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Review Paper No. 2

Ground Motion and Seismic Damage from Underground Nuclear Explosions

P J Atkins
F H Grover
K Parker
H I S Thirlaway

FOREWORD

This Review is one of a series on topics relevant to the Peaceful Uses of Nuclear Explosives (PNE) prepared by AWRE under contract to the United Kingdom Atomic Energy Authority.

The aim of the series is to provide a reasonably comprehensive review and some assessment of published work, to indicate areas of uncertainty and to provide answers to some of the questions likely to arise during the initial consideration of possible PNE projects.

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A. INTRODUCTION

A1. General

In any underground explosion - chemical or nuclear, contained or uncontained - most of the energy released is irreversibly transferred to the earth or the atmosphere in the immediate neighbourhood of the explosion point as the divergent shock wave does work on the surrounding medium. This gives rise to such effects as vaporisation, melting, crushing and fracturing of rock and heating of the atmosphere.

Eventually the stress level in the shock front falls below the elastic limit and at greater distances the amplitude of the stress wave attenuates, in accordance with the classical theory of elasticity, giving rise to seismic waves. These waves carry a relatively small proportion of the total explosion energy, typically up to 2 or 3%. The arrival of these waves at any particular surface point gives rise to transient motion generally referred to as <u>ground motion</u>. Depending on the yield of the explosion and the proximity of the surface point, the ground motion may give rise to <u>seismic damage</u> in buildings and other structures or cause landslides, rockfalls and similar phenomena where the topographical conditions are appropriate.

The social and economic consequences of seismic damage are a most important factor in the assessment of any large scale explosive engineering project. In evaluating this factor it is necessary to consider three principal problems:-

(1) The measurement and prediction of ground motion resulting from explosions.

(2) The measurement and prediction of the seismic damage resulting in specified structures as a result of a given ground motion - in short <u>the structural response</u>.

(3) The assessment and prediction of the social and economic consequences of the seismic damage resulting from the explosion(s).

Naturally there is ground motion within the inelastic, close-in region around the explosion point and this can cause very considerable damage. The arrival of strong shock waves at the ground surface or strata boundaries can give rise to <u>spalling</u> - the splitting off and acceleration of surface material by reflection of the outgoing shock wave. The present review is not concerned with these effects (nor with ground motion induced by air blast) but the reader should be warned that the literature does not always distinguish clearly between ground motion in the non-elastic region (generally outside the hydrodynamic zone) and in the elastic (seismic) region.

A2. Notes on Terminology

A variety of synonyms for ground motion and seismic damage are to be found in the literature including the following:-

Ground Shock

This term, often used as a synonym for ground motion, is open to objection because ground motion is not necessarily associated with a physical shock. True shock wave effects such as spalling are experienced only at points near the explosion but ground motion is experienced over a much wider area.

Ground Response, Earth Motion, Strong Motion, Seismic Disturbance, Seismic Motion

When used in connection with underground explosions, these terms are often synonymous with ground motion although they may refer to motions experienced beneath the ground surface (particularly in the case of strong motion). In seismology strong motion refers to motion which can be "felt" without the aid of instruments such as seismometers.

Free-Field Particle Motion

Measures of maximum radial components of particle motions in the first half-cycle of the stress wave from an explosion in a homogeneous medium of infinite extent are termed free-field particle accelerations, velocities and displacements respectively (Wh 68). These terms generally apply to the non-elastic region and are defined here only to avoid confusion when the reader consults the literature. Any measurements approximating to free-field motion must be made below the ground surface in direct line with the source.

Seismic Effects

This term may refer to ground motion, seismic damage, or both.

Damage

Damage to structures, particularly buildings, is sometimes distinguished as architectural (superficial) which is aesthetically objectionable (for example, plaster cracking in houses) or structural when the load bearing capacities of structural elements are seriously reduced or totally destroyed.

Structural Response

It is important to distinguish between the motion of any point of a structure and that of the ground on which it stands. The static and dynamic characteristics of a structure determine the structural response - the resultant amplification or damping of the ground motion which may lead to damage.

B. THE MEASUREMENT OF GROUND MOTION

B1. Seismic Waves - Nomenclature and Characteristics

"P" (Primary) waves are the first to arrive from the centre of the disturbance. These are longitudinal elastic "body" waves which transfer energy by oscillatory particle motion perpendicular to the wavefront; they have a propagation velocity varying from 1 to 8 km/s near the earth's surface to about 13 km/s in the interior - the velocities depending on the elastic properties of the medium through which they travel.

These are followed by "S" (Secondary) waves which are transverse body waves producing particle motion tangential to the wavefront. These waves travel at about 0.6 of the velocity of the corresponding "P" waves. "S" waves may also be referred to as "shear" waves.

"L" (Love) waves are horizontally polarised transverse surface waves which travel only within the earth's crust at a maximum velocity of about 4.5 km/s.

Finally, there are the Rayleigh waves which also travel near the surface (though not confined to the crust) at a maximum velocity of about 4 km/s and cause particles to execute retrograde elliptical motion.

B2. The Propagation of Seismic Waves

The small percentage of the energy which is not absorbed as heat and mechanical fracturing in the vicinity of seismic events is radiated as elastic (seismic) energy. The frequency bandwidth of the signal as recorded at a long distance is typically 1 to 10^{-2} Hz. At near distances signals up to 10^{2} Hz may be observed.

The internal boundaries of the earth subject the seismic waves to reflections and refractions which are governed approximately by the laws of geometrical optics. Because of the general increase of velocity with depth, the surface waves suffer dispersion; the result is a smooth succession of waves, with the longer wavelengths arriving earlier than the shorter. The nature of such a complex series of oscillations is controlled mainly by the characteristics of the transmission paths and only slightly by the source of the disturbance. A sharp change in velocity of body waves takes place at a depth of about 30 km under continents and 10 km under oceans; this occurs at a "layer" known as the Mohorovicic discontinuity (M). At the elastic discontinuity formed by the M and at a critical incident angle, determined by the P velocities on either side of the M, nearly all the energy from a source within the crust is carried by a wave which is "refracted" along the boundary with the velocity of the deeper layer. The amplitude of the wave is proportional to $1/R^2$ with an exponential term which brings the net result close to $1/R^3$ out to 1000 km. At ranges less than 500 km, first motion amplitudes are expected to be larger than at any greater range.

B3. The Measurement of Seismic Waves

Seismic energy radiates to all parts of the earth and can be detected at the surface by damped pendulum systems - seismometers - and recorded as seismograms by associating mechanical, optical or electromagnetic transducers with the seismometers, the whole constituting a seismograph. For a given event, the properties of the interior of the earth determine the propagation velocities and the amplitudes, and frequency spectra of seismic waves. The experimental requirement is a network of seismographs to give signal arrival times, amplitudes and frequencies on a common standard.

B4. Seismic Noise

Seismic noise may originate in the immediate neighbourhood of the station and be due to random influences such as the wind in the trees, thermal stresses in buildings, industrial and domestic activity, or it may arise from remote sources - particularly from deep oceans. Local noise may be similar in character to communications noise and can be minimised by careful choice and arrangement of the observation site, but remotely generated noise will appear as a definite source of interference whose waves will have a characteristic propagation velocity. Most of the interference experienced originates in the oceans. In addition to the effects of currents and tidal action, storms create sources of seismic disturbance, but the resultant signals from such sources have certain characteristics and are frequently coherent.

Earthquakes, and quarry and mine blasts, radiate seismic signals similar to those described for explosions. In the context of supporting measurements for PNE they also constitute an unwanted source of seismic noise.

B5. The Generation of Seismic Waves by an Explosion

When an underground explosion takes place an intense pressure wave is generated and the interaction of this with the surrounding medium is an extremely complex process, particularly at those pressure levels where the rock is being crushed or cracked. However, the pressure level decays very rapidly with distance and the stage is soon reached where the medium behaves essentially elastically, with the consequence that its behaviour is amenable to mathematical expression.

In order to avoid the complicated region immediately around the explosion point it is convenient to define around the shot point a spherical surface whose radius is chosen simply by the criterion that beyond that radius the medium behaves purely elastically.

Experimental measurements of the displacement as a function of time of this surface have been reported from US underground shots in several media and, by combining these results with predictions based upon scaling laws, a wide range of conditions can be treated.

The characteristics are a permanent displacement which is attained after an overshoot, the time scale - eg, the time to reach maximum displacement - and actual displacements varying both with the size of the explosion and with the medium. The essential features of an explosion are the radial symmetry, the relatively simple and smooth variation of displacement with time, and the absence of shear waves.

B6. Application to PNE

Measurements of ground motion for PNE projects are made in three distinct zones of the elastic region:-

(a) A numerical technique calculates the propagating stress field and resultant effects on the medium surrounding the explosive source, using in situ and laboratory analyses of the rock materials and predicted yield for input data. Seismic coupling or efficiency is obtained by calculating the displacement history of a particle in the elastic region; it is expressed in terms of the source function (reduced displacement potential) that determines the displacement of a particle at any point in the elastic region. The source function is also determined empirically by measurements made within a few tens of meters of the elastic boundary surrounding the source where the effects of transmission are minimal. An experimental estimate of yield is thereby obtained with a precision of about 10%. At greater distances from the source corrections for the propagation path must be applied, and the uncertainties involved reduce the precision of yield estimates at best to about 30%.

(b) Ground motion at a given location is, among other factors, a complex function of the geometry and physical properties of the source to receiver path. Seismic waves affecting the surface propagate through materials having, in general, large horizontal and vertical variations in these properties. Pre-shot surveys cannot always be sufficiently precise in detail to permit accurate predictions to be made. Specially arranged measurements up to distances of several tens of kilometres from the source are therefore required to compare observed with calculated ground motion, relate them to damage claims and to enlarge empirical experience for other projects.

(c) At greater distances (beyond the range of possible seismic damage) seismic measurements provide supplementary data on yield, and on transmission path characteristics. The latter are immediately useful if further explosions are planned for the area. In this case, temporary recording stations to distances of about 1000 km would be a charge on the project. Normally measurements in this zone would be adequately covered by other research interest, and beyond 1000 km any remaining requirements for seismic data would be satisfied by the permanent stations of the standard network. High quality microfilm copies of recordings are available at cost price.

One of the more important measurements to be contributed by the standard network would be on post-shot seismic activity when projects take place in seismic areas. Stress release phenomena resembling normal earthquakes follow underground explosions of 10 kton or more, but the seismic effects have always been much smaller than those of the explosion.

B7. PNE Stimulation of Earthquakes and Tsunamis

The question of whether or not large explosions could trigger earthquakes large enough to cause damage is still controversial. Only three large explosions have been detonated in a high seismic area: Longshot 80 kton, Milrow 1 Mton and Cannikin 5 Mton, all in Amchitka Island, Aleutian Islands. No unusual post-shot seismic activity followed. It could be demonstrated theoretically that earthquakes occur frequently enough in highly seismic areas to provide adequate triggering mechanisms, if they are needed. Equally, however, if they are needed, there is a finite, if small, probability of PNE explosions in seismic areas providing them. The fears about large underground explosions being the cause of earthquakes in distant seismic areas have been shown to be groundless.

Seismic sea waves (tsunamis) occur where seismic areas border ocean deeps - as in the case of the Aleutian Islands. They are generated by widespread and step-like changes in the level of the sea floor; underground explosions could be held responsible only if they were responsible for earthquakes which cause the sea-floor displacement.

C. FACTORS AFFECTING GROUND MOTION

As will be seen from Sections A and B the ground motion observed at any receiving station is a complex function of many variables. Some of these will now be discussed in more detail.

C1. Variables at the Explosion Point

Commencing with the explosive, variables include the type of explosive (nuclear, chemical, type of chemical, etc) and its yield (total energy release). Next to be considered is the way in which the explosion is presented, and variables include the physical extent of the explosive (point or extended source), the depth, whether in direct contact with surrounding rock or fired in a cavity; and finally variables exist in the geology of the surrounding medium. Broadly speaking these parameters determine the proportion of the yield which is released in the form of elastic waves; the fraction of total energy release converted into seismic energy is called the seismic energy efficiency. For the same yield the seismic energy efficiency is generally greater for chemical explosives than for nuclear explosives in cratering explosions, and probably also in contained explosions. The amount of seismic energy propagated from the explosion point is reduced when the surrounding medium has a dry void content (Sp 65, Sp 66) and in the limit this can be represented by a contained underground explosion made at the centre of a large spherical cavity, when the seismic energy efficiency may be reduced by a factor of several hundreds. The phenomenon is known as decoupling, but this is not usually of importance in nuclear explosive engineering where maximum use of the available energy is sought.

It was confirmed from the Gasbuggy and Rulison experiments that the seismic energy efficiency increases with increasing explosive emplacement depth, for the same yields in a given medium, so that cratering explosions are likely to give rise to least ground motion. This is confirmed by observation and by theory (Section D4).

The derivation of seismic energy efficiencies for underground nuclear and chemical explosions has been discussed by a number of authors. A good account is that by Mueller (Mu 69b) which contains references to earlier work. He approximates the explosion by a spherically symmetric negative exponential pressure function acting at the elastic radius (that radius beyond which the medium responds elastically), calculates the elastic wave motion caused by this input and derives the seismic energy in terms of the pressure, the elastic radius and the elastic constants of the medium. The pressure and elastic radius are derived from explosion data, including close-in free-field data and far-field seismic data. Table C1 gives values of seismic energy efficiencies derived by Mueller and others for representative underground nuclear explosions. The lower efficiencies from cratering (Danny Boy, Sedan, Schooner) and decoupled (Sterling) events are clearly demonstrated. All derivations of seismic energy efficiencies involve certain approximations and some caution is necessary in comparing values derived by different methods. For example, the very different efficiencies for Danny Boy and Boxcar seem difficult to explain on scaled data alone. There is some evidence that seismic energy efficiency increases with yield as well as with depth of burial although Mueller's method of calculating seismic energy efficiency appears to give higher values than obtained by other workers.

TABLE C1

Seismic Energy Efficiencies

Event	Explosion Medium	Yield, kton	Scaled Depth of Burial, ft/kton$^{1/3}$	Seismic Energy Efficiency, %	Reference
Scooter (HE)	Alluvium	0.5	152	0.80	Mi 63
Danny Boy	Basalt	0.42	147	0.35	Lo 64
Sedan	Alluvium	100	137	0.06	Mi 63
Schooner	Tuff	35	107	0.32	Mu 69b
Hardhat	Granite	4.9	553	{ 0.15 2.0	Mi 67 Tr 66
Shoal	Granite	13.1	519	{ 1.8 0.7	Mu 69b Tr 66
Handcar	Dolomite	12	577	{ 0.3 2.01	Mi 64 Pe 69
Benham	Tuff	1100	467	4.2	Fo 70, Mu 69b
Boxcar	Rhyolite	1200	359	3.4	Fo 70, Mu 69b
Gasbuggy	Lewis shale	29	1380	{ 1.56 2.6	Pe 69 Fo 70
Rulison	Mesaverde shale	40	2469	3.3	Fo 70
Gnome	Salt	3.4	787	2.2	Ca 62b
Salmon	Salt	5.3	1552	{ 0.47 5.8	Mu 67 Mu 69b
Sterling (decoupled)	Salt	0.38	3751	{ 0.0084 0.019	Mu 69b Pe 68

HE = High explosive (chemical)

C2. Variables Relating to the Travel Path

The variables relating to the travel path have been discussed in Section B.

C3. Variables Relating to the Receiving Station

While peak ground displacements, velocities and accelerations might reasonably be expected to depend primarily on yield and straight-line distance from the explosion to the receiving station, it is a fact that considerable variations are experienced at equidistant stations. In particular, receiving stations situated on alluvium and other loosely packed materials experience considerably stronger ground motion than stations on hard rock, due to local amplification of the incoming seismic waves.

D. ANALYSIS AND PREDICTION OF GROUND MOTION

D1. Introduction

In characterizing ground motion as distinct from any resulting damage it is a natural first step to consider quantities which are either directly measurable or are easily derivable from measurements. The main parameters of interest are:-

Peak particle displacement

Peak particle velocity

Peak particle acceleration

Frequency content of ground motion

Later work has concentrated chiefly on derived functions that can be more easily correlated with building damage (Sections D9 to D15) and only an outline of the early work will be given here.

D2. Formulae for Seismic Peak Amplitudes

The most extensive analysis of seismic peak amplitudes appears to be that by Murphy and Lahoud (Mu 69a). This uses data for 99 underground nuclear explosions (98 at the Nevada Test Site together with the Faultless event in central Nevada) with yields ranging between 1 and 1200 kton and source-to-station distances between 0.25 and 600 km. In the case of free-field (radial) motion dimensional analysis leads to relations in the form

$$dW^{-1/3} = f_1(R/W^{1/3}) \qquad \text{D-1}$$

$$v = f_2(R/W^{1/3}) \qquad \text{D-2}$$

$$aW^{1/3} = f_3(R/W^{1/3}) \qquad \text{D-3}$$

where d, v and a are peak displacement, velocity and acceleration, W is the yield and R is the distance. It is possible to analyse the data using power law forms for the functions f_1, f_2 and f_3, and this was done in much of the early work, but the exponents are only constant over very limited regions of scaled ranges. Moreover, these cube-root scaling laws fail once surface (reflection) effects introduce characteristic lengths which do not scale with yield. Because of these limitations it is now usual to analyse peak amplitudes in terms of the functional relationship

$$A = KW^nR^{-m} \qquad \text{D-4}$$

A is the peak amplitude while K, m and n are constants. The results of Murphy and Lahoud's analysis are shown in table D1. The presentation reflects the fact that after yield and distance the most significant cause of variation is the type of geological medium at the receiving station (Da 67). The regression analysis is made in logarithmic space so that the standard errors are percentage errors. The fits to data from events with yields exceeding 200 kton are very little different from those for all events, indicating that the exponents show no substantial yield dependence.

TABLE D1

Regression Equations for Peak Amplitudes, Contained Nuclear Explosions

Type of Motion	Station Media	Equations: *$A = KW^nR^{-m}$	Number of Data Points	Standard Error of Estimate	95% Confidence Intervals on Exponents
Acceleration	Total	$a = 1.09 \times 10^{-1}W^{.61}R^{-1.43}$	N = 1207	σ = 2.33	n ± 0.034 m ± 0.038
	Alluvium	$a = 9.00 \times 10^{-2}W^{.624}R^{-1.36}$	N = 819	σ = 2.13	n ± 0.050 m ± 0.078
	Hard rock	$a = 1.57 \times 10^{-1}W^{.656}R^{-1.68}$	N = 388	σ = 2.54	n ± 0.044 m ± 0.050
Velocity	Total	$v = 4.92 \times 10^{0}W^{.646}R^{-1.34}$	N = 509	σ = 2.13	n ± 0.044 m ± 0.050
	Alluvium	$v = 5.10 \times 10^{0}W^{.635}R^{-1.31}$	N = 400	σ = 1.97	n ± 0.046 m ± 0.050
	Hard rock	$v = 3.36 \times 10^{0}W^{.77}R^{-1.51}$	N = 109	σ = 2.42	n ± 0.062 m ± 0.140
Displacement	Total	$d = 4.19 \times 10^{-1}W^{.761}R^{-1.18}$	N = 1072	σ = 2.29	n ± 0.034 m ± 0.042
	Alluvium	$d = 4.49 \times 10^{-1}W^{.767}R^{-1.14}$	N = 767	σ = 2.20	n ± 0.040 m ± 0.044
	Hard rock	$d = 3.78 \times 10^{-1}W^{.852}R^{-1.39}$	N = 305	σ = 2.19	n ± 0.060 m ± 0.082

*The units of acceleration (a), velocity (v) and displacement (d) are g, cm/s and cm, respectively; R is the distance in kilometres and W is the yield in kton.

As far as the Nevada Test Site is concerned and for predictions in similar geological situations the formulae of table D1 are probably the best available, superseding those of Davis (Da 65a) and other workers mentioned in Murphy and Lahoud's paper. However, it should be noted that considerably different values of K, m and n may lead to data fits which are almost as good as those of Murphy and Lahoud (Mu 69a), particularly when the large values of the (multiplicative) standard errors are considered. For example, Cloud and Carder (Cl 69) find

$$a = 1.6 \times 10^{-1}\ W^{0.75}\ R^{-2}\ \text{g} \qquad \text{D-5}$$

$$d = W^{0.85}\ R^{-1.73}\ \text{cm (hard rock receiving station)} \qquad \text{D-6}$$

$$= 3\ W^{0.85}\ R^{-1.73}\ \text{cm (deep alluvium receiving station)} \qquad \text{D-7}$$

in an analysis covering events with yields from a few tons up to a megaton.

In attempting to separate the effects of the explosion medium and geology at the receiving station Power* (Po 67c) writes the constant K of equation D-4 in the form

*See also Kn 69, page 229.

$$K = \ell s K',$$

where K' is another constant,
ℓ is the local geology response factor,
s is the source coupling efficiency.

Values of ℓ are 3.0 to 3.4 at alluvium receiving stations as compared to 1.0 at hard rock stations, while relative source couplings, s, are calculated using curves for "b" displacements of P-waves calculated by Springer (figures 6 and 7 of Sp 65 or Sp 66). Power's specific purpose was the calculation of peak particle velocities for yields of 1 Mton. The maximum variation in K as ℓ and s vary is about 100.

D3. Frequency Spectra

The frequency spectra of ground motion are perhaps most conveniently considered by means of response analyses. Since these analyses are of importance in determining structural response and seismic damage they are considered separately in section D9 to D15 and the present discussion is limited to a few general remarks.

Considering idealised seismograms composed of harmonic components, it is clear that peak particle velocities occur at lower frequencies than peak particle accelerations, while peak particle displacements occur at still lower frequencies (Mu 69a). Since there is experimental and theoretical evidence (Mo 64, Mu 70a) that the amplitude of low frequency components increases more rapidly with yield than high frequency components, it is not unexpected to find from table D1 that yield exponents increase in magnitude in the order acceleration-velocity-displacement. Again there is experimental (Ca 62a, Ly 69a, Ly 69b) and theoretical (Ew 57) evidence that high frequency components decay more rapidly with distance than low frequency components and this explains why the absolute value of the distance exponents in table D1 decreases from acceleration to velocity to displacement. Low frequency components are enhanced relative to high frequency components by going to higher yields and greater distances. These simple qualitative results go far to explain observed values of peak ground motion - acceleration, velocity and displacement; they are conveniently summarised in table D2.

TABLE D2

Qualitative Dependence of Ground Motion on Frequency Content of Seismic Waves

Variation	Low Frequencies (say < 2 Hz)	Moderate Frequencies (say 2 to 10 Hz)	High Frequencies (say > 10 Hz)
Increased yield	Relatively enhanced		Relatively reduced
Increased range	Attenuation	Greater attenuation	Still greater attenuation
Greater depth of explosion*	Relatively reduced		Relatively enhanced
Important component of ground motion	Displacement peaks	Velocity peaks	Acceleration peaks

*See discussion in Section D4.

D4. Theoretical Analyses

Many theoretical examinations of seismic wave propagation represent the source as a spherically symmetric pressure function acting at an elastic radius from the explosion, beyond which the medium behaves elastically. A fairly recent example is that of Mueller and Murphy (Mu 70a). They concentrate on comparing observations at a common distant receiving station from two nearby events and therefore are able to eliminate the transmission function (approximately equal in the two cases) describing transfer of seismic energy from the source to the receiving station. There follows a widely applicable general theory for the scaling of ground motions resulting from underground nuclear explosions. Amongst the predictions of the theory are:-

(a) An increase in the dominant frequency and peak ground acceleration with depth of burial of the explosive so that cratering explosions give rather weaker peak ground acceleration than typical contained explosions, while "overburied" explosions such as Gasbuggy and Rulison give stronger peak ground acceleration.

(b) Frequency dependent exponents for the variation of ground motion with yield typically range from 0.90 at high frequencies to 0.45 at low frequencies.

(c) Yield scaling exponents as a function of frequency which agree reasonably well with those derived from a statistical analysis of pseudo-relative velocity data from nuclear detonations at the Nevada test site.

(d) Yield scaling exponents for peak particle vector accelerations (0.53) and displacements (0.76) which agree reasonably well with those given in table D1 (same scaled depth of burial).

(e) Depth of burial scaling exponents for peak particle vector accelerations and displacements of +0.58 and -0.33 respectively:-

$$\frac{a_1}{a_2} = \left(\frac{h_1}{h_2}\right)^{0.58} \left(\frac{W_1}{W_2}\right)^{0.33} \qquad \text{D-9}$$

$$\frac{d_1}{d_2} = \left(\frac{h_2}{h_1}\right)^{0.33} \left(\frac{W_1}{W_2}\right)^{0.87} \qquad \text{D-10}$$

(f) Ground motion values for Gasbuggy and Rulison derived by scaling Nevada Test Site data which agree fairly well with observation.

D5. Free-Field Motions

Although this review is not concerned with free-field particle motions as such, it is of interest to know the ranges within which the concept of free-field motion is valid. Relevant information has been collected by Wheeler and Preston (Wh 68) and analysed using formulae D-1, D-2 and D-3. In alluvium formula D-3 holds for $R/W^{1/3} <$ 175 ft/kton$^{1/3}$; between 175 and 420 ft/kton$^{1/3}$ the peak particle acceleration arises from the elastic precursor to the main stress wave and $a = KW^{0.4} R^{-1.2}$. For peak velocities and displacement a change in slope occurs at a distance of 350 ft/kton$^{1/3}$. Generally speaking, data are available up to ranges between 2000 and 4000 ft/kton$^{1/3}$ in several media. At greater distances it is the peak displacement which most closely follows a free-field scaling law (Ad 61, Mu 69a), a fact which is consistent with the relative insensitivity of long wavelengths (low frequencies) in inhomogeneities in the medium and the tendency of peak displacement to occur at low frequencies. For the same reason peak velocity follows the cube root scaling law more nearly than peak acceleration.

D6. Chemical and Nuclear Explosions

A point of some interest is the comparison of ground motion from chemical and nuclear explosions. Although no comprehensive theory appears to exist there is a certain amount of empirical information. Most of the chemical explosives data are for cratering explosions; there have been few completely contained chemical explosions.

Mickey (Mi 63, page 19) computes seismic energy efficiencies for Scooter and Danny Boy, respectively chemical and nuclear explosive cratering events with nearly equivalent yields at the same scaled depth. The results (0.8 and 0.21% respectively) suggest that coupling is about four times greater than in the nuclear case, particularly since Danny Boy was fired in basalt which perhaps would be expected (Sp 65, Sp 66) to produce greater coupling than the alluvium of the Scooter site. Pasechnik et al. (Pa 60) estimated that nuclear explosions produce $\frac{1}{4}$ to $\frac{1}{2}$ of the seismic energy of high explosive cratering detonations with the same yield.

A series of chemical explosions in the 180 to 6200 lb range, fired prior to Gnome, produced higher frequencies, lower displacements and higher accelerations than expected from predictions based on higher yield events (Ca 62a, Ca 62b, Sw 62).

A preliminary to the Rainier 1.7 kton underground nuclear explosion seismic measurements was a completely contained 50 ton high explosive detonation on which seismic measurements were made. The derived predictive formula generally overestimated the close-in, strong motion from Rainier measured by Carder and Cloud (Ca 59) and provides some evidence that contained chemical explosions give larger ground motion than nuclear explosions of the same yield. The formula also overestimated the yield of a 125 ton high explosive cratering experiment but this can be explained on the basis that ground motion effects increase as the emplacement depth is increased.

D7. Data for Contained Explosions in Media other than Tuff and Alluvium and off NTS

For PNE applications it will be necessary to take into account various geological environments and it is useful to consider the following data (most of the NTS measurements are for explosions in alluvium or tuff, with a few in granite, rhyolite, dolomite and limestone):-

Explosions in Salt

Data are available from the high explosive Cowboy experiments and from the nuclear explosive Gnome (Ca 62b, Sw 62) and Salmon (Be 65, Mi 67) events (including preliminary experiments with high explosives). Data from the decoupled Sterling event (Da 68) are not directly applicable but may be used to derive yield scaling factors. On the basis of so few events the best predictive equations that can be derived are (Da 68):-

$$a = 3.38 \times 10^{0}\ W^{0.32}\ R^{-1.95}\ \mathrm{g} \qquad \text{D-11}$$

$$v = 3.92 \times 10^{1}\ W^{0.55}\ R^{-1.64}\ \mathrm{cm/s} \qquad \text{D-12}$$

$$d = 1.05 \times 10^{0}\ W^{0.87}\ R^{-1.60}\ \mathrm{cm.} \qquad \text{D-13}$$

These formulae, which obey cube root scaling laws, do not allow for alluvial amplification at the receiving station, nor do they take account of the different frequency content of the seismic energy from the events on salt. They do give higher values of a, v and d than the general formulae of table D1.

Explosions in Granite

Explosions in granite include Shoal, Hardhat, Piledriver and the French nuclear explosions in the Hoggar massif of the Sahara. Of the American explosions, detailed ground motion results seem to have been published only for Shoal (Be 64), the radial exponent having values -1.85, -2.00 and -1.55 for peak acceleration, velocity and displacement respectively. For Sahara granite Guerrini and Garnier (Gu 69) give formulae based on cube root scaling for scaled ranges up to 1 km/kton$^{1/3}$:-

$$a = 2.2\ W^{0.48}\ R^{-2.44}\ \mathrm{g} \quad {}^{+\,60\%}_{-\,40\%} \qquad \text{D-14}$$

$$v = 10\ W^{0.58}\ R^{-1.73}\ \mathrm{cm/s} \quad {}^{+\,50\%}_{-\,30\%} \qquad \text{D-15}$$

$$d = 0.2\ W^{0.8}\ R^{-1.40}\ \mathrm{cm} \quad {}^{+\,40\%}_{-\,30\%}. \qquad \text{D-16}$$

At distances between 15 and 50 km the peak velocity is given by (Fe 70a, Fe 70b):-

$$v = (4.26 \pm 1.06)\ W^{0.85}\ R^{-(1.3 \pm 0.1)}\ \text{cm/s} \qquad \text{D-17}$$

for W less than 20 kton.

$$v = 11.8\ W^{0.51}\ R^{-1.3}\ \text{cm/s} \qquad \text{D-18}$$

for W greater than 20 kton.

The French results suggest that for a given energy, ground motion induced is lower for explosions in tuff, and lower still for explosions in alluvium.

Explosions in Dolomite

Data are available only for the 12 ± 1 kton Handcar event (En 68, Mi 65).

Explosions in Sandstone/Shale/Siltstone

Data from the Gasbuggy and Rulison experiments are important in that they refer to a further explosion medium and to much greater ("overburied") depths than most other available data. Results from the Rio Blanco shot (17 May 1973) are not yet available.

Experimental data for Gasbuggy have been reported by three groups of workers (Na 68, Fo 69, Pe 69). Predictions were based on the formulae derived by Davis (Da 65) for the Pahute mesa modified by a multiplicative factor of 4 in the case of peak surface particle displacement. These formulae led to general underprediction of peak vector acceleration and overprediction of vector displacement, with peak vector velocity reasonably well predicted. Departures from NTS experience can be broadly accounted for by the seismic spectrum scaling theory of Mueller and Murphy (Mu 70a).

The ground motion experienced at Rulison has been summarised by Loux (Lo 70). Data are reported by the Environmental Research Corporation (En 69) and by Navarro and Wuollet (Na 70). Foote et al. (Fo 70) give a comprehensive analysis. Again the great depth of burial enhances high frequency seismic motion giving higher velocities and still higher accelerations for the same yield than experienced at the Nevada Test Site or even at Gasbuggy. Predictions for Rulison (We 69) were obtained by scaling Gasbuggy results with yield according to the exponential dependence determined at the Nevada Test Site (see table D1). The post-shot analysis (Fo 70) showed:-

(a) Good agreement between predicted and observed peak particle velocities and displacements, but peak particle accelerations slightly higher than predicted.

(b) Accelerations and velocities significantly in excess of those expected on NTS experience alone, but displacements some 20% less at 10 km.

(c) Improved predictions when Gasbuggy data are scaled for yield and emplacement depth (8625 ft at Rulison, 4240 ft at Gasbuggy), all of which can be largely, but not completely, explained on the basis of seismic scaling theory (Mu 70a) as due to the greater depth of burial and the increased seismic energy efficiency (see table D1) of the dense sedimentary formations in which Gasbuggy and Rulison were exploded. The report by Foote et al. (Fo 70) discusses predictions of peak particle motion for other yields and emplacement depths in media similar to those at Gasbuggy and Rulison. These predictions are given in detail by Whipple and Williams (Wh 70) for yields of 40, 80 and 120 kton and depths of burial of 4000, (2000) and 12000 ft. The scaling factors applied to hard rock observed values from Rulison for peak displacements and accelerations are those of equations D-9 and D-10 respectively, although the exponent of 0.33 for yield in D-10 is probably too low (see table D1). The scaling factor for peak velocity is derived from those applying to pseudo-relative velocity (see section D10).

D8. Cratering Explosions

Data are available from a considerable number of high explosive experiments and from six nuclear explosions; references for the latter are given in table D3.

TABLE D3

Ground Motion Data for Nuclear Cratering Events

Event	Date	Yield, kton	Medium	References
Danny Boy	5.3.62	0.42	Basalt	Lo 64
Sedan	6.7.62	100	Alluvium	Mi 63
Palanquin	14.4.65	4.3	Rhyolite	Da 65b
Cabriolet	26.1.68	2.3	Rhyolite	Kl 69
Buggy	12.3.68	5 × 1.1 (row)	Basalt	Ca 69
Schooner	8.12.68	35	Tuff	Ha 69

In cratering events the dominant seismic energy shifts to lower frequencies as compared with contained (more deeply buried) events. As expected from table D2, peak velocities and accelerations are lower than in contained events of the same yield. Over and above the spectrum change it appears (Mu 70a) that cratering explosions produce less ground motion than contained explosions of the same yield. This is reasonable in that as the scaled depth decreases so should the seismic energy efficiency of the explosion (Mu 69b); that this is generally the case can be seen from table C1. Other results from cratering explosions are:-

(a) The predictive formulae of table D1 give conservative values of peak ground motion for cratering events at NTS and it seems likely that this would be true for predictive formulae for contained explosions applied to cratering explosions at sites away from NTS.

(b) The predictive equations (Kl 69) shown in table D4, based on analysis of data from Danny Boy, Sedan, Palanquin and Cabriolet, gave reasonable predictions for Schooner.

TABLE D4

Regression Equations for Peak Amplitudes, Cratering Nuclear Explosions

Type of Motion	Station Media	Equations	Number of Data Points
Acceleration	Alluvium	$a = 3.21 \times 10^{-2} W^{.497} R^{-1.30}$	16
	Hard rock	$a = 1.94 \times 10^{-1} W^{.300} R^{-1.64}$	16
Velocity	Alluvium	$v = 9.86 \times 10^{-1} W^{.724} R^{-1.15}$	18
	Hard rock	$v = 9.79 \times 10^{-1} W^{.475} R^{-1.80}$	8
Displacement	Alluvium	$d = 9.76 \times 10^{-2} W^{.818} R^{-1.02}$	19
	Hard rock	$d = 1.53 \times 10^{0} W^{.600} R^{-1.70}$	18

Units of acceleration velocity and displacement are g, cm/s and cm respectively; R is in km and W in kton.

These equations should be used with caution since they are based on so few data points.

(c) The peak ground motion from a row charge explosion (for example, Buggy) of n times W kton is intermediate between, but closer to, that from a single explosion of W kton than to that from a single explosion of nW kton (Ca 69). Moreover, at Buggy there were no measurable azimuthal asymmetries in the seismic data.

D9. The Concept of Spectral Response Functions

Peak values of the ground (particle) acceleration, velocity and displacement are of considerable value in characterising ground motion, but for estimations of damage the response of structures must be considered. The ground motion itself is measured with seismometers having non-uniform response to frequency and which are subject to noise. From the seismograph records, corrected as far as possible for instrument response and noise, it is possible to derive several functions which characterise the ground motion.

D10. Damped Spring Response Spectra

In many cases it is valid to consider a structure as a linear combination of single-degree-of-freedom systems having elasticity and damping.

Consider the single-degree-of-freedom structure described by

$$m\ddot{y} + c\dot{y} + ky = 0 \qquad \text{D-19}$$

where m is the mass, k the stiffness, c the damping coefficient and y the displacement relative to the ground from some static equilibrium position. On displacement of the ground by distance x the equation of motion becomes

$$m\ddot{y} + c\dot{y} + ky = - m\ddot{x} = P(t) \qquad \text{D-20}$$

where P(t) is the effective external force.

The solution of D-20 can be written in the form

$$y = \frac{1}{m\omega_D} \int_0^t P(\tau)e^{-\beta\omega(t-\tau)} \sin [\omega_D(t - \tau)]d\tau \qquad \text{D-21}$$

where $\omega = (k/m)^{\frac{1}{2}}$ is the circular frequency of undamped motion,
$\omega_D = \omega(1 - \beta^2)^{\frac{1}{2}}$ is the damped frequency,
$\beta = c/2m\omega$ is the damping ratio.

D-21 is valid for $c < c_c = 2m\omega = 2\sqrt{km}$, the critical damping coefficient. The natural frequency f and the period T of undamped motion are given by

$$f = \omega/2\pi = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad \text{D-22}$$

$$T = 1/f = 2\pi/\omega = 2\pi\sqrt{(k/m)} \qquad \text{D-23}$$

By suitable manipulation of D-21 ("Duhamel's integral"), peak values of absolute and relative displacement, velocity and acceleration can be obtained. These will be denoted in the following by AD, RD, AV, etc.

In addition to these six response spectra, there are two further important spectra which, as their names pseudo-relative velocity (PSRV) and pseudo-absolute acceleration (PSAA) imply, approximate under most conditions to the relative velocity (RV) and absolute acceleration (AA) spectra respectively.

<u>(Peak) Pseudo-Relative Velocity (PSRV)</u>

This is defined by

$$PSRV(\omega,\beta) = \omega_D RD(\omega,\beta) \qquad \text{D-24}$$

<u>(Peak) Pseudo-Absolute Acceleration (PSAA)</u>

This is defined by

$$PSAA(\omega,\beta) = \omega^2 RD(\omega,\beta) \qquad \text{D-25}$$

D11. Relation of Basic Response Spectra and Pseudo-Spectra

It can be shown that there must be a finite value of ω, say ω^+, for which RV = PSRV (Je 64). For underground nuclear explosions ω^+ usually lies between 6 and 10 while for earthquakes ω^+ is generally in the range 10 to 20. ω^+ may vary substantially and the approximation RV = PSRV is good over a much wider range of ω in undamped systems than in highly damped systems. Also, RV = PSRV if the following approximations are made:-

(i) β small so that $\beta' = \beta(1 - \beta)^{-\frac{1}{2}} \approx \beta$.

(ii) In the equation for RV (first differentiation of D-21) the term β' is dropped and

$\cos \omega_D(t - \tau)$ is replaced by $\sin \omega_D(t - \tau)$.

The justification for this last approximation is that it gives reasonable results in practice (Mu 62) and enables all quantities to be expressed in terms of the same integral, namely

$$S_V(\omega,\beta) = \underset{t}{\text{Max}} \left| \int_0^t a(\tau)e^{-\beta\omega(t-\tau)} \sin \omega(t - \tau)d\tau \right|. \qquad \text{D-26}$$

In the equation for RD, ie, the peak absolute value of y in D-21, ω_D is replaced by ω on the assumption that β is small $\left[\omega_D = \omega(1 - \beta^2)^{\frac{1}{2}}\right]$.

From equations D-24, D-25 and D-26 it follows that:-

$$RD(\omega,\beta) = S_V(\omega,\beta)/\omega \qquad \text{D-27}$$

$$RV(\omega,\beta) = PSRV(\omega,\beta) = S_V(\omega,\beta) \qquad \text{D-28}$$

$$AA(\omega,\beta) = PSAA(\omega,\beta) = \omega S_V(\omega,\beta) = \omega^2 RD(\omega,\beta), \qquad \text{D-29}$$

and these three functions are related in a simple harmonic fashion (+ ω^2 in D-29 because the absolute value is considered). The validity of the approximation has been demonstrated by Hudson (Hu 62) in the case of earthquake motion.

In Section E it will be seen that PSRV and PSAA are significant indicators of likely seismic damage in many cases. A considerable effort is now devoted to the measurement and prediction of these quantities.

D12. Representation of Peak Spectral Response Functions

Figure 1 (page 24) shows a typical peak spectral response function S_V plotted on the four way logarithmic graph paper which is very useful for representing such functions. From D-27, D-28 and D-29 it follows that:-

$$\log RD = \log PSRV - \log \omega \qquad \text{D-30}$$

$$\log PSAA = \log PSRV + \log \omega, \qquad \text{D-31}$$

so that the three quantities can be represented on logarithmic paper by using log RD and log PSAA axes at ± 45° to the log PSRV axis. In the particular example shown the peaks of PSAA, PSRV and RD occur for decreasing frequencies as expected, but in this case the three frequencies concerned are practically equal.

D13. Derivation of PSRV from Seismographs

Seismograph data can be analysed using either analog or digital computers. Various methods have been described by, amongst others, Hudson (Hu 62), Jenschke et al. (Je 64), Schopp (Sc 66), Frock et al. (Fr 68) and Kennedy (Ke 69b, Ke 69c).

D14. Fourier Spectra

Jenschke et al. (Je 64) have investigated the use of Fourier spectra as indicators of structural response although it is immediately obvious that the transformation does not include any structural function. These investigations were limited by the lack of a computer program to generate the inverse Fourier transform.

D15. Power Spectral Density

There have been investigations into the value of power spectral density (PSD) as a characterisation of seismograms (Je 64, Po 69). The concept is of considerable importance in random noise theory (Be 58), the terminology deriving from the concept of the power developed by a current flowing under unit resistance.

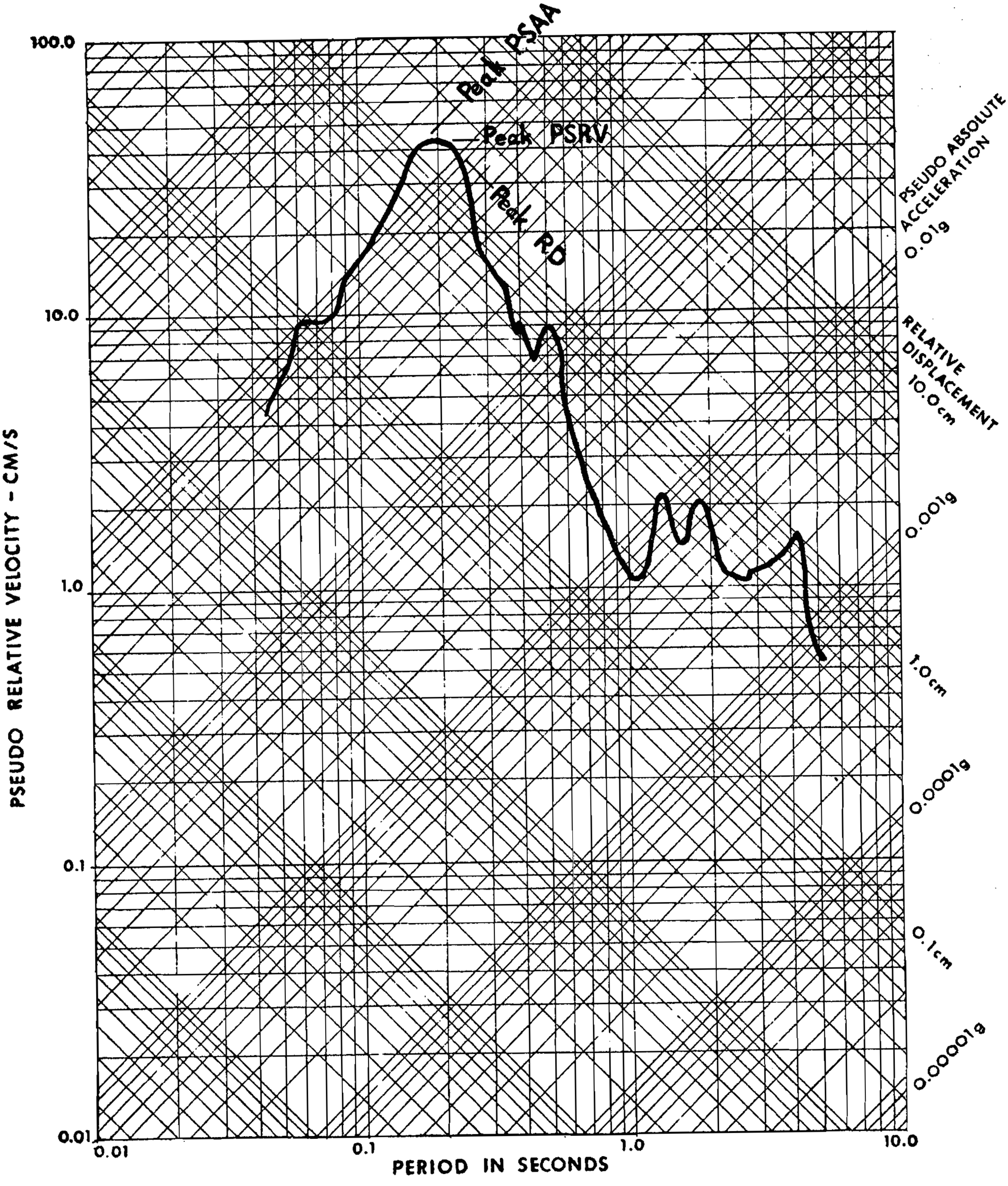

FIGURE D1. TYPICAL PEAK SPECTRAL RESPONSE FUNCTION, S_V

Data are for radial component at Rulison, 9 km
from surface ground zero
Damping is 5% (β = 0.05)

E. SEISMIC DAMAGE

E1. Introduction

Blasting operations using chemical explosives have been employed in civil engineering, mining and quarrying for many years. Safety and damage criteria have been developed chiefly from empirical data. These criteria usually depend on estimates of ground motion velocity and period. For example, the USA have employed for residential type structures a criterion $(\text{acceleration})^2 \times (\text{frequency})^{-2} = 1$ for negligible damage in the frequency range 1 to 10^3 Hz approximately. This criterion is called the "energy ratio" (ER), although its dimensions are clearly those of velocity squared (ER = 1 is equivalent to 4.8 cm s^{-1}).

With the advent of PNE it was recognised that the time history of ground motion from nuclear explosions would not be the same as that from chemical explosions, and particularly that low frequencies would be enhanced. Nevertheless, the ER criterion was used in estimating damage from early PNE shots. The concept of a damage threshold of 5 to 10 cm s^{-1} was "rudely shattered" as a result of the Salmon explosion in a salt dome near Hattiesburg, Mississippi, on 27 October 1964 (Ho 71). Claims for damage to 40% of buildings were made at velocity contours down to 1.0 cm s^{-1} or rather less.

Since the Salmon shot, a great deal of work has been done to understand the mechanism of building damage and to find ground motion parameters which would be correlated with it.

Experimental work has been carried out at the Nevada Test Site and the surrounding off-site areas, including the city of Las Vegas, and on the PNE shots to date. Some Russian and French data are also available. Most of the work, however, has been in the form of mathematical analyses of building response to the ground motion spectra. Finally, methods have been developed of estimating by computer the probability distribution of building damage over large areas or even whole countries.

E2. Categories of Seismic Damage

The damage to structures from ground motion can vary from, say, slight cracking of plaster and mortar, similar to what often happens to a building through normal ageing, to the catastrophic destruction typical of major earthquakes. For PNE investigations damage is often divided between "architectural", which may be undesirable and annoying, but does not breach the integrity of the structure as a whole, and "structural", which is defined as that which impairs the function and use of a structure.

This division is obviously somewhat arbitrary in practice since it reflects neither the attitudes of the occupants nor the costs of compensation or repair of buildings.

E3. Damage Indicators and Correlation with Damage

It will have been seen from Section D that if certain simplifying assumptions are made, ground motion can be described in terms of simple oscillators covering a fairly narrow frequency band, roughly from about 0.1 to 100 Hz. Any energy from nuclear explosions outside this band is regarded as small enough to be neglected, although for small chemical explosions frequencies up to 1000 Hz may be important.

In a similar manner, any surface structure can also be regarded as a damped oscillator. Section D lists and describes several well-known methods by which the response of the structural oscillator can be determined given the imposed ground motion. The solution may be "exact" (insofar as a linear second degree equation does describe the real environment) or special functions, such as pseudo-relative velocity, PSRV and pseudo-absolute acceleration, PSAA, may be developed.

Typically, the frequency band to which structures respond most violently is an inverse function of their height. One or two storey buildings will be sensitive to a band of from 5 to 20 Hz approximately. Peak accelerations derived from a typical ground motion spectrum show comparatively little variation over this range, by a factor of 3 or less. Hence, in this case, small variations in frequency response are unlikely to have much effect on damage. Holzer (Ho 71) states that, for 1 or 2 storey US residential-type structure the threshold of damage is generally about 0.01 g and that 50% complaints can be expected at about 1 g. These figures may require modification for other than typical US structures.

Buildings higher than two storeys may exhibit more complicated responses intrinsically because of the greater chance of multiple-mode oscillations. Also, a typical ground motion spectrum shows that acceleration can vary by nearly three orders of magnitude over the frequency band to which the taller buildings are most sensitive. For these reasons it would seem prudent to analyse the response of each tall building separately. Tokarz and Bernreuter (To 70) state that both time-response and spectral analysis methods give reasonable predictions if the exciting motion and building mathematical model is known reliably. The spectral analysis method is quicker and easier but gives less detailed information. Industrial structures may be analysed in the same way as high-rise buildings.

E4. Spectral Matrix Method

Obviously the methods discussed in Section E3 will be time consuming and expensive if many structures are involved, particularly if the area at risk includes modern cities or industrial complexes.

A Spectral Matrix Method (SMM) for rapidly assessing damage and costs of repair or compensation has been developed by Blume and Associates. Basically, the "capacity" of a structure, its yield point, is estimated and compared with the "demand", the forces deduced from a predicted ground motion spectrum. A monetary factor can be introduced to estimate costs. The prediction scheme takes into account statistical variations in the factors. The method is especially adaptable to computer processing and a whole region can be included in one run. Details are given in (Bl 71).

E5. Conclusions

Methods are available for estimating damage to structures from ground motion, but their application so far has been to rather small relatively undeveloped areas. Almost the only exception is the city of Las Vegas, some 65 miles from Nevada Test Site. Thus, it cannot be said that any of the methods have passed the test of general experience. Indeed, the only method regarded in the USA as generally valid for many years failed when applied to PNE. This suggests that while predictions based on the methods mentioned may give rough estimates suitable for early planning, in practice a close inspection of the chosen area and of the structures at risk in it, together with confirmation of the area's predicted seismic characteristics by tests, will be essential until more experience has been gained.

F. ESTIMATION OF SEISMIC DAMAGE COSTS

F1. Relationship between Explosion Yields and Earthquake Magnitudes

Since the most common experiences of ground motion and seismic damage arise from natural earthquakes, a comparison between them and PNE shots in terms of energy release would a priori seem to be useful in assessing damage.

(a) Earthquakes

Earthquakes at present can only be categorised in terms of the effects recorded at a distance, although estimates of their total energy release have been made. Generally speaking, the energy derived from an earthquake appears in all of the wave modes theoretically possible in an elastic near-spherical body, such as the earth. These have been discussed in Sections A and B.

A number of different scales for denoting earthquake energy and effects have been set up over the past century. Two scales commonly used at present and one which has been proposed are described briefly below.

(i) In 1935 Gutenberg and Richter suggested a logarithmic magnitude scale which could be correlated with energy release. Originally, the magnitude, M, was based on the maximum amplitude of a standard short period seismograph. Various extensions have introduced some arbitrariness.

On this scale, the "smallest felt" earthquake is assigned a magnitude M = 1.5 approximately. The largest earthquakes experienced fall between M = 8.7 and M = 8.9.

The energy relationship as revised in 1956 is

$$1.5M = \log_{10} (4 \times 10^{-5}E) \qquad \text{F-1}$$

where E is in joules.

Since 1 kton = 4.2×10^{12} J by definition, it is possible to calculate the magnitude of a PNE shot, knowing, or estimating, the seismic energy efficiency.

Magnitudes derived from seismographs may overestimate the energy of an explosion considerably. One reason for this is that the symmetry of an explosion generates a distribution of seismic waves different from that of an earthquake. P, SV and Rayleigh waves predominate, so that the magnitude figure, depending largely on P wave amplitude, gives a falsely high result for total seismic energy in equation F-1, which is essentially based on the earthquake situation (Bu 63).

(ii) An earthquake "intensity" scale (the term is not precisely defined) was developed by Mercalli and modified by

Wood and Neumann in 1931. In this there are twelve scale numbers for ground motion, from that "felt by few people" to "total damage" (Bu 63).

(iii) A more sophisticated "engineering intensity scale" has been proposed by Blume (Bl 70).

The plotted ground motion response (cf, figure D1) is divided into nine standard bands for both period and pseudo-relative velocity (PSRV). Bands are numbered in ascending order from 1 to 9. The period bands are taken in succession and the PSRV band number in which the trace falls is noted. Should one or more period bands be empty, the symbol "X" is marked for each empty band. Thus, in all cases a nine-digit code is obtained, describing the spectrum trace fully. By simple averaging, three - or one - digit codes can be given for broader approximations.

(b) Nuclear Explosions

The "yield" of a nuclear explosion is generally considered to be its total energy release. There is at present no direct method of measuring this total energy in any environment. For the planning and estimating necessary for PNE it would appear that the "maximum credible" designed yield would be sufficiently accurate. The yield of underground nuclear explosions can be measured close-in to an accuracy of about ± 10% (Section B6a). At long distances, yield can be found from the amplitude of Rayleigh waves. Thirlaway (Th 72) states that, after corrections, yields from Rayleigh waves measured above 100 kton should be within 50% and those below within a factor of two.

(c) Conclusions

Paragraphs (a) and (b) may be summarised as follows:-

Earthquakes

Effects at a distance can be measured accurately.

Source energy is known only by inference.

Sources of damaging earthquakes are extended over many cubic kilometres.

Full gamut of elastic waves is produced.

Explosions

The seismic energy efficiency and the effects at a distance must be inferred before the shot.

Total energy yield is known beforehand to a good accuracy.

Source is almost a point in relation to the volume of the earth.

Mainly P, SV and Rayleigh waves are produced with P waves predominating.

It therefore seems unlikely that an attempted correlation between earthquake magnitudes and PNE yields would cast much light on the cost of seismic damage from PNE at present. However, the "engineering intensity scale" of Blume would seem a useful tool for comparing the ground motion effects of earthquakes and explosions on a rather more quantitative basis than the present "magnitude" and "intensity" scales.

F2. The Seismic Damage Effects of the Kielce Explosion

(a) On 22 July 1967 the wreck of the ship Kielce blew up about 5 km off Folkestone Harbour. There was some damage to residential buildings in Folkestone and about £9000 was paid out in compensation. An analysis of this event has been made by Yeo (Ye 72). This sub-section will consider seismic damage effects only; the implication on damage costs is discussed in Section F3.

(b) Although it was known that Kielce was carrying explosives, the nature and quantities were not on record. Seismic recordings of the explosion gave a magnitude of $4\frac{1}{2} \pm \frac{1}{2}$. Using the relationship in equation F-1, this implies a seismic energy yield of 0.033 kton for the median value, within a range 0.006 to 0.19 kton. These figures may not be particularly useful in the present context but do serve to indicate the spread of energy values inherent in the earthquake magnitude scale.

(c) From the observed P-wave amplitudes, Thirlaway has estimated the explosion total energy yield as equivalent to 2 kton in water or hard rock. From this Yeo finds that the 0.02 g PSAA contour was about 9 km radius from ground zero and that the maximum PSAA on land, in the Folkestone harbour area, was about 0.065 g. If a PSAA of 0.01 to 0.02 g is accepted as the threshold for minor damage to residential structures, the above values are certainly consistent with the described scale and nature of the damage due to the explosion.

(d) One of the best documented US PNE shots is Rulison. This was a 40 kton device emplaced at 8400 ft in saturated sandstone-shale and fired on 10 September 1969. The data from this event have been widely used and quoted. For example, Rizer (Ri 70) has given general prediction formulae for seismic damage and compensation costs based largely on Rulison. He correlates scaled data from shots Handley, in tuff, and Piledriver, in granite, to Rulison and develops scaling laws for the dependence of PSAA on yield and depth of burial (DOB) as follows:-

$$\text{Yield factor} = \left(\frac{W}{40 \text{ kton}}\right)^{1/3} \qquad \text{F-2}$$

$$\text{DOB factor} = \left(\frac{\text{DOB}}{8400\ \text{ft}}\right)^{0.58} \qquad \text{F-3}$$

$$\text{PSAA sought} = \text{PSAA}_{STD} \times \text{yield factor} \times \text{DOB factor.}$$

$PSAA_{STD}$ is read from the appropriate curve for emplacement rock type, derived from the Rulison, Handley and Piledriver events.

(e) An attempt was made to correlate the Kielce data with those of Rizer. It was at once noticed that the PSAA-distance curves for Rulison-Handley-Piledriver were all less steep than those used by Yeo and that the PSAAs read off were, in most cases, in all cases for hard rock sites, considerably greater than those used by Yeo (table F1).

TABLE F1

Source	PSAA, cm s^{-2}	
	Range 10 km	Range 100 km
Yeo:-		
100 kton on hard rock sites	250	2.5
100 kton on alluvium sites	550	5.5
*40 kton on hard rock sites	190	1.9
*40 kton on alluvium sites	410	4.1
Rizer Figure 4		
Rulison (saturated sandstone-shale)	800	20
†Handley (saturated tuff)	500	15
†Piledriver (unsaturated granite)	350	10

*These were scaled from 100 kton by $W^{1/3}$.
†These were scaled to 40 kton and 8400 ft DOB by F-2 and F-3.

(f) An attempt was also made to scale the Kielce explosion for yield and DOB using equations F-2 and F-3. The major problem here was the selection of a reasonable DOB. The literature generally states that explosions under water are likely to have high seismic energy efficiencies. Early estimators considered that 20 kton at 30 m under water would have about the same efficiency as 20 kton at 300 m underground (Bu 63).

Another problem was that that range of DOB for which equation F-3 was valid was not known.

Finally, it was decided to use the underground "just contained" DOB of $350W^{1/3}$ ft, since apparently for the Kielce explosion there was little disturbance above the sea surface. The resulting PSAAs are compared in table F2 with those obtained by Yeo.

TABLE F2

Range, km	PSAA quoted by Yeo, g	PSAA scaled by Rizer's Method, g	
		to Piledriver (unsaturated granite)	to Rulison (saturated sandstone-shale)
5	0.065	0.09	0.18
9	0.02	0.033	0.075

(g) It is considered that the scaled PSAAs are if anything low, since, as has been said, a high seismic energy efficiency has always been attributed to immersion in an aqueous medium. The problem then is to explain the discrepancies in the context of the known damage from the Kielce explosion. Perhaps the Folkestone structures were stronger than typical US ones, but this seems unlikely. It is felt that Yeo's quoted figures for PSAA cannot be far wrong, at least not by a factor approaching two.

There is a possibility that the total energy yield of the Kielce explosion was over-estimated by at least a factor of three, and possibly by a factor of more than ten. (See Review No. 4. No Rayleigh waves were recorded from Kielce.)

A further possibility is that seismic energy efficiency scales with yield to an exponent greater than one-third. This is to some extent borne out by seismic energy efficiency figures from US shots, although it must be remembered that different workers have obtained values which may be internally consistent but differ appreciably in absolute magnitude from one scale to another (cf, table C1). For example, a comparison between Rulison and Gasbuggy, of roughly the same yields, would appear to confirm that seismic energy efficiency increases with DOB. On the other hand, Boxcar, 1.2 Mton at one-eighth the Rulison scaled DOB, shows about the same seismic energy efficiency. Accepting equation F-3 as correct, this single instance would give a yield factor in equation F-2 of about $W^{0.5}$. It is probably coincidental that the same factor would also account roughly for the Kielce PSAA discrepancies. However, Rizer's $W^{1/3}$ scaling law apparently depends on Holzer's work published later (Ho 71). Holzer considers rock displacement and pressure and, by means of Fourier transforms, gives an energy-frequency relationship for a spectrum 0.5 to 20 Hz. It is known that small explosions produce a spectrum weighted towards higher frequencies, up to 1000 Hz. Probably the most likely explanation for the energy-damage relationship of the Kielce explosion is that much energy was concentrated in higher frequency bands to which the Folkestone buildings were not particularly vulnerable. In any event, the seismic energy-damage relationship on Kielce does not fit easily in Rizer's prediction scheme which purports to have wide generality.

F3. The Cost of Seismic Damage

(a) Introduction

Although there does not appear as yet to be a standard US method of estimating the cost of seismic damage, a number of schemes have been proposed. The tendency is to revise methods from the experience of successive PNE shots so that the later schemes, particularly for residential structures, are in the main empirical. In the following a few typical methods developed after the Salmon shot (1964) will be described and discussed briefly.

(b) Residential Type Structures

The term "residential type structures" is usually taken to include all one or two storey structures as well as dwelling houses, eg, churches, filling stations, small office blocks and shops, etc.

(i) Hughes (Hu 68) estimates the cost of seismic damage by dividing the area around the detonation into three zones limited by PSAA values, as follows:-

Zone	PSAA
I	$\leq$ 0.016 g
II	0.017 g to 0.099 g
III	$\geq$ 0.1 g

"Complaints Factors" (CF) are given for all three zones and additionally a "Damage Factor" (DF) is given for Zone III only. Costs are then estimated as follows:-

Zone	
I	Total structures in zone × CF × $400
II	Total structures in zone × CF × $1000
III	Total structures in zone × CF × DF × average value of structures.

Parker (Pa 70) has consolidated Hughes' method into a diagram from which damage costs can readily be obtained from a yield-distance curve.

(ii) Rizer (Ri 70) has compared complaints and paid claims for a number of NTS shots with those from Rulison. Regression curves were obtained for the percentage of complaints, and the lesser percentage of paid claims, against PSAA. The total cost is then obtained by multiplying the number of claims by $400. This sum is the crude average paid per claim up to 16 October 1970 (30 July 1970 for Rulison). The figure obtained does not include administration costs nor that of any pre-shot survey, etc.

(c) <u>All Structures</u>

In the Spectral Matrix Method (SMM) of Blume (Bl 71), a "dollar exposure", E_{zk}, is defined as the cost if all the structures of class k in zone z were to be replaced completely. To obtain the probable total cost of class k, E_{zk} is multiplied by a dimensionless damage probability, F_k. Finally, all classes and zones are summed to give cost probabilities over the entire area considered. This method inherently gives the probability of not exceeding any specified gross cost for seismic damage.

(d) <u>Discussion</u>

(i) For the purpose of this sub-section it will be assumed that seismic effects can be predicted with an acceptable degree of accuracy. The remaining variables are the response of the structures and the cost of their repair or replacement.

(ii) It seems unlikely that modern city buildings and industrial plant generally in any part of the world would have significantly different responses to ground motion from those studied in the USA. The only exceptions might be those structures deliberately designed to resist earthquake ground motion.

Residential type structures are likely to be more varied in building type. For example, the wood-frame house still common in North America is almost unknown in Britain and is not usual in Europe generally. On the other hand, Europe has a preponderance of load-bearing brick wall structures, of which many are old and may have been cheaply built. There appears to be few data on the comparative response to ground motion of the various types of residential structure and this is an obvious gap in our knowledge of the effects of PNE shots. It may be reassuring that there is little difference in the response to air blast between wooden and brick two storey houses, whether for moderate damage or total destruction.

On the above reasoning, it is thought that the US scales of damage to all types of structure can be somewhat tentatively accepted as valid for all the "developed" areas of the world.

(iii) It will have been noticed that the methods of Hughes and Rizer give costs as a direct function of PSAA. Since ground motion will vary continuously outwards from the explosion, it will be necessary to divide the area into suitably small zones, with little change in PSAA across them, and then sum all zones to obtain the predicted total cost. This could be a somewhat lengthy and tedious procedure if the area under consideration is large and has a fairly high structure density. The Spectral Matrix method is basically similar but has deliberately been designed for rapid computation. In all cases, a considerable store of data on structure density and type is assumed. This would appear to make a pre-shot survey mandatory if reliable results are desired, unless the area is already very well known or is very sparsely populated.

(iv) The methods of Hughes and Rizer are used below to predict the damage costs of the Kielce explosion.

Location:	Folkestone, Kent
Population:	44000
Area:	4000 acres (16 km^2)
Number of Residential Structures:	12000 (this is the figure given by Yeo. It seems low in relation to population allowing for the "Residential Type Structures" which are not dwelling houses)
Explosion:	2 kton at 5 km SE of the harbour
Ground Motion*:	0.065 g at 5 km
	0.02 g at 9 km

Procedure

Divide the land area into annular regions based on PSAA. There is not sufficient information to discriminate for variation in geology. Estimate the number of structures in each region as a function of area. From the 1 in. OS map the built up area is about 12 km^2 = 3000 acres.

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*As obtained from Hughes - Rizer would have predicted higher accelerations, see tables F1 and F2.

Region No.	Region Radii, km	Median PSAA, g	Area, km^2	No. of Structures
1	5 - 6	0.055	2	2000
2	6 - $7\frac{1}{2}$	0.035	6	6000
3	$7\frac{1}{2}$ - 9	0.025	4	4000

Estimate damage cost by Hughes' method:-

Region 1.	2000 × 5.0% × \$1000 =	\$100000
Region 2.	6000 × 2.5% × \$1000 =	\$150000
Region 3.	4000 × 1.0% × \$1000 =	\$40000
	Total	\$290000

Estimate damage cost by Rizer's method:-

Region 1.	2000 × 1.0% × \$400 =	\$8000
Region 2.	6000 × 0.5% × \$400 =	\$12000
Region 3.	4000 × 0.2% × \$400 =	\$3200
	Total	\$23200

There is well over an order of magnitude between the two estimates but it should be remembered that Rizer predicts PSAAs two or three times as high as those of Hughes for the same situation. Application of these PSAAs would roughly treble his damage costs.

The actual compensation paid out on Kielce was £9000, or say \$23000, exclusive of insurance companies' overheads.

(v) There are two further points of difficulty which cannot be decided here. After the Kielce explosion, 50% of the compensation was paid out on only 5% of the claims. It seems that no cost estimate scheme to date could have predicted this. The second is the "real" relation of the pound sterling to the US dollar. A nominal rate of £1 = \$2.50 has been used above because, although US incomes are known to be much higher than the British on this exchange rate, in the USA the costs of houses, and durable consumer goods generally, do not seem to be over-priced at this rate.

F4. General Conclusions

(a) The Prediction of Ground Motion

The prediction of ground motion amplitude for a given yield and environment does not as yet seem to be an exact science. This is perhaps to be expected when the comparatively small number of underground nuclear explosions documented is contrasted with the many possible variables.

In PNE planning, at present, the "worst case" should be chosen with a reasonable assurance that it will not happen.

(b) Structural Response

The Damped Spring Response method seems adequate to predict the response of structures given valid data. There would appear to be no reason at present to depart from semi-classical solutions of the basic equation nor to adopt higher time derivatives or non-linearities in the description of the structures.

(c) The Extent of Seismic Damage

There is some uncertainty, at least a factor of two and perhaps as much as a factor of six or seven, in the threshold ground motion acceleration for damage to residential type structures, which are likely to be the bulk of those at risk in most circumstances. Conservative predictions, and a liberal attitude towards compensation, would appear to be necessary initially if only on the grounds of public relations. Complex structures are likely to be relatively much fewer and will be more carefully analysed and appraised. These, therefore, should not constitute any great problem.

(d) The Cost of Seismic Damage

Estimating the cost of seismic damage, in actual repairs or in compensation, is likely to remain a difficult problem since subjective and emotional factors are involved. It has been shown (Section F3(d)(iv)) that a fairly recent US method would have predicted eleven times the compensation actually paid out after the Kielce explosion. A more recent and less conservative US estimate is high by a factor of three. PNE planners for the time being may well be faced with the dilemma of taking an uncalculated risk or arriving at an unacceptably high figure for damage compensation. It seems clear that the cost of seismic damage needs to be investigated further, but it is not so clear how this can be done without more PNE shots. An analysis of existing raw data, if available, might be worthwhile since the US method of using unweighted averages seems unnecessarily crude. The only recent well-documented case of extensive seismic damage in the UK, the Kielce explosion, highlights this fact since with an average of £95 per paid claim, the highest sum paid was £1200 and the lowest £2. There may also possibly be untapped sources of data on this subject in the commercial world. A further possibility is the closer study of damage from moderate earthquakes. In practice, however, on-the-spot scientific study of fortuitous natural phenomena has usually proved very difficult.

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