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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THE DYNAMIC RESPONSE OF UNDERGROUND NUCLEAR POWER PLANTS

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This paper summarizes a preliminary assessment of the earthquake engineering implications of siting nuclear power facilities underground. While not a definitive, this study is illustrative in its considerations and comparisons of nuclear power facilities sited on the surface and underground. The results are believed to be adequate for the satisfaction of the objectives of the study; i.e., the establishment of bounding characteristics for the underground seismic design problem. The major findings of the study were:

1. Placement of structures below grade can result in reductions in internal equipment dynamic loads of a factor of two or more as compared to surface facilities.
2. Observations of earthquake induced motion as a function of depth for small amplitude events suggest a strong reduction with depth. For large amplitude events, this reduction may not be as great.
3. To the extent that current analysis procedures are acceptable for surface sited plants, such procedures should be generally applicable to subsurface facilities. The treatment of soil-structure interaction during large earthquakes represents the possible major exception to this observation, and probably requires the use of nonlinear soil models. However, this is true for both surface and buried plants.

   It is felt, however, that for the purpose of obtaining a preliminary comparison between surface and buried plants, that linear methods should suffice.

Subsequent to the above analytical investigations, an experimental comparative response investigation was conducted for a partially embedded (5 percent of height) and fully buried (one height soil overburden) cylindrical concrete structures subjected to explosives generated ground waves. Structures were approximately 1/25 scale models of PWR containment structures, with height and diameter of 2.3 meters and 1.5 meters, respectively. These tests, supported by the Electric Power Research Institute, were executed with planer arrays of buried explosives. Comparing response spectra from resulting time histories tended to confirm the analytical trends; reductions of a factor of about two were noted with burial.

1. Introduction

As part of an effort to evaluate the suitability of siting nuclear power plants at or below grade, the earthquake engineering implications were assessed for a seismically active region (California, U.S.A.). This paper is based in part upon a report [1] addressing such issues of appropriate methodology, methodology limitations and design criteria; the material herein is more limited in scope. This work is illustrative in its considerations rather than definitive. However, the results are believed to be adequate for the objectives of the study - i.e., the establishment of bounding characteristics as input to a conceptual design study.

This work herein relied upon three major information sources: very limited earthquake response data as a function of media and depth; two-dimensional linear elastic finite element calculations for comparison to the reviewed earthquake data; the results of an explosives generated ground motion experiment[1] to compare the response of two small rigid concrete cylinders (height, diameter = 2.3 m, 1.5 m), one fully buried and one embedded only 25 percent of its height.

2. Limitations

The major limitations of the study are two-fold:

1. the great bulk of earthquake motion data available was only for very small events - much less than of concern for nuclear plants in seismically active regions;
2. while nonlinear soil-structure interaction may be very important for buried facilities subjected to strong earthquake excitation, only linear calculational models were used herein.

Because of the limited resources available, a premium was placed upon the application of inexpensive computational procedures[2] to perform the minumum set of parametric studies. The emphasis of this brief study was the examination of trends, comparison to experimental data, and the determination of internal equipment design criteria for use in conceptual design studies; only relative amplitudes were of interest.

3. Seismic Assessment

3.1 Review of Experimental Data on Seismic Ground Motion as a Function of Depth

The observation that seismic ground motion generally decreases with depth has been reported by various investigators over the past 80 years. Amplifications between deep strata (soil and rock) and the surface have ranged from factors as low as nearly unity to more than an order of magnitude, depending upon site conditions, depth, measurement quantity (peak acceleration, peak velocity, peak displacement MM Intensity), and frequency content and

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[1] Part of a series in soil-structure interaction sponsored by the Electric Power Research Institute (Palo Alto, California); Dr. Conway Chan, Program Manager; Dr. Walt Loewenstein, Director, Nuclear Safety and Analysis Department.

[2] Two-dimensional nonlinear explicit finite element calculations are possible, but at costs of perhaps several thousand dollars per time history. Existing programs can execute 7 to 10 million element time-steps per hour on CDC7600 hardware.

amplitude of site input motion. A major limitation of the bulk of the data is the small amplitudes contained in the data base, typically less than 0.1 g. This limitation is significant, as discussed later. Leeds presents data showing peak acceleration attenuating by about a factor of 30 between surface and -20 meters. [2] Saita reports a factor of three to five attenuation in peak acceleration between underlying soil at 20 m depth and the surface of an alluvial soil site. [3] Shima has reported that amplitudes at surface are always greater than those underground. [4] Inouye reported attenuations of 1:1 to 3:1, and Nasa reported attenuations of 1:1 to 4:1 with depth and frequency. [5,6]

3.1.1 Rock Sites

Figure 1 illustrates some of the results reported by Kenai for investigations of horizontal displacements as a function of depth down to 450 meters for small amplitude excitations. [7] The studies included measurements of some 15 small earthquakes at the surface, -150 meters, -300 meters and -450 meters at a rock site overlying a mine. The labels (1st, 2nd, etc.) refer to comparisons made of the first, second, etc., strong peaks in the time histories.

The Kinugawa Power Station (Japan) site, which consists of rock with P-wave velocities of 3500 m/sec (11,150 ft/sec) to 3900 m/sec (12,800 ft/sec), was instrumented with both displacement and acceleration transducers to a depth of 68 meters (223 ft) at 17 meter intervals. [8] Force time histories were reported for the site for small motion events (peak surface accelerations about 0.15 g). Little apparent difference exists between displacement histories at surface and -68 meters. There is significant variation in accelerations, however, as shown in Figure 2; the bulk of the data suggests an acceleration amplification of about two, with a range of approximately 1.2 to 2.6.

3.1.2 Soil Sites

On 1/8/77, nine accelerograms were obtained in a borehole installation at the University of California at Berkeley's Richmond field station. These small amplitude recordings* (0.01 g) were obtained by three vertically aligned triaxial accelerometers. The instruments were placed in a backfilled hole in alluvial soils over bedrock at a 14.6 meter depth (48 ft) in the alluvial soil, and at a 40 meter depth (131 ft). Apparent reduction factors in peak acceleration between the surface and 40 meter depth were approximately 1/1.7 for horizontal acceleration and about 1/3 for vertical acceleration.

The variation of recorded maximum acceleration as a function of depth for a single earthquake with a peak surface acceleration of 0.11 g has been reported. [9] These values were recorded in the basements of buildings founded at various depths below the ground surface in downtown Tokyo. The site consists of layers of silty sands and clays to a depth of 24 meters (80 ft) over gravelly sand and sandy clays to a depth of at least 240 meters (800 ft). Average reductions run from a factor of about two at 7 meters (25 ft) to about four at 24 meters (80 ft).

Figure 3 shows acceleration time histories for an 0.02 g peak surface acceleration at a hard sand site with 30 meters (98 ft) of silt overburden. [10] The recordings at the surface and -27 meters (121 ft) show an attenuation factor of two on peak acceleration.

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*Courtesy of Dr. Thomas McEvilly, Dept. of Geology and Geophysics, University of California, Berkeley, Ca. The northwest and northeast recordings at 131 ft should be interchanged.

In addition to the significant body of free field response data, interesting results have been reported for the measured seismic response of the Humboldt Bay nuclear power station (Eureka, California) to the Ferndale earthquake of April 1975. That particular event induced site surface motions of 0.25 g to 0.30 g as measured by surface accelerometers and 0.14 g on the foundation of the deeply embedded structure founded at a depth of about 24 meters (80 ft). The site consists of layers of sand and clay to a depth of approximately 20 meters (65 ft) over a much deeper stratum of dense sand. [11] The indicated measurements suggest again that reductions of peak response with depth can be significant; this case, however, is complicated by possibly significant soil-structure interaction.

The previous subsections have presented some of the available data on attenuation of ground motion as a function of depth for both soil and rock sites, and have referred to additional investigations. Most of the data supports the position that, *for small amplitude events*, peak responses in soil may be attenuated by factors greater than 2.0 and in rock by factors of 1.1 to 1.7. Tables 1 and 2 present some of the available data. There is some evidence to suggest that the reduction factors observed here will not be as great during the larger earthquakes that are of concern for nuclear power plants.

One may interpret the foregoing data as follows: low frequency elements of the motion exhibit less reduction in magnitude with respect to depth beneath the surface than do corresponding high frequency components of the motion. That is, reduction factors are greater for accelerations than for displacements. Outside of "typical" ranges, this statement has its limitations. For example, it is known that very high frequency motion is highly attenuated from bedrock to surface in soils. At rocky sites, displacement is generally small relative to alluvial sites, while acceleration at high frequencies is fairly high.

3.2.2 Analysis

To supplement the existing data, an analytical study was performed for a "typical" soil site (ν_s = 300 m/sec^2 near surface) and a hypothetical "hard" site (ν_s = 620 m/sec^2 near surface). A nuclear containment structure with typical mass and stiffness properties and typical size (32 meters high x 32 meters wide) was placed in five different soil-structure configurations:

A - No structure, free field
B - Surface plant
C - Bermed plant
D - Buried plant, supported
E - Buried plant, unsupported.

Two-dimensional finite element techniques were used to model the soil-structure systems as shown in Figure 4. The models were simplified to only gross motions and relative amplitudes were of interest for examination of trends.

The models were excited by two sets of earthquakes. In the first case ("standard"), the El Centro earthquake was applied horizontally at bedrock and the Taft earthquake vertically at bedrock. Both earthquakes were scaled to yield spectra similar to a 0.5 g NRC 1.60 earthquake at bedrock. The scaling involved a single multiplicative factor which caused the historical earthquake response spectra to equal, on the average, the NRC 1.60 spectra in the range of 1 to 10 Hz. In the "standard" case, these scaled earthquakes were assumed to occur at bedrock. In the second case ("deconvoluted"), the scaled El Centro and Taft earthquakes were deconvoluted down to bedrock and then applied to each model. In this way, an 0.5 g NRC 1.60 type spectrum was forced to occur on the surface free field, rather than at bedrock. The case one and case two studies indicated that the bedrock motion was amplified as it propagated upwards to the surface. The acceleration portion of the spectra was amplified more than the displacement portion. This was evident in both the standard and deconvoluted cases for both horizontal and vertical responses and for both a typical Central Valley site and a hypothetical hard site. The experimental data and theoretical analysis yield similar results. Thus reduction factors are greater for acceleration than for displacement (both experimentally and theoretically), and generally more pronounced for soft sites than for hard sites.

This study also suggested how containment response would be reduced with depth of burial. As a measure of this reduction, spectra at the top of the containment ("roof spectra") and at the foundation ("base spectra") were chosen. One such spectral set is shown in Figure 5 for each of the four different containment placements (surface, bermed, buried supported and buried unsupported). With increased depth of burial, the roof spectrum is significantly reduced. When buried at depth the horizontal response is reduced by the side wall support while the vertical response is increased, presumably because of coupling to higher responding layers near the surface. The overall effect, however, of side wall and roof support from the soil would be beneficial. The relative reduction factors in peak acceleration response found in this study suggest that the combined effect of reduced input and additional support may decrease roof response spectra acceleration by a factor of two to five. These results are probably conservative as we have used the same damping for surface and buried plants. The two sites modeled yielded similar reductions in response. This preliminary study suggests that horizontal and vertical floor response spectra will roughly equal free field spectra of depth, in contrast to a surface plant which has upper floor spectra significantly greater than the surface free field.

3.3 Explosives Generated Ground Motion Studies of Buried and Surface Sited Concrete Cylinders

Subsequent to the above analytical investigations, an experimental comparative response investigation was conducted for a partially embedded (25 percent of height) and fully buried (one height overburden of recompacted soil) right cylindrical concrete structures subjected to explosives generated ground waves placed at a dry site with $v_s \cong 350$ m/sec. Structures were approximately 1/24 scale models of PWR containment structures, with height and diameter of 2.3 meters and 1.5 meters, respectively. These tests, supported by the Electric Power Research Institute (see Paper K13/13, 5th SMIRT) were executed with planer arrays of buried explosives; the maximum distributed charge mass was 43 metric tons in a single event.

Paper K13/13 of this conference discusses the details of the experimental program of interest here. The test structures were subject to two separate events; the first induced free field surface accelerations of approximately 1.5 g's at the structure range and the second produced approximately 5.5 g's at the same location with 2 - 2.5 cycles of input. The second event, generated by 26 metric tons in a planer array at a range of 37 meters (120 ft) placed at an average depth of 19 meters (63 ft) generated significantly greater frequency content above 10 Hz.

Figure 6 show response spectra (5 percent damped) generated from the acceleration time histories measured at the top of the test structures in a direction parallel to the horizontal component* of the propagating ground waves. The spectra for both events show significant reductions in "roof" response spectra for the fully buried structure relative to the surface-embedded cylinder; reduction factors up to 2 may be observed, although factors of 1 to 1.5 appear more representative. These results are generally consistent with previous sections of this paper.

4. Summary

Subject to the limitations described above, this study finds that the placement of structures below grade can result in reductions in dynamic loads to internal equipment by factors of two or more as compared to surface facilities. This conclusion is supported by small amplitude earthquake data, linear elastic dynamic studies, and an explosives generated ground motion study. The largest uncertainty in the study is believed to be nonlinear soil-structure interaction influences during 20 to 30 cylces of strong ground motion. The results herein are believed, however, to provide a conservative result.

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*The propagating wave front had vertical and horizontal components as the waves swept up and out from the burial site.

TABLE 1: REDUCTION FACTORS IN MAXIMUM VERTICAL AND HORIZONTAL RESPONSE - SOIL

Description	Depth	Reduction Factor Acceleration	Velocity	Displacement
Hard loam	5.4 m	1/4.7	1/2.8	1/2.2
Alluvial ground	10.0 m 20.0 m	negligible 1/3 - 1/5	- -	- -
30 m silt overlying hard stratum	37.0 m	1/2 - 1/4	-	-
Alluvial ground with depth of 40 meters overlying bedrock	15.0 m	1/1.3 (horizontal) 1/1.1 (vertical)	- -	- -
	40.0 m	1/1.7 (horizontal) 1/3 (vertical)	- -	- -
Layers of top-soil, gravel, silt sand to below 350 meters; s-wave velocity approximately 150 m/sec at surface, then 300 m/sec from -10 m to -70 m	50.0 m	1/2.5 (averaged)	-	-
		1/1.8 - 1/3.2 (frequency dependent)	-	-

TABLE 2: REDUCTION FACTORS IN MAXIMUM HORIZONTAL RESPONSE - ROCK

Description	Depth	R_A	R_V	R_D
Hard, coarse-grained tuff	67.0 m	1/1.5 - 1/2	-	1/1
P-wave velocity (average) = 3700 m/sec	34.0 m	1/1 - 1/1.5	-	-
Liparite	38.0 m	1/2	-	-
Amphibolite	150.0 m	-	-	1/1.2 1/1.7

FIGURE 1: ATTENUATION OF RESPONSE WITH DEPTH.

(DISTRIBUTIONS OF HORIZONTAL DISPLACEMENTS AT DIFFERENT DEPTHS)

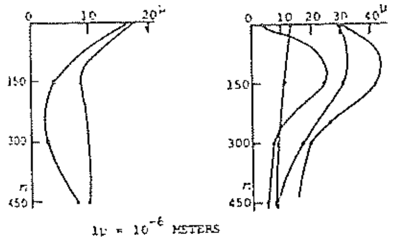


FIGURE 2: LARGEST ACCELERATION ON SURFACE ROCK AND AT BASE ROCK

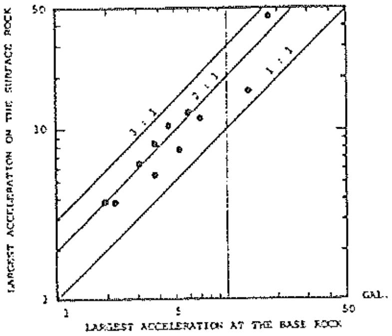


FIGURE 3: SURFACE AND UNDERGROUND ACCELERATION RECORDS OBTAINED AT URAYASU, CHIBA PREFECTURE

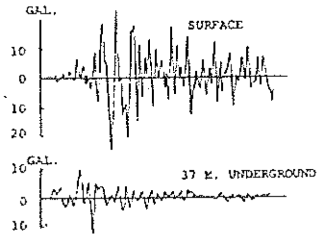


FIGURE 4: [illegible]

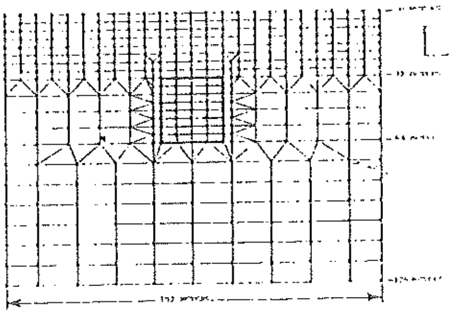
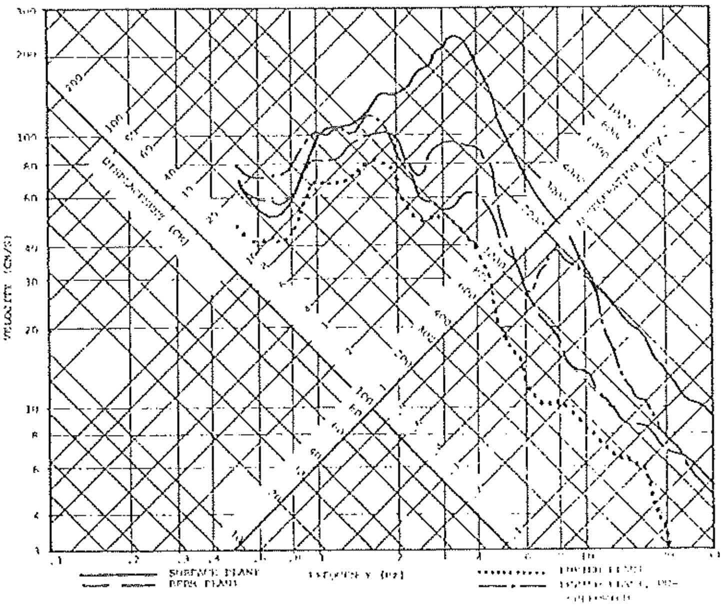


FIGURE 5: HORIZONTAL ROOF SPECTRA
HYPOTHETICAL [illegible] CITY



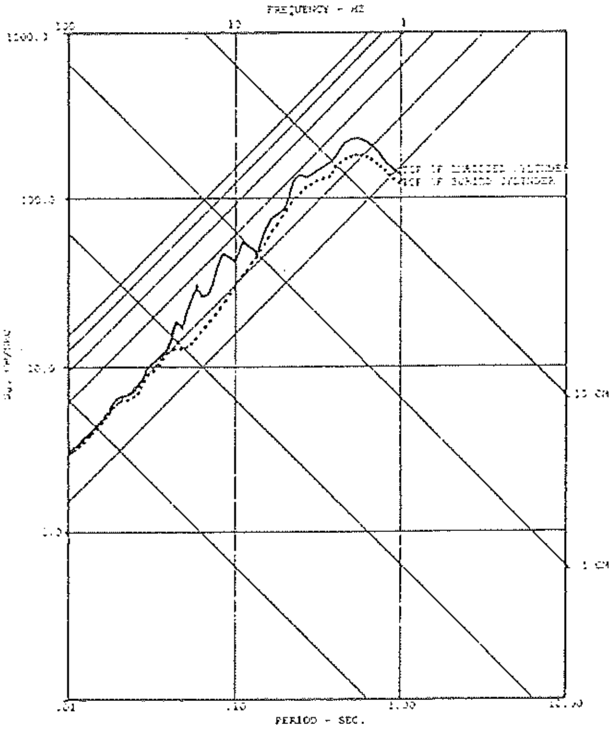


Figure 6: Response Spectra (5% Damped) For Cylinders Subjected to Explosives Generated Ground Motion