THE SIMULATION OF EARTHQUAKE GROUND MOTIONS WITH HIGH EXPLOSIVES

by

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SYNOPSIS

High explosive detonations appear to be the best available means of simulating the effect of earthquake ground motions on soil and soil-structure systems. Sufficient data are available to indicate that reasonable simulation is possible using explosive arrays alone or in combination with enhancement techniques. Example data are presented and a method for expanding the explosive data base using finite difference wave propagation calculations is described.

INTRODUCTION

Experimental data are necessary to verify current earthquake resistant design techniques and/or provide the basis for new or improved techniques. Available data from earthquakes are limited and will continue to be limited by uncertainties with regard to time and place of occurrence and by the limited amount of inplace instrumentation to record response. A more adequate data base must, therefore, come from simulations. The major limitations of simulation sources such as field shaking machines and shake tables are size of affected region, some limitation on the amplitude of motion parameters, and almost a complete inability to simulate effects on soil and soil-structure systems. Being composed of or surrounded by the medium through which the earthquake waves propagate, the response of such systems cannot be adequately evaluated independently of the medium. Explosive simulation is the only viable means of providing reliable data on soil and soil-structure systems.

Available explosive data demonstrate a simulation potential, but the data are not quite adequate for the design of experiments with confidence. Since field experiments to evaluate every potential simulation parameter would be prohibitively expensive, calculations are being used by the University of New Mexico as numerical experiments. However, geometries, explosive inputs and material properties involved are so complex that clear analytical relations between the various parameters are not evident. In an experimental program, an investigator would seek empirical or semi-empirical relations using simple theoretical concepts and dimensional analysis and determine empirical constants from the experimental results. A similar approach is being applied to the analysis of calculation results. The calculation output is viewed as measured data from an experiment and analyzed by the same methods used to analyze experimental data. This approach implies that calculations can substitute for experiments at only a fraction of the experimental cost.

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SIMULATION CRITERIA

Criteria representing the range of motion amplitudes, frequency content and duration for the evaluation of prototype and model systems, are necessary to provide guidelines against which various simulation approaches can be judged. Watabe's recommendations (Ref. 1) given in Table I, encompass the range for prototype and model structures suggested in most existing literature. For nuclear power plant design Matthiesen et al (Ref. 2) present conservative estimates of displacement, velocity and acceleration versus distance as a function of earthquake magnitude. As an example, at a distance of 10 miles from a magnitude 8 earthquake, the displacement, velocity and acceleration estimated by reference 2 are approximately 18 inches, 36 inches per second and 1g, respectively. The suggestions of reference 1 and 2, as well as other sources, provide guides which may be used to establish simulation objectives.

Simulation objectives need not be too rigid, because simulation in itself implies that some characteristics of the full-scale environment will not be precisely reproduced. No simulation, shake table, explosive or otherwise will fully reproduce every feature of an earthquake and its interaction with a structure. In designing a simulation, it is necessary to determine those characteristics of the full-scale environment which are essential to adequately evaluate the system of interest. In earthquake simulation, the important features which must be simulated for a particular structure are directly related to the response characteristics of the structure. If the characteristics of the structure are such that maximum response will be achieved at an early stage during the duration of the earthquake, then it will not be necessary to simulate the complete duration. If the structure is not acceleration sensitive, but velocity sensitive, then certain acceleration amplitude features may be compromised while still achieving an adequate simulation. Simulation adequacy, therefore cannot simply be judged by the degree with which it matches certain specified motion and frequency criteria but, rather by the insight it yields into how the structure will behave in the prototype environment. Furthermore, explosive simulation can produce environments equally as complex as those of an actual earthquake and excite structures of prototype size.

SIMULATION METHODS

Single high explosive charges of reasonable size do not generate earthquake frequency content or durations at acceleration levels of interest in earthquake engineering, nor do they load areas of sufficiently large extent to test prototype size structures. However, various methods involving multiple charges and/or media emplacement techniques have the potential for enhancing high explosive effects. Such methods generally involve one or more of the following techniques:

- Increasing the size of the affected area by using multiple charges in two-dimensional arrays
- Employing explosives with longer burn times
- Decoupling explosives by detonating in drums or cavities
- Focusing energy into a specific region using special arrays
- Lengthening motion duration in a specific region by sequential firing of charges

- Emplacement of barriers or trenches (boundary relief) in the media to obtain reflections which tailor the motions or increase durations
- Attenuation of high frequency components by increased range

*The University of New Mexico (Ref. 3) performed a series of 13 experi*ments in a silty sand to investigate enhancement techniques with potential for lengthening motion duration and sustaining large displacements while maintaining relatively low levels of velocity, acceleration and stress. In addition, two very large planar explosive experiments (Refs. 4 and 5) of about 40 tons each have been conducted at the same site. The experiments included single hole cylindrical charges, and curved and planar two-dimensional arrays. Techniques tested were focusing, decoupling, and boundary relief.

The focusing concept employs a geometric arrangement of explosives to concentrate energy from a large array into a small area to increase durations and displacements in the region. Decoupling is the detonation of charges within air cavities in the soil (no direct contact) to reduce the input pressure to the soil and extend the duration of the driving function. Boundary relief consists of providing a reflective boundary in the test medium (usually by trenching) to obtain reflections which maintain displacement and velocity intensities over longer periods of time.

Horizontal velocities measured on various unenhanced planar array shots at the mid-depth of the array are shown in Figure 1 as a function of range scaled by the areal charge density. The data suggests an initial attenuation rate consistent with one-dimensional planar attenuation after which the attenuation rate becomes that associated with a cylindrical charge. The initial decay rate of $R^{-0.6}$ compares with an expected planar attenuation rate from material inelasticity estimated to be between $R^{-0.3}$ and $R^{-0.8}$. The final attenuation rate of $R^{-2.2}$ is consistent with the attenuation rate from a line charge. The transition range between initial and final attenuation rates for all events except Shot 3 is about 1.3 times the array depth (the least array dimension). Shot 3 transitions earlier due probably to the fact that the array length is on the order of the array depth.

Horizontal displacements and accelerations behave in a similar manner. Approximate expressions for the variation of motion amplitudes at ranges less than 1.3 times the array depth are

$$a\alpha = 9000\left(\frac{R}{\alpha}\right)^{-1.3} \; ; \quad v = 100\left(\frac{R}{\alpha}\right)^{-0.6} \; ; \quad \frac{d}{\alpha} = 0.84\left(\frac{R}{\alpha}\right)^{-0.3}$$

where

a, v and d = acceleration in g's, velocity in ft/sec and displacement in feet, respectively
R = *range in feet*
α = areal charge density in lbs/ft^2 of PETN equivalent explosive

Beyond 1.3 times the array depth, the velocity, acceleration and displacement amplitudes decay as $R^{-2.2}$, R^{-3} and $R^{-1.8}$, respectively. At the ground surface, horizontal amplitudes are about the same as at the array mid-depth and vertical amplitudes are on the order of 1/2 to 2/3 the horizontals.

Empirically predicted horizontal motions, using the above relations, as a function of areal charge density at the 1g acceleration level from arrays of 50 and 200-foot depth are given in Tables II and III. The frequencies given are gross frequencies associated with the largest outward motion. Frequencies both above and below those shown will occur. Durations are conservatively estimated from experimental data correlations. It is believed that the motions given in Tables II and III encompass a range which is satisfactory for evaluating the response of many model or prototype engineering systems. A 10 lb/ft^2 charge density in a 200-foot deep array yields a peak velocity and displacement which are on the order of 80% and 40%, respectively, of those estimated by reference 2 and presented in an earlier paragraph for a magnitude 8 earthquake.

A partial measurement record on a planar array event is shown in Figure 2. The peak velocity is 1.6 feet/sec, the peak displacement about 2.8 inches and the associated peak acceleration about 0.9g. Significant motion lasts for greater than 1 second and the major frequency associated with the peak motion is about 2Hz. It is believed that this motion is in the range of motions desired for an earthquake simulation.

Although planar array data indicate significant simulation potential, the data exhibit large scatter and some ambiguities. Calculations are in progress to supplement and extend the data so that high confidence relations can be developed for field experiment design. Calculations for single hole cylindrical charges indicate that it is feasible to obtain qualitatively correct parameter relationships. Example results for radial displacements calculated in one-dimensional cylindrical geometry are shown in Figure 3. The displacements scale reasonably well.

CONCLUSIONS

Sufficient high explosive data are available to indicate that reasonable earthquake simulation for soil and soil-structure systems is possible using explosive arrays alone or in combination with enhancement techniques.

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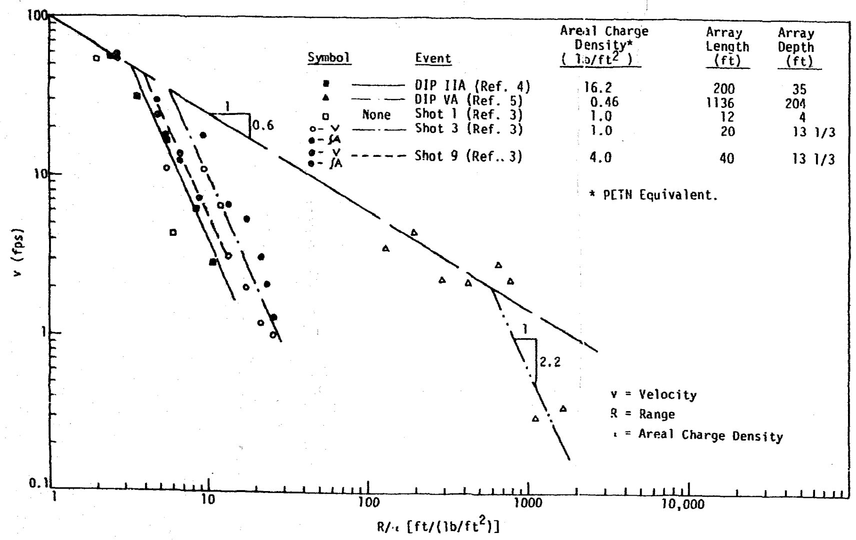

Figure 1 Particle Velocity Versus Range for Planar Arrays

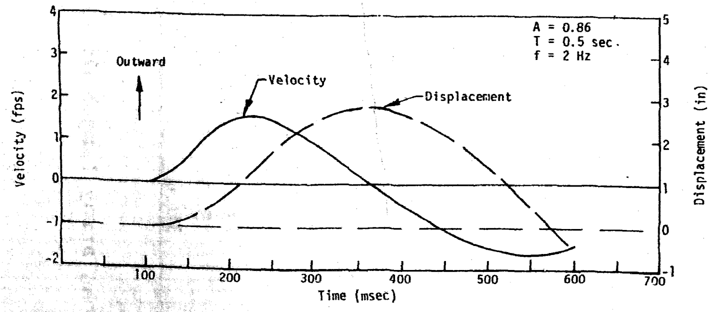

Figure 2 Horizontal Longitudinal Velocity and Its Integration at Range of 200 Feet and Depth of 20 Feet on DIP IIA (Ref. 4)

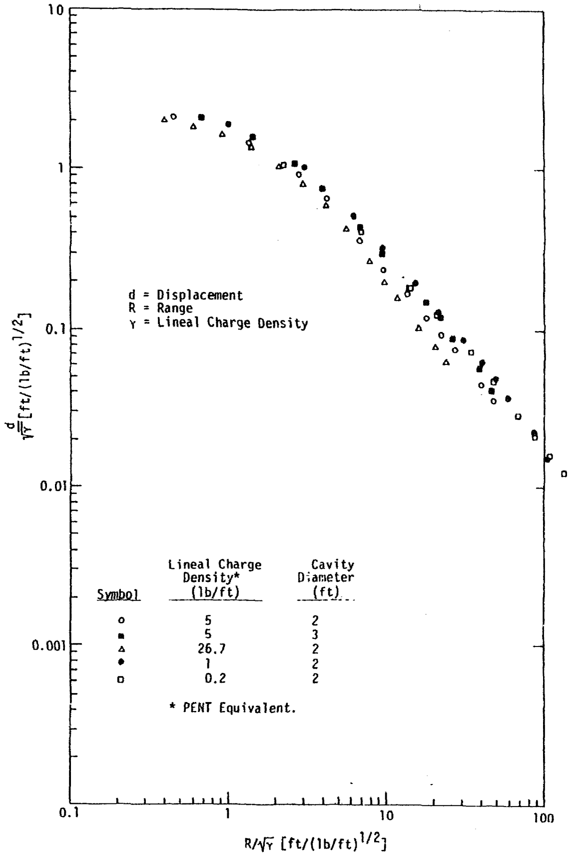

Figure 3 Displacement Versus Range for One-Dimensional Cylindrical Calculations

Table I. Suggested Bounds on Earthquake Motions (Ref. 1)

	Acceleration (g's)	Velocity (ft/sec)	Displacement* (inches)	Frequency (Hz)
PROTOTYPE	0.1 to 1.5	0.2 to 4	0.01 to 200	0.1 to 20
MODELS	0.1 to 3	0.2 to 4	0.01 to 40	0 to 100

*Watabe's upper bound on displacement is possible in the vicinity of surface faulting or as a result of liquefaction. Simulation of these phenomena is not considered herein.

Table II. Estimated Motions at the 1g Acceleration Level from a 50-Foot Deep Array**

Areal Charge Density (lb/ft^2 PETN Equiv)	Range (ft)	Velocity (ips)	Displacement (inches)	Frequency (Hz)	Duration (Sec)
0.1	175	2.6	0.02	28	0.07
0.2	190	3.2	0.04	16	0.13
1.0	220	6.5	0.30	4.5	0.44
5.0	250	13.0	1.9	1.3	1.6
10.0	270	17.0	4.1	0.75	2.7

Table III. Estimated Motions at the 1g Acceleration Level from a 200-Foot Deep Array**

Areal Charge Density (lb/ft^2 PETN Equiv)	Range (ft)	Velocity (ips)	Displacement (inches)	Frequency (Hz)	Duration (Sec)
0.1	380	3.6	0.05	23	0.09
0.2	410	6.0	0.10	13	0.15
1.0	480	11.0	0.60	3.6	0.56
5.0	560	20.0	3.6	1.1	1.90
10.0	600	28.0	7.8	0.61	3.30

An array length of about 4 to 5 times the array depth is assumed.

DISCUSSION

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Earthquake wave motion are both shear and compressional. How explain motion which an compressional could simulate earthquake wave motion could you explain ?

Author's Closure

Not received.