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THE EFFECTS OF SEISMIC WAVES ON STRUCTURES
AND OTHER FACILITIES

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ABSTRACT

The effects of explosion-induced ground motion must be evaluated in planning and executing any nuclear excavation project. For some projects ground motion intensity may dictate the use of less-than-optimum yields to minimize damaging effects. In remote areas, weighing the alternatives of outright purchase of some property or use of smaller yields may be required. The cost of indemnifying owners against damage must be considered in any case.

Discussions of the effects of ground motion on three broad types of facilities - engineered structures, residential buildings, and equipment required for the support of nuclear excavation operations - are presented. A method of predicting the response of single- and multi-storied buildings, the response spectrum technique, is discussed, with emphasis on the application of explosion-induced spectra.

Conclusions drawn from several tests of damage to residential-type buildings are presented. Included are data from four investigations of damage caused by commercial and industrial blasting and the results of several studies made in conjunction with underground nuclear detonations.

Finally, a survey of damage to the equipment required to carry out excavation projects is summarized.

NOMENCLATURE

Symbols listed in order first used in text or figures, unless defined where first used.

k	stiffness
m	mass
x	displacement of mass
$\ddot{x}$	acceleration
W	weight (in section on Engineered Structures)
N	normal force
ΣF_h	summation of horizontal forces
p	natural frequency, radians/sec
t	time
x_0	initial displacement
v_0	initial velocity
$\dot{x}$	velocity
$\ddot{y}$	ground acceleration
e	base of natural logarithm
β	percent critical damping
τ	time at which impulse acts; same as t_n
$\dot{u}$	relative velocity
p_d	damped natural frequency
c	$2\beta p$
S_v	$\left[-e^{-\beta p t} \int_0^t e^{-\beta p \tau} \ddot{y}(\tau) \sin p_d(t - \tau) d\tau \right]_{\max}$
T	period, sec
kip	1000 lb
W	yield in kt (in section on Support Facilities)

THE EFFECTS OF SEISMIC WAVES ON STRUCTURES AND OTHER FACILITIES

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INTRODUCTION

It has been pointed out that the detonation of large yield devices underground produces seismic signals - ground motion - at considerable distances from the explosion. It is important that the significance of such motion in terms of damage potential be thoroughly evaluated in planning any Plowshare application.

While economics is not the only consideration in assessing the possible damage, it is probably the principal one. Very early in the study of a project yields would be selected which produce the optimum crater or chimney size, for example. The damage to cultural features which might be expected from the ground motion caused by the selected yield must be evaluated. If such damage were limited to isolated cases of minor cracking of plaster in old homes, agreements could probably be reached with the owners involved with a minimum of difficulty. If, on the other hand, more extensive damage could be reasonably expected, several alternatives would have to be considered. The yields tentatively selected as most efficient might be reduced to a "safe" level. However, the dimensions of the project may be such that this reduction would require yields which would not be sufficient to do the job, or to make nuclear excavation not competitive with conventional procedures. In some cases it might be obvious that damage would be so great that the property involved would have to be purchased outright, while in other situations the best solution would be to employ optimum yields fully expecting damage which could be indemnified at a more attractive cost

than would be incurred by using such small devices that no damage or only negligible damage would occur.

In any event, means of evaluating the damage potential of the various alternatives would be necessary. In this paper the present state of the art of these evaluations is discussed, as related to broad types of facilities: buildings in which stresses and deformations can be analyzed using established engineering principles, i.e., "engineered structures"; "nonengineered structures" such as residential buildings; and some of the facilities used for construction and support in a nuclear excavation or mining project.

RESPONSE OF ENGINEERED STRUCTURES TO GROUND MOTION

It appears that the effect of explosion-induced ground motion on engineered structures can best be discussed by making use of an approach universally employed in the earthquake engineering field, the response spectrum technique. Its most straightforward application assumes for a building linear elastic behavior; viscous, or velocity, damping; rigid floor girders; and concentration of all the mass of each story at ceiling level. The use of these assumptions permits engineered structures to be treated as lumped mass-spring-dashpot vibrating systems.

In Fig. 1 is shown a single degree of freedom (SDF) system with the equations which describe the free vibration of the mass.

To visualize the response of a single degree of freedom system to a time-dependent nonperiodic force, we should begin by examining the impulse response of the mass. An impulse acting on the mass will cause a change in velocity, from which it is possible to determine the motion of the mass as shown in Fig. 2.

If the time-varying driving force can be expressed as a series of impulses, the motion of the mass can be defined by summing the response due to the individual impulses as in Fig. 3 if the system is linear.

The previous discussion applied to motion resulting from a force acting on the mass directly. A slight modification yields a procedure

(a) Undamped single-degree-of-freedom system.

(b) Free-body diagram of mass displaced distance $\underline{x}$.

$$\sum F_h = 0$$

$$m\ddot{x} + kx = 0$$

$$\ddot{x} + \frac{k}{m} x = 0$$

$$\text{Letting } \frac{k}{m} = p^2$$

$$\text{Solution: } x = A \cos pt + B \sin pt$$

$$\text{From initial conditions: } A = x_0; B = v_0/p$$

$$x = x_0 \cos pt + v_0/p \sin pt$$

(c) Equation of free vibration of mass.

GLL-644-768

Fig. 1. Free vibration of SDF system.

$$\text{Impulse} = F_0 \Delta t$$

Impulse = change in momentum

$$F_0 \Delta t = m \Delta \dot{x}$$

If system is initially at rest, $v_0 = 0$, $x_0 = 0$

$$F_0 \Delta t = m \dot{x}$$

$$\dot{x} = \frac{F_0 \Delta t}{m}$$

$$x = x_0 \cos pt + \frac{v_0}{p} \sin pt$$

$$x = 0 + \frac{F_0 \Delta t}{pm} \sin pt$$

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Fig. 2. Impulse response of SDF system.

Impulse response: $x = \frac{F_0}{mp} \sin pt$

Displacement at time t due to impulse $F(t)_n$:

$$x = \frac{F(t)_n}{mp} \sin p(t - t_n)$$

Displacement at time t due to series of impulses $F(t)$

$$x = \int_0^t \frac{F(t)}{mp} \sin p(t - t_n)$$

GLL-644-770

Fig. 3. Response of SDF system to driving force $F(t)$.

which can be used in cases where the excitation is at the base of the spring. If the displacement of the mass is x , and of the base, y , then

$$m\ddot{x} + k(x - y) = 0.$$

Subtracting $m\ddot{y}$ and letting u be the relative displacement of the mass with respect to the base:

$$m\ddot{u} + ku = -m\ddot{y}.$$

This is analagous to a system driven by a force $-m\ddot{y}$ applied to the mass, the displacement being relative.

Considering a system with viscous damping slightly changes the equation used thus far. The impulse response of such a system is given by:

$$u = e^{-\beta p(t-\tau)} \frac{\dot{u}}{p_d} \sin p_d(t - \tau).$$

or

$$u = e^{-\beta p t} \frac{F_0 d\tau}{m p_d} e^{-\beta p \tau} \sin p_d(t - \tau).$$

The response to a series of impulses is then:

$$u = e^{-\beta p t} \int \frac{F_0(\tau)}{m p_d} e^{-\beta p \tau} \sin p_d(t - \tau) d\tau.$$

Making use of the analogy mentioned earlier:

$$u = \frac{e^{-\beta p t}}{p_d} \int \ddot{y}(\tau) e^{-\beta p \tau} \sin p_d(t - \tau) d\tau.$$

A plot of the maximum values of this equation against various damped frequencies (p_d) is known as a velocity spectrum. The equation yields a spectrum for each value of damping, β .

As stated earlier, engineered structures can be considered as vibrating systems for analysis of their response to ground motion. In this case a one-story building would be treated as a single-degree-of-

freedom system. The dynamic parameters, k , m , c (or β), p_d , are readily determined to the required accuracy. Because structures are invariably designed with excess gravity load capacity, the horizontal motion of the responding structure is of primary importance.

An idealized structure is shown in Fig. 4. For this structure the velocity spectrum obtained from any ground motion, $\ddot{y}$, might be as shown in Fig. 5, which is characteristic of both the structure and the ground motion. A more interesting case is the general one of the effect on various structures of some time-varying ground motion. The principal structural characteristics involved are β and p_d . Five spectra associated with the surface motion recorded near an underground nuclear blast are shown in Fig. 6. Two features are obvious. First that structures having certain periods (or frequencies) respond more violently to the given ground motion; and second, that the amount of damping greatly influences the response, with even a small amount of damping markedly reducing peak spectral values.

Since the integral must be evaluated for the entire ground motion, the amount of computational work is tremendous, requiring some type of computer.

The use of response spectra to determine the effect of a given motion is surprisingly simple once the spectrum is obtained. For estimating the effect on a particular building, the procedure outlined in Fig. 7 might be used.

This value could be compared with the lateral force for which the building was designed and a determination made of the likelihood of damage. It should be emphasized that each spectrum is uniquely related to the earth-motion history employed in obtaining the spectrum. For evaluating the response of a particular building to some planned detonation, some standard spectra would be highly desirable. Computer programs are in existence for preparing spectra from accelerograms of earlier shots, and it is anticipated that standard spectra for a broad range of situations will be available in the future.

For unit deflection restoring force = $\frac{12 \cdot EI}{L^3} = k$

Fig. 4. Idealized SDF structure.

Fig. 5. Response (spectrum) of structure to blast-induced ground motion.

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Fig. 6. Relative velocity spectrum for one GNOME accelerogram. Damping - 0, 2, 5, 10, 20% critical. S_v in units of 10 cm/sec. Frequency P in rad/sec.

Maximum shear ($v_{\max}$) in columns = $kx_{\max}$

$$x_{\max} = \int e^{-\beta p t} \frac{-\ddot{y}}{P_d} e^{-\beta p \tau} \sin P_d(t - \tau) d\tau \equiv \frac{S_v}{P_d}$$

$$v_{\max} = \frac{KS_v}{P_d}$$

$$k = mp^2$$

$$v_{\max} = mp_d^2 S_v / P_d = mp_d S_v$$

If the structure of interest has a period of 0.5 sec ($p_d = 2\pi/0.5$) and damping is 20% critical, from the spectrum S_v is 0.9 fps. If the weight of the structure is 20 kips, the base shear would be:

$$\frac{20 \text{ kips} \times 12.56 \text{ r/sec} \times 0.9 \text{ fps}}{32.2 \text{ ft/sec/sec}} = 7 \text{ kips}$$

GLL-644-774

Fig. 7. Calculation of column shear.

Though this discussion has been limited to one-story buildings (single-degree-of-freedom systems) the same procedures can be used for multistory buildings.

A multistory building may vibrate in as many mode shapes as it has degrees of freedom. In structures having low damping, each mode is independent of all others, so that the maximum response of the building can be obtained by simply adding together the response in the individual modes.

While the dynamic parameters of single-degree-of-freedom structures have in many cases been reduced to tables, some calculation is required to determine these for multistory buildings. These procedures, which are extensively documented in the structural dynamics literature, generally involve assuming certain parameters - mode shapes, for example - and calculating other parameters, checking for consistency between the assumed parameters and their values derived from the calculations. Of course, for existing buildings, it may be possible to actually measure the period and modal deflections.

The response calculated by superposition of modes represents an upper limit because the maximum response in the various modes need not occur simultaneously. A study of the response of one building to an earthquake has shown that the calculated response exceeded the recorded by about 30%. A more realistic estimate of response might be obtained by adding some fraction, say one-half, of the higher mode response to the fundamental mode.

Other factors which might cause actual response to be less than that which would be calculated include inelastic behavior and participation by nonstructural members. Slight yielding of the many joints in a large building or minute cracking of concrete could absorb a tremendous amount of the input energy. Features such as walls and stairwells cause a significant departure from the assumed configuration.

While these procedures produce quite satisfactory results when applied to "older" buildings, there is a need for much additional work on the response of the modern buildings with their long, uninterrupted

clear spans, a situation where the rigid girders assumption is clearly not justified.

Obviously, the likelihood of damage to engineered structures, which usually represent a large investment, would be studied by experts during the planning of any Plowshare project.

Structural engineers who have studied the problems are confident that present knowledge would permit such projects to be executed without risking damage to large buildings.

DAMAGE TO RESIDENTIAL-TYPE STRUCTURES

As a first step in resolving the question of what constitutes damaging ground motion to residential-type buildings, a search was made of available literature on the effect of industrial high-explosive detonations on residential-type construction since it is expected that damage to this type building represents one of the limiting problems in carrying out Plowshare projects. The four reports covered by this paper appear to be the most complete of those available.

Investigations studied all involved the assumption of simple harmonic ground motion so that maximum acceleration, velocity, and displacement are uniquely related for a given frequency (f). Therefore, if

$$X = A \sin 2\pi ft$$

$$x = A$$

$$v = 2\pi fA$$

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

where X = displacement at time t , x = maximum displacement, v = maximum velocity, and a = maximum acceleration. All the investigators plotted their results on log-log graphs with "displacement" ordinates and "frequency" abscissas. Therefore, a -1 slope represents velocity (A and f to the first power) while a slope of -2 represents acceleration (A to the first power; f to the second).

Because of the great variety of structure types studied and the uncertainty of design and construction details, both of the buildings

covered by these reports and those which will be the subject of future concern, empirical relationships based on a number of explosions which resulted in damage seem preferable to detailed theoretical analyses.

Experience has shown that the frequencies associated with underground nuclear blasts are in the range below 10 cps. Predominant frequency decreases as yield and range increase; and higher frequencies occur in hard rock than in low-velocity rock and soil. Unfortunately, there appears to be little data published covering the very low frequency range.

Throughout this section, damage refers to cracking of plaster, the weakest structural element in most houses, and therefore the first to show distress. The extent of damage is as indicated in the section on each investigation and in the conclusions.

Investigations

U. S. Bureau of Mines

One of the earliest investigations undertaken to study the effect of blasting operations on residential structures was reported by the U. S. Bureau of Mines in USBM Bulletin 442 (1942). Beginning in 1935, the Bureau instrumented a number of residential-type structures adjacent to operating quarries. The blasts associated with normal operations caused no detectable damage.

Vibrating machines were then developed which produced wave forms said to be sufficiently similar to those of high-explosive detonations for correlation. These machines, consisting of counter-rotating unbalanced rotors, were installed in several buildings in an attempt to excite each building as a unit to the point where some cracking of plaster occurred, but the machines were not able to produce large enough amplitudes to cause damage.

Tests were begun to study the effect of vibration of individual floor and ceiling panels using the shaking machines, which the investigators felt duplicated the effect of a quarry blast acting on the entire

building. In each test a machine was fixed to the center of a panel, and seismometers were located at several points on the panel. The test consisted of adjusting the amplitude and frequency of panel motion until damage resulted or to some preselected level, recording the motion on the seismometers, and noting the extent of damage.

Approximately 160 tests were conducted in buildings of frame, brick, and masonry construction in the frequency range of 2 to 40 cps with most damage-producing tests at frequencies of 8 to 20 cps. Results of these tests are shown in Fig. 8. It was concluded that the damage region could best be delineated by the bold solid line. This line, having a slope of -2 represents a constant acceleration of 32 ft/sec^2 (1.0 g). The lighter solid line represents an acceleration of 3.2 ft/sec^2 (0.1 g). It was considered that an acceleration of 1 g is the best damage index and that an acceleration of 0.1 g defines the threshold of damage.

The validity of these results as an indication of potential damage due to actual blasting is doubtful. The machine-induced vibrations are steady state sinusoids rather than complex transients (as would be the case with the blast) and also of somewhat longer duration than that of explosion-induced motion. The basis for correlating the machine and the blast-wave forms is not clear.

F. J. Crandell

In 1949 Crandell published a paper in which he proposed an "Energy Ratio," defined as $(\text{acceleration/frequency})^2$, as an indicator of structural damage. As a result of a number of excavation shots in areas built up with homes, schools, and churches (more than 1000 buildings were involved), Crandell found that for average structures there was no damage in cases where $\text{E.R.} < 3$. Accelerations were recorded on the surface adjacent to buildings using an accelerograph which Crandell had developed. His report does not indicate his method for determining frequency. Whereas $\text{E.R.} < 3$ indicated a safe condition, an E.R. of 6 normally resulted in damage to residential-

Fig. 8. Displacement vs frequency (USBM) "No Damage" not indicated.

type buildings which had not been prestressed by settlement or shrinkage. An interpretation of these data is complicated by the omission in the paper of a definition of damage.

This work involved charges ranging from 1 to 100 pounds, and structures were all located less than 250 feet from the detonation. It appears that frequencies considered are in the 2- to 80-cps range.

Although Crandell recommends use of the Energy Ratio, manipulation of his equation and insertion of his limits results in the following restatement of his concept:

$$E.R. = \frac{a^2}{f^2} \quad (a \text{ in ft/sec}^2, f \text{ in cps})$$

$$a = 2\pi f v$$

$$E.R. = 4\pi^2 v^2$$

$$v = \frac{\sqrt{E.R.}}{2\pi} \quad (v \text{ in ft/sec}).$$

Damage to normal residential-type buildings is likely to occur when the velocity of the surface adjacent to the structure exceeds 4.7 in./sec. No damage would be expected in cases where maximum surface velocity is less than 3.4 in./sec.

Langefors, Kihlstrom, Westerberg

In the course of a major project in Stockholm in the 1950's a study was made of the effect of small charges (up to 220 pounds) detonated in hard rock close to a number of buildings. The buildings appear to be mainly of masonry construction. In planning this project it had been decided that from an economic standpoint it would be advantageous in some cases to use such large charges that damage was inevitable. It was felt that greater savings would be realized by repairing this damage than by limiting charges to those which would cause no damage. As a result of this decision considerable damage information was collected.

Because of the small charges, hard-rock medium, and the proximity of measurement, high frequencies (50 to 500 cps) were recorded in this investigation.

In each test a Cambridge vibrograph was set up adjacent to a building. After a detonation the extent of damage experienced was plotted on a graph of amplitude vs frequency (see Fig. 9). It was found that separation of the graph into regions of similar damage levels could best be done by lines having slopes of -1. On log-log plots this slope implies velocity, and the investigators calculated the velocities represented by each line as shown in Table I.

TABLE I.

Extent of damage	Velocity	
	mm/sec	in./sec
Fine cracks	110	4-1/3
Cracks	160	6-1/3
Serious cracks	230	9

While the frequencies involved in this study are far above those experienced in underground nuclear blasts, one of the investigators had previously reported that for frequencies less than 10 cps, velocity is the parameter which can best be correlated to a given damage level. However, his values for limiting velocities are not presently available.

Edwards and Northwood

During construction of the St. Lawrence Seaway, six buildings, three on till and three on wet sand-clay, slated for destruction were used to study earth-motion-damage relationships. The ground surface adjacent to each building was instrumented with accelerometers, velocity gauges, and displacement seismographs. Before each test a building was examined, paper tabs were pasted over cracks, plumb-bobs were installed, and a level survey made. Tests consisted of detonating

Fig. 9. Displacement vs frequency (Langefors, Kihlstrom & Westerberg)
 "No Damage" not indicated.

charges of increasing size at decreasing ranges until damage occurred. The 26 charges varied from 42 to 750 pounds with 5 being less than 120 pounds, and 3 more than 550 pounds. Distances from shot to building were 25 to 200 feet with half the tests being conducted at distances of 95 to 160 feet. The ground motion and movement of the building were recorded for each shot, and the building carefully examined for visible damage, as indicated by torn paper tabs and new cracks, changes in elevation, and vertical nonalignment.

Of the three types of instruments used, only the accelerometers were used as had been planned. Velocity gauges showed evidence of moving parts striking stops so that useable velocity records were not obtained during the tests. The available displacement meters were too sensitive to record at damage levels. This was overcome by firing small calibration shots and measuring displacement at a building and at a remote location. For the actual test shot, only the remote meter was used, and the displacement at the building inferred.

Damage levels were defined as follows:

Threshold: Opening of old cracks and formation of new plaster cracks, dislodging of loose bricks.

Minor: Superficial, broken windows, falling plaster, cracks in masonry.

Major: Serious weakening of structure; large cracks, settlement, lateral movement.

The investigators generally related damage to the type soil on which a building was founded. In the buildings on the sand-clay soil, vertical cracks which were associated with large settlements predominated. The buildings on till usually showed horizontal cracks or shattering of basement walls. On both soils chimneys often showed the first signs of damage. Test results are shown in Fig. 10. Although there is considerable scatter, as would certainly be expected from the diverse nature of the buildings tested, the trend of points plotted for major, minor, and threshold damage suggests a best fit having a slope of approximately -1, which indicates each level of damage is associated

Fig. 10. Displacement vs frequency (Edwards & Northwood) "No Damage" not indicated.

with a constant velocity. The authors concluded that their results support the criteria of Langefors et al., and that a peak velocity of approximately 4.5 in./sec appears to represent a damage threshold for a variety of foundation materials.

Conclusions

Even though the data from any one of the reports studied show considerable scatter, when all data are compiled on one graph, such as Fig. 11, covering the frequency range from 2 to 400 cps, a clearer indication of surface-motion-damage relationships emerges. Damage levels from the individual studies are regrouped as shown in Table II.

TABLE II. Damage levels regrouped for plotting Fig. 11.

Fig. 4	USBM	Langefors, <u>et al.</u>	Edwards & Northwood
Threshold	Fine cracks	Fine cracking	Threshold
Minor	Falling plaster	Cracking	Minor

Clearly, the wave forms involved in surface motion are not pure sinusoids; however, successive differentiations generally result in displacement, velocity, and acceleration values which are not unreasonable. Thus, it would seem valid to designate the first derivative of displacement, which plots as a line with -1 slope on log-log paper, as velocity. If this is done, then it appears that some velocity can be related to the threshold of damage for the type buildings studied.

Because of the dissimilarity in structural characteristics between "identical" small buildings, it is not surprising that there is considerable scatter in plotting test results. Perhaps grouping buildings by construction type would result in sets of data which are in good agreement. The fact that each group of tests was interpreted by different people doubtless introduces some inconsistency. Finally, the entirely different

Fig. 11. Results of four test series.

input motion and the fact that panel, rather than ground surface, measurements were made in the USBM work might explain the great departure of these data from the values taken from the other investigations.

Combining the data of the four test series clearly supports the criterion that a velocity of approximately 4.5 in./sec represents a limit below which average residential-type buildings should suffer little or no damage, and that velocities of less than $3\frac{1}{3}$ in./sec (E.R. = 3) are associated with negligible damage. Further, in the frequency range predominating at intermediate distances from underground nuclear detonations, displacements of less than $2\frac{1}{2}$ mm (0.1 in.) would appear to represent a conservative, safe surface-motion limit.

As a matter of interest, selected data collected by USC & GS in connection with three recent underground nuclear detonations are shown in Fig. 11. Information pertaining to these events is summarized in Table III.

TABLE III.

<u>Event and Type</u>	<u>Approximate yield (kt)</u>	<u>Shot medium</u>
Danny Boy (cratering)	0.43	basalt
Gnome (contained)	3.1	salt
Sedan (cratering)	100	alluvium

Tests on Nuclear Experiments

In order to examine the applicability of the high-explosive damage criteria to nuclear-explosion-induced motion and to better define damage more serious than cracked plaster, a series of tests has been undertaken. The tests involve the erection of 16-foot square one-room model houses of various types of construction at distances from underground nuclear detonations at which selected velocities are predicted. Analysis

of test data includes correlation of observed damage with the measured ground motion intensity.

Preliminary results of early tests of two concrete block and two frame houses suggest that no damage is experienced when peak velocities are 20 cm/sec. On one experiment where peak velocity is estimated at approximately 80 cm/sec, the entire plywood-sheathed house was shifted about 2 inches on its foundation, there was some cracking of plaster, and binding of the door indicated some relative movement in the building. The condition of the house was impaired only in an aesthetic sense; and except for homes, where appearance is of prime importance, such damage would be considered minor.

It should be emphasized that these test houses are not necessarily directly representative of average buildings as they are newly-built in accordance with a rigid building code, and their size and shape are not typical.

On one experiment the lateral stability of residences on unbonded concrete-block pillars was studied. A pair of structures, different only in that timber cribs were placed adjacent to the pillars under one, was subjected to peak ground motion of 1.3-g acceleration, 20 cm/sec velocity, and 1.5-cm displacement. A second pair was located where the peak motion was 0.75 g, 10 cm/sec, and 1 cm. The postshot survey of the structures showed that the relative displacement had been so small, approximately 0.5 inch, that the 8-inch-wide block pillars had not approached overturning. Damage was limited to minor distortion of the wooden frame, which was not sheathed, cracking of some of the blocks, and slight displacement of a few of the blocks making up the foundations.

Although no dwellings have been subjected to motions in what would appear to be the damaging range, four houses were within 4 miles of the 3-kt Gnome shot. The complete absence of damage indicates that for nuclear-explosion-induced motion 2 cm/sec is clearly "non-damaging"; that being the peak velocity in the area of the houses.

DAMAGE TO CONSTRUCTION SUPPORT FACILITIES

A survey of construction support facilities damage suffered as a result of underground nuclear detonations has been made to provide information for planning and executing future detonations. Facilities which have been subjected to intense ground motion, and are therefore included in the survey, are: buildings; equipment such as generators, air compressors, and pumps; trailers; and storage tanks.

Prefabricated Metal Buildings

A few commercially available prefabricated metal buildings of various sizes have been subjected to severe ground motions on underground shots, and in no cases have the buildings been damaged. These standard structures are made of rigid gable steel bents with anchor bolts cast in individual column foundations or continuous footings. Longitudinal stiffness is provided by steel tie rods, and the structural frame is sheathed in corrugated metal panels.

A building of this type was not damaged in any way when subjected to 0.4 g, 10 cm/sec, 4 cm ground motion.

On the Gnome event four of the buildings were erected without special reinforcement approximately 1200 feet from surface zero, and none suffered structural damage, although three did show minor effects of the ground motion, which at that location is estimated to have been 5 g, 150 cm/sec, 10 cm. One building showed a slight (3/8 inch) differential set; and the concrete slab, which was monolithic with the deeper hoist foundation, was slightly cracked. Another house was not itself affected, but a ceramic toilet inside the building was shattered. The only evidence of motion at the third building was the jarring loose of one window screen. The fourth small metal building showed no effects whatever.

Postshot examination of all these buildings showed neither permanent displacement, except for the tilting of the one house, nor yielding of anchor bolts or tie rods.

As a result of this experience it appears that the prefabricated buildings can withstand the effects of ground motion at scaled ranges as small as $1000 W^{1/3}$ without suffering any structural damage.

Plywood "Field Office" Type Buildings

While the extreme variation in quality of these buildings complicates a discussion of potential damage, it is clear that small plywood buildings can be of sufficiently rugged construction to survive very severe ground motions.

The vent house and two smaller (10 ft $\times$ 10 ft) plywood buildings at the Gnome shaft showed no shock damage although they were not reinforced. These buildings were of 1/2-inch plywood over 2 $\times$ 4 studs on 16-inch centers.

Even when these buildings break away from the ground, damage is limited. One small building 1500 feet from ground zero of a 200-kt detonation suffered some crushing of its skids and the building was slightly racked, but none of the seams were opened. In a skid-mounted office the nails in the floor had to be redriven following a shot, but there was no other damage even though the ground motion is estimated at 0.75 g, 80 cm/sec, 10 cm.

Plywood buildings 10 ft $\times$ 10 ft $\times$ 10 ft with 2 $\times$ 4 studs on 16-inch centers are situated at ground zero on all deep shots, and the extent of damage suffered ranges from "none" to "demolished"; however, ground motion estimates are not available for correlation with damage.

Minor distortion would not generally be considered a problem because these buildings are most frequently intended only for protection from the elements.

The inherent rigidity of plywood panels makes possible the construction of strong, tight, small buildings if the individual panels are firmly connected. Diagonal bracing or lamination of panels should provide a small building with sufficient strength to survive motion at ranges of $200 W^{1/3}$ feet if a shelter is required at this short range.

Damage to Mechanical Equipment

Observed damage to machinery such as motors, generators, pumps, and air compressors falls into two categories: failure of suspension systems, which leads to misalignment of parts or possibly more serious damage due to the forcing together of parts or dropping of assemblies; and cracking of brittle, cast-metal components.

On Gnome there was no damage to mechanical equipment although several pieces were in regions of severe ground motion. Fifteen hundred feet from ground zero four generators - two 500 kw on concrete machine foundations and two 600 kw skid mounted - were apparently unaffected by the detonation. Acceleration is estimated to have been 4 g; velocity, 100 cm/sec; displacement, 10 cm.

While the hoist at the Gnome shaft was not itself damaged by the explosion, axle bearings subsequently burned out as a result of differential settlement of the foundation on which the machinery rested.

A small electric pump located in the Gnome drift had been mounted on shock absorbers and suffered no shock damage.

On the one event, Bilby, for which damage has been reported, equipment was concentrated at four locations. Damage suffered includes bending and shearing of suspensions, misalignment, effects of impact of machinery components coming together or dropping on the ground, and cracking of brittle, cast housing and engine blocks.

Failure of Suspension Systems

The majority of the equipment surveyed had longitudinal steel skids resting on the ground with a transverse steel channel, on which the front of the engine rested, welded to the skids. At the rear of the engine a bracket was welded or bolted to the skids and to the engine block or clutch housing. The most frequently observed damage involved failure of the front and/or rear mounts, which, while sufficiently strong to support the load under normal conditions, are susceptible to failure under impulsive loading due to the inertia of the heavy supported machinery.

Of a total of approximately 30 pieces of skid-mounted equipment at the four locations where damage occurred, 10 were actually affected to the extent that they required repair, which generally consisted of realignment and rewelding of bent beams and twisted or broken brackets and welds. However, in two cases more serious damage occurred. One pump engine broke loose from its supports and moved into the radiator, bending the fan blades and radiator fins. On an air compressor the oil pan and block were broken when the engine dropped as a result of failure of the rear mounting brackets.

In addition to such damage associated with suspension failures, two cases of misalignment of parts have been reported, both involving drill rigs, which were at points where the estimated ground motion was 0.5 to 0.7 g, about 80 cm/sec, 5 to 7 cm. Both were blocked up with masts chained to stands. The rig nearer ground zero was oriented with the mast radial with respect to the shot, while the second rig, which was further away by about 2000 feet had the mast positioned transversely and was situated about 500 feet from the Yucca Fault. On both rigs the chain securing the mast broke, permitting twisting of the draw works motors, located on the rig platform, out of line. Repairs to the nearer rig required 2 days, while the other rig was out of operation for 5 days.

Before Bilby, however, a rig similar to the two discussed above suffered no damage even though it was only 400 feet from ground zero of a low-yield shot.

On Gnome two drill rigs were parked about 1 mile from the shot (1 g, 15 cm/sec, 2 cm). No special precautions were taken to protect these rigs beyond normal transporting procedures. The rubber tires and springs of the trucks on which the rigs were mounted may have prevented damage, but damage on Bilby should probably be attributed to failure of the securing chains.

Damage to generators, compressors, pumps, steel tanks, and drill rigs is summarized in Table IV.

TABLE IV.

Acc. (g)	Vel. (cm/sec)	Disp. (cm)	Equipment	Damage
1	150	15	9 air compressors	Cylinders on one 1000 cfm compressor broke off. Front support beams on 3 bent.
			3 mud pumps	Oil pan and block on one pump broke when engine dropped due to failure of mounting brackets. One cracked exhaust manifold.
			1 light plant 1 fuel tank	Collapsed due to excessive negative camber of wheels. Neither tank nor generator damaged.
			Two 500-bbl tanks	Both bent at saddles.
0.5	50	5	Drill rig w/3 engines on platform	Alignment of engines destroyed and 2 radiators cracked when chains securing mast broke.
			Light plant	Axles on trailer bent slightly.
0.75	80	7	Drill rig w/3 engines on platform	Engines required complete re-alignment. One water jacket cracked.
			10 compressors	One block cracked; 4 to 5 supporting beams bent or rear brackets failed.
			Two 500-bbl tanks	One split at joint between end and sidewall; other bent at saddles.
			2 mud pumps	None
0.75	80	7	Two 500-bbl tanks	One split at joint between end and sidewall; other bent at saddles.
			3 mud pumps	Radiator fins and fan on one slightly bent when engine moved after separating from mounts. Clutch housings on other two cracked.

Cracking of Cast Metal

As with suspension failures, cracks in engine blocks and other cast-metal components have been limited to machinery mounted on rigid skids. A total of ten cases of this type damage were found. The most common location of cracks was at points where mounting brackets were attached. Two large pumps were subjected to 0.75 g, 80 cm/sec, and 7 cm, and as a result the clutch housings on both cracked at the bracket. On an adjacent pump the welds on the brackets broke, but there were no cracks.

Two pumps and an air compressor located at one station (1.5 g, 150 cm/sec, 15 cm) were damaged to varying degrees. On one pump only the exhaust manifold was cracked. On a second both the oil pan and block cracked when the rear mounts failed. The compressor, a 1000 cfm Y-type, had the heavy cylinders broken off at the neck, and the drive pulley was cracked.

Two pieces of equipment at a second station (0.75 g, 80 cm/sec, 7 cm) suffered cracks. The bottom tank on the radiator of one drill-rig engine was split and had to be replaced, and the block on an air compressor was cracked.

The only other damage to castings was the cracking of the block on a compressor (0.5 g, 50 cm/sec, 5 cm) which required replacement of the entire block, and the cracking of two water jackets on drill rig engines.

Because of the small sample available for consideration and the use of interpolated ground motion, a rigorous interpretation of the effect of ground motion on engines would have little meaning. However, certain conclusions can be drawn. Cracking of cast blocks and housings might be expected on 25 to 33% of the skid-mounted engines exposed to ground motions of 0.5 to 1 g, 50 to 100 cm/sec, 5 to 10 cm, if the equipment is not anchored to the ground or provided with some form of shock mounting. About as frequently, varying degrees of failure of mounting systems might be experienced.

Comparison of the effects of Gnome and Bilby suggest that damage might be restricted by preventing equipment from achieving free fall and smashing against the ground. On Gnome the 150-kw generators similar to the equipment damaged on Bilby were subjected to ground-motion intensities estimated at about 4 times those experienced by the damaged engines on Bilby, but the Gnome generators were anchored to a concrete foundation so that the ground, foundation, and generators moved as a unit. In this situation the generators would not have been subjected to the sharp rebound motions characteristic of free fall which can be several times the initial peak values, on which the Bilby estimates have been based.

In view of this it appears that Bilby damage would have been much less serious had the equipment been firmly tied to the ground. Damage could have been further reduced by placing equipment on some type of shock-absorbing mount, such as frangible pads (used under trailers on Gnome and Bilby), conventional trailer systems, tire casings, or heavy coil springs.

Damage to Trailers

It appears that trailers, being sufficiently strong to withstand highway shocks, can generally survive explosion-induced motion with minimum precautions.

Three electronics trailer vans were located at the Gnome shaft. These trailers were supported on transverse steel outriggers which rested on 1-foot-thick styrofoam pads. The trailers suffered no damage, but were tilted due to differential crushing of the styrofoam. The slender posts on platforms adjacent to the trailers were twisted, but this difficulty was easily corrected.

Two other vans were located about 2600 feet from Gnome surface zero. One of these was placed on a large air-filled bag, but no special steps were taken to protect the second. Neither of these trailers was damaged.

On Bilby a trailer complex was located where acceleration is estimated to have been approximately 3 g; velocity 300 cm/sec; and displacement 40 cm. Most trailers were supported on timber cribbing under the trailer body with the wheels resting on thin (4-inch) frangible pads. Guys were strung between the trailer tops and buried anchors in order to have the trailers and ground move together. No damage was done to the trailers. However, the front struts were driven into the ground, and the cribbing was disarrayed and no longer bore any of the trailers' weight. While the trailers themselves were undamaged, some damage was done to the contained electronics equipment. The slack in the guys and the postshot scattering of the cribbing suggest that the trailers were separated from the ground.

Several trailer-mounted cooling units at the Gnome shaft were overbalanced by the surface motion, but none seem to have been damaged.

The only significant damage to trailers was observed on Bilby. At points where acceleration was estimated at 3 g; velocity 300 cm/sec; and displacement 40 cm; the light tubular axles of small, loaded two-wheel trailers were bent, causing a slight negative camber of the wheels. Three four-wheel trailers on which were mounted fuel tanks and lighting sets have experienced accelerations, velocities, and displacements estimated at about 1 g; 80 cm/sec, and 20 cm, resulting in complete collapse of the wheels as a result of severe negative camber; however, neither the tanks nor lighting set suffered any damage.

Damage to Steel Storage Tanks

As would be expected, the quality of materials and workmanship greatly affect the vulnerability of metal storage tanks. On Gnome a 126,000-gallon 14-gauge bolted tank and a 6000-gallon welded-steel tank were at surface zero (70 g, 560 cm/sec, 170 cm). The 6000-gallon tank, which was of 1/4-inch steel and was buried, suffered no noticeable damage. While the top of the larger tank was slightly buckled, it was not otherwise affected. At the Gnome shaft two small

(about 1000 gallon) tanks -- one empty, the other filled with water -- appeared unaffected. A full 8000-gallon fuel tank mounted in a concrete cradle 1500 feet from Gnome suffered no damage.

Within 5 miles of the Gnome site were some ten small, privately owned water and fuel tanks, all of which appear to be standard catalog-ordered farm tanks. These were of a variety of types -- steel plate and corrugated steel with welded, bolted, and riveted joints. None showed any evidence of leaking or other damage after the detonation.

At NTS two 500-barrel steel water tanks were demolished and four others slightly damaged as a result of one shot. These tanks of 3/16-inch steel reportedly contained about 1 foot of water. None had baffles to reduce sloshing. Although at different locations, both destroyed tanks were subjected to ground motion of about 0.75 g, 80 cm/sec, and 7 cm. Examination of the tanks showed that the steel was torn in a pattern which crossed the weld connecting the end and side wall at intervals of about 2 feet. At the opposite end of the tanks, the paint was flaked in the same pattern. At both stations where tanks were destroyed, as well as at a third, there were identical tanks which suffered only severe bending at the four supporting saddles. It appears that the ground motion was about 50% greater at the station where both tanks were slightly damaged than at the two stations where a tank was split open.

The difference in the level of damage to the identical tanks and the anomalous survival of tanks subjected to more severe ground motion than two tanks which were demolished emphasize the effect of the variation in quality of construction. No decision on locating steel tanks to assure survival in regions of strong ground motion should be made without a rigorous structural analysis of the tanks. However, the Gnome experience emphasized that, if necessary, steel tanks can be designed and fabricated to withstand the effect of severe motion.

Miscellaneous Effects

At one NTS location are a Butler building machine shop, a number of trailers connected by wooden platforms, and miscellaneous small buildings. While no structural damage has been reported as a result of nuclear shots, acceleration of 0.3 g, velocity of 30 cm/sec, and displacements of 2 cm are estimated to have been caused by Bilby at this area. The only damage reported was the destruction of approximately 160 feet of fluorescent fixtures caused by the opening of links in the light chain on which the fixtures were suspended. In the area, slight shifting of some of the office trailers on their wood-crib foundations required some realignment. Several office machines were thrown from, or slid off of, desks, and desks and tables moved as much as a foot.

Following Bilby, cracks in the asphalt paving on a bunker slope (0.75 g, 70 cm/sec, 7 cm) were found to have opened up and the majority of the asphalt moved down the 45° slope 1 to 2 feet. Numerous small cracks were known to exist earlier in the 3-inch-thick paving.

A switching station 1200 feet from Bilby survived with no damage to electric equipment, the only damage being a slight (2-inch) twist in the angles on which the heavy equipment was mounted.

Around Gnome ground zero, a large number of 25-foot wooden utility poles were erected in 5-foot concrete bases. These poles were not damaged by the shot. Approximately 1000 feet from Bilby were two 50-foot guyed steel towers. Although the surface in the area was severely cracked, particularly at the wide-flange section anchors, and the steel guys were loose, these old 8-inch-diameter towers seem unaffected by the detonation. A light, 150-foot, guyed communication tower was located about 2000 feet from Gnome and was not affected by the detonation.

A massive concrete bunker (0.75 g, 80 cm/sec, 7 cm) settled 4 inches as a result of Bilby. The principal result of this was a power outage in the bunker, the incoming power lines having been sheared

off at the outer face of the wall where they entered the bunker. A 15-second power outage occurred some distance from the shot at Bilby zero time. A postshot survey of electrical facilities disclosed no cause for this, and it was concluded that a short had occurred when power lines in the area swayed together due to motion of the poles.

SUMMARY

The effect of nuclear-explosion-induced ground motion on various types of facilities has been summarized.

Evaluation of the potential damage to engineered structures can be made by using response spectrum techniques. The fundamentals of response spectra and one application have been presented.

Damage to residential-type buildings is most likely to occur as cracks in walls. It appears that peak surface velocities of about 10 cm/sec represent the threshold of damage in older homes having plastered interiors, while 20 cm/sec peak velocities appear to be non-damaging for well-built new homes with plastered walls or stuccoed exteriors.

Buildings and equipment of the types found at most large construction projects can survive very severe ground motions. Damage to mechanical equipment is summarized in Table IV.

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