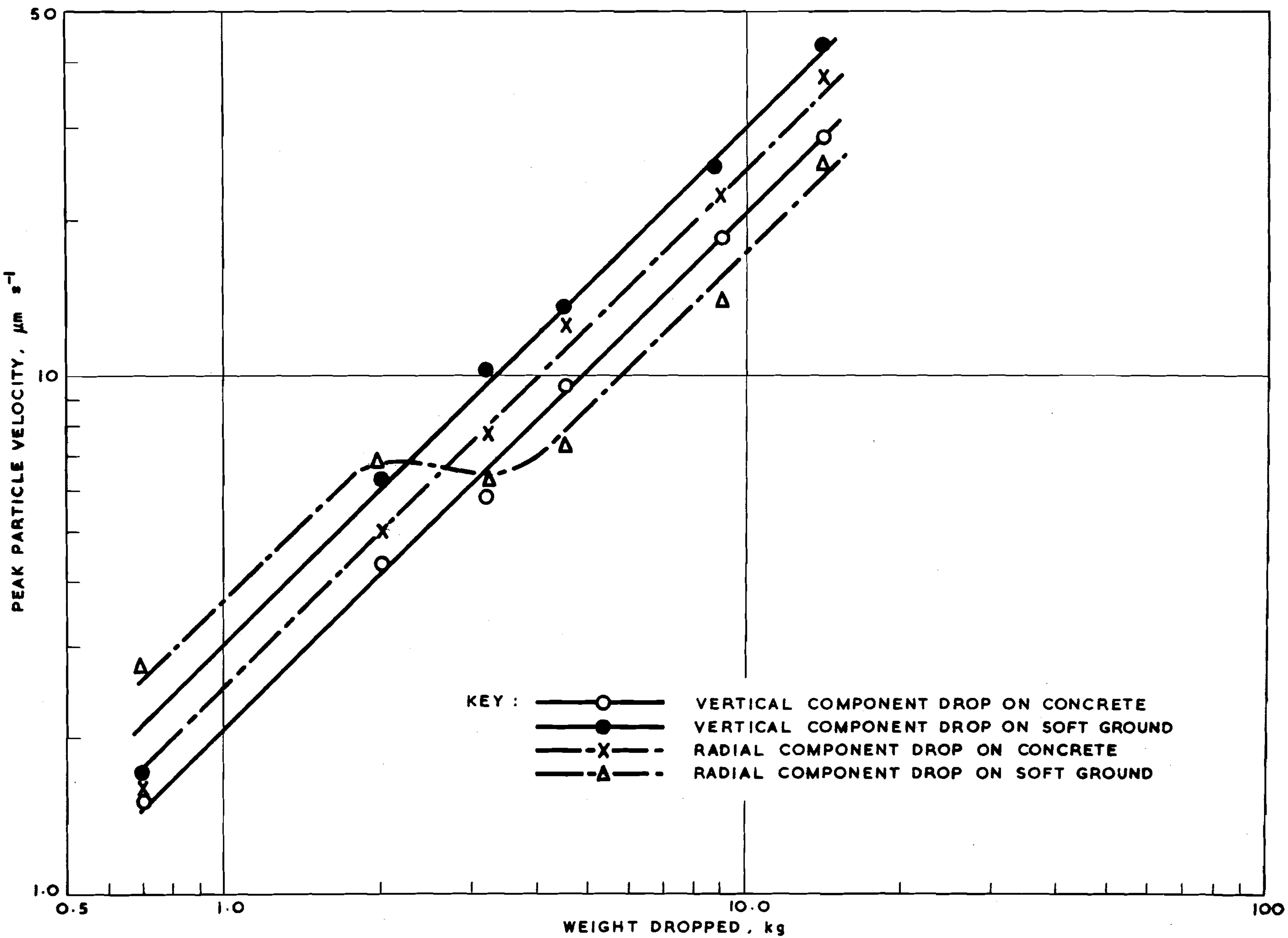


FIGURE 11. AMPLITUDE VERSUS SIZE OF WEIGHT RELATIONSHIP FOR COMPONENTS OF GROUND MOTION

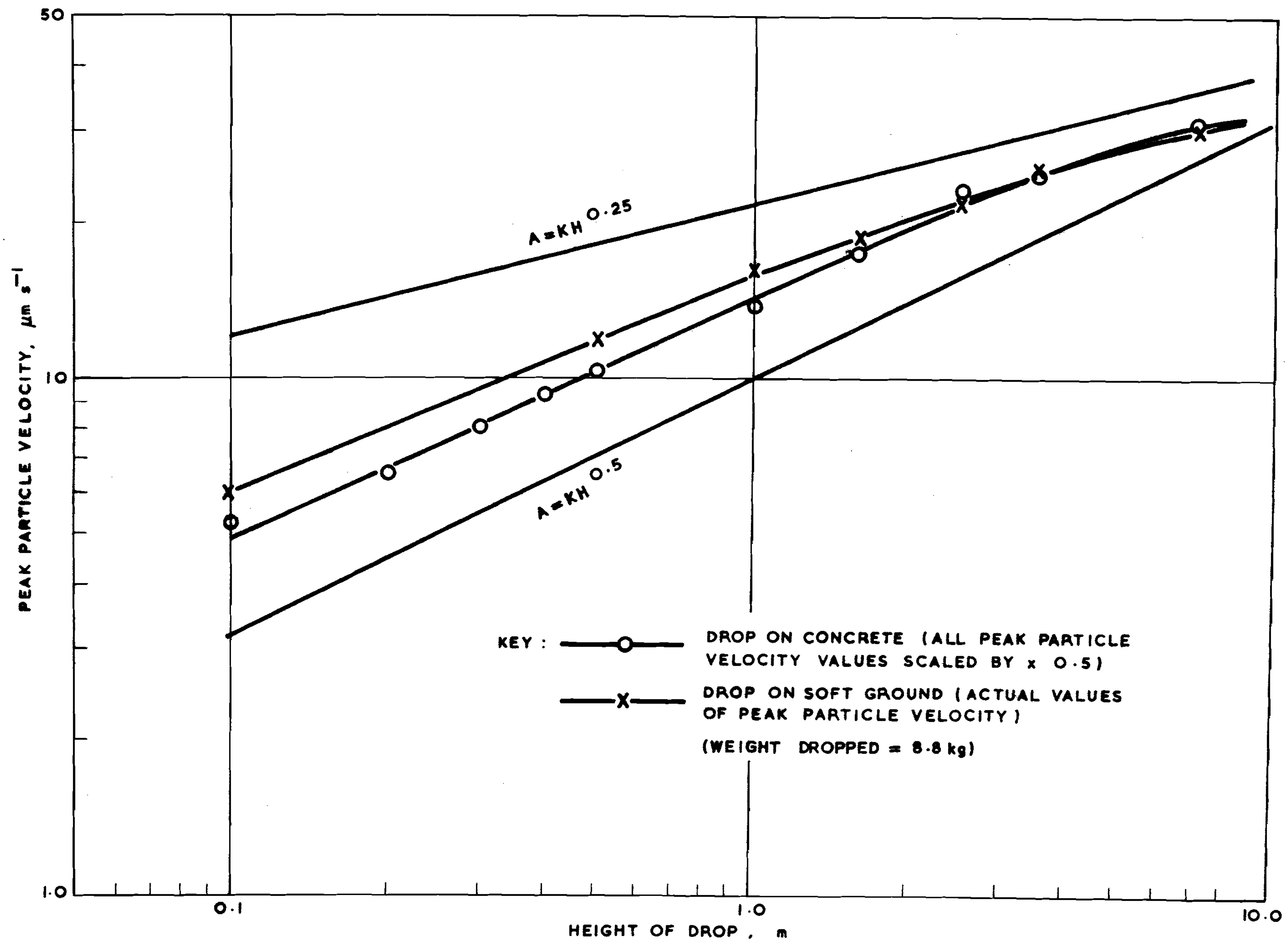


FIGURE 12. AMPLITUDE VERSUS HEIGHT OF WEIGHT RELATIONSHIP FOR VERTICAL COMPONENTS OF GROUND MOTION