CONTROL OF THE DYNAMIC ENVIRONMENT PRODUCED BY UNDERGROUND NUCLEAR EXPLOSIVES*

D. L. Bernreuter, E. C. Jackson, and A. B. Miller
Lawrence Radiation Laboratory, University of California
Livermore, California 94550

INTRODUCTION

One important aspect of any underground nuclear explosion is recording, retrieval and analysis of experiment and/or device performance. Most of the information is recorded or conditioned on sensitive electronic equipment and often transmitted via antennas that must remain in alignment. Sometimes diagnostic packages are located in towers near surface ground zero (SGZ). Also, some equipment is needed for timing and firing as well as safety requirements. Generally it is desirable to locate this equipment as close to SGZ as possible. This paper is a summary of LRL's method of controlling the dynamic environment in order to get good quality data and protect equipment while optimizing the cost.

The overall problem blends together: (1) definition of input, i.e. ground shock parameters; (2) shock sensitivity or fragility level of equipment to the input and purpose (i.e. does it record or transmit through shock arrival time?); and (3) design of a fail-safe shock mount (SM) system to modify the shock environment when required.

Before any SM system can be designed, items 1 and 2 must be answered as the ground shock can vary over a wide range and the sensitivity/fragility of the equipment can vary from less than 1/2 g to more than 100 g's, particularly if recording is done through shock arrival time. Keeping antennas in alignment is a somewhat different problem. Whenever possible the design of the SM system is based only on peak input parameters of the ground motion since detailed time histories of the ground motions are very difficult to predict. For towers and other systems which require detailed time histories, computer codes have been developed which allow a parametric study of the input ground motion's effect on the response of the system. This paper deals mainly with the close-in region where the dynamic environment is quite severe. In this region, non-standard methods and analysis are required. Out of this region, more standard methods can be used.

PREDICTION OF THE DYNAMIC ENVIRONMENT

Prediction of the surface ground motion for our purposes relies heavily on empirical data and methods. A procedure for scaling and extrapolation from one event to another is required, since there is seldom available a previous event similar enough, i.e., yield, depth of burial (DOB), geology, and measurements of ground motion, for direct comparison.

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Reference 1 gives a detailed discussion of scaling rules which have been worked out from a combination of theory and empirical data to relate the parameters from events of different yields. No corrections (in the scaling rules) are made for geology, DOB, etc. To scale for yield, all ranges (distance from center of detonation) are divided by the cube-root of the yield expressed in kilotons. Accelerations are scaled by multiplying by the cube-root of the yield, velocities are not changed, displacements and time are corrected by dividing by the cube-root of the yield. It is difficult to predict detailed time histories of the ground motion parameters other than for very closely related events; even then there are often important differences in the structure of the pulse. Peak values can be predicted somewhat better.

Most of the published data dealing with surface motion are for distances greater than 5 kilometers. To extropolate this data in closer leads to gross errors, as the nature of the ground motions is different. Close-in the ground motion is governed by the spall phenomenon and "slap down" as the spall gap closes. Just out of the spall zone, the first arrival of the stress wave is the peak value. Somewhere in this region (out to about 5 km) the maximum disturbance shifts from the first arrival to later arrivals; hence reflected waves, shear waves, surface waves and geological anomalies play a much greater role far out. For estimating the ground motion in close, we use the curves given in this paper, which are based on unpublished data. For ground motion farther out, data from Murphy and Lahoud[2] and Mickey[3] may be used.

There are three classes of events to consider:

1. Over-buried—gas stimulation
2. Fully contained
3. Cratering

Very little data exist for 1 and 3. However, since the lithostatic pressures are so much smaller than those created by the device, little difference should exist in the scaled ground motions between 1 and 2. There is also some correlation of surface ground zero (SGZ) data between 2 and 3, i.e., for cases in tuff and rock, indicating that data obtained for fully contained events are applicable to cratering events. Other than yield, DOB and range effects, the other important parameter which greatly influences the ground motion is geology. In general, velocity correlates best and acceleration and displacement correlate poorly as they are more strongly influenced by both geology and yield, as can be seen in part from the scaling. In fact, geology plays such an important role that it is very difficult to sort out the different effects, particularly for the surface motion because the layers near the surface are usually much more nonhomogenous and weathered than the deeper layers.

The most important geological parameter is the porosity along with the degree of saturation of the media. This can be seen from Fig. 1 which gives the peak (positive) particle velocities versus scaled range for various geologies for fully contained events. As can be seen, velocities for hard rock and saturated (to the surface) media are almost the same as velocities for saturated tuff around the center of detonation with a dry tuff overburden.

The effect of geology shows up even more strongly in the peak particle acceleration. In the spall zone—a typical time history is given in Fig. 2—the slap-down acceleration is often much higher than the initial acceleration; however, there appears to be no way to correlate the slap-down acceleration. At slap down, the radial and tangential components of acceleration also have large spikes and there may be more than one spike. The spall zone will normally extend out to about where the peak particle velocity has fallen to about 2 fps. Normally at the edge of the spall zone the slap down is soft, but not always. The initial peak particle acceleration correlates somewhat better. Figure 3 gives the initial scaled peak particle acceleration versus scaled

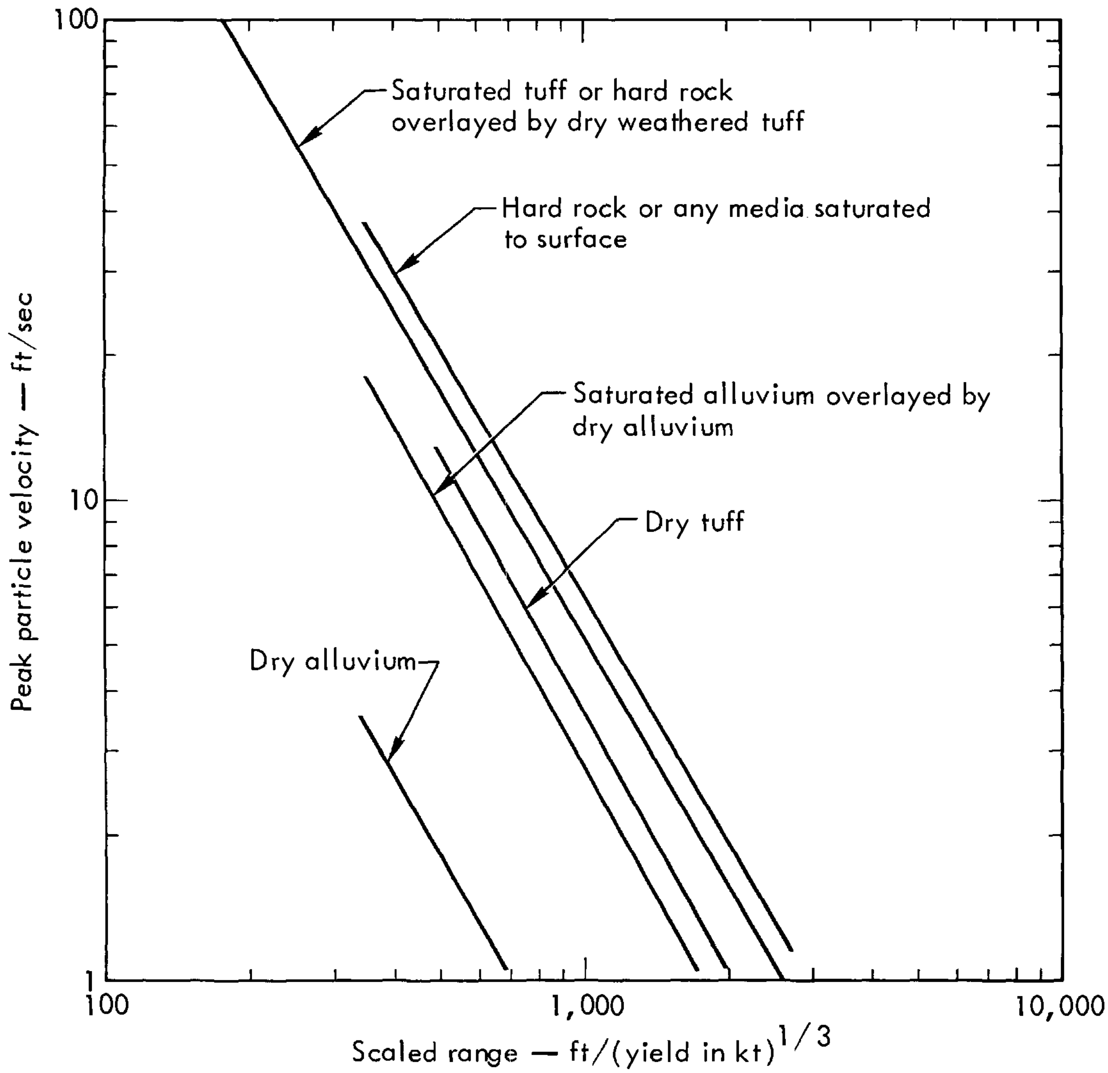

Fig. 1. Peak particle surface velocities for various geologies.

range for the same geologies as Fig. 1. Notice the great difference between the hard-rock-saturated case and the weathered cases. Furthermore for the fully contained case, initial peak accelerations appear to be limited by surficial material to less than 10 g's for dry tuff and 6 g's for dry alluvium. This is obviously not true for cratering events near SGZ. However, out of the crater this will be true once again.

Reliable peak displacement data are difficult to get and do not correlate too well. Figure 4 taken from Ref. 4 gives some idea of the order of magnitude of the peak particle displacement.

In close, the vertical component of ground motion is the largest, while the radial and tangential components are relatively small and do not seem to correlate as they are mostly a function of local geological anomalies. Out of the spall zone the peak radial component is usually smaller, but not always.

It is difficult to determine how the surface ground motion from a cratering event differs from a fully contained one. The SGZ data (velocity) from cratering events agree with an extrapolated curve of SGZ peak particle velocities from fully contained events for rock cases, indicating that proper extrapolation of fully contained data can be of use in predicting the ground motion from cratering events. This isn't true for alluvium cases; here free field data

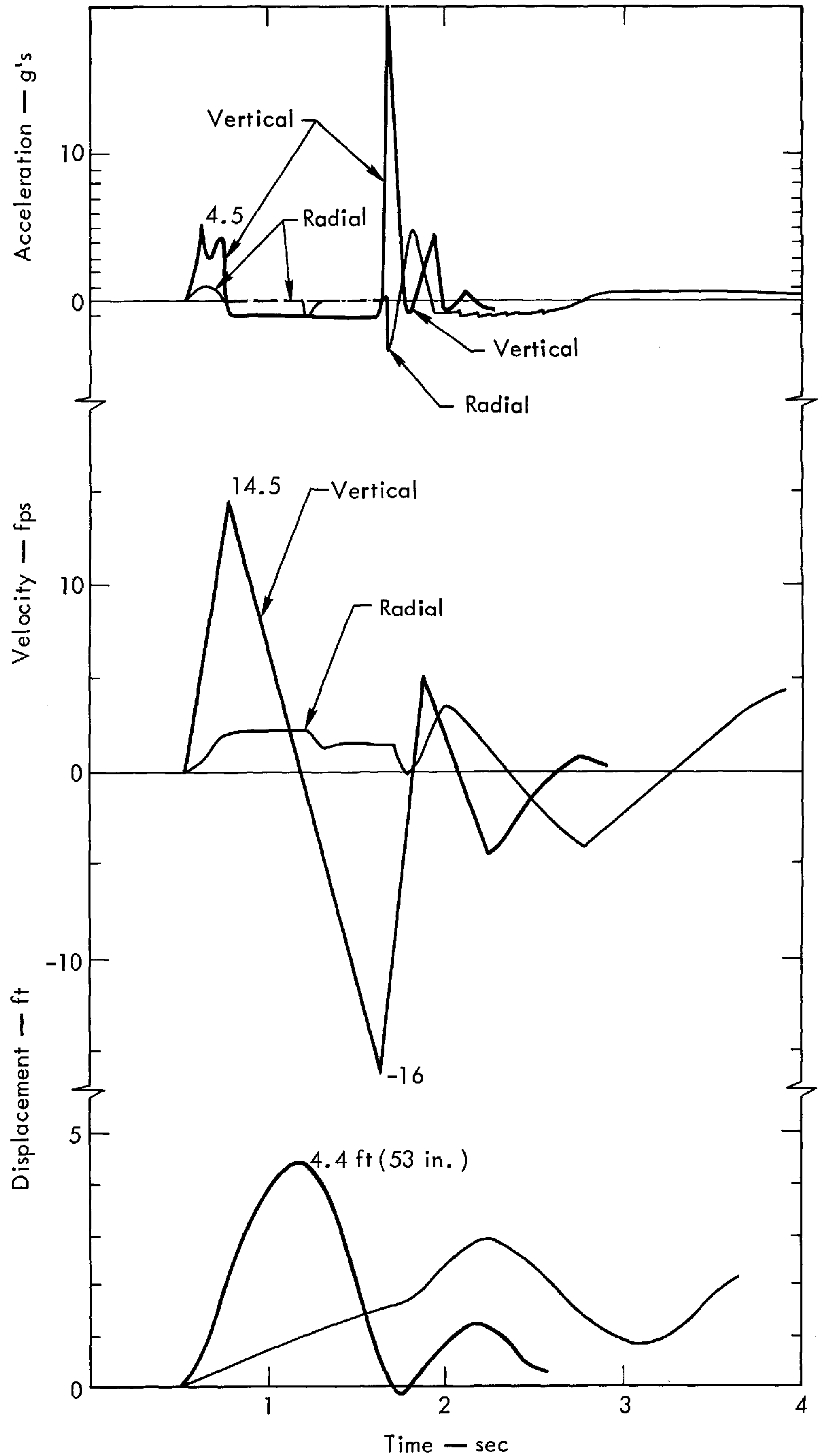

Fig. 2. Typical time history of ground motion parameters within the spall region.

given in Ref. 5 should be doubled and used. The ground motion should attenuate somewhat more rapidly due to the greatly different geometry.

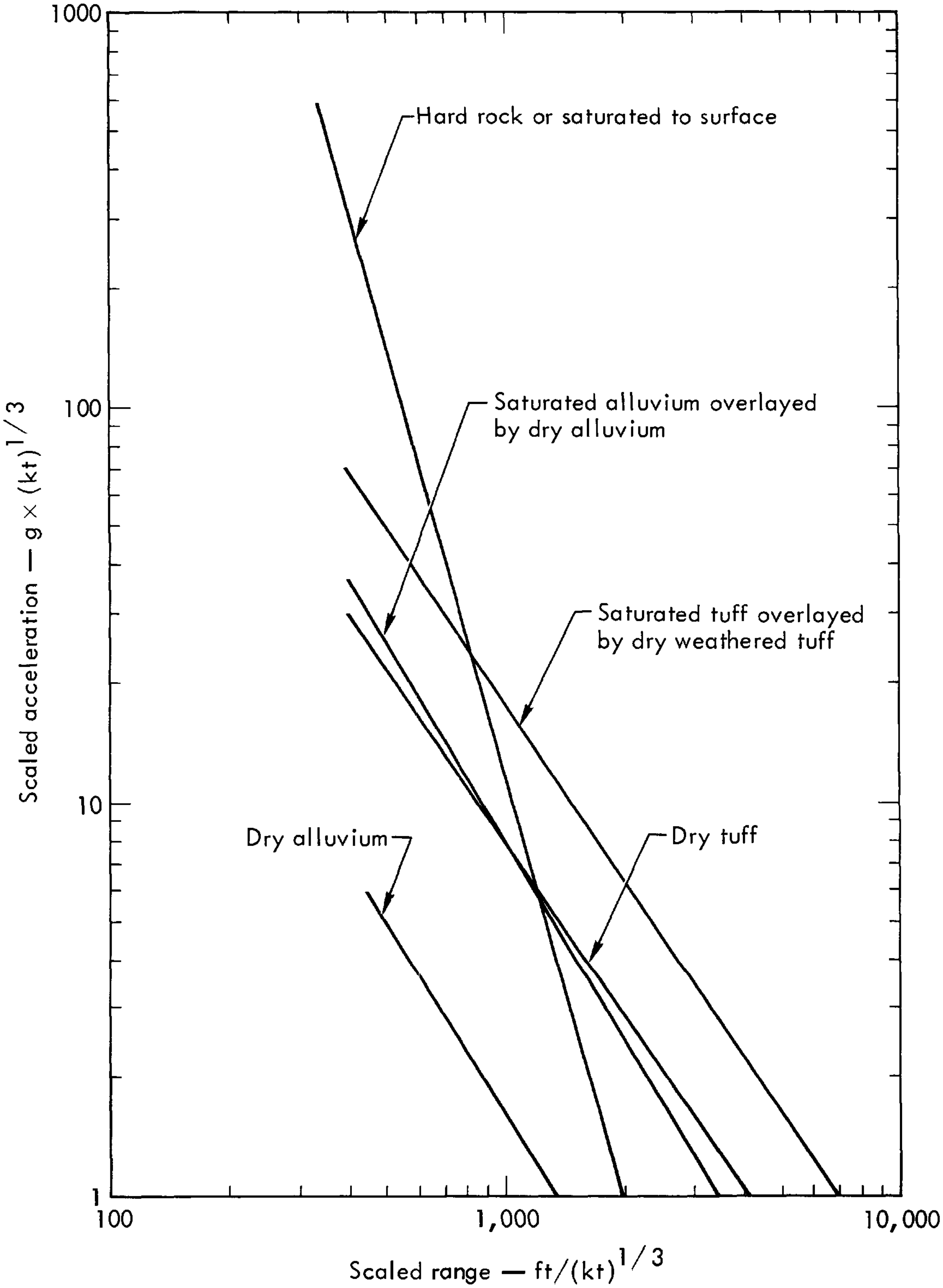

Fig. 3. Scaled initial peak-particle accelerations for various geologies. Note: Surface values for acceleration are material-limited for geologies with a weathered surface layer. This fact is obscured by the acceleration scaling.

It should also be noted that for events fired in salvos as canal cratering experiments the velocities seem to add (both close in and far out) if proper phase lags and attenuation are taken into account for travel time and distance.

This motion is greater than the motion of a single device with the same geology and same total yield.

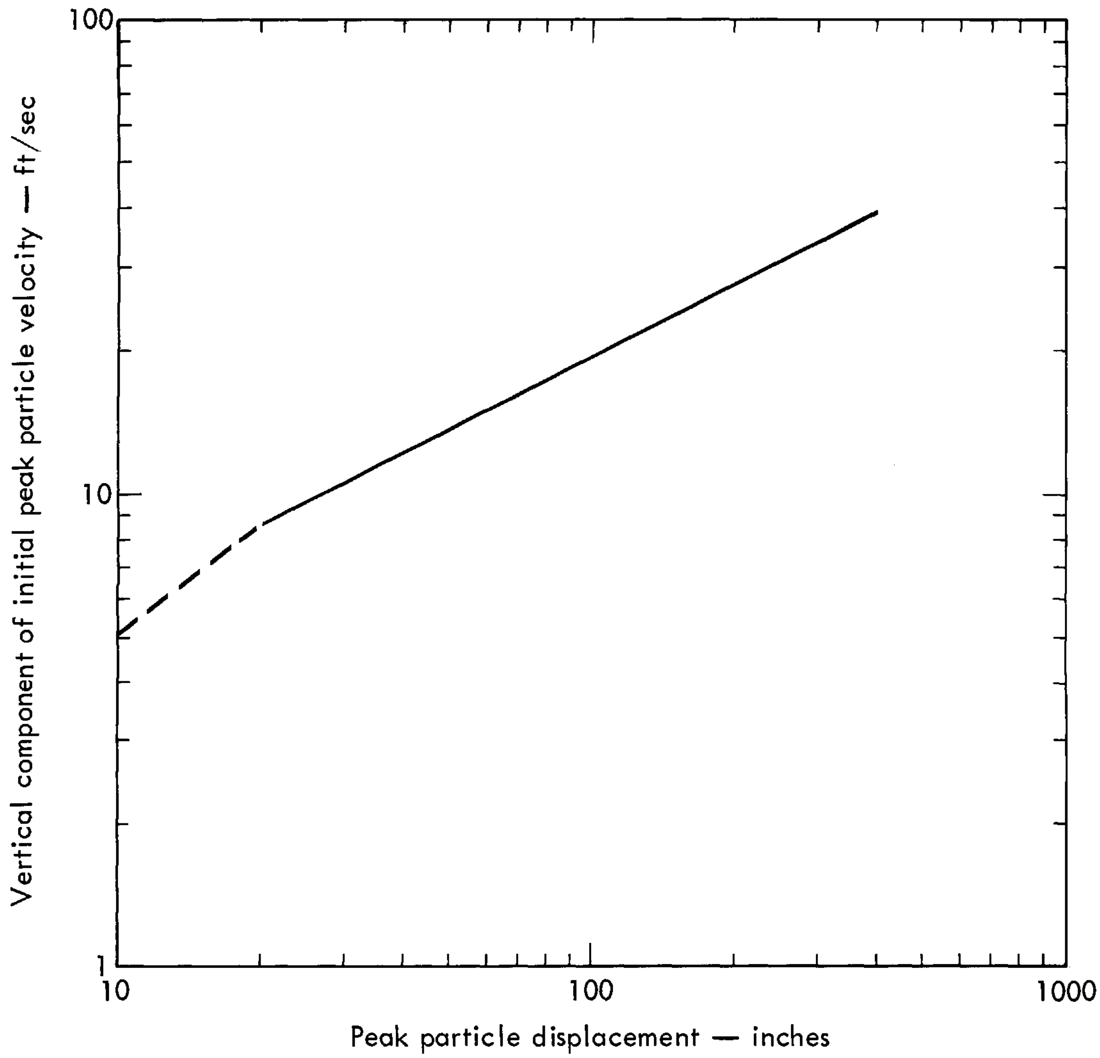

Fig. 4. Peak-particle displacement.

CONTROL OF DYNAMIC ENVIRONMENT

In order to design a shock-mounting system or determine if one is necessary, the shock and vibration fragility level of the equipment must be known. Fragility level can be defined as the point where equipment performance degrades or physical breakage occurs. In some cases it is cheaper to accept some physical damage if it does not affect the integrity of the experiment, rather than paying for the cost of shock-mounting the item. In order to classify equipment for shock mounting purposes, we can define three fragility levels: soft is less than 4 g's, medium is 4 to 20 g's, and hard is more than 20 g's. Also, we must consider pulse duration, rise time and the vibration characteristics of the equipment.

In most cases, it is desirable to locate the recording facilities close to SGZ to minimize signal attenuation and cable costs. The close area is usually within the spall region, although outside the expected crater. Figure **2** is a time history curve of the ground motion for a large event, but the characteristics are typical of the spall region. The slap-down acceleration spikes are usually greater than 10 g's and less than 25 g's. In a very few cases, they have reached as much as 30 to 40 g's. When the higher "g" level spikes occur, the duration time is usually quite short. A 20-g spike is on the order of 5 to 10 milliseconds duration. The vertical slap-down pulse is usually followed by a radial pulse which can be either away from or toward surface ground zero. Tangential pulses occasionally are significant also.

Hard Equipment

This type of equipment is usually support items (air conditioners, motor generator sets, engine generator sets, etc.) that is not required to operate after shock arrival time. It is usually cheaper to accept some damage and pay for repair rather than shock-mount this type of equipment. The basic equipment is shock-resistant, therefore particular attention should be paid to maintenance details such as loose batteries, loose voltmeters, etc. We usually crib this equipment on wood and tie it to the ground. The wood helps mitigate the narrow high "g" spikes. Loose equipment can bounce above the ground surface after initial shock, and then experience damaging impact loads upon its return just after slap down. This impact load may be greater than the slap-down acceleration within the ground. When tied to the ground via elastic tie-downs (nylon rope, wire rope, rubber bungee, etc.) and ground anchors, the input load is limited to the slap-down acceleration, or initial acceleration which seldom but occasionally exceeds the slap down.

Medium Equipment

Most electronic gear falls in this class, and most of this type have finished recording before the shock arrival time. Therefore, only prevention of physical damage is usually required. Most oscilloscopes and attached cameras can withstand more than 7 g's, although we had one camera attachment break at 6 g's (measured). Some of our newer equipment is being designed for more than 20-g environment.

Soft Equipment

We have some equipment that fits in this category and most of it is recording through shock arrival time. In order to evaluate its shock capacity, this equipment usually requires proof tests on vibration and/or shock testing machines. In some cases, the supporting power equipment must also be shock-mounted. Typical examples of equipment falling in this category are some tape recorders and similar recording devices, and in some case relays which do not have mechanical locking features.

SHOCK MITIGATION SYSTEMS

The basic requirement of all shock mitigation systems is controlled relative displacement and force transmission between the shock input and the package or system to be isolated. The fundamental classification of shock and vibration systems is the manner in which it stores, absorbs, or dissipates energy. A great many different materials and methods are used in shock and vibration isolation—metal springs, rubber spring dampers, fluid dampers, pneumatic springs, crushable materials, friction devices, frangible tubes, plastic strain absorbers, and many more. A complete discussion of all parameters involved in shock-mounting items for underground detonations would be quite long, therefore in this paper we will describe only a few of the methods we have been using. A detailed compilation of basic analysis methods and materials can be found in Ref. 6.

An economical design concept applicable to this type of system is limit design in which the full resistance of the structure is mobilized and is not limited by any weak links in the system. All modes of failure (i.e. buckling, shear, flexure, torsion, joints, friction, etc.) should be considered with appropriate dynamic material properties. It is desirable to avoid brittle types of failure. Plastic distortion of structural elements may be permitted in order to achieve a fail-safe system.

Pneumatic Shock Isolation System

One system that has been around many years is a long stroke (about 3.5 ft) pneumatic spring system that was designed for low-yield experiments. A small plunger protrudes into an oversized cylinder. Air or gas pressures in the cylinder pushes against the plunger and forces the cylinder and supported mass upward until the stop is reached. The bottom end of the plunger is attached to a set of wheels that limit the horizontal loads. The pressure can be set at just slightly higher than that required to support the weight of the object. Then the slightest upward push of the ground against the wheels will lift the plunger off its stop and move it into the cylinder. Since the cylinder is oversized the increase of gas pressure is very slight, and therefore the acceleration level transfered to the supported mass is almost constant and very small.

Descriptively speaking, the system is a slightly damped pneumatic spring with a non-linear spring rate. Most energy is stored so the trailer bounces several times. It is useful for fragile (soft) equipment with relatively small ground motion conditions. We have used it with large ground motion conditions (about 43 in. displacement) but with styrofoam back-up pads. In this case, we solved the non-linear equations of motion with an analog-to-digital computer program in order to predict the relative motion and preferred pressure levels. The trailer responded as predicted, and its peak displacement during the Faultless Event is evident in Fig. 5 (excerpted from movies, Ref. 7).

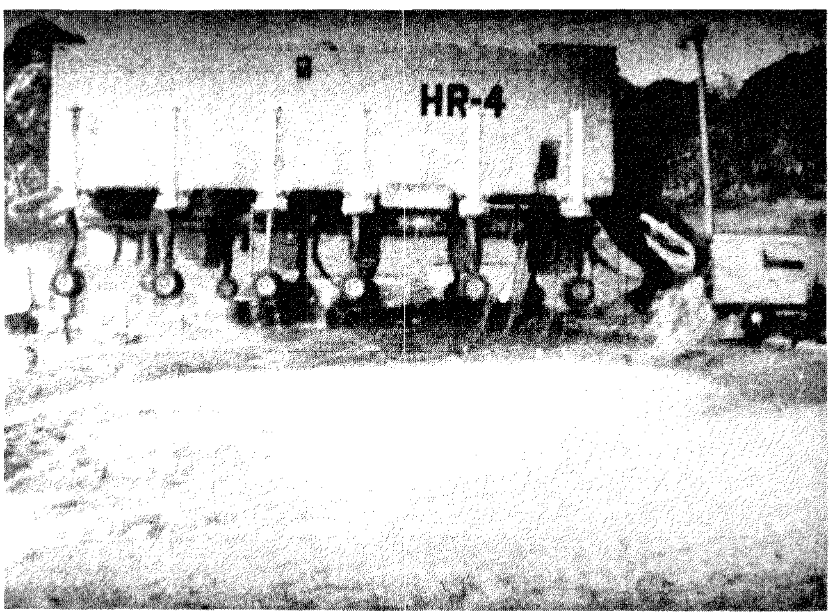

Fig. 5. Peak displacement of trailer mounted on pneumatic shock isolation system during Faultless Event.

Universal Guided Column System

A newer system we have developed for very large ground motions is called the Universal Guided Column System. It is designed for vertical ground motions exceeding 10 fps (~28-in. displacement) and up to a maximum of 24 fps (~12- ft displacement) for the current version and 32 fps (~22-ft displacement) for a follow-on version.

A typical installation is shown in Fig. 6. It is an energy absorption system using a crushable material, either honeycomb or expanded rigid foam. The vertical controlled crush load is transferred to the trailer via a cross-beam. Each end of this beam contains a guide in which a column is inserted. This column extends through the crushable material down to the surface pad. A pivot joint attaches the bottom of the column to a metal disc. The crushable material sits between the metal disc and the beam, as shown in Fig. 7. All

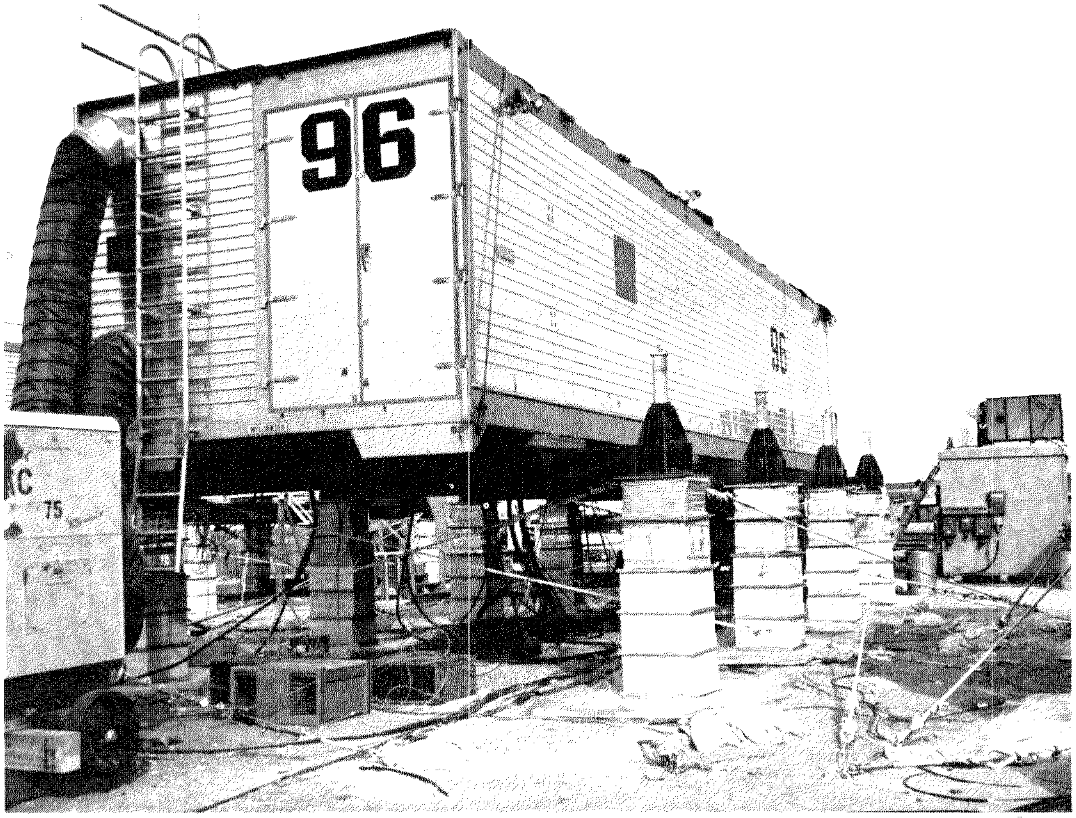

Fig. 6. Typical installation of Universal Guided Column (U.G.C.) system.

horizontal loads are transferred to the metal disc and therefore into the guiding metal column. Horizontal loads into the disc are controlled by anti-friction surface pads made of Teflon, grease and acrylic. The pad design is based on many laboratory friction tests and field experience. The horizontal force is transferred to the beam by way of the metal column, which imposes a twisting moment into the beam. The beam is therefore a box-type structure so it can withstand the torsional loads. The magnitude of this twisting moment is a function of the coefficient of friction for the surface pad and the crushable material height and crush load.

We have found that the maximum horizontal dispacements occur after slap down and after the crushable material has compressed. Therefore, the surface pad is designed to have very low friction for a limited displacement while the structure is mounted up high and then to increase after the crushable material crushes and the moment arm is decreased. Nylon rope tiedowns are also used to prevent excessive horizontal displacements and to absorb some of the energy.

We first used this system for the Faultless Event in January 1968, but the application at that time was even more severe than normal. The requirements were not only to mitigate the large slap-down spike, but also to keep a microwave antenna in accurate alignment. Figure 8 is a post-shot photograph of the system. The polystyrene foam vertical crush pads are the cylindrical

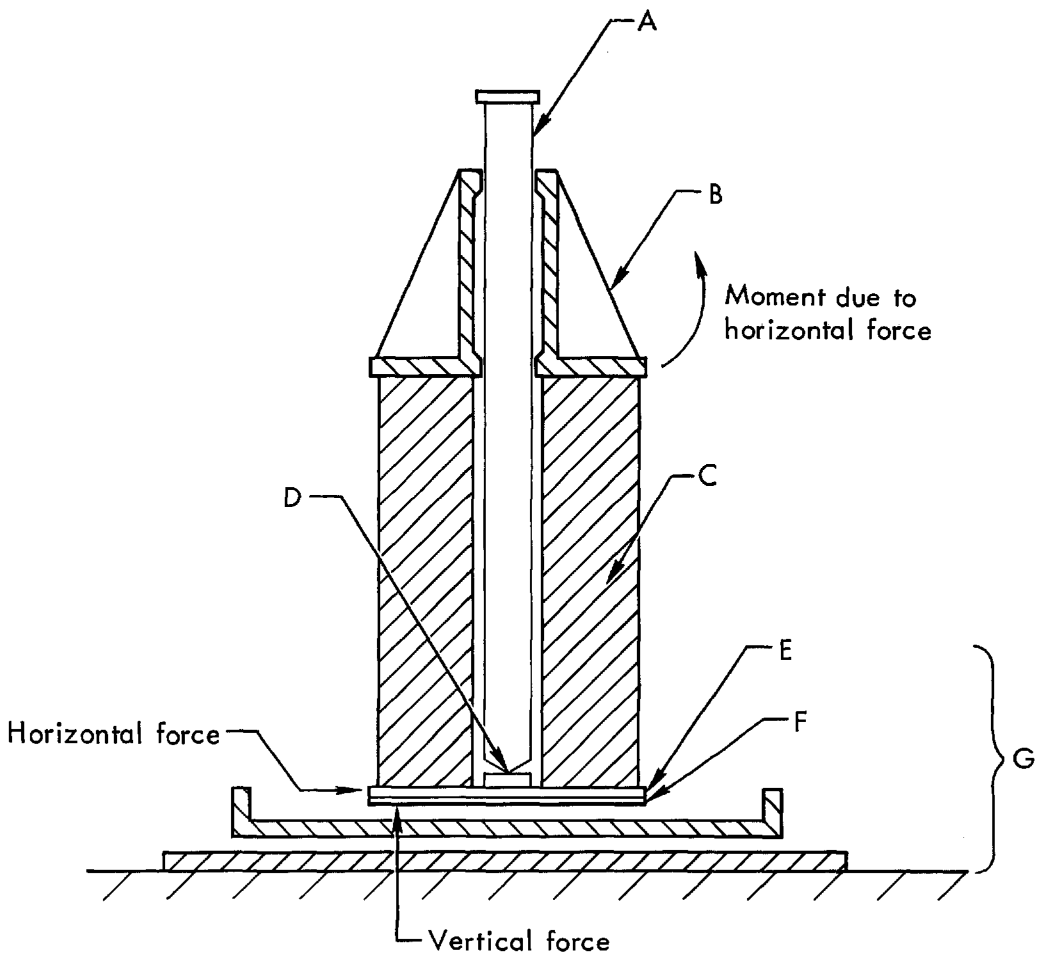

Fig. 7. U.G.C. characteristics: (A) Column, (B) crossbeam, (C) crushable material, (D) pivot joint, (E) metal disc, (F) Teflon, (G) anti-friction surface pad, exploded for clarity.

sections that are wrapped with tape. Outboard of these is four 10-in.-diam pipes that were embedded into the ground. Pulling the column toward this stationary pipe is preloaded bungee. In between the stationary pipe and the shock-mount structure are wedge-shaped foam pads which have plywood and steel banding wrapped around them. The requirement was to keep the antenna in alignment within 2 degrees. The combination of low-friction surface pads and preloaded bungee returned the trailer to its original position in the horizontal plane. The crushing was uniform at all four pillars within 1 in.; therefore, the misalignment of the antenna was less than 1 degree. Another antenna, also not shown in the photograph, was located on the top of the metal pole which was tied down by guide wires and bungee loops.

Another use of this system is shown in Fig. 9 which was taken after the Jorum Event. In this case, the center of gravity of the payload was far from the geometric center. On the left-hand side can be seen a diesel generator which was included on the shock mount platform for plus time power. In this case each foam pillar was sized differently to account for the center of gravity, and the system ended up level after it went through a 40-in. vertical ground motion environment. Inside the shack we had electronic conditioning equipment and a tape recorder for recording accelerometer data during the shock arrival time. By using this system we are able to record shock and ground motion data up close to SGZ with minimum cable lengths, and overall minimum costs with a high degree of reliability.

Fig. 8. Post-shot photo of trailer on U.G.C. system with horizontal alignment control.

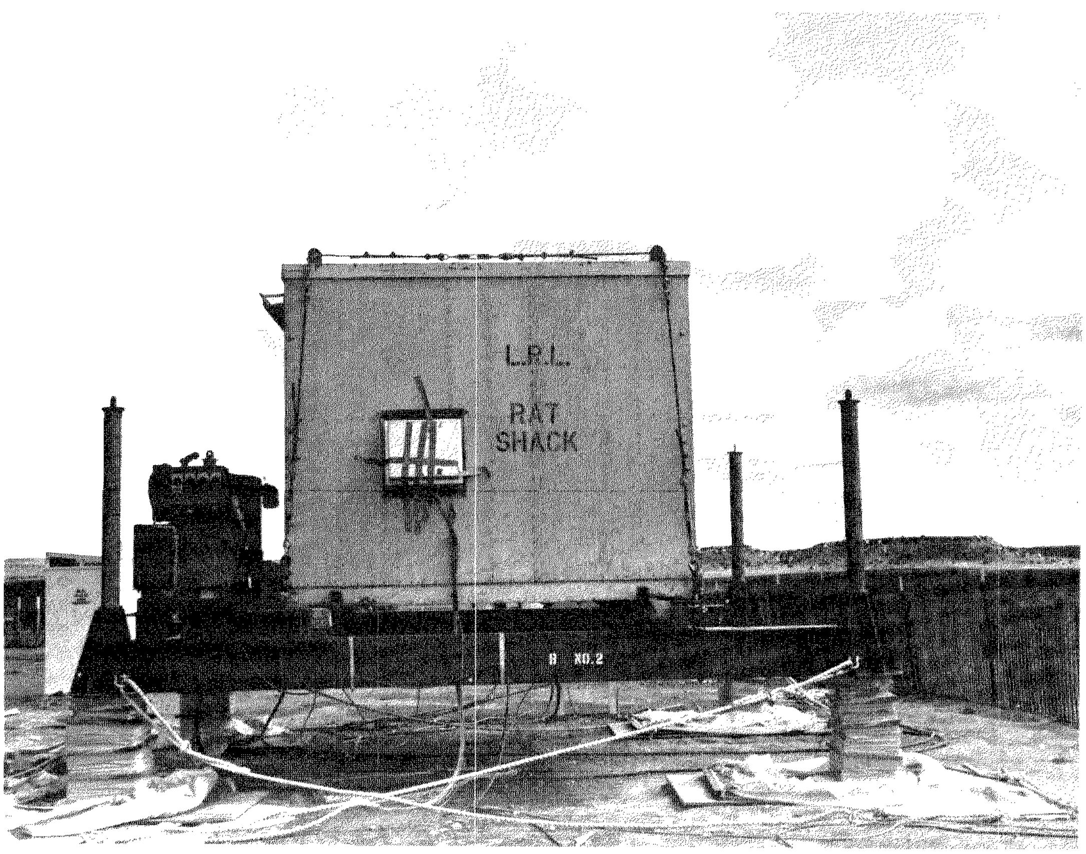

Fig. 9. Another application of U.G.C. system.

Part of the reliability and adaptability of this system is due to the type of crush material we use and how it is designed. Figure 10 shows a typical compressive load-deflection curve for a polystyrene foam and a honeycomb material. When either material has crushed more than 75%, the load increases rapidly. The transmitted shock level at this time, especially with honeycomb, can be greater than the slap-down acceleration in the ground. Therefore, any shock mount system using these types of crush materials has failed when crushing exceeds about 75% of the original height. It is advisable to design for less than this amount of crush for the worst case conditions.

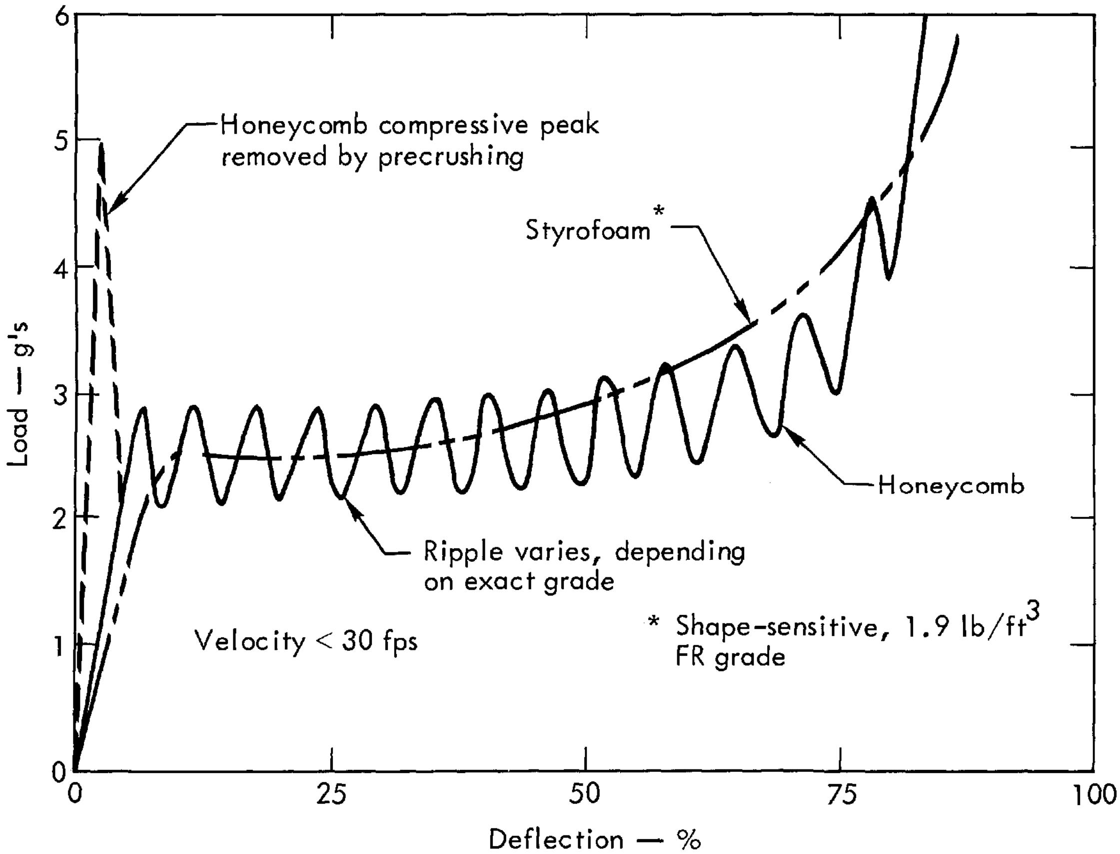

Fig. 10. Typical dynamic load-deflection curve for a honeycomb and a styrofoam material.

The choice of energy absorbing material or device may be based on a number of factors. In our use of crush materials we have found that the honeycomb has no advantages over commercially available polystyrene foam. The honeycomb must be precrushed, it costs more, and is harder to work in the field. On the other hand, the foam has had very repeatable properties, is easy to trim to size in the field and is relatively inexpensive. One word of caution though is that it must be protected from certain types of solvent and extensive weathering. The dynamic crush strength of both foam and honeycomb (especially paper honeycomb) are functions of the impact velocity. The dynamic increase in static crush strengths for velocities less than 30 fps is less than 20% for styrofoam. The advertised values for most honeycombs is up to 30% and about 75% for paper honeycomb.

The simplified analysis for a crushable system is based on an energy balance of a free-fall constant deceleration system and is given below:

$$\begin{aligned} Wd + W\Delta h &= \text{total potential energy} \\ &= \text{total energy to be absorbed} \\ &= WC\Delta h \end{aligned}$$

where:

W = weight of payload
$d = V^2/2g$ = free fall height
V = negative velocity prior to impact
Δh = deceleration (crushing) stopping distance
C = total crush load in g's.

Solving for crush height and introducing a term (K) to account for crushing during the initial acceleration pulse, we get

$$\Delta h = \frac{Kd}{C-1}$$

Note that C-1 is the positive acceleration of the payload. In early designs of crushable systems we made parameter studies.to determine values for K. These studies were based on solving the equations of motion with an analog-to-digital computer code, wet working point with tuff or similar overburden, various "equivalent" acceleration vs time histories, and crush loads (C) for medium fragile equipment. For these conditions $K = 1.50$, and this value has been verified by experience. For wet working point with alluvium overburden, $K = 1.25$ (based on experience). For pure free fall, $K = 1.00$.

Total initial height of crush material (h) is then given by: $h = \Delta h/p$, where $p \equiv$ fraction of total thickness for constant load shock absorption. For reliability, this parameter varies with input conditions.

Foam and Reusable Cribbing System (F&RC)

For many events, the ground motion is less than 10 fps and we use the F&RC system for trailers and vans. It includes permanent reuseable wood cribbing with an angle-iron base tied up to the trailer (Fig. 11). This forms a

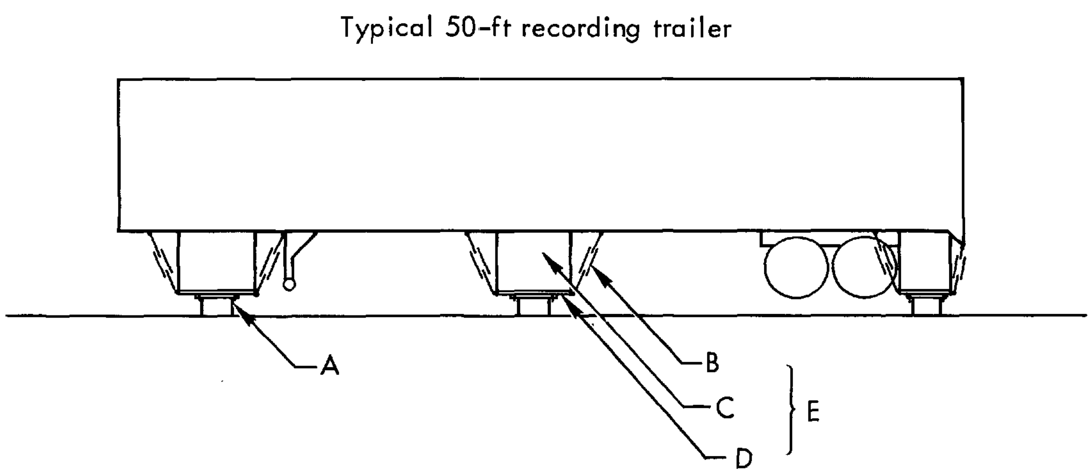

Fig. 11. F&RC shock-mitigation system: (A) Replaceable foam pad bolted to cribbing, (B) turnbuckle tie, (C) wood cribbing with plywood scabbing, (D) angle iron frame, (E) reusable cribbing assembly.

solid extension of the trailer structure to the normal suspension height and is capable of withstanding the horizontal loads. Under this, when required, we bolt simple foam and plywood crush pads. Styrofoam is used because for the required heights and surface areas it is strong enough to withstand the horizontal shear forces without the additional guide structures required for reliable honeycomb systems. This system insures sufficient clearances for crushing, and is "G.I." proof when compared to simple designs.

By applying the engineering methods summarized in this paper, we have standardized our shock-mount systems, decreased costs by reusing most components, and increased reliability while locating recording bunkers closer to surface ground zero. These closer-in locations with corresponding shorter cable runs permit significant savings which are well beyond the cost of shock-mounting.

TOWERS

Towers and other tall, large, elastic structures require a somewhat different approach than the smaller bunkers described above. The details of the acceleration phase might become important with respect to the dynamic response of a structure which contains elements which respond to a high-frequency or fast rise-time input. For example, in surveying the design of a steel tower which might be used to house special experimental hardware at surface ground zero, one might suspect that certain beams or columns might amplify the effect of short-duration pulses, say 10 to 40 msec or so, even though the fundamental natural frequency of the overall tower might be quite low, say in the neighborhood of 1/2 to 5 Hz.

Because of the difficulty of predicting the time history details of the acceleration pulse for a future experiment, it has been necessary to study the sensitivity of the computed structural response to a variety of shock signatures.

Some workers in this field have proposed and have actually used for some years the concept of harmonic spectra or other types of spectral breakdown of the transient pulse. We have found in the case of towers that it is appropriate to survey a variety of shock signatures where the following parameters are varied:

1. Peak value of acceleration
2. Duration of individual pulses
3. Number and spacing of high-amplitude individual pulses
4. Total duration of complete pulse.

Certain limitations must be placed upon the parametric survey. It would not be proper, for example, to vary the peak value of acceleration and its duration independently of one another since then the peak velocity and the velocity changes would vary beyond the predictable limits. Through a combination of theoretical study and computer trial runs, it has been found that a valid correlative function among the various trials is an impulse type of quantity which is obtained as follows: Multiply the root-mean-square value of the acceleration times the total time of duration of the complete pulse for which the RMS value has been computed. This quantity might be termed the RMS acceleration impulse. Further multiplication by a representative mass would convert this into an impulse based on RMS force.

By keeping the RMS impulse invariant throughout the trial pulse survey, it is possible to arrive at a curve of peak response versus overall pulse duration time for a number of different shapes of pulse. It is found that there is a variation of peak response with overall pulse time, but not too much variation of the limits of the peak values as the detailed shape is changed within reason, as long as the RMS impulse is held constant. It is advantageous to introduce a very small amount of damping to prevent prolonged ringing of the higher frequency modes. The computed response with a very small amount of damping is consistent with strain gage records which have been obtained with a real structure in an actual test. A detailed write-up of both the codes and full-scale test is currently under way by the authors.[8]

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