A COMPARATIVE ANALYSIS OF THE GROUND MOTION MODELS OF TERA CORPORATION AND THE U.S. GEOLOGICAL SURVEY

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B-81-187

February 19, 1982

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TABLE OF CONTENTS

1.0 INTRODUCTION

This report summarizes a comprehensive study designed to compare the ground motion model for horizontal peak ground acceleration developed by the U.S. Geological Survey (Joyner and Boore, 1981; Joyner et al., 1981)*; and a similar model developed by TERA Corporation (Campbell, 1980; 1981). Although both models include recent earthquake data, estimates of horizontal peak ground acceleration (PGA) become significantly divergent at magnitudes exceeding 6.5 to 7.0 within 10 kilometers of the fault, Figure 1-1. Because of the interest in predicting peak acceleration from large, nearby earthquakes, emphasis has been placed on understanding the reasons for these differences.

Comparisons were divided into three main areas, (1) the functional form of the ground motion models, (2) the regression analyses used to calibrate the models, and (3) the data bases. For each, differences between the two models are discussed and the results of sensitivity studies are used to identify and prioritize their effects on the prediction of PGA, especially for conditions appropriate for San Onofre Nuclear Generating Station (SONGS). The design earthquake for SONGS is an M_S 7.0 event located on the Offshore Zone of Deformation (OZD), a fault zone located 8 kilometers from SONGS at its closest approach.

The ground motion model presented by Joyner et al. was based on 181 recordings obtained at distances of 0.5 to 370 kilometers from 22 earthquakes of moment magnitudes 5.0 to 7.7 and is given by the expression

$$\ln PGA = -2.833 + .645\, M_m - \ln R' - .00587R' \qquad (1\text{-}1)$$

$$R' = (R_s^2 + 7.3^2)^{1/2}$$

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* There are slight differences in the ground motion models presented by Joyner and Boore (1981) and Joyner et al. (1981). The former, published in the Bulletin of the Seismological Society of America, represents an update of the latter, published as U.S. Geological Survey Open-File Report 81-365. Although comparisons presented in this report are based on Open-File Report 81-365, the small differences between this and the "Bulletin" paper result in similar conclusions. The small differences between these two models are shown in Figure 1-2.

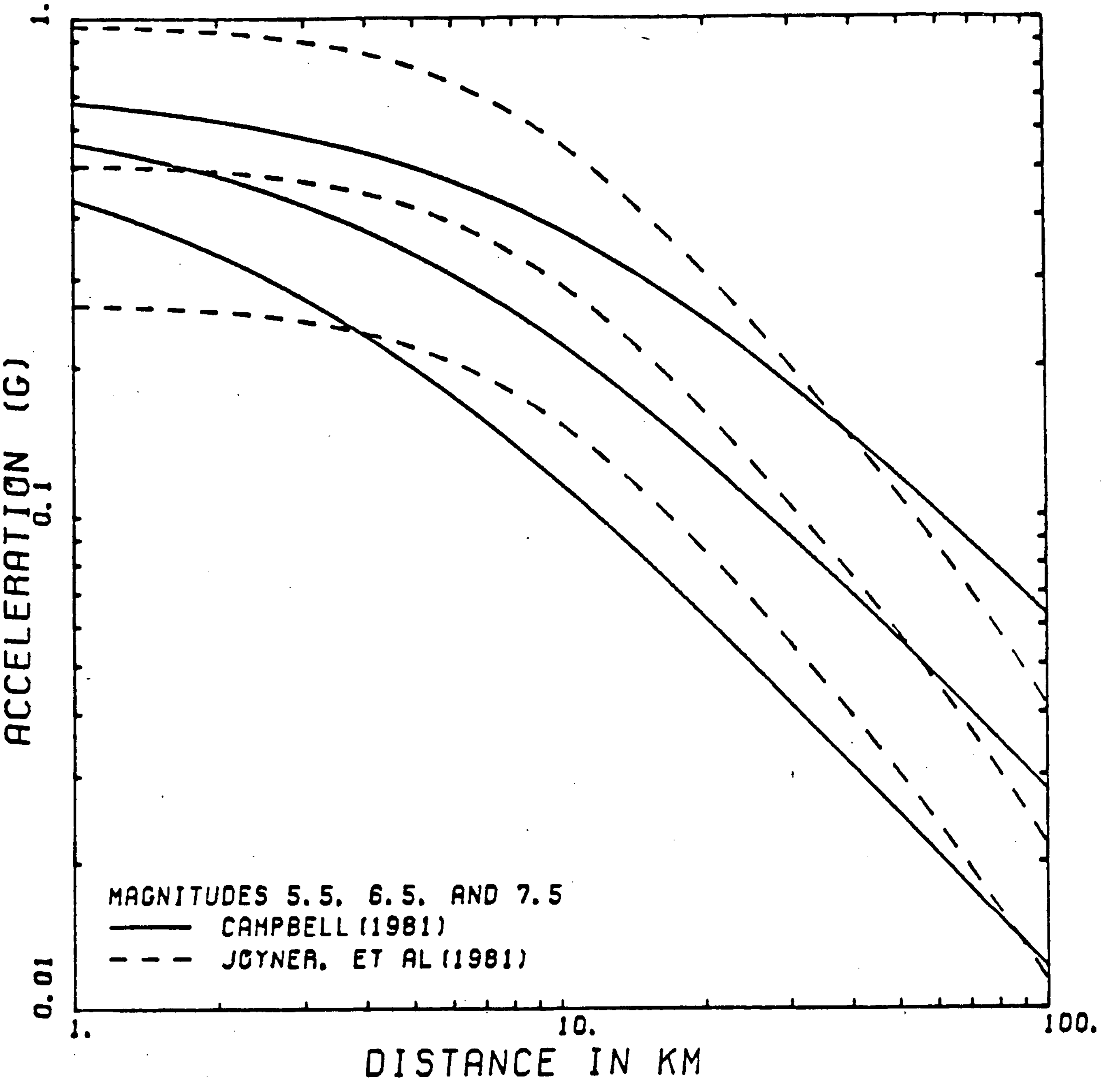

FIGURE 1-1

COMPARISON OF GROUND MOTION MODELS
CAMPBELL (1981) - JOYNER, ET AL (1981)

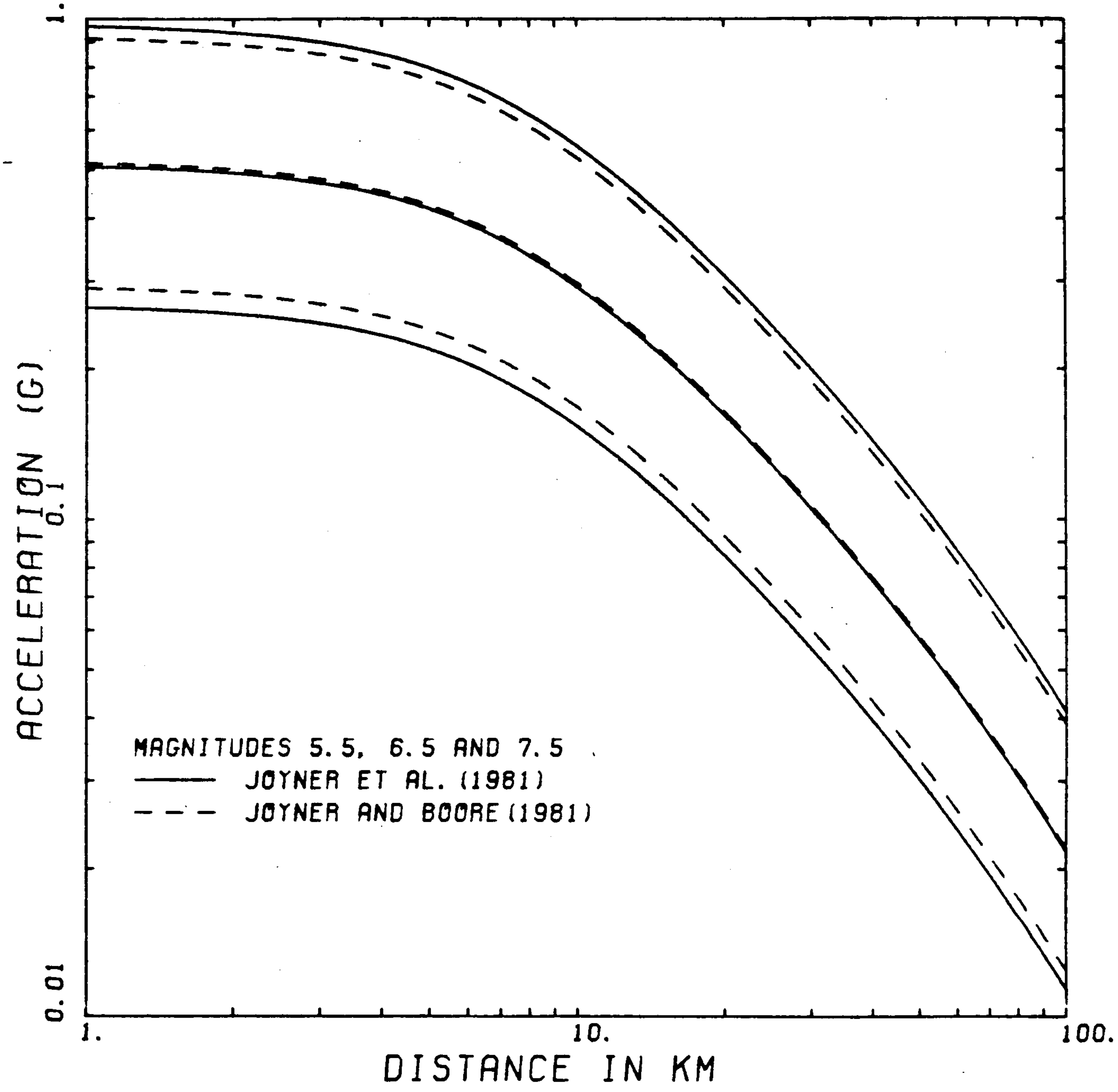

FIGURE 1-2

COMPARISON OF GROUND MOTION MODELS
JOYNER AND BOORE (1981) -- JOYNER ET AL. (1981)

In this expression, converted to log base e from the original log base 10, R_s is the shortest distance between the recording station and the surface projection of the fault rupture surface in kilometers, M_m is moment magnitude, and PGA is the maximum horizontal component of peak acceleration in gs. The standard error of the regression is reported to be 0.62, representing an 84th-percentile estimate that is 1.86 times the median predicted value of PGA.

The ground motion model presented by Campbell was based on 116 recordings obtained at distances of 0.08 to 50 kilometers from 27 earthquakes of magnitudes 5.0 to 7.7 and is given by the expression

$$\ln PGA = -4.144 + .868\, M_r - 1.09 \ln (R_r + .061 e^{.700M}) \qquad (1\text{-}2)$$

In this relationship, R_r is the shortest distance between the recording station and the fault rupture surface in kilometers, M_r is a magnitude scale chosen to be consistent with both moment and Richter magnitudes, and PGA is the mean of the two horizontal components of peak acceleration in g's. The standard error of the regression is reported to be 0.37, representing an 84th-percentile estimate that is 1.45 times the median predicted value of PGA.

Three data sets were used in the sensitivity studies. They are:

1. The TERA near-source data base (Campbell, 1981),
2. The USGS data base which includes data recorded at distances as great as several hundred kilometers (Joyner et al., 1981), and
3. A USGS near-source data base derived from the USGS data using distance criteria set forth by Campbell (1981).

A more complete discussion of these data sets appears in Section 3.0.

Explanation Of Tables

The results of the sensitivity studies are summarized in a series of tables (Tables 2-1 to 4-1). In these tables USGS refers to the Joyner et al. study, and TERA refers to the Campbell study. In this respect, the column headed "Analysis" refers to the particular application of least-squares regression analysis used by each investigator, "Model" refers to the particular functional form that is used, and "Data Base" refers to the particular set of parameters and data that is used. The notation in parentheses refers to the three data sets described in the previous paragraph, with "near" referring to the application of the distance criteria of Campbell (1981) designed to restrict data to the near-source region.

Under the section labeled "Statistical Parameters", σ refers to the standard error of the regression given with respect to the natural logarithm of PGA. The r^2 term (goodness-of-fit parameter) represents the percent of variance in the natural logarithm of PGA that is explained by the regression model.* DMS refers to the degree-of-magnitude-saturation which, in terms of the coefficients defined in Equations 2-1 and 2-2, is computed from the expression

$$\mathrm{DMS}(\%) = \frac{c_2 d}{b} \times 100 \qquad (1\text{-}3)$$

This parameter quantifies the degree to which PGA is independent of magnitude at <u>zero distance</u>, using far-field magnitude scaling as the means of comparison. DMS is equal to 0% for magnitude-independent attenuation ($c_2=0$), whereas DMS is equal to 100% when total saturation of PGA with magnitude has occurred ($c_2 = b/d$).

The column labeled $P(c_2 > 0)$ gives the probability that the coefficient c_2 is greater than zero. Since c_2 is the parameter that accommodates magnitude

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* Since the USGS analysis was done in two steps (see Section 3.0), two r^2-values are given, one representing each step.

saturation, this probability represents the confidence with which the magnitude saturation properties of the ground motion model are statistically significant. Because of the nonlinear form of the expressions containing this coefficient, the Monte Carlo simulation techniques described by Gallant (1975) were used to determine the probability distribution of the coefficient c_2. An "NA" entry in this column is used to indicate that no such simulation was performed. No entry in this column means that a magnitude-independent attenuation model was assumed ($c_2 = 0$).

The last two columns give the PGA predictions for conditions appropriate for SONGS, i.e., a magnitude of 7.0 and a closest distance to the OZD of 8 kilometers. For these two columns, "m" refers to the median prediction and "m+1σ" refers to the median-plus-one-standard-error estimate, or 84th-percentile prediction, of PGA.

2.0 FUNCTIONAL FORMS

A comparison of Equations 1-1 and 1-2 reveals several differences in the functional forms used to characterize the scaling of PGA with magnitude and distance. A generalized expression for the two models is given by the equation

$$\ln \mathrm{PGA} = a + bM + d \ln R' + eR' \tag{2-1}$$

where

$$R' = \left[R^n + (c_1 e^{c_2 M})^n \right]^{1/n} \tag{2-2}$$

The differences between the two functions are described below along with the results of sensitivity studies used to quantify the effect of these differences on the prediction of PGA.

Magnitude Saturation

Joyner et al. used a magnitude-independent shape for the distance attenuation form of their model, equivalent to setting $c_2 = 0$ in Equation 2-2. This required constant magnitude scaling with distance, precluding any magnitude saturation (reduced magnitude scaling) of PGA at small distances. Campbell's functional form included this factor in order that it may be statistically determined by near-source data. The sensitivity of the predictions to this assumption is presented in Part (a) of Table 2-1 and in Figure 2-1.

Although the USGS data support only a small reduction in the standard error when c_2 is allowed to be fit by the data,* the r^2-values for the regression on magnitudes, or second phase of their regression analysis, are found to increase by eight percent, indicating that the model including c_2 provides improved magnitude scaling characteristics over the $c_2 = 0$ model. In contrast, both a reduction

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* This is explained in Section 4.0 by the large scatter inherent in their data, which results from the application of data selection criteria less strict than that applied by Campbell.

TABLE 2-1

RESULTS OF SENSITIVITY STUDIES ON THE FUNCTION FORM

ANALYTICAL PARAMETERS			STATISTICAL PARAMETERS				PGA(g) at M=7, R=8 km	
Analysis	Model	Data Base	σ	r^2	DMS(%)	$P(c_2>0)$	m	$m+1\sigma$
			(a) Magnitude Saturation					
USGS	USGS	USGS (All)	0.616	.84/.72	0.0	--	0.46	0.85
USGS	USGS	USGS (Near)	0.602	.68/.51	0.0	--	0.37	0.67
USGS	USGS	TERA (Near)	0.423	.81/.88	0.0	--	0.41	0.63
USGS	USGS	USGS (All)	0.613	.84/.78	68.1	>.99	0.38	0.70
USGS	USGS	USGS (Near)	0.600	.69/.57	53.3	NA	0.34	0.63
USGS	USGS	TERA (Near)	0.414	.82/.92	91.2	NA	0.40	0.61
TERA	TERA	TERA (Near)	0.384	0.791	0.0	--	0.35	0.51
TERA	TERA	TERA (Near)	0.372	0.808	87.5	>.99	0.33	0.48
			(b) Distance Term					
USGS	USGS	USGS (All)	0.613	.84/.78	68.1	>.99	0.38	0.70
USGS	USGS	USGS (Near)	0.600	.69/.57	53.3	NA	0.34	0.63
USGS	USGS	TERA (Near)	0.414	.82/.92	91.2	NA	0.40	0.61
USGS	TERA	USGS (All)	0.622	.84/.90	80.7	NA	0.36	0.66
USGS	TERA	USGS (Near)	0.601	.68/.72	90.7	NA	0.31	0.56
USGS	TERA	TERA (Near)	0.420	.81/.96	100.0	NA	0.37	0.56
TERA	USGS	TERA (Near)	0.376	0.809	84.4	NA	0.35	0.51
TERA	TERA	TERA (Near)	0.372	0.808	87.5	>.99	0.33	0.48
			(c) Anelastic Attenuation					
TERA	USGS(w/abs)	USGS (All)	0.595	0.713	39.8	NA	0.44	0.80
TERA	USGS(w/o abs)	USGS (All)	0.597	0.710	28.4	NA	0.46	0.83
			(d) Geometrical Attenuation					
TERA	USGS (d=-1)	USGS (All)	0.595	0.713	39.8	NA	0.44	0.80
TERA	USGS (d=fit)	USGS (All)	0.596	0.713	40.7	NA	0.44	0.80

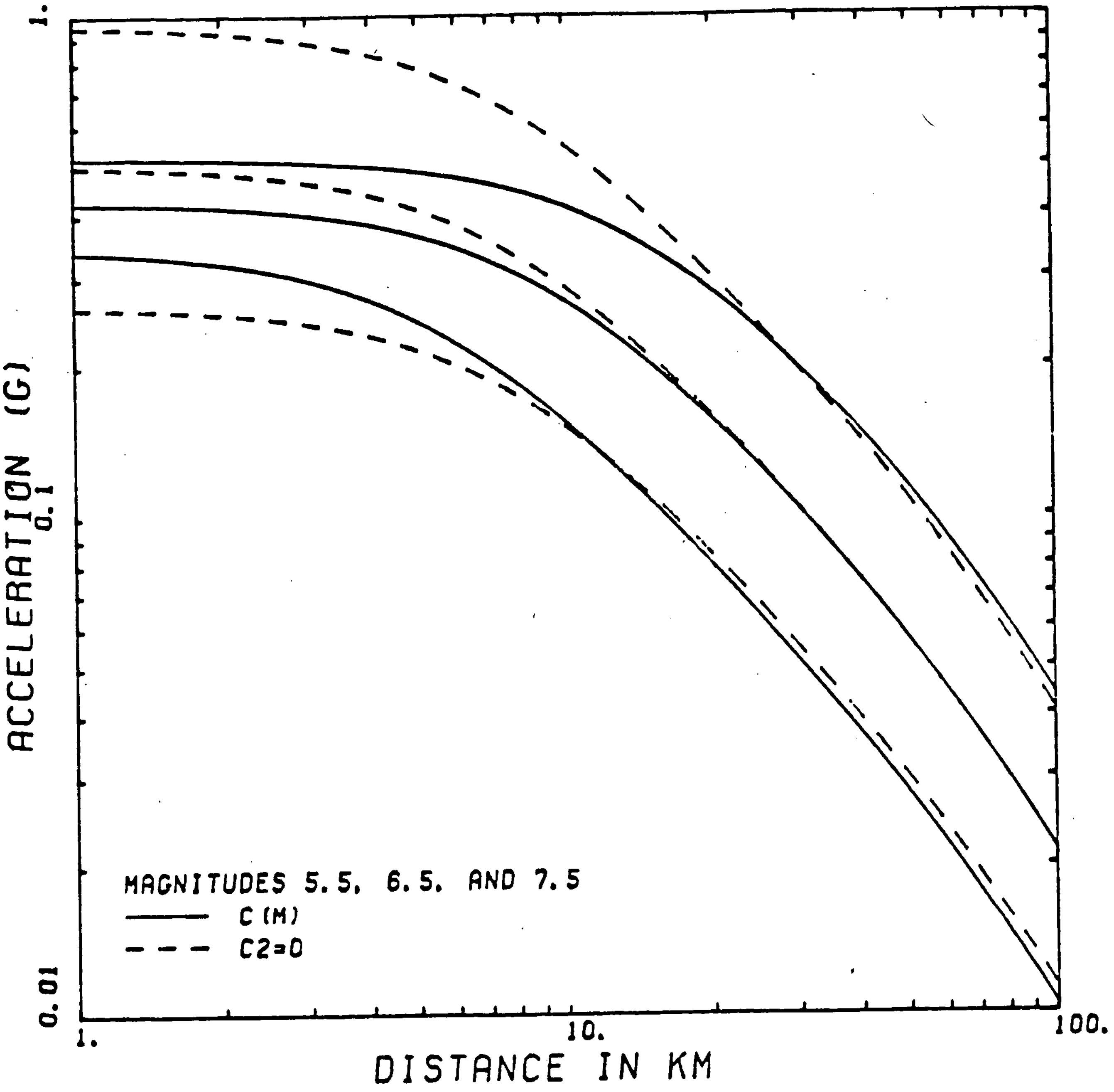

FIGURE 2-1

EFFECT OF MAGNITUDE SATURATION TERM
USGS DATA, USGS MODEL, USGS ANALYSIS

in the standard error and an improvement in r^2 are supported by the TERA data when c_2 is included in the model.

A rather significant level of magnitude saturation (DMS = 68.1%) is found when the analysis leading to the ground motion model of Joyner et al. is repeated allowing c_2 to be fit by the data. In this analysis, the probability that c_2 is greater than zero is >0.99 as in the TERA model, indicating that magnitude saturation is statistically supported by their data. Based on all the USGS data, the predictions of PGA for SONGS increase 21 percent when c_2 is set equal to zero. This is significantly higher than the 3 to 9 percent increases in the median predictions and the 6 to 11 percent increases in the 84th-percentile predictions based on either the TERA or USGS near-source data when c_2 is set equal to zero. This suggests that magnitude saturation is an important issue with regard to USGS predictions of PGA for SONGS. From Figure 2-1, we see that magnitude saturation effects become even more significant at magnitudes larger than 7.0.

Distance Term

The USGS model uses slant distance to define the distance term R' in Equation 2-1 which is equivalent to setting $n = 2$ in Equation 2-2. The TERA model, on the other hand, uses the form for R' equivalent to setting $n = 1$ in Equation 2-2. The sensitivity of the predictions to these alternate definitions of R' is presented in Part (b) of Table 2-1 and in Figure 2-2. Using the USGS analysis, somewhat higher standard errors are obtained using the TERA definition of R'; however, a better fit, represented by larger r^2 values, is obtained in the magnitude regression phase of the analysis. The TERA definition of R' does support more magnitude saturation, especially when all the USGS data or the TERA data are used. The statistics are virtually identical when alternate definitions of R' are used with the TERA analysis and data. In all cases the USGS definition of R' results in a 6 to 10 percent increase in the median predictions and a 6 to 13 percent increase in the 84th-percentile predictions for SONGS.

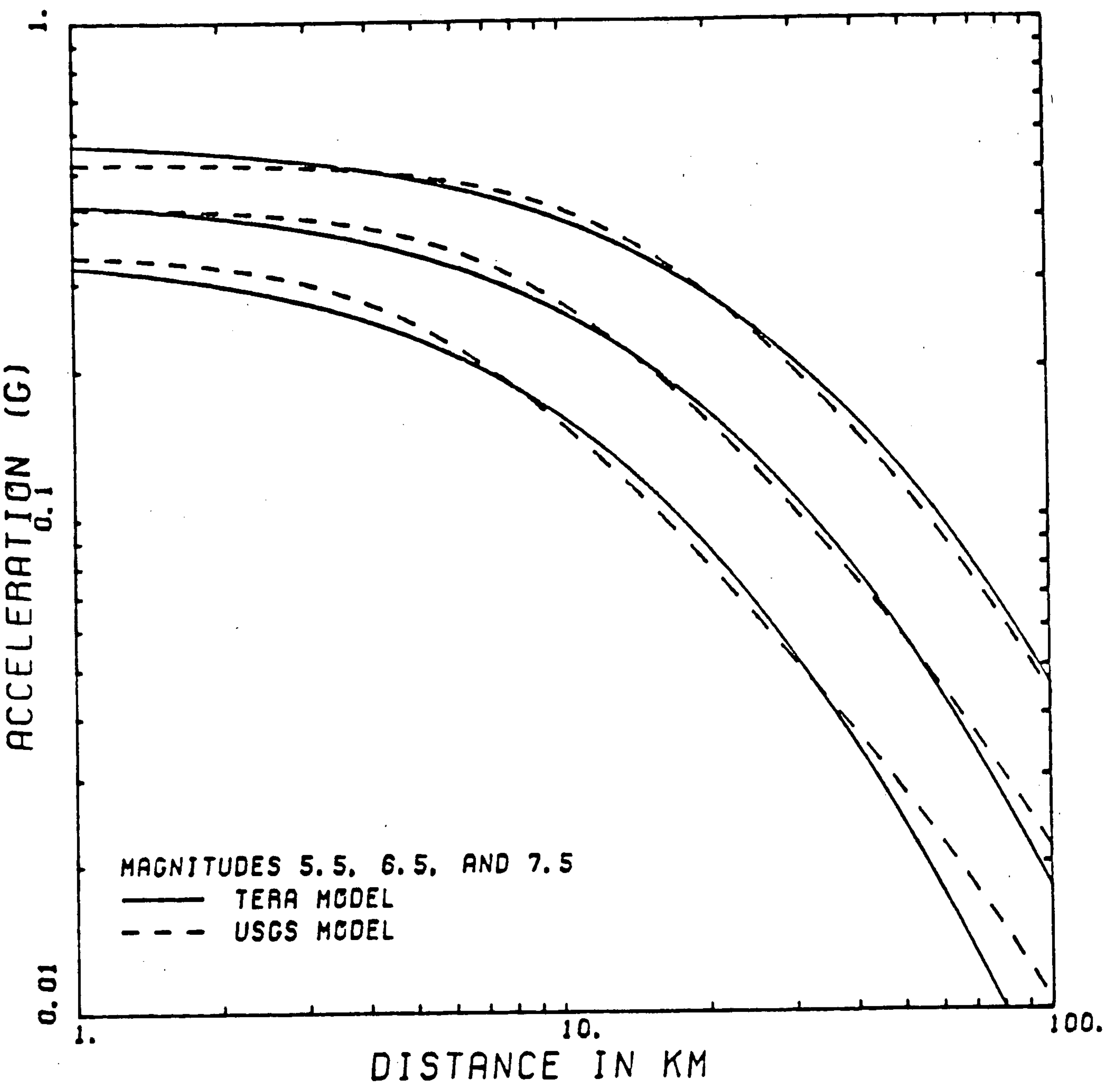

FIGURE 2-2

EFFECT OF DISTANCE TERM (R')
USGS DATA AND USGS ANALYSIS TECHNIQUE

Anelastic Attenuation

The USGS model includes an absorption term e which was intended to account for anelastic attenuation effects. Analysis showed that this parameter was nonzero only when data recorded at distances farther than about 100 kilometers were included. Therefore, sensitivity to this parameter was restricted to the USGS data set which included all distances. For this purpose, the TERA analysis and USGS model were used. The results are presented in Part (c) of Table 2-1 and in Figure 2-3. Although statistical differences are negligible whether or not the absorption term is included, predictions at SONGS are about five-percent larger when it is omitted.

Geometrical Attenuation

Based on a theoretical point-source approximation of geometrical spreading, Joyner et al. set $d = -1$ in Equation 2-1. The sensitivity of the results using the TERA analysis and the USGS model and data, which included an absorption term, is given in Part (d) of Table 2-1 and in Figure 2-4. The lack of sensitivity to this constraint is due to the statistically selected value of d being very close to the assumed value of -1.

Discussion

The results of the sensitivity analysis indicate that the largest difference between the Joyner et al. and Campbell functional forms comes from the assumption of magnitude-independent attenuation with distance by the former. The USGS data were found to support a magnitude-dependent shape at a greater than 99-percent level of confidence, which reduced the USGS median prediction at SONGS by 17 percent from 0.46 g to 0.38 g. In contrast, assuming a magnitude- independent shape in the TERA analysis increased predicted values of SONGS by only six percent. The use of the USGS definition of R' caused a six-percent increase in the predicted PGA at SONGS for both analyses, while the inclusion of either an absorption or geometric spreading term was not found to substantially affect the predictions.

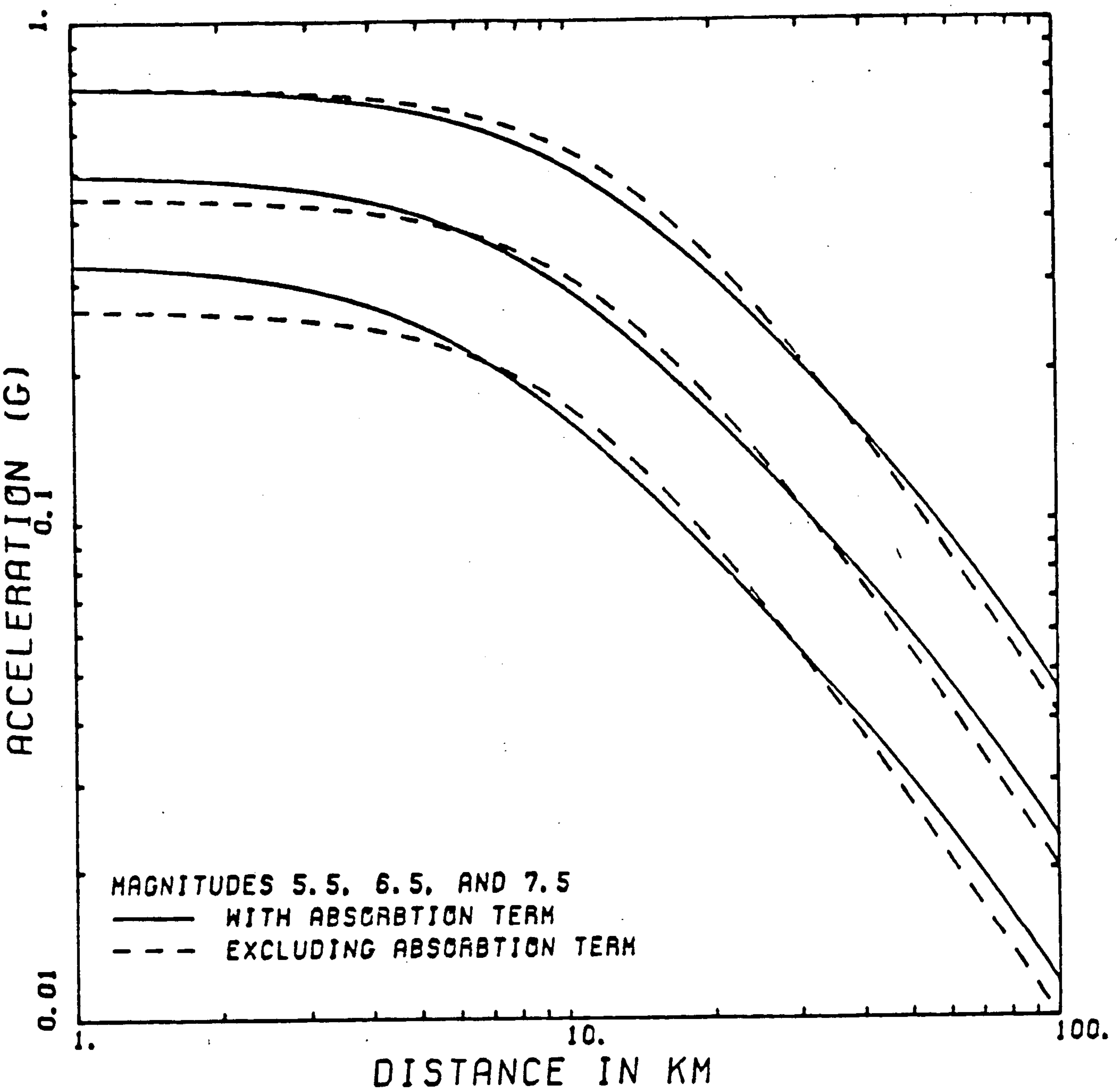

FIGURE 2-3

EFFECT OF ANELASTIC ATTENUATION TERM
USGS DATA, USGS MODEL, TERA ANALYSIS

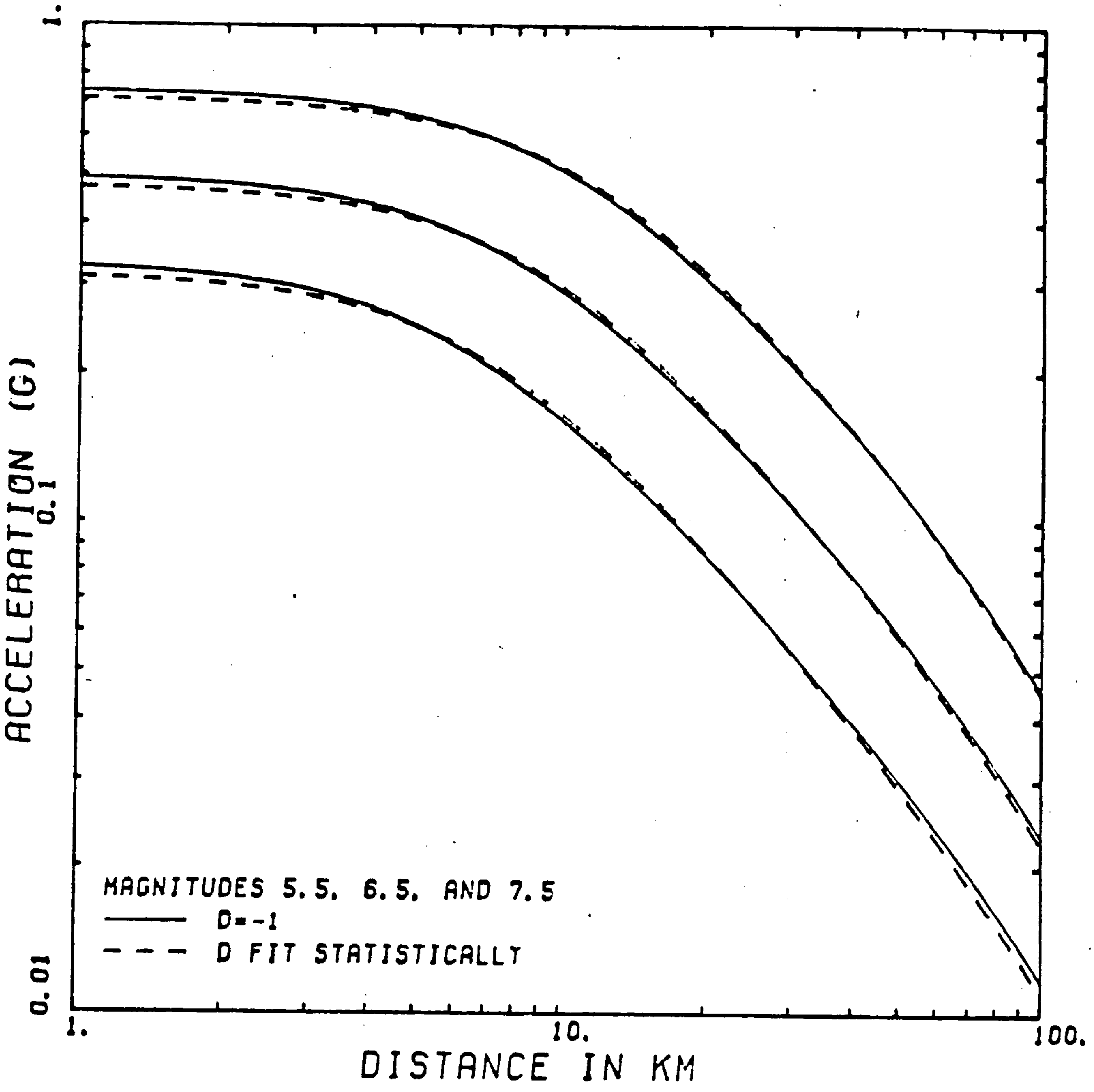

FIGURE 2-4

EFFECT OF GEOMETRIC ATTENUATION TERM
USGS DATA, USGS MODEL, TERA ANALYSIS

A combination of including magnitude saturation effects and the TERA functional form with the USGS analysis and data resulted in a 22-percent reduction in the predicted PGA at SONGS while supporting a DMS of 80.7 percent.

3.0 ANALYSIS TECHNIQUE

Joyner et al. used a two-step procedure for determining the coefficients in equations 2-1 and 2-2. In the first phase of the analysis, linear-least-squares methods were used to estimate the distance attenuation parameters d and e by using a "dummy" variable (blocking technique) to independently scale each earthquake. The nonlinear coefficient c_1 (remember that c_2 was set equal to zero) was established by trial and error, finding the value which gave the lowest standard error of estimate for the regression. In the second phase, linear-least-squares methods were used to estimate the intercept a and the far-field magnitude scaling term b by regression on the "dummy" variables estimated from the first phase of the analysis.

Campbell used a weighted, multiple nonlinear regression analysis method to simultaneouly establish all the coefficients (including c_2) in Equations 2-1 and 2-2. Weights were assigned to each observation so that data from each earthquake occurring within a specified distance range would have an equal weight in the analysis. Nine such distance intervals within the range zero to 50 kilometers were used to establish these weights.

Both the two-step procedure used by the USGS and the weighted analysis used by TERA were intended to balance the important information on attenuation offered by well-recorded earthquakes, whose recordings are well distributed with respect to distance, with the important information on magnitude scaling offered by all events, whether they are well-recorded or not.

Optimization of Fit

The USGS two-step analysis optimizes the fit of each phase by minimizing the standard error by the method of least squares. However, since the second or magnitude scaling phase of the analysis uses the earthquake scaling variable established from the first phase, the regression analysis leading to the estimation of the coefficients a and b is conditional on the given set of scaling variables. Thus, only the fit of the attenuation parameters is optimized, precluding an overall optimization of the ground motion model. The addition of the variances from each step used by Joyner et al. to estimate the standard error of PGA will always over-estimate the true variance. An estimate of the degree of this over-estimation may be found in Table 3-1. Based on all the USGS data, the USGS two-step analysis gives a standard error that is 3 to 7 percent higher than that obtained from the one-step TERA analysis. Based on either the near-source data of USGS or that of TERA, the USGS analysis was found to give standard errors that are even higher, 11 to 14 percent higher than TERA's analysis technique.

Magnitude Scaling

Inspection of Table 3-1 and Figures 3-1 and 3-2 reveals that in all cases the USGS analysis resulted in a larger degree of magnitude saturation than the TERA analysis. This resulted in the TERA analysis being associated with predictions for SONGS that were 11 to 24 percent greater for the median and 8 to 16 percent greater for the 84th-percentile than the USGS analysis when the USGS data were used. An opposite trend was observed for the TERA data where a 12 to 14 percent increase in the median prediction and a 16 to 19 percent increase in the 84th-percentile prediction occurred when the USGS analysis was used.

This latter result was found to come from the strong influence of the 1976 Gazli and 1978 Tabas earthquakes (representing two of 27 events in the TERA data base) in establishing the far-field magnitude scaling coefficient <u>b</u> in the second phase of the USGS analysis, even though the recordings from these events are located within five kilometers of the fault. More appropriately, these two events should only be contributing to the near-field scaling of PGA. The significance of this is borne out in the differences in far-field magnitude scaling between the two analyses. While both analysis techniques result in significant amounts of magnitude saturation such that attenuation characteristics are similar, the USGS analysis using the TERA model and data resulted in a 35-percent larger increase in PGA per magnitude unit than that given by the TERA analysis.

TABLE 3-1

RESULTS OF SENSITIVITY STUDIES ON THE ANALYSIS TECHNIQUE

ANALYTICAL PARAMETERS			STATISTICAL PARAMETERS				PGA(g) at M=7, R=8 km	
Analysis	Model	Data Base	σ	r2	DMS(%)	P(c_2>0)	m	m+1σ
		USGS Model						
USGS	USGS	USGS All)	0.613	.84/.78	68.1	>.99	0.38	0.70
USGS	USGS	USGS (Near)	0.600	.69/.57	53.3	NA	0.34	0.63
USGS	USGS	TERA (Near)	0.414	.82/.92	91.2	NA	0.40	0.61
TERA	USGS	USGS (All)	0.595	0.713	39.8	NA	0.44	0.80
TERA	USGS	USGS (Near)	0.525	0.532	0.4	NA	0.42	0.71
TERA	USGS	TERA (Near)	0.376	0.809	84.4	NA	0.35	0.51
		TERA Model						
USGS	TERA	USGS (All)	0.622	.84/.90	80.7	NA	0.36	0.66
USGS	TERA	USGS (Near)	0.601	.68/.72	90.7	NA	0.31	0.56
USGS	TERA	TERA (Near)	0.420	.81/.96	100.0	NA	0.37	0.56
TERA	TERA	USGS (All)	0.582	0.679	62.4	NA	0.40	0.71
TERA	TERA	USGS (Near)	0.529	0.525	39.8	NA	0.38	0.65
TERA	TERA	TERA (Near)	0.372	0.808	87.5	>.99	0.33	0.48

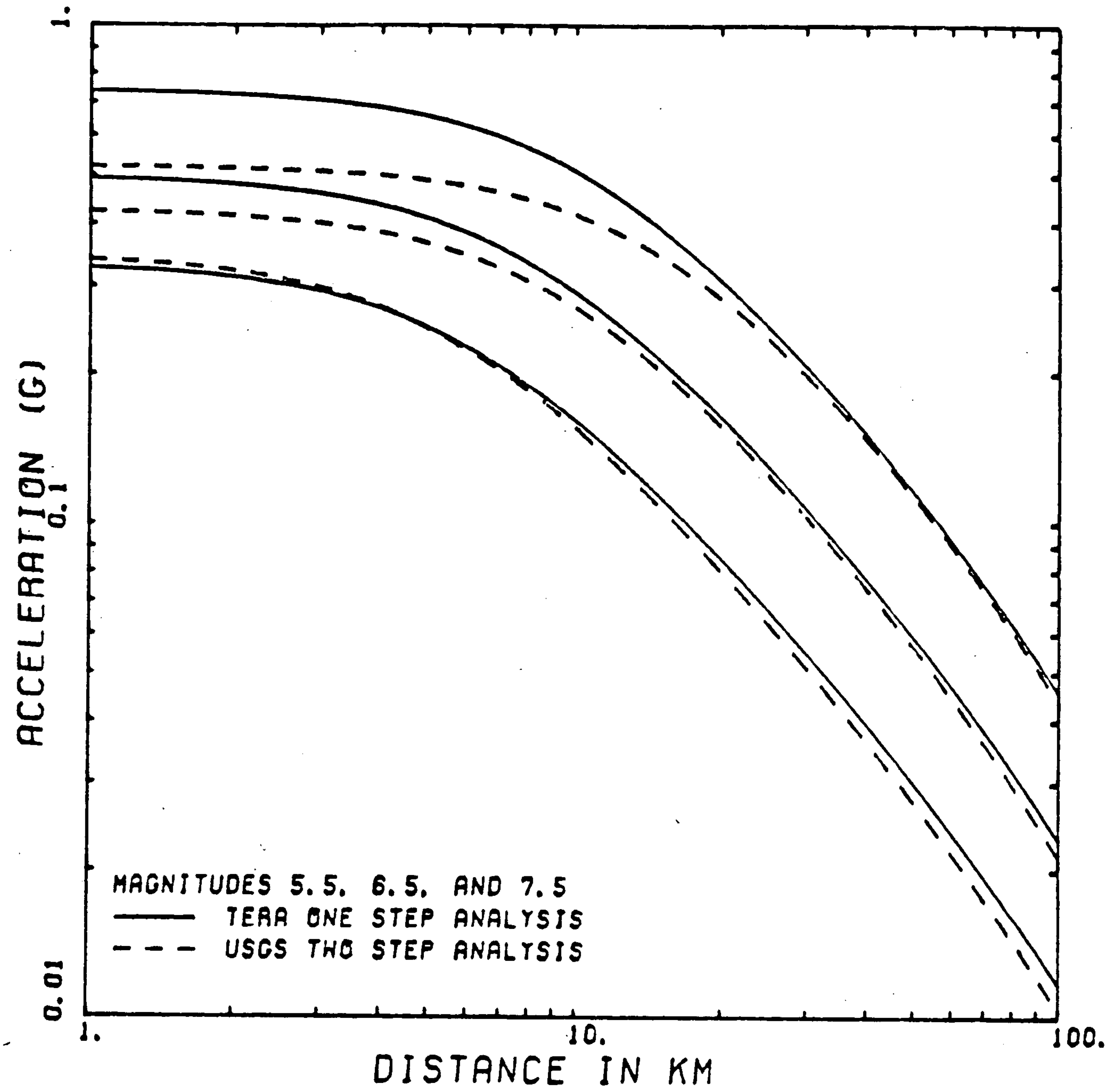

FIGURE 3-1

COMPARISON OF ANALYSIS TECHNIQUES
USGS DATA, USGS MODEL

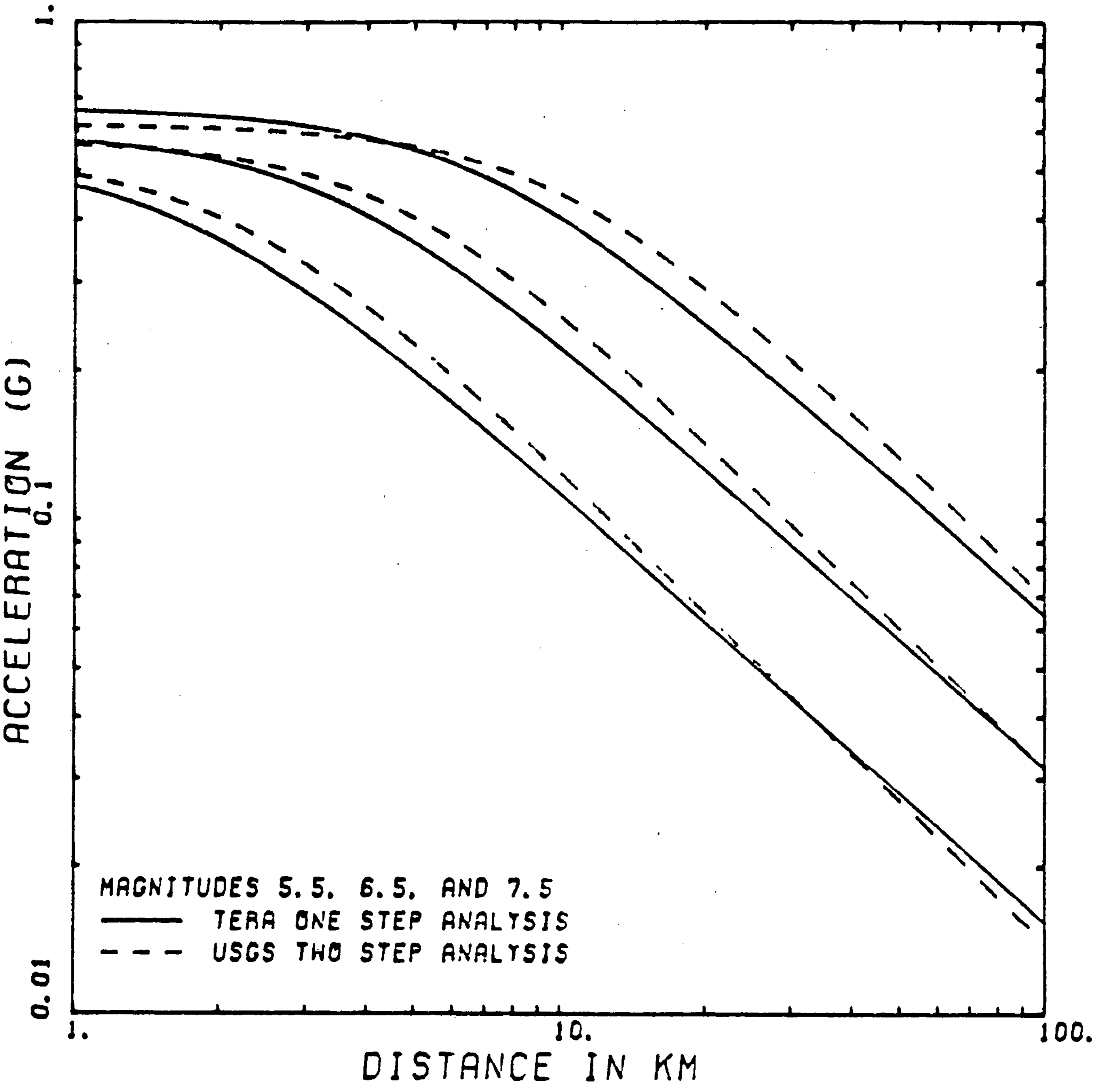

FIGURE 3-2

COMPARISON OF ANALYSIS TECHNIQUES
TERA DATA, USGS MODEL

Discussion

The sensitivity analysis presented in this section reveals that the two-step regression analysis used by Joyner et al. has two major shortcomings compared to the weighted, multiple regression technique used by TERA. First, the two-step analysis prohibits an optimization of the overall fit, tending to over-estimate the standard error. Second, while poorly recorded events have little influence in the first phase of the analysis where the attenuation characteristics are established, they have substantial influence in determining the far-field magnitude scaling characteristics of PGA in the second phase of the analysis independent of the distance range of their recordings. Therefore, earthquakes which have significant near-field recordings that are relatively limited in number have virtually no influence in determining magnitude scaling in the near-field; rather, they are used to establish a generalized scaling relationship independent of distance.

4.0 DATA BASES

Although much of the recent near-source data are common to both studies, there are many differences between the two data sets. These differences can be classified into two main categories: differences in the definition of the parameters and differences in the data selection criteria. Differences in the definition of the parameters may be summarized as follows:

- The USGS used the maximum horizontal component to characterize PGA whereas TERA used the mean of the two horizontal components,
- The USGS used closest distance to the surface projection of the fault rupture surface as the measure of distance whereas TERA used closest distance to the fault rupture surface itself, and
- The USGS used moment magnitude to characterize the size of an earthquake whereas TERA used either M_s (for magnitudes ≥ 6.0) or M_L (for magnitudes < 6.0) consistent with both Richter and moment magnitude.

Differences in the data selection criteria may be characterized as follows:

- The USGS used data recorded at distances as far as several hundred kilometers whereas TERA used only near-source data,
- The USGS included data recorded on all types of geological conditions whereas TERA excluded sites underlain by shallow soils (less than 10 meters deep),
- The USGS excluded large buildings (greater than two stories) whereas TERA did not,
- TERA excluded recordings having a maximum horizontal component less than 0.02g whereas the USGS did not,
- The USGS excluded recordings obtained on dam abutments whereas TERA did not,
- The USGS excluded data for which distance was not known to an accuracy of five kilometers or less whereas TERA required only that distances be reasonably accurate, and

- The USGS included data for earthquakes that occurred after the 1979 Imperial Valley earthquake whereas TERA did not.

The sensitivity of the results to these differences are briefly discussed below.*

Distance Selection

To study the effect of the far-field data on the USGS results, the distance selection criteria proposed by Campbell was applied to the USGS data to create a near-source USGS data base. The USGS analysis was then repeated for both the magnitude-dependent and magnitude-independent shapes using this near-source data. The results are summarized in Part (a) of Table 4-1 and in Figure 4-1. We found that predicted values at SONGS increased about 12 percent for the magnitude-dependent case and about 25 percent for the magnitude-independent case when far-field data were included. Standard errors were found to decrease only two percent when far-field data were excluded. The reduction in the degree of magnitude saturation when the far-field data are excluded can be attributed to the presence of an absorption term $\underline{e}$ in the analysis which included the far-field data (Part (c) of Table 2-1). The near-source data could not statistically support a nonzero absorption coefficient.

Structure Size

The USGS study excluded large structures (buildings having two or more stories). However, since they did not tabulate these excluded records, the effect of this constraint was studied with the TERA analysis and data and is summarized in Part (b) of Table 4-1 and in Figure 4-2. We found that by excluding large buildings there was only a slight increase in both the predicted PGA at SONGS

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* In addition, the revision of the USGS study that appeared in the article in the Bulletin of the Seismological Society of America excluded earthquakes with records at only one instrument location. This eliminated several near field recordings from analysis, whose effects are demonstrated in Figure 1-2.

TABLE 4-1

RESULTS OF SENSITIVITY STUDIES ON THE DATA BASE

ANALYTICAL PARAMETERS			STATISTICAL PARAMETERS				PGA(g) at M=7, R=8 km	
Analysis	Model	Data Base	σ	r^2	DMS(%)	$P(c_2 > 0)$	m	m+1σ
(a) Distance Selection								
USGS	USGS	USGS (All)	0.613	.84/.78	68.1	>.99	0.38	0.70
USGS	USGS	USGS (Near)	0.600	.69/.57	53.3	NA	0.34	0.63
USGS	USGS	USGS (All)	0.616	.84/.72	0.0	--	0.46	0.85
USGS	USGS	USGS (Near)	0.602	.68/.53	0.0	--	0.37	0.67
(b) Structure Size Selection								
TERA	TERA	TERA (All Struct.)	0.372	0.808	87.5	>.99	0.33	0.48
TERA	TERA	TERA (Small Struct.)	0.363	0.819	92.6	>.99	0.34	0.49
(c) Parameter Selection								
TERA	TERA	TERA (Small Struct.)	0.363	0.819	92.6	>.99	0.34	0.49
TERA	TERA	TERA (R_s)	0.366	0.812	54.7	NA	0.33	0.48
TERA	TERA	TERA (R_s, M_m)	0.373	0.804	33.4	NA	0.35	0.51
TERA	TERA	TERA (R_s, PGA_{max})	0.417	0.765	63.5	NA	0.36	0.55
TERA	TERA	TERA (R_s, M_m PGA_{max})	0.422	0.759	55.3	NA	0.38	0.57
(d) Data Selection								
TERA	TERA	TERA (R_s, M_m PGA_{max})	0.422	0.759	55.3	NA	0.38	0.57
TERA	TERA	TERA (Shal. Soil)	0.458	0.735	21.2	NA	0.40	0.63
TERA	TERA	TERA (Shal. Soil, USGS Earthquakes)	0.509	0.617	3.9	NA	0.39	0.66
TERA	TERA	USGS (Near)	0.529	0.525	39.8	NA	0.38	0.65
TERA	TERA	USGS (All)	0.582	0.679	62.4	NA	0.40	0.71
(e) Model and Analysis								
TERA	TERA	USGS (All)	0.582	0.679	62.4	NA	0.40	0.71
USGS	USGS	USGS (All)	0.613	.84/.78	68.1	>.99	0.38	0.70

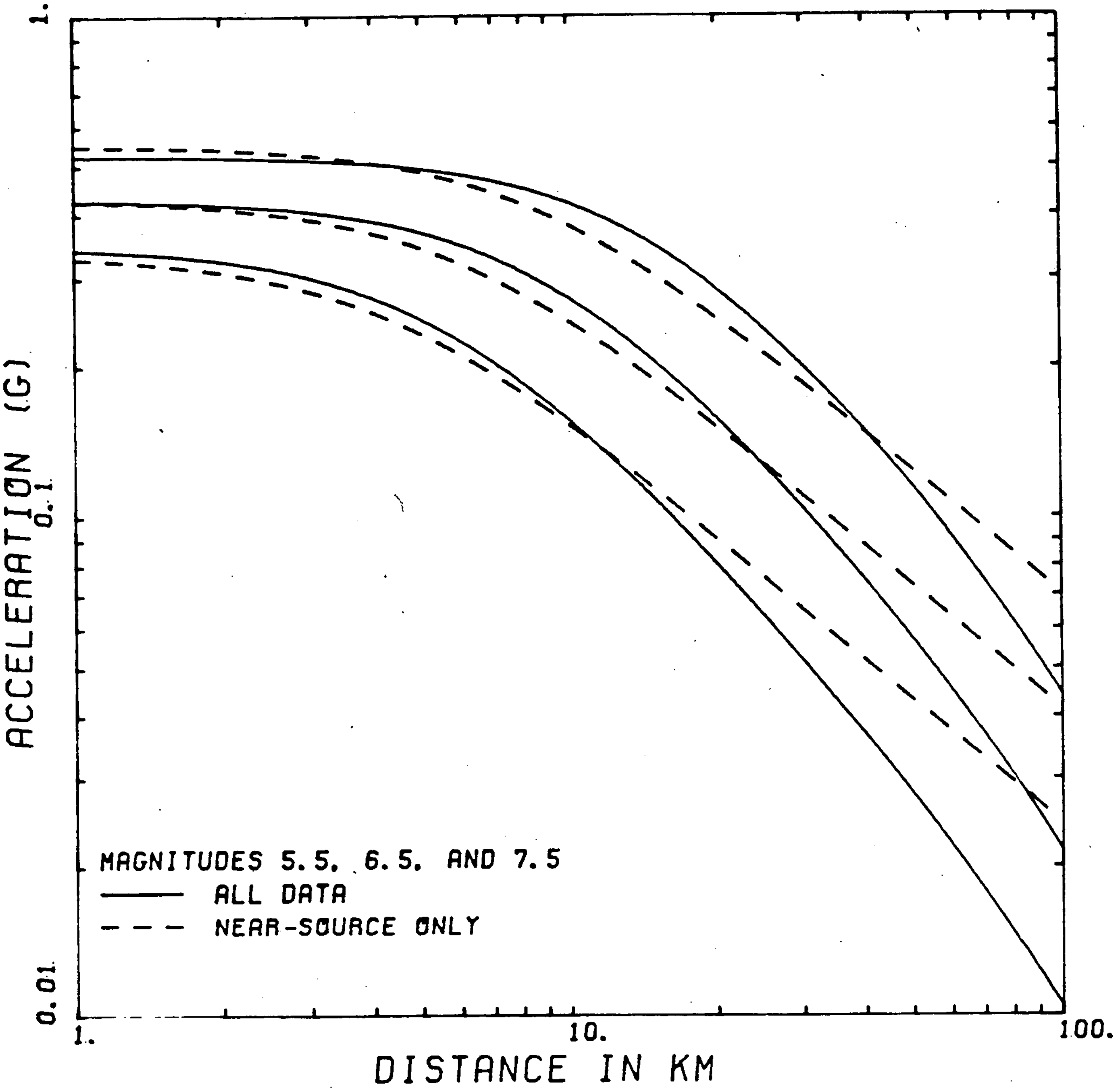

FIGURE 4-1

THE EFFECT OF DISTANCE SELECTION
USGS DATA -- USGS MODEL -- USGS ANALYSIS

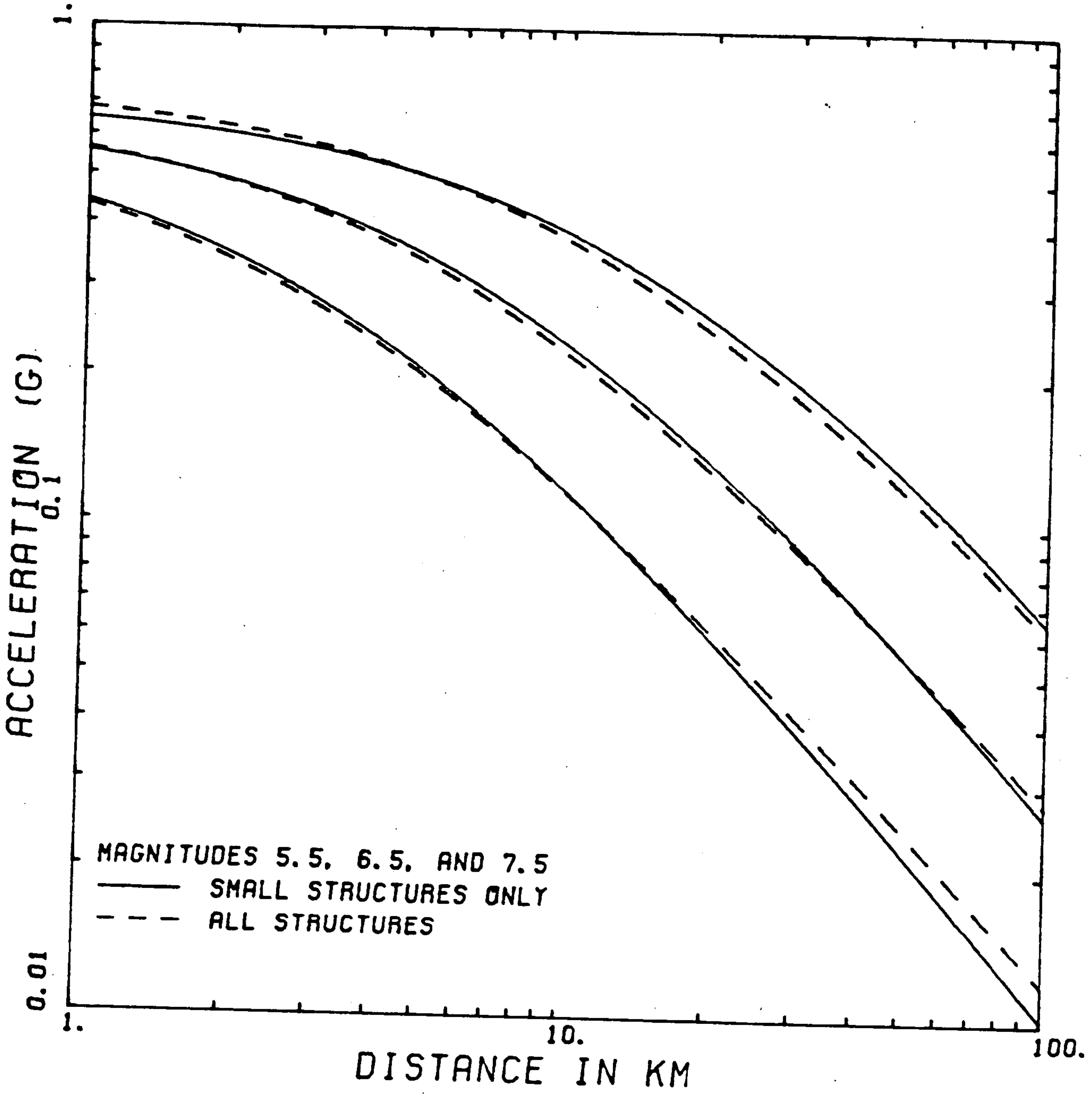

FIGURE 4-2

THE EFFECT OF STRUCTURE SIZE SELECTION
TERA DATA -- TERA MODEL -- TERA ANALYSIS

and the degree of magnitude saturation, accompanied by a slight decrease in the standard error.

Parameter Selection

The sensitivity of the results to parameter selection criteria was studied using the TERA analysis and data, since alternate definitions of parameters were not generally available for the USGS data. These results appear in Part (c) of Table 4-1 and in Figures 4-3 and 4-4. Sensitivity is compared to the analysis based on the TERA data, excluding large structures, to be consistent with the selection criteria of Joyner et al.

The effect of using closest distance to the surface projection of the fault rupture surface R_s was to substantially reduce the degree of magnitude saturation from 93 to 55 percent, consistent with the change in the definition of distance, accompanied by a slight decrease in predicted PGA for SONGS. In addition, using moment magnitude instead of TERA's magnitude scale further decreased the degree of magnitude saturation to 33 percent. This was accompanied by a slight increase both in the predicted values at SONGS and in the standard error. The largest change in both the standard error and the predictions occurred when the maximum component (PGA_{max}) was used in place of the mean of the two horizontal components. Predicted values at SONGS increased about nine percent for the median and 12 to 14 percent for the 84th-percentile, while the standard error increased about 13 percent. The maximum component was found to support more magnitude saturation than the mean of the two horizontal components.

To summarize, the use of the USGS definition of parameters resulted in a 16-percent increase in the standard error accompanied by a seven-percent decrease in the goodness of fit and a 12-percent increase in the median prediction of PGA at SONGS. The increase in the standard error and median predicted values was primarily due to the use of moment magnitude and PGA_{max}. The decrease in the degree of magnitude saturation to a final value of 55 percent was primarily a result of reductions due to the use of closest distance

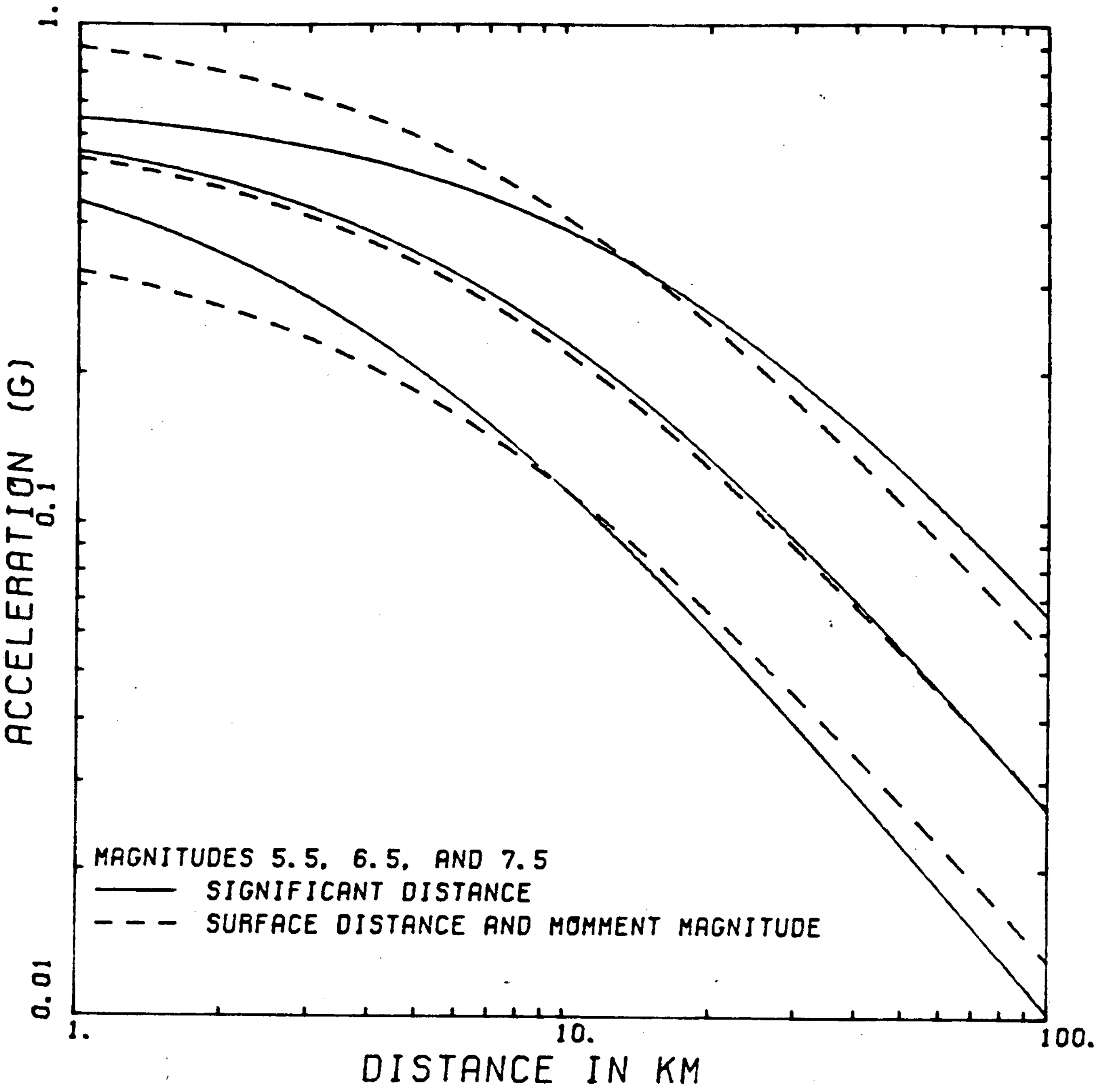

FIGURE 4-3

THE EFFECT OF SURFACE DISTANCE AND M
TERA DATA -- TERA MODEL -- TERA ANALYSIS

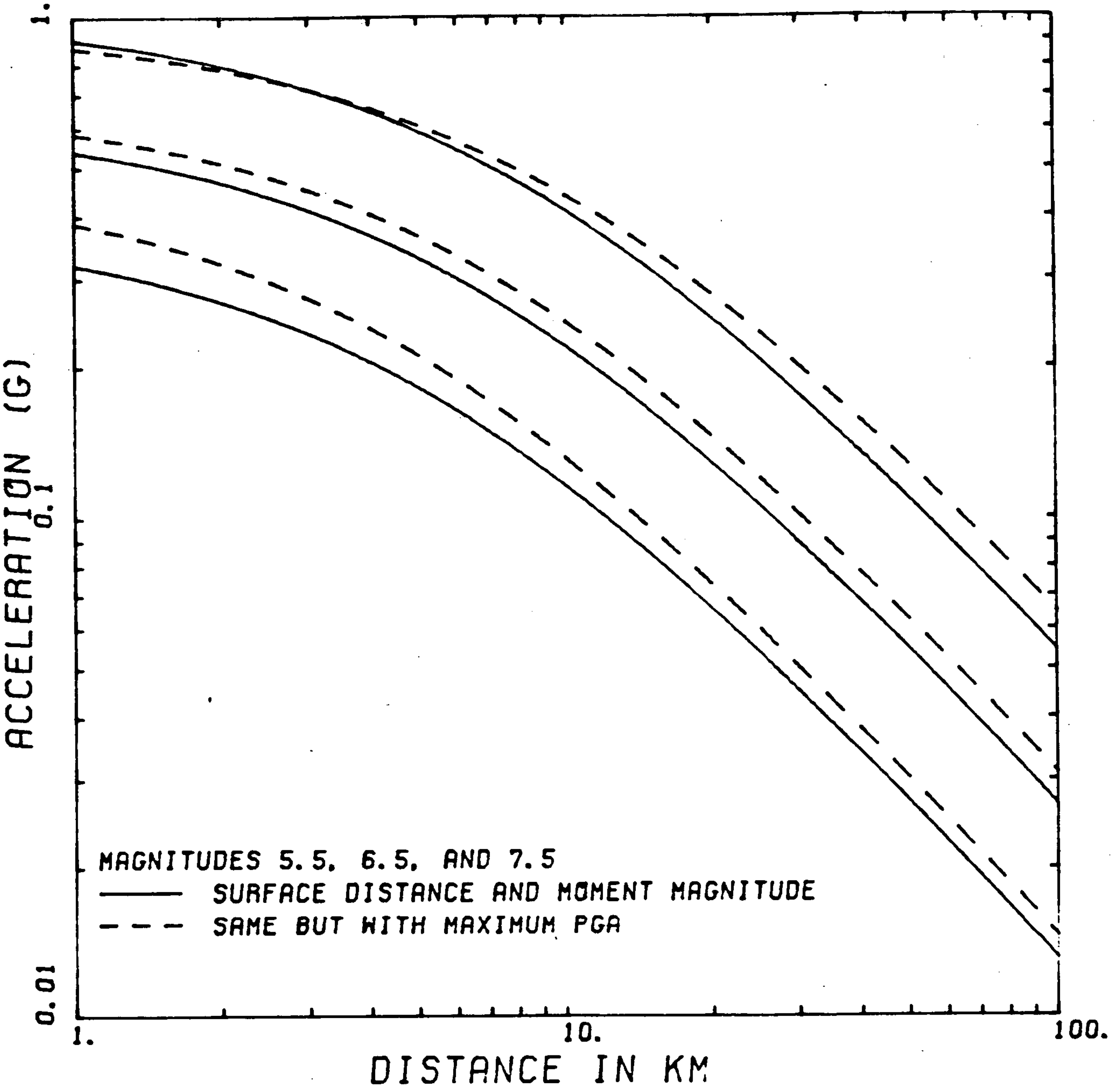

FIGURE 4-4

THE EFFECT OF MAXIMUM PGA
TERA DATA -- TERA MODEL -- TERA ANALYSIS

to the surface projection of the fault rupture surface and moment magnitude (65 percent reduction), partially compensated for by an increase due to the use of PGA_{max}.

Data Selection

The sensitivity of the results to data selection criteria appear in Part (d) of Table 4-1 and in Figures 4-5 and 4-6. Using the TERA analysis and TERA data, comparisons were generated using the USGS definition of parameters, as discussed in the preceding section. Adding recordings on shallow soil sites substantially decreased magnitude saturation from 55 percent to 21 percent. At the same time, these recordings increased the standard error by nine percent and increased the median and 84th-percentile predictions at SONGS by five and eleven percent, respectively. In addition, using only the USGS's selected earthquakes increased the standard error by another 11 percent while reducing the degree of magnitude saturation to a value of only four percent. A further increase of four percent in the standard error occurred when the USGS near-source strong- motion data were used. In this case, however, the degree of magnitude saturation increased to about 40 percent.

In summary, median predictions at SONGS remained relatively stable throughout the variation in data selection criteria. However, standard errors increased a total of 25 percent accompanied by a substantial reduction in the degree of magnitude saturation.

Model and Analysis

Although discussed in more detail in Sections 2.0 and 3.0, for completeness we have included the sensitivity to the USGS analysis and model in Part (e) of Table 4-1 and in Figure 4-7. The use of the USGS analysis and model increased the standard error by five percent and decreased the median and 84th-percentile predictions of PGA at SONGS by five and one percent, respectively.

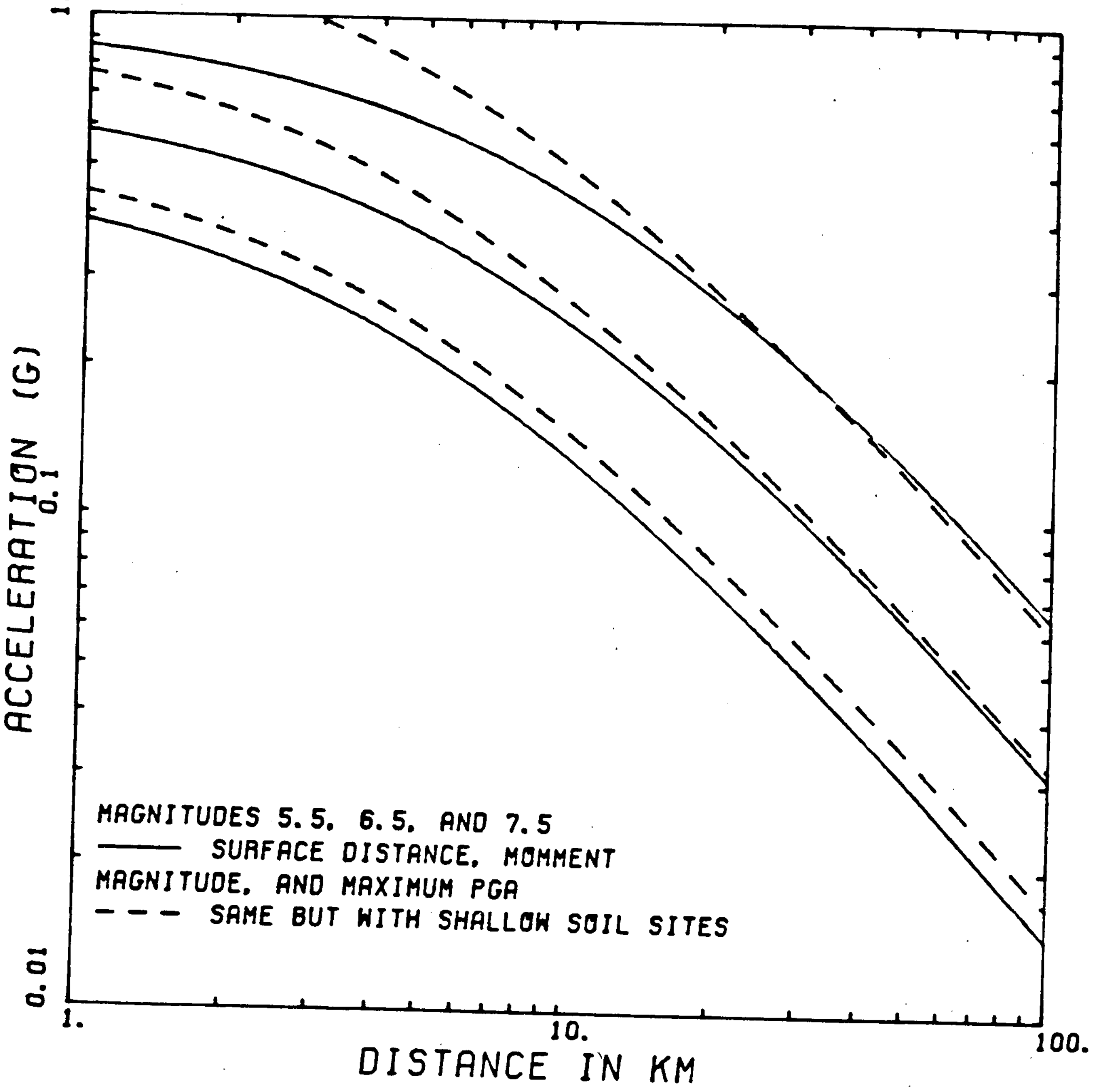

FIGURE 4-5

THE EFFECT OF SHALLOW SOIL SITES
TERA DATA -- TERA MODEL -- TERA ANALYSIS

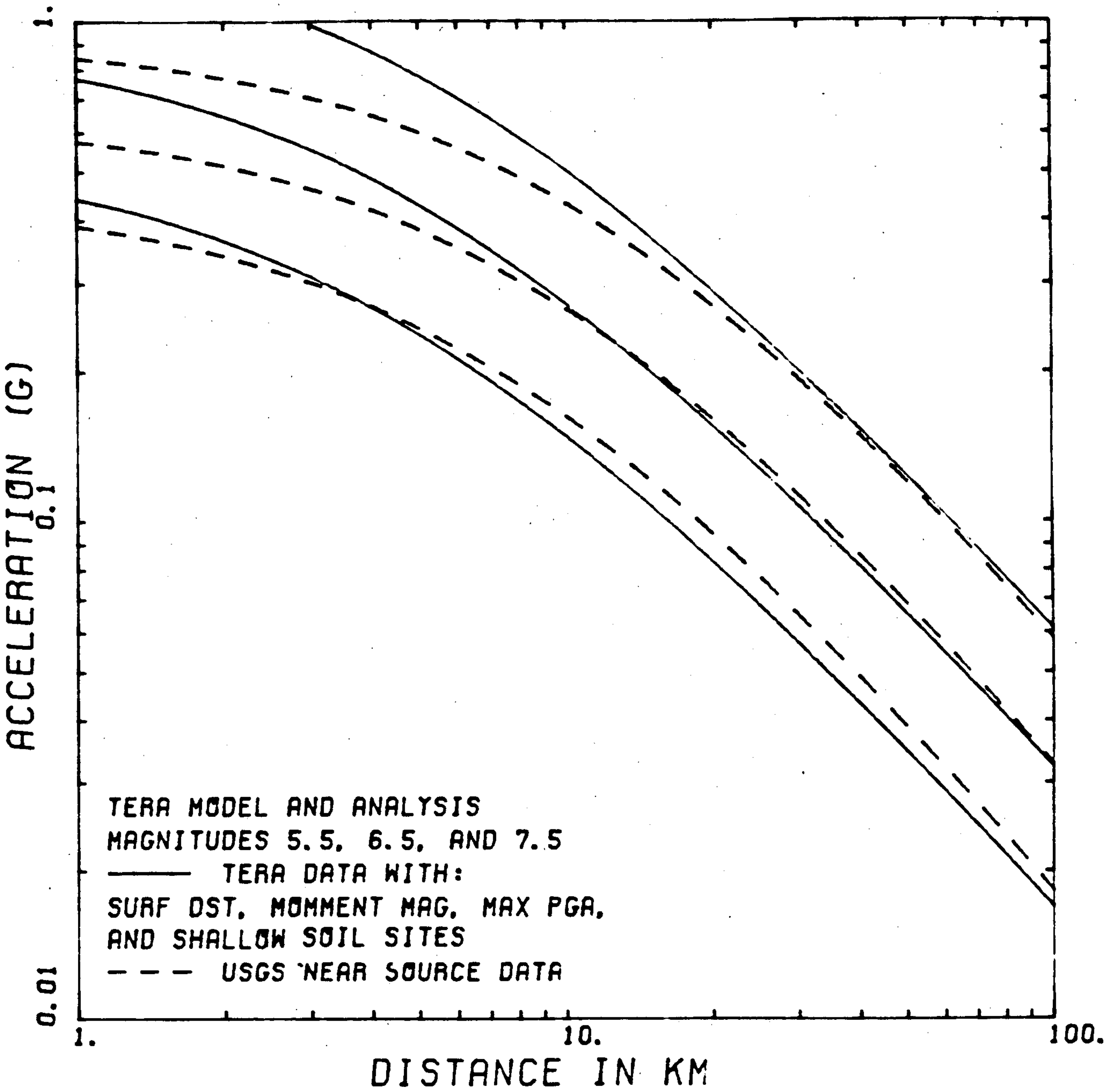

FIGURE 4-6

THE EFFECT OF DATA SELECTION
COMPARING TERA AND USGS NEAR SOURCE DATA

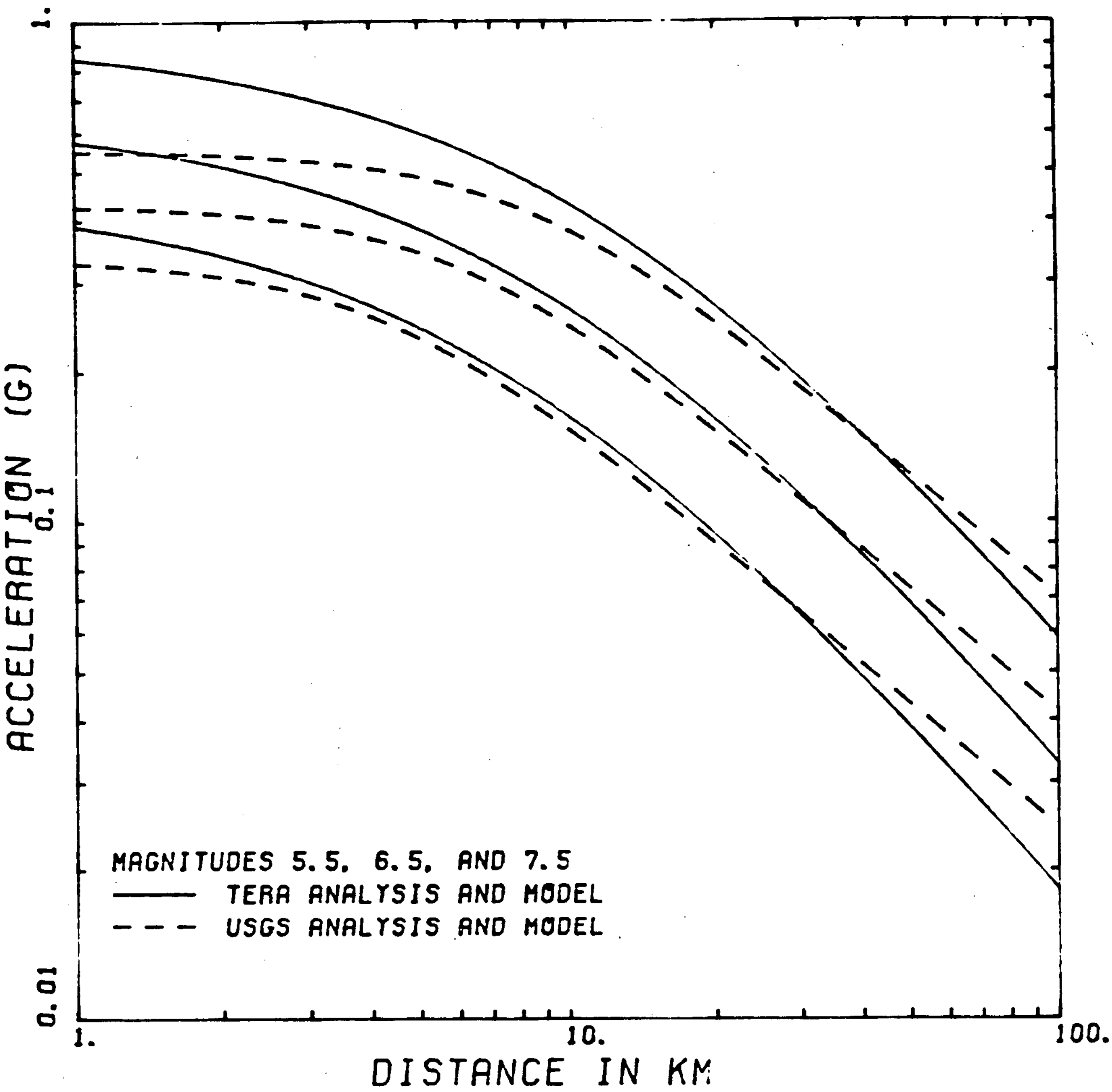

FIGURE 4-7

THE EFFECT OF MODEL AND ANALYSIS
USGS NEAR SOURCE DATA

Discussion

The sensitivity study in this section has shown that application of the parameter and data selection criteria of Joyner et al. results in a substantial increase in the standard error accompanied by a substantial decrease in magnitude saturation properties. Using the TERA analysis and data, excluding large structures, as the basis for comparison, we found the major components leading to the overall increase of 69 percent in standard error were the use of the maximum horizontal component of peak acceleration, the addition of recordings on shallow soils, the use of the USGS earthquakes, the use of far-field data, and the use of the USGS model and analysis. All other changes accounted for individual increases in the standard error of less than five percent.

The largest contribution to the 27-percent decrease in the degree of magnitude saturation was found to come from the use of surface distance and moment magnitude, the addition of recordings located on shallow soils, and the use of the USGS earthquakes. Reversals in this trend came from the use of the maximum horizontal component of PGA, and the use of USGS strong-motion data.

The median prediction of PGA for SONGS remained relatively stable throughout the sensitivity analysis, increasing a modest 12 percent from 0.33g to 0.38g, the increase principally due to the use of the maximum horizontal component of PGA. A trend towards a higher 84th-percentile prediction resulted from the steady increase in the standard error as USGS data and parameter selection criteria were applied.

5.0 CONCLUSIONS

The ground motion model developed by Joyner et al. (1981) predicts a median and 84th-percentile peak horizontal acceleration of 0.46g and 0.85g, respectively, for parameters appropriate for SONGS (R_s = 8 km, M_m = 7). This may be compared to predictions of 0.33g and 0.48g for SONGS using the Campbell (1981) relationship. The difference between the two median predictions were found to be quite sensitive to two decisions made by Joyner et al.

The first decision was to make the attenuation properties of their relationship independent of magnitude. By repeating their analysis allowing their shape to become an exponential function of magnitude, the median and 84th-percentile predictions at SONGS were reduced to 0.38g and 0.70g, respectively. Since these values represent the maximum horizontal component, in order that they may be compared with the estimates of the mean of the two horizontal components, they should be further divided by a factor of 1.09 (see Section 4.0). When this is done, the median value becomes 0.35g which compares favorably with the value of 0.33g given by the Campbell relationship.

To assess the appropriateness of including a magnitude-dependent shape to the Joyner et al. relationship, we developed an empirical distribution for c_2, the coefficient that controls the magnitude dependence, using the Monte Carlo simulation techniques described by Gallant (1975). Standard hypothesis testing techniques as applied to this distribution indicated c_2 to be greater than zero at a level of confidence exceeding 99 percent, statistically confirming the significance of the magnitude-dependent shape of their relationship. More recently, Joyner (personal communication, 1981) has attributed this significance to the inclusion of an aftershock of the 1979 Imperial Valley earthquake in their analyses. However, when we excluded this event and repeated their analysis, we again found c_2 to be greater than zero at a greater than 99-percent level of confidence.

A second decision made by Joyner et al. was to use far-field data in order that their relationship would be valid to distances of several hundred kilometers. We found that by simply restricting their data to the near-source region, using criteria set forth by Campbell, that predictions at SONGS for the median and 84th-percentile value of PGA were reduced to 0.37g and 0.67g, respectively. By further allowing attenuation properties to become a function of magnitude, these values were further reduced to 0.34g and 0.63g. The two median values when converted to mean peak horizontal acceleration become 0.34g and 0.31g, which again compare favorably to the Campbell prediction of 0.33g.

The 84th-percentile predictions of PGA from the three relationships described in the previous paragraphs, when divided by a factor of 1.13 to represent mean peak horizontal acceleration, range from 0.56g to 0.62g, some 17 to 29 percent higher than the value of 0.48g given by the Campbell relationship. The sensitivity studies described earlier in this report found a variety of reasons for the larger standard error in the Joyner et al. analyses ranging from their analysis technique to their data selection criteria. The largest contribution comes from their particular parameter and data selection criteria, which not only increased the 84th-percentile predictions of PGA but also deteriorated the magnitude-dependent attenuation properties of this parameter.

Based on the analyses presented in this report, we may conclude that the median prediction of peak horizontal acceleration at SONGS offered by the Joyner et al. (1981) relationship is quite consistent with that offered by the Campbell (1981) relationship when appropriate magnitude-dependent attenuation properties and near-source data are considered. In addition, we find that the substantial reduction in uncertainty associated with the predictions based on the Campbell relationship is primarily attributed to the application of strict criteria designed to select consistent and stable earthquake parameters and accurate, quality strong-motion data for the analysis of near-source attenuation characteristics of peak acceleration.

6.0 REFERENCES

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