FINAL REPORT

EVALUATION OF PEAK HORIZONTAL GROUND ACCELERATION ASSOCIATED WITH THE HOSGRI FAULT AT DIABLO CANYON NUCLEAR POWER PLANT

Submitted to:

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1.1 SUMMARY OF RESULTS

We present in Figures 1-1 and 1-2 the results of our analysis for magnitude 7.5. Figure 1-1 displays the results using the above boundary conditions (termed, henceforth, the Physical Model) in terms of the median, and median plus and minus one-standard-deviation predictions. Figure 1-1 also shows the data used for this analysis, normalized by the physical model to M 7.5. The identification of non-North American data in this plot suggests a conservative bias to these accelerations. Note that the Physical Model yields a median peak horizontal acceleration for M 7.5 at 5.8 kilometers (the appropriate magnitude and distance of concern for DCNPP) of 0.41 g. Because the regression analysis established that the median plus one-standard-deviation value is 1.52 times the median, the median plus one-standard-deviation acceleration is 0.62 g.

Figure 1-2 presents similar results for our Statistical Model--a model identical to the aforementioned but without the two physically modeled boundary conditions. Due to the greater influence of the systematically biased non-North American data, this model yields slightly higher accelerations at the same distance. For M_s 7.5 at 5.8 kilometers, this model predicts a median acceleration of 0.48 g and a median plus one-standard-deviation of 0.72 g. We will show in a later section that purely statistical treatments of the data yield results very consistent with the Physical Model. We provide, however, in this summary, results based on all the data to establish the technical breadth for our conclusions. In order to provide specific insight into the breadth of the conclusions, we note that the analysis includes some of the largest accelerations ever recorded. These accelerations include Tabas, Iran, 0.80 g; Gazli, USSR, 0.81 g and 0.65 g; Koyna, India, 0.63 g and 0.49 g; and 1979 Imperial Valley, 0.81 g and 0.66 g. For completeness, we have included an acceleration of 0.73 g inferred for the S25°E component from a seismoscope record at USGS Station 1013 during the 1966 Parkfield earthquake (Trifunac and Hudson, 1970), which augments the 0.51 g peak acceleration recorded for the N65°E component. Many of these data are suspected to be biased on the high side, such as the non-North American data (see Section 4.0). All these data were included in the analysis, in

2.0 DATA AND ANALYSIS TECHNIQUES

In this section are described the organization, selection criteria and analysis of an extensive acceleration data base compiled for this study. This overall data base, termed the Near-Source Data Base in this study, consists of acceleration data recorded at distances less than 20 to 50 kilometers of a worldwide set of earthquakes with shallow rupture. On the basis of various physical and statistical arguments, components of this data base were selected for analysis of peak acceleration at the DCNPP. This data base is termed the DCNPP Data Base. The selection criteria (Section 2.2), the data base (Section 2.3) and the analysis techniques (Section 2.4) are described below.

2.1 NEAR-SOURCE DATA BASE

The Near-Source Data Base is an extensive collection of over 1,000 acceleration-distance-magnitude data points from 166 earthquakes. The data base contains earthquake information concerning the event, such as event name, date, time, latitude, longitude, quality of the location, local Richter magnitude, body-wave magnitude, surface-wave magnitude, depth, and focal mechanism. The station information in the data base includes the site of the strong-motion instrument, such as USGS station number, latitude, longitude, structure type, size classifications, instrument type and location, owner, geology and station name. The strong-motion portion of the data base contains the largest and smallest horizontal acceleration components, earthquake identification, date, USGS station number, epicentral distance, and significant distance.

This data base represents, to the best of our knowledge, all available published peak acceleration data, recorded in the United States through March 1979, that meet the following criteria:

- Errors in earthquake location less than 5 kilometers.
- Distances within 20, 30, and 50 kilometers for magnitudes less than 4.75, between 4.75 and 6.25, and greater than 6.25, respectively.

- Earthquakes with rupture surfaces within 25 kilometers of the surface.

- Accelerograms having a minimum PGA of 0.02 g, which triggered early enough in the record to capture the strong phase of shaking.

- Accelerograms recorded on instruments either in the free field, in the basement of buildings, or on the ground level of structures without basements. Recordings from upper levels of buildings were specifically excluded, as were records from instruments in the upper basements of buildings.

In addition, several significant earthquakes which occurred either outside the United States or since March 1979, and which also met the selection criteria were included: the August 6, 1979 Coyote Lake (M_L 5.9) and October 15, 1979 Imperial Valley (M_S 6.9) earthquakes in California; the December 10, 1967 Koyna, India earthquake (M_S 6.5); the July 21, 1967 Fairbanks, Alaska earthquake (m_b 5.6); the December 23, 1972 Managua, Nicaragua earthquake (M_S 6.2); the July 30, 1972 Sitka, Alaska earthquake (M_S 7.6); the October 3, 1974 Lima, Peru earthquake (M_S 7.6); the May 17, 1976 Gazli, USSR earthquake (M_S 7.0); the 1978 St. Elias, Alaska earthquake (M_S 7.2); and the September 16, 1978 Tabas, Iran earthquake (M_S 7.7).

The Near-Source Data Base was developed without any restriction on either the age of the record, the recording instrument, the recording site geology, the tectonic province of the earthquake, the earthquake fault type, or the earthquake magnitude.

The primary sources for the strong-motion data were the Department of Commerce's annual publication, "United States Earthquakes," and the U.S. Geological Survey's quarterly Seismic Engineering Program Reports. Information on earthquake locations and magnitudes was obtained from local seismic networks whenever possible, such as the seismological centers at the California Institute of Technology (Southern California) and University of California at Berkeley (Northern California). Other major sources included NEIS' Preliminary Determination of Epicenters and the Bulletin of the International Seismological Centre. In addition, many special reports and papers in journals were used either to verify original sources or to develop additional related data.

Source-To-Site Distance

Peak acceleration data were restricted to recording stations for which an accurate estimate of significant distance (the shortest distance between the station and the fault rupture surface) was available or could be determined. These distances were computed from surface fault expressions and areal-depth distributions of aftershock sequences. Data were selected if distances were within 30 kilometers for $M < 6\ 1/4$ and within 50 kilometers for $M > 6\ 1/4$. The significant distance of 5.8 kilometers for DCNPP was determined using the closest distance to the surface trace of the Hosgri fault.

Site Geology

Consistent with the overall approach described in Section 1.0, we have included accelerations from a range of site conditions in the DCNPP data set. Although we believe that the site geology at DCNPP is best represented by sedimentary rock (our Soft Rock classification), we included several other site types in our DCNPP data set so that statistical trends between the site types could be examined. This examination would then provide a basis for the final selection of site types relevant to estimating peak accelerations at DCNPP. Stations known to be situated at sites underlain by shallow soil deposits or extremely soft soils are not consistent with site conditions at DCNPP and were not included in the data base. Statistical analysis has shown that the accelerations recorded at these sites are significantly different from those recorded on the other site types. The site types included in the analysis are summarized in Table 2-1. The Pacoima Dam record of the San Fernando earthquake was specifically excluded from the analysis for two reasons. First, the site experienced extreme topographic amplification (Boore and Zoback, 1974). Second, the large gradation in wave propagation velocities near the surface combined with low damping (Duke et al., 1971) creates a condition of high frequency resonance, thus placing the site in a very suspect category.

2.4 REGRESSION ANALYSIS

The general attenuation function used for modeling near-source peak accelerations at DCNPP is expressed by the following expression:

$$PGA = a\, e^{bM} \left[R + C(M)\right]^{-d} \qquad (2\text{-}1)$$

where PGA is peak ground acceleration in g's, R is significant distance in kilometers, and M is magnitude. This functional form was selected because, when used with nonlinear regression analyses, it is capable of modeling possible magnitude and distance saturation effects that may be suggested by the data. A form with properties similar to this was originally proposed by Esteva (1970). Our investigation of this form is unique in that we employ nonlinear regression techniques to quantitatively evaluate all the coefficients in the equation. While the coefficients in this expression can be determined directly from the data, we chose to investigate both a Physical Model, which would allow predictions outside the range of data used in this analysis, and a Statistical Model, which would allow us to statistically test whether PGA saturates with decreasing distance and increasing magnitude. After discussing several important characteristics of these models, we show (in the next section) that the predictions at DCNPP are rather insensitive to the assumptions used in these models.

The coefficient $\underline{a}$ in Equation 2-1 scales the amplitude of the peak acceleration at magnitudes and distances equal to zero. The coefficient $\underline{b}$ controls magnitude scaling of PGA at large distances ($R \gg C$). The coefficient $\underline{d}$ controls the rate of decay of PGA with distance at large distances. The C-term provides an added degree of freedom by allowing the magnitude scaling of PGA to be a function of distance in the near-source region.

Again, following Esteva (1970), we characterize the C-term as an exponential function of magnitude:

$$C(M) = c_1\, e^{c_2 M} \qquad (2\text{-}2)$$

The weights were then normalized so that their sum totalled the number of components used in the analyses. This assured that the statistics of the analyses would represent the correct number of degrees-of-freedom. The definition of the distance ranges and the distribution of earthquake recordings within each range are presented in Table 3-1.

The results of the regression analysis for the median value of peak horizontal acceleration yield the following expression for the Physical Model:

$$PGA = 0.0185e^{1.28M} (R + 0.147e^{0.732M})^{-1.75} \quad (3-2)$$

where $\underline{d}$ was constrained to a value of 1.75 and c_2 was defined by Equation 2-3 as discussed in the previous section. The median plus one-standard-deviation value of PGA may be obtained by multiplying the median value by a factor of 1.52.

The results of the regression analysis when all coefficients in Equation 2-4 are determined by the analysis yield the following expression for the Statistical Model:

$$PGA = 0.0159e^{0.868M} (R + 0.0606e^{0.700M})^{-1.09} \quad (3-3)$$

The median plus one-standard-deviation value of PGA may be obtained by multiplying the median value by a factor of 1.50.

These results for M 7.5 at 5.8 kilometers yield values of 0.41 g and 0.62 g for the median and median plus one-standard-deviation values of PGA for the Physical Model, and 0.48 g and 0.72 g for the median and median plus one-standard-deviation values of PGA for the Statistical Model. Plots of Equation 3-3 as a function of magnitude and distance showing the data, as well as various plots of the residuals, are displayed and discussed in Section 4.0, Comparisons and Conclusions.

3.4 BUILDING EFFECTS

In Section 3.2 we pointed out the difficulty in separating the effects of site geology, building size and instrument location. These difficulties motivated partitioning the DCNPP data base in order to isolate important trends. We follow the same approach in this section. For this analysis we partition the data base into two subgroups, both situated on soil, represented by embedded and ground-level recordings as follows:

- Small (1-2 story) buildings or free field stations
- Large (3-20 story) buildings

The effects of both embedment and building size were studied by regression analysis of the above selected data. Due to limitations in these data, valid comparisons could only be made between small building/free field recordings at ground level and those obtained in basements of large buildings. This comparison indicated that PGA recorded in basements of large buildings were on the average 20 percent to 25 percent lower than those recorded at ground level.

Although the entire DCNPP Data Set tends to support these results, as will be shown in Section 4.0, the inclusion of large buildings in the analyses have not significantly affected the prediction of free field PGA for DCNPP.

We feel that this effect is sufficiently important that we have performed a separate case study into this topic. In order to minimize as many of the above-mentioned biases as possible (site geology, distance, magnitude), we restricted the investigation to paired recordings from nearby stations.

Three types of comparisons of peak accelerations from strong motion accelerograms are presented in this report. First, peak accelerations measured in the free field (accelerograph located on the ground surface in an instrument shelter or small building) were compared with those measured by an accelerograph located in the basement of an embedded structure (Tables 3-3 and 3-3A).

Second, peak accelerations recorded in the free field were compared with those recorded at the ground level of a nearby building without a basement (Tables 3-4 and 3-4A). Third, peak accelerations recorded at ground level sites in structures are compared with peak accelerations measured in the basement of closeby embedded structures in order to study the effect of embedment (Tables 3-5 and 3-5A). These effects are summarized in terms of the mean reduction in percent in the mean horizontal free field or ground-level recorded values as compared to nearby building or embedded recordings. A positive reduction means that free field/ground-level recordings were higher, and a negative reduction means they were lower than those recorded in nearby structures.

The Imperial County Services Building is the only structure to record higher peak accelerations than its nearby free-field station. There are several reasons why this might have occurred. First, there is an indication that the free-field recording may be anomalously low compared to other nearby free field recordings (Figure 3-1). A possible explanation includes the saturated near-surface soil conditions due to intense summer and fall irrigation practices. Second, the recorded motion in the building may have been complicated by the failure of the structure, that occurred before or just after the occurrence of the peak accelerations in the recording.

The comparison between the El Centro Differential Array and El Centro Station 9 may not be totally justified due to the relatively large (1.3 km) distance between these two stations. However, examination of recordings within the vicinity of these two stations shows no consistent attenuation over this distance range. Furthermore, soil and geologic conditions, including the depth of the water table, are very similar at these two stations. This suggests that the comparison offered by these stations is valid.

Omitting the Imperial County Services Building, the mean reductions in free-field horizontal accelerations due to the presence of structures and in ground-level building recordings due to embedment range from 22 percent to 66 percent with a mean of 39 percent. The data suggest a slight tendency to smaller reductions for the larger magnitude earthquakes. When only magnitude 5.0 or

A fifth model, with properties similar to a form proposed by Donovan and Bornstein (1978), was a log-linear relationship of the form

$$\ln PGA = A + BM + D\ln R + E\ln^2 R + FM\ln R \qquad (4\text{-}1)$$

To assess the effects of the non-North American data, these models were tested against three partitions of the data; the worldwide data base (weighted), only North American data (weighted), and the worldwide data base (unweighted). Many investigators have noted that foreign recordings may be inappropriate for inclusion in predictions of ground motion for western U.S. sites, due to tectonic differences and questionable data quality. On the other hand, sufficient high-magnitude recordings do not exist for the western U.S. to allow meaningful analysis without extrapolation at the magnitude 7.5 level. These three data base partitions test the sensitivity of non-North American data to conclusions regarding PGA saturation with magnitude and the prediction for DCNPP. The first data base gives non-North American earthquakes substantial weight in the analysis. The second data base eliminates these recordings altogether. The third data base is analyzed <u>without</u> weighting, thereby treating each data point individually, consequently reducing the effect of non-North American recordings which are represented by only a few recordings.

Mean predictions at 5.8 kilometers for magnitudes 6.5, 7.0 and 7.5 for these various models are presented in Table 4-1. Also included in this table are the ratios of the median plus one-standard-deviation estimates to the median value and the r^2 values of the regression. The r^2 values represent the percentage of the variance in the observations which could be explained by the model. The results of an F-test on the mean square errors from each of these models as compared to the Statistical Model suggested that the C = 0 model had a significantly higher standard deviation at the 90 percent confidence level, and thus, it should be rejected as statistically invalid. Results from the C=0 model are, therefore, not presented. Among the other models, little variation is observed for the magnitude 6.5 predictions, and variations between the Statistical and Physical Models of less than 16 percent are observed at the other

magnitudes. This, of course, should be compared with a one-standard-deviation value that is approximately 50 percent higher than the median (significantly higher than variations among the median predictions).

Thus, the statistical analyses of this near-source acceleration data base showed that, statistically, the proposed Physical Model for predicting near-source accelerations consistently fit the different data as well as or better than these other models. The proposed Physical Model is in close agreement with the Statistical Model which also supports saturation of PGA with increasing magnitude.

Figures 4-1 and 4-2 plot the Physical and Statistical models for the weighted North American and the weighted and unweighted worldwide data bases. The close agreement between the Physical Model and the Statistical Model for the weighted North American and the unweighted world wide data bases tend to support saturation of PGA at small distances to a constant value for all magnitude earthquakes.

TABLE 4-1

SENSITIVITY RESULTS FOR MODEL VARIATIONS

WORLDWIDE DATA BASE (WEIGHTED)

Model	Peak Acceleration at 5.8 km(g)			Median + 1σ / Median	r^2
	6.5	7.0	7.5		
C = Physically Determined	.32	.37	.41	1.52	.76
C = Statistical Fit	.31	.39	.48	1.50	.78
C = Constant	.31	.43	.61	1.51	.77
Log-Linear	.31	.39	.48	1.47	.80

NORTH AMERICAN DATA (WEIGHTED)

Model	Peak Acceleration at 5.8 km(g)			Median + 1σ / Median	r^2
	6.5	7.0	7.5		
C = Physically Determined	.29	.32	.36	1.48	.76
C = Statistical Fit	.29	.34	.38	1.48	.76
C = Constant	.29	.40	.55	1.52	.73
Log-Linear	.29	.35	.43	1.47	.76

WORLD-WIDE DATA BASE (UNWEIGHTED)

Model	Peak Acceleration at 5.8 km(g)			Median + 1σ / Median	r^2
	6.5	7.0	7.5		
C = Physically Determined	.29	.33	.37	1.50	.75
C = Statistical Fit	.29	.33	.36	1.50	.75
C = Constant	.28	.38	.52	1.53	.72
Log-Linear	.30	.37	.45	1.48	.76

TABLE 4-2

SENSITIVITY RESULTS FOR VARIATIONS IN FAR-FIELD DECAY RATE

Decay Rate (d)	Peak Acceleration at 5.8 km(g)			$\frac{\text{Median} + 1\sigma}{\text{Median}}$	r^2
	6.5	7.0	7.5		
1.09 (Statistical Model)	.31	.39	.48	1.50	.78
1.50 (Physical Model)	.32	.38	.43	1.49	.79
1.75 (Physical Model)	.32	.37	.41	1.52	.77
2.00 (Physical Model)	.31	.35	.44	1.51	.77

4.3 FOCUSING POTENTIAL

While focusing may be a result of either near-source geometrical factors or dynamic properties of the source, or both, most of the questions raised in near-field studies so far are concerned with the dynamic aspect. The focusing of energy in the direction of rupture propagation, at the expense of points in the opposite direction from which the rupture front moves away, has been extensively utilized for the far-field modeling of rupture dynamics. The far-field observations involve low frequencies capable of representing gross (average) dynamical properties of the source. Table 4-3 lists the earthquakes of our data base for which focusing has been suspected to occur at one or more stations. It is therefore generally accepted that all strong earthquakes with extended source dimensions produce focusing to varying degrees.

In order to test for the effect of focusing on peak acceleration, we have conducted a special study of the accelerations from two well-recorded earthquakes--the 1971 San Fernando and the 1979 Imperial Valley earthquakes.

Our data base contains 46 readings of PGA from the former and 52 readings from the latter. We have, therefore, chosen these two earthquakes to test for the effect of focusing, which we have quantified at each recording station by the focusing potential factor (Ben-Menahem, 1961; Boore and Joyner, 1978)

$$F = \frac{1}{\frac{\beta}{V_R} - \cos\alpha}$$

with α as the angle subtended by the direction of a ray from the hypocenter to the station, and by the direction of rupture propagation. β and V_R are the speed of propagation of the shear waves and rupture front, respectively. We have adopted a vertical fault plane striking N37° W for the Imperial Valley earthquake and a 110° striking fault plane dipping 42° to the northeast for the San Fernando earthquake. The direction of rupture is taken to be northwest and nearly updip (rake angle of 70°, from Langston, 1978), respectively, having an average rupture

5.0 COMPARISONS AND CONCLUSIONS

In the previous sections, the development of the near-source data base and the regression model were described, and the results of sensitivity studies which tested many of the model characteristics and predictions were presented. In this section we present supporting data, comparisons with other investigators results, and the conclusions drawn regarding the behavior of horizontal PGA in the near-source region.

5.1 PHYSICAL CHARACTERISTICS

An important characteristic of an empirical model is a comparison of its prediction with the data. In Figure 5-1, we present the Statistical Model's predictions versus distance for magnitude 7.5. The plus and minus standard error bounds are included in the figures to indicate the odel's capability to fit the data. The data have been normalized to this magnitude by Equation 3-3 and grouped into three magnitude bands. As expected for the lognormal distribution, one observes about one-third of the data falling outside of the standard error bounds. Note also the distinct tendency of PGA to saturate with decreasing distance.

For closer scrutiny of the data we have included the model's prediction at magnitudes 6.5, 7.0 and 7.5 (Figures 5-1A, 5-1B, and 5-1C) which are plotted against the actual data within a one-half magnitude range of the respective predictions. Non-North American data have been boxed, for reference, demonstrating their bias towards higher accelerations.

A similar plot of the data and model predictions at 5.8 kilometers as a function of magnitude is provided in Figure 5-2. These data have been normalized by Equation 3-3 to 5.8 kilometers. This figure shows a distinct tendency of PGA to saturate with increasing magnitude.

Figure 5-3 displays the model's prediction at 5.8 kilometers plotted against all data with a significant distance of less than 10 kilometers. In this figure the data have not been normalized, thus producing a slightly greater scatter.

5.2 COMPARISON WITH OTHER STUDIES

The results of the Statistical Model described in Section 2.0 have been compared with the data recorded during the 1979 Imperial Valley earthquake, with SAM V predictions for that earthquake (Blume, 1977), and with USGS Circular 795. The 1979 Imperial Valley earthquake was chosen for this comparison because it has the most extensive set of near-source recordings for a western U.S. earthquake.

The comparison of the Statistical Model predictions (at a magnitude of 6.9) with the Imperial Valley data in Figure 5-4 shows that the regression model is "conservative" with respect to the data. This trend is expected since the mean predictions for this earthquake were lower than the "mean" for this magnitude predicted by the model.

The comparison with SAM V in Figure 5-5 shows remarkably good agreement. The median SAM V prediction is inside the one-standard-deviation bounds.

Figure 5-6 compares USGS Circular 795 70 percent confidence limits (Figures 23-25 from USGS 795) with the 1979 Imperial Valley earthquake data and the Statistical Model predictions for that earthquake. Major differences exist between this study and that in USGS Circular 795 that should be considered when making comparisons. Specifically, USGS Circular 795 included only the highest peak horizontal recording. Note also that the 70 percent confidence results for magnitudes 5.0-5.7 and 6.0-6.4 are essentially based on local magnitudes (M_L), which for the 1979 Imperial Valley earthquake had a value of 6.6 (the surface wave magnitude was 6.9). USGS Circular 795 results for magnitude 6.0-6.4 are consistent with both the largest component of the peak horizontal acceleration recorded during the Imperial Valley earthquake and the results of the Statistical Model over the applicable distance range.

5.4 CONCLUSIONS

Based upon the analyses presented in Section 3.0, the sensitivity studies discussed in Section 4.0, and the comparisons presented in this section, we have drawn the following conclusions with regard to horizontal peak ground acceleration (PGA) predictions in the near-source region:

- The predicted median peak instrumental accelerations of 0.41 g (Physical Model) and 0.48 g (Statistical Model) for a magnitude 7.5 earthquake at 5.8 kilometers firmly establish the conservatism of the 1.15 g peak instrumental acceleration DCNPP used in the seismic design. The 1.15 g value is considerably greater than even the 0.62 g and 0.72 g median plus one-standard-deviation values of PGA predicted by these models.

- The results of this study establish that accelerations tend to saturate with increasing magnitude at small distances. When conservatively biased non-North American data are omitted, results support a constant value of PGA at the fault rupture surface as suggested from earthquake source dynamics.

- Both the 1979 Imperial Valley earthquake data and the results of this analysis support saturation of acceleration with decreasing distance. This establishes the inappropriateness of linear extrapolation of far-field data in estimating near-source accelerations.

- Accelerations recorded on sedimentary rock (our Soft Rock classification) consistent with the DCNPP site, are lower than those recorded on either soil or Hard Rock, confirming the conservatism of incorporating both soil and hard rock in predictions of PGA for DCNPP.

- A 20- to 25-percent reduction in PGA was found to exist for recordings obtained in the basements of large buildings, when compared to ground-level recordings in small (1- and 2-story) buildings or in the free field. This is consistent with a mean reduction of 33 percent observed for paired recordings from a case study of building effects.

- An extensive sensitivity analysis has confirmed the robustness of the predictions of PGA at the distances and magnitudes appropriate for DCNPP. Variations in predicted accelerations under a wide range of parametric perturbations were well within the one-standard-deviation estimates given by the Physical and Statistical Models.