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FREE-FIELD GROUND MOTION
PRODUCED BY EXPLOSIONS

by

W R Perret

JULY 1963

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FREE-FIELD GROUND MOTION PRODUCED BY EXPLOSIONS

I INTRODUCTION

The environment of an explosion must react to the extremely rapid release of highly concentrated energy by absorbing and transmitting it. The energy may be released by either chemical or nuclear processes, but reaction of a solid environment such as earth to the two types of source will differ only in relation to the very much greater energy density derived from nuclear processes. Close to the source, energy losses will result primarily from melting and vaporizing; at somewhat more remote distances energy will be absorbed by crushing, splitting and shearing, and by associated viscous motion; and finally, only spherical divergence will reduce energy densities at great distances.

Some of the results of these reactions of rocks and soils to large explosions will be discussed. In addition, several experiments planned to measure ground motion produced by chemical and nuclear explosions in soil and in rock will be described. The discussion will be confined to that portion of the force field which is most likely to be of concern to shelter design and construction, with only brief reference to characteristics of other portions of the field to establish continuity.

Energy released by an explosion manifests itself in several forms, but the most pertinent is the development of a large quantity of very hot gas which exerts pressure on its surroundings. When the environment is solid, soils or rocks, the pressure is very great, megabars for nuclear sources and hundreds of kilobars for chemical sources, and the environment reacts in such a manner that material motion and pressure may be described by use of hydrodynamic relations (Fig. 1). This type of reaction persists until the pressure has decreased, by spherical divergence and by doing work on the environment, to about 100 kilobars. This is only an approximate limit; it may be higher in very hard rock and much lower in some soils.

Fig. 1 Explosion response domains in earth.

Beyond the region of hydrodynamic response, the environment reacts by several nonlinear dissipative processes such as crushing and flowing. Here energy is dissipated at a rate nearly as rapidly as in the hydrodynamic domain. This nonlinear-response domain extends from about 100 kilobars outward to pressures equivalent to the elastic limit of the environmental material. This limit ranges from a few kilobars for hard rocks to a few bars for some soils. There does not presently exist a fully satisfactory mathematical model analogous to the hydrodynamic one, for describing energy transmission and absorption within the domain of nonlinear response.

Rock or soil environments respond in a linear manner beyond the nonlinear region since the nominal boundary is the elastic limit and at all pressures less than that limit reaction must be elastic. Perhaps an effective criterion for the elastic-response domain is that the pressure or particle velocity shall decrease only by spherical divergence and thus be inversely proportional to radial range. This situation holds over most of the linear domain except very near the transition from nonlinear response. Particle velocity and displacement in this region near the transition actually decreases as a sum of an inverse square and an inverse first power of distance. Of course, as the distance increases the $1/R^2$ -term becomes negligible.

It is rather obvious that the hydrodynamic domain is not of direct concern to the construction of shelters because materials for that purpose are not suitable for use at stresses of the order of 100 kilobars or more. For a similar reason the higher pressure levels of the nonlinear-response domain are only indirectly of interest. However, all of this nonlinear-response region is of some concern to shelter design because it is pertinent to know in what manner and at what point relative to an explosive source the pressure field approaches magnitudes which will permit realistic design for survival of structures. Similarly, the higher pressure portions of the linear- or elastic-response domain are of interest to development of shelters.

With this background established, let us investigate how reactions of a specific soil and a solid rock develop in the nonlinear- and linear-response regions. It appears, at first glance, that we should measure stress and strain in the region of interest surrounding an explosive source. However, problems

of instrument design and particularly of instrument placement have shown that more reliable and consistent results derive from measurement of particle motion in terms of acceleration, velocity, or displacement. Without going into detail concerning the reasons for greater reliability of particle motion measurements, it can be pointed out that perturbations produced by placement of gages are considerably more severe in their reaction on stress- or strain-gage response than on the response of accelerometers or velocity gages. For the latter types of gage it is requisite only that the gage package match in density the surrounding material, that it be bonded securely to its surroundings, and that its dimensions be very small relative to the pressure or velocity wavelength.

II

UNDERGROUND EXPLOSIONS

The Nevada Test Site of the United States Atomic Energy Commission lies in the semiarid basin and range terrain of southern Nevada and includes several extensive valleys of deep alluvial fill. Several large explosions, both chemical and nuclear, have been detonated in the desert alluvium for the purpose of studying crater development. Of these explosions, data from several will be discussed. These data will be presented as observed, but will also be normalized to a common energy release equivalent to one kiloton of TNT for comparative study.

Simple cube-root scaling is applicable in the cases to be discussed. This is based, as indicated in Fig. 2, on the assumption that energy released is directly proportional to the weight or volume of the constant density explosive, whence linear dimensions and transit times will vary directly with the cube root of energy yield expressed in terms of weight of TNT.

Dimensional analysis based on cube-root scaling shows that for two charges of weights W_1 and W_2 the relations for various motion parameters and radial distances shown in the slide are applicable. Here a is acceleration, u is particle velocity, δ is displacement, and R is radial distance. The exponents m , n , and p are experimentally determined; m is approximately one in the linear-response region.

TNT ENERGY $\propto$ WEIGHT (W) $\propto$ VOLUME $\propto$ (RADIUS)³

RADIAL DISTANCE, R $\propto$ W^{1/3} & DURATION TIME, T $\propto$ W^{1/3}

ACCELERATION: $a_2 = a_1 (W_1/W_2)^{1/3} [(R_2/R_1)(W_1/W_2)^{1/3}]^{-n}$

PARTICLE VELOCITY: $u_2 = u_1 [(R_2/R_1)(W_1/W_2)^{1/3}]^{-m}$

DISPLACEMENT: $\delta_2 = \delta_1 (W_2/W_1)^{1/3} [(R_2/R_1)(W_1/W_2)^{1/3}]^{-p}$

Fig. 2 Scaling laws.

The Scooter experiment comprised a million pounds (0.5 kiloton) of TNT stacked in an approximate sphere of 14-foot radius, centered 125 feet beneath the surface of desert alluvium at the Nevada Test Site. Part of the measurement program in this experiment was observation of radial motion at five stations on a horizontal radius at shot level between 50 and 300 feet from the charge center. Accelerometers formed the primary instrumentation for these observations, but they were supplemented at four stations by a newly developed velocity gage.

Data obtained from Scooter were converted to particle velocities and to displacement by integration. The significant portions of all records and integrations from one station, at 200-foot radial range, are presented in Fig. 3. At this station, peak pressure was about 26 bars or 380 psi. There is good agreement in peak values of integrated acceleration and velocity and between doubly integrated acceleration and singly integrated velocity. Failure of the velocity gage record to return to zero suggests an unbalance in the gage after the initial outward pulse. This fault has an obviously adverse effect on the displacement curve beyond about 70 milliseconds.

First signal arrivals at each gage indicate a compressional wave velocity of 4260 feet per second, but the velocity with which particle velocity peaks were propagated was only about 2100 feet per second, indicative of the dispersive character of the desert alluvium.

Plots of Scooter data versus range are presented in Fig. 4 to show the type of power law attenuation that occurs. All data analysis figures include quantities in both metric and English systems. Scooter data will not be discussed in detail here but will be referred to later. It should be noted, however, that in the particle velocity graph the highest point is that derived from integration of acceleration at the closest station; it implies a pressure of the order of 3.7 kilobars, possibly within the hydrodynamic region.

Another chemical explosion detonated in the same environment yielded data which complement those of Scooter. This experiment, Jangle HE-2, comprised 40,000 pounds of TNT stacked in an approximate sphere centered 14 feet beneath the ground surface.

Fig. 3 Ground-motion curves, Scooter, 200-foot range.

Fig. 4 Peak ground motion versus range, Scooter.

Data derived from Jangle HE-2 were primarily accelerations which have been integrated to particle velocities and displacements. These measurements were made at relatively greater radial ranges than those from Scooter, and together the two experiments normalized to one kiloton describe fairly well the reaction of desert alluvium to a chemical explosion.

These two sets of normalized data, plotted in Fig. 5, indicate a transition from the more rapid attenuation in the nonlinear domain to the lower attenuation rate in the linear domain. This transition is not likely to be so abrupt as the intersection of two lines suggest, but it occurs at a range of about 700 feet and a particle velocity of 0.7 foot per second. Under the pertinent conditions of depth and material this velocity corresponds to 2.2 bars, or 32 psi.

Let us now consider the reaction of sound hard rock to an explosion, using the Gnome experiment as a suitable example. Gnome was a 3.1-kiloton nuclear explosion deep in bedded salt near Carlsbad, New Mexico. This explosion occurred 1200 feet below the surface at the end of a horizontal tunnel within horizontally bedded evaporite composed primarily of halite but including some polyhalite and occasional thin layers of clay. The salt is overlain by about 700 feet of stratified anhydrite, dolomite, and sandstone.

Accelerometers and velocity gages were installed on a horizontal radius, as shown in Fig. 6. These gages were placed in borings extending into the rock from the access tunnel.

Records of particle velocity from all horizontal radius accelerometers (solid lines) and velocity gages (dashed lines) in the Gnome experiment are shown in Fig. 7. The first four of these records were terminated early by cable damage caused by spalling of rock slabs at the tunnel wall. All records shown include the complete initial outward velocity peaks, but only the three most remote records were sufficiently long to indicate the full velocity pulse.

Acceleration records indicated that the compressional wave velocity in the Salado salt at Gnome site is 14,165 feet per second and that the material is negligibly dispersive.

Fig. 5 Desert alluvium particle velocity versus range.

Fig. 6 Gnome site plan and elevation.

Fig. 7 Particle-velocity records, Gnome.

Observed acceleration and particle velocity data peaks are plotted versus radial range in Fig. 8. The acceleration plot shows attenuation as the inverse 5.3-power of range out to about 400 feet, followed by slower attenuation as the inverse 2.7-power of range out to the most remote gage at about 1600 feet. Particle velocities follow a similar pattern, being attenuated as the inverse 3.6-power of range out to 330 feet and as the inverse 1.4-power of range from 330 feet to the most remote gage. Double data points at five of the stations indicate the difference between integrated-acceleration velocity peaks and those recorded by velocity of gages. Records from these gages were not, in general, suitable for integration to displacements because of their short duration.

It is of interest to compare the reaction of the two media, dry porous soil and solid rock as presented in Fig. 9. Here all data are normalized to one kiloton and response of the porous desert alluvium is represented by dashed line. It should be noted here that data from large nuclear explosions in tuff, in desert alluvium, and in granite yield analogous curves of which those for porous tuff and alluvium fall generally parallel and close to the porous soil curves; those for jointed granite are similarly parallel and close to the salt curves.

In the acceleration plot, throughout the nonlinear-response domain, peak accelerations in the porous medium are lower by more than two orders of magnitude than those in the solid rock. This is emphasized on the acceleration graph by the spread between curves at the 200-foot radial range. This spread represents a factor of about 130. To understand this difference it is sufficient to recognize (1) that peak accelerations are more closely dependent upon the rate of increase of the pressure or particle velocity wave front than on any other feature of the source or environmental response, and (2) that energy losses, especially through absorption of high-frequency phases, will flatten the wave front more rapidly in friable porous soil than they will in solid hard rock.

Particle velocity curves are even more instructive than the acceleration curves. Peak particle velocities and peak pressures may be expected to follow similar patterns of attenuation and, at least in the first approximation, peak stress is the product of bulk density, propagation velocity, and peak particle velocity. Of course, the propagation velocity used here should be that of the stress wave peak and not that of the initial signal, provided these velocities differ notably, as they do in porous materials.

Fig. 8 Peak ground motion versus range, Gnome.

Fig. 9 Ground motion comparison, porous soil and hard rock.

The salt curve indicates more rapid velocity attenuation within the non-linear domain than does the soil curve, although throughout that portion of the domain represented by the curves the soil curve is lower by a variable factor of more than four.

Transition from high attenuation rates characteristic of the nonlinear region to those near $1/R$ is not abrupt, and frequently the lower attenuation rate is nearer $R^{-1.5}$ than R^{-1} because the R^{-2} -term, previously noted, has not become negligible. This transition should occur where peak pressure was approximately equal to the elastic limit of the material. For the data shown in the figure the transition occurs at a particle velocity of about 44 feet per second in salt and 0.7 foot per second in soil. Calculation of the pressure, which corresponds to 44 feet per second particle velocity in salt, 1.22 kilobars, or about 18,000 psi. This represents the dynamic compressional elastic limit for salt and is in agreement with data derived from other types of measurements in a salt dome. Collateral information has suggested that another transition occurred near the 1000-foot range at Gnome, corresponding to about 7 feet per second particle velocity, or about 212 bars, or 3120 psi pressure. This is a reasonable value for the tensile elastic limit of salt under 1200 feet of overburden. This latter value corresponds with the elastic limit determined from the slope transition in jointed granite particle velocity data, 6.6 feet per second, or 298 bars, or 4370 psi.

Transition from nonlinear to quasi-linear response in desert alluvium occurred at a particle velocity of 0.7 foot per second under Scooter conditions of depth and material which corresponds to about 2.2 bars, or 32 psi, as previously noted. Data derived from similar material at a 1200-foot depth gave a higher value for the transition, 3.8 bars, or 56 psi, a reasonable increase under the greater geostatic pressure.

Corresponding data for tuff which is highly porous but stronger than desert alluvium show that the transition occurs at a particle velocity of about 6 feet per second or at a pressure of about 66 bars, or 970 psi, intermediate between soil and hard rock, as would be expected.

The foregoing information may be summarized as follows:

- (1) Particle velocity and stress in hard massive rock such as salt or granite are attenuated in the nonlinear-response domain as an inverse power of radial distance between 3.6 and 2.4, or roughly as the inverse cube of distance to the transition to linear response at a pressure between 200 and 300 bars (3000 and 4500 psi) which occurs between 400 and 900 feet from a one-kiloton explosion.
- (2) Accelerations in this type of rock are attenuated more rapidly, as the inverse fifth power of distance, in the nonlinear region.
- (3) Particle velocity and stress in friable porous rock and soils are attenuated in the nonlinear response domain as an inverse power of radial distance between 3.8 and 2.7, or roughly as the inverse 3.3-power of distance to the transition to linear response at a pressure between 2.2 and 3.8 bars (32 to 56 psi) for soil, or somewhat higher for porous rock; the transition occurs between about 400 and 700 feet from a one-kiloton explosion.
- (4) Accelerations within porous materials are lower than those in hard rock by a factor of about 100.
- (5) Accelerations in porous materials are attenuated in the nonlinear region as an inverse power of distance between 5.8 and 4, the lower value being representative of stronger material such as tuff or desert alluvium under high geostatic pressures.

III

LOW-ALTITUDE ABOVE-SURFACE EXPLOSIONS

Consider the sort of loading to which soil or rock will be subjected by an explosion at the ground surface or at relatively low altitude above the surface. An explosion at the ground surface will obviously develop direct ground shock analogous to that developed by an underground burst, but this should induce the same sort of reactions and should follow the same patterns as those previously described for underground explosions. Additional ground motion and stress inherent to surface and above-surface bursts will be produced by the incidence of air blast at the ground surface.

A program of measurement of vertical ground displacement produced by incident airblast was undertaken during 1957 at the Nevada Test Site. The explosion of interest was the Priscilla event, a 37-kiloton nuclear explosion positioned by balloon 700 feet above the ground zero point in Frenchman Flat. Frenchman Flat is a level playa lake bed. The soil is a fine-grained silt, weakly cemented by caliche and uniform to a depth of at least 400 feet with a few local thin lenses of small gravel below 200 feet. Figure 10 presents a density and seismic velocity profile of the instrumented site. The high-velocity layer in the vicinity of 20-foot depth results from locally concentrated caliche cementation.

Four stations were instrumented at positions shown in Fig. 11. Each of these stations was equipped with five gages designed to measure relative displacements between a surface canister and anchors 10, 30, 60, 100, and 200 feet deep. The surface canisters and anchors each contained additionally a gage to a record incident overpressure. A few positions also included horizontal radial accelerometers. Only data from the relative displacement gages will be discussed.

The relative displacement gages, shown in Fig. 12, comprised a length of music wire stretched through flexible metal tubing from the anchor to the transducer unit. The latter included a spring-loaded drum over which the wire was wound and which drove a ten-turn helical potentiometer as the relative movement of the gage anchor and transducer unit caused the wire to rotate the drum.

Explosion of the Priscilla device caused reflected peak overpressures of 270, 187, 120, and 59 psi at the four surface stations, as shown in Fig. 13. Arrival times of these signals at the various stations imply propagation along the instrument line at a decreasing velocity which was, however, greater than seismic velocity in the soil throughout the instrument spread. Thus first signals at the surface stations and at all deeper ones must have originated from incidence of the air-blast overpressure at the surface station. In fact, an estimate of the time of arrival of any signal generated at ground zero by the air blast and transmitted through the ground shows that such a signal could not have arrived at any gage sooner than several hundred milliseconds after the signal generated at the ground surface directly above the gage.

Fig. 10 Soil properties profile, Frenchman Flat, Nevada test site.

Fig. 11 Schematic profile of Priscilla ground-motion station.

Fig. 12 Sandia relative displacement gage.

Fig. 13 Air overpressure at Priscilla stations.

The ground motion caused by air blast is illustrated in Fig. 14 by records of the relative displacement gages at the station 650 feet from ground zero. Negative displacements represent shortening of the distance between the transducer element and the anchor for each gage. Initial motion is downward or negative at all gages and occurs simultaneously. This is logical, since the transducers of all five gages are attached to the surface canister which must move downward before any of the anchors are affected by the incident air blast. The downward pulse is followed by upward motion, in some cases to positions above the initial one; the motion culminates in a small constant negative displacement.

A plot of maximum relative displacements for all gages versus gage spans or depth of anchors, shown in Fig. 15, indicates that at each station there is very little difference between the maxima for the 100- and 200-foot span gages. This implies that anchors 200 feet deep were subjected to negligible movement. Since the anchors at 200 feet did not move, it follows that motion indicated by the 200-foot span gages is the true downward motion of the surface canister. Furthermore, since at any station all gages are attached to the surface canister, differences between the displacement curve for the 200-foot span gage and the curve for any shorter span gage represents the true motion of the anchor of the shorter span gage.

Difference curves which represent true or absolute displacement at the surface and at 10, 30, 60, and 100 feet below the surface 650 feet from surface zero are presented in Fig. 16. It is evident that the curve for the 100-foot depth is not so smooth as for the shallower points. This roughness is inherent to the process used in deriving absolute displacement curves; these data are small differences between larger quantities the average deviations of which are nearly as great as the differences.

Some measure of reliability of the derived absolute displacements may be had by comparing residual surface displacements of the 200-foot span records with differences between preshot and postshot first-order surveys at a number of surface stations. A plot of these data is presented in Fig. 17. The four most distant points of the surveys were the surface canisters at the instrument stations. At 650 feet from surface zero the observed residual displacement was 3.3 inches downward; the survey difference was 3.33 inches downward. Results at the

Fig. 14 Relative displacement records, 650-foot station, Priscilla.

Fig. 15 Peak relative displacement versus gage anchor depth.

Fig. 16 Absolute displacement of gage anchors, 650-foot station, Priscilla.

Fig. 17 Permanent displacement profile along gage line, Priscilla.

other stations were similar and culminated at 1350 feet in a residual upward displacement of 0.2 inch and a survey difference of 0.05 inch upward. Disagreement between residual displacements observed by the two procedures was less than 0.2 inch. Laboratory studies of gage performance have shown that they are capable of following motion more rapidly by at least a factor of two than required by the rise of displacement curves.

The data derived from this experiment are presented in two forms. Contours of maximum displacement on a cross section of the ground in the plane of the gage stations are shown in Fig. 18. These contours describe relatively flat bowl-like shells of equal displacement. The data do not cover sufficiently high pressure ranges to define the shape near ground zero, but the residual displacement survey has suggested that there was a large downward inflection nearer the center of the bowls.

A semilogarithmic plot of peak displacement data versus depth for each instrument station is shown in Fig. 19. These data define straight lines which for all data sets have the same slope and are defined by the equation

$$\delta = \delta_0 e^{-0.014D},$$

wherein displacements δ and δ_0 are in inches and depth D is in feet. Surface displacements δ_0 derived from the graph are smaller than the observed surface displacement peaks, probably attributable to inherently greater compressibility of the first few feet of playa soil. Surface displacements δ_0 are not related in any simple manner to the input air-blast function.

The coefficient of depth in the exponential of the displacement equation is the same at all stations and implies that attenuation of displacement with depth is independent of the loading overpressure or impulse functions and depends wholly upon mechanical characteristics of the soil.

A final word of caution is needed concerning use of the data discussed in this paper. All of the information is valid within limits of experimental error which are less than 25 percent. However, in some instances interpretation of the data must be limited to a specific type of environment. Most severely limited

Fig. 18 Peak displacement contours on vertical section through gage stations, Priscilla.

Fig. 19 Peak displacement versus depth, Priscilla.

are the data for air blast-induced vertical motion from Priscilla. These data apply to a very special type of soil and, although the general form of the displacement-depth relationship probably represents typical reaction of any soil to this type of loading, direct application of the equation with unaltered coefficients and without further understanding of how mechanical properties of a soil affect those coefficients could be seriously misleading.

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