

LOW-RISE BUILDING DAMAGE CAUSED BY AN
EARTHQUAKE AND AN UNDERGROUND EXPLOSION

by

R. E. Scholl

and

I. Farhoomand

John A. Blume & Associates
Research Division
San Francisco, California

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ABSTRACT

This report summarizes an investigation conducted to compare low-rise building damage caused by an earthquake with that caused by an underground nuclear explosion.

The methodology used in deriving the motion - damage relationships is described. The derived motion - damage relationships are given both in terms of the incidence of damage (damage ratio) and damage cost (damage cost factor).

Motion - damage relationships derived from the earthquake data are compared with similar data for low-rise buildings subjected to the ground motion of an underground nuclear explosion. Overall results show that for the same spectral acceleration the earthquake caused slightly more damage. Differences in ground motion characteristics for the two types of disturbances provide the most probable explanation for this discrepancy.

I. INTRODUCTION

URS/John A. Blume & Associates, Engineers/Research Division (JABARD) conducts structural response investigations for the Atomic Energy Commission (AEC), Nevada Operations Office, to determine the effects of ground motion on a wide variety of structures. The study described herein is directed toward obtaining basic ground motion - damage relationships for low-rise buildings. This and other data will ultimately be used in the development of more improved methods for predicting damage caused to low-rise buildings by ground motion.

A. Background

There are two distinct procedures that may be employed for predicting low-rise building damage: the theoretical and the empirical. The theoretical procedure is presently most applicable for evaluations of individual structures, for either design or damage prediction; the empirical procedure is most applicable to damage prediction for groups of structures. This study was conducted along the lines of the empirical procedure.

There have been numerous investigations conducted for the purpose of developing damage thresholds for low-rise buildings subjected to ground motion, but to a large extent the data samples involved in those studies were too small to either suggest or provide a description of the random nature of the problem. Jackson¹ has furnished a reasonably complete summary of these studies.

The need for reliable procedures for predicting structure damage resulting from man-induced ground motion has existed for a long time; it became significantly more urgent a decade ago with the commencement of the AEC's underground nuclear testing program. Arising from the AEC's need for the development of improved damage prediction procedures, JABARD has been provided with the opportunity to conduct ground motion - low-rise building damage studies for both an earthquake and an underground nuclear explosion (UNE).

The underground nuclear explosion ground motion and damage data used in this study were obtained from the Project RULISON gas stimulation experiment.² The earthquake ground motion and damage data were obtained from the San Fernando earthquake of February 9, 1971.³

Both the earthquake and underground nuclear explosion studies generally involved minor damage. One consideration for the RULISON underground nuclear explosive yield selection was the minimization of damaging effects to culture. Because this will be the case in the AEC's future effects-prediction needs, JABARD was also very interested in studying minor damage for the earthquake, which caused severe damage in some areas of greater Los Angeles, and minor damage in others. After conducting a general reconnaissance of damage caused by the San Fernando earthquake, JABARD concluded that the severity of damage in the city of Glendale was appropriate for the AEC's needs. Figure 1 shows the approximate location of the earthquake epicenter with respect to the nearby populated areas.

B. Scope and Purpose

Ground motion - damage relationships were derived for overall damage and for the most frequently damaged building components. Overall ground motion - damage relationships were developed in terms of frequency of damage and damage cost.

The similarities and differences in motion - damage relationships for the two kinds of ground motion are compared with the similarities and differences in their ground motion characteristics.

The results presented here are a summary of two studies conducted to investigate motion - damage relationships for the two kinds of ground motion. More detailed results have been documented for the underground nuclear explosion study^{4,5} and the earthquake study.⁶

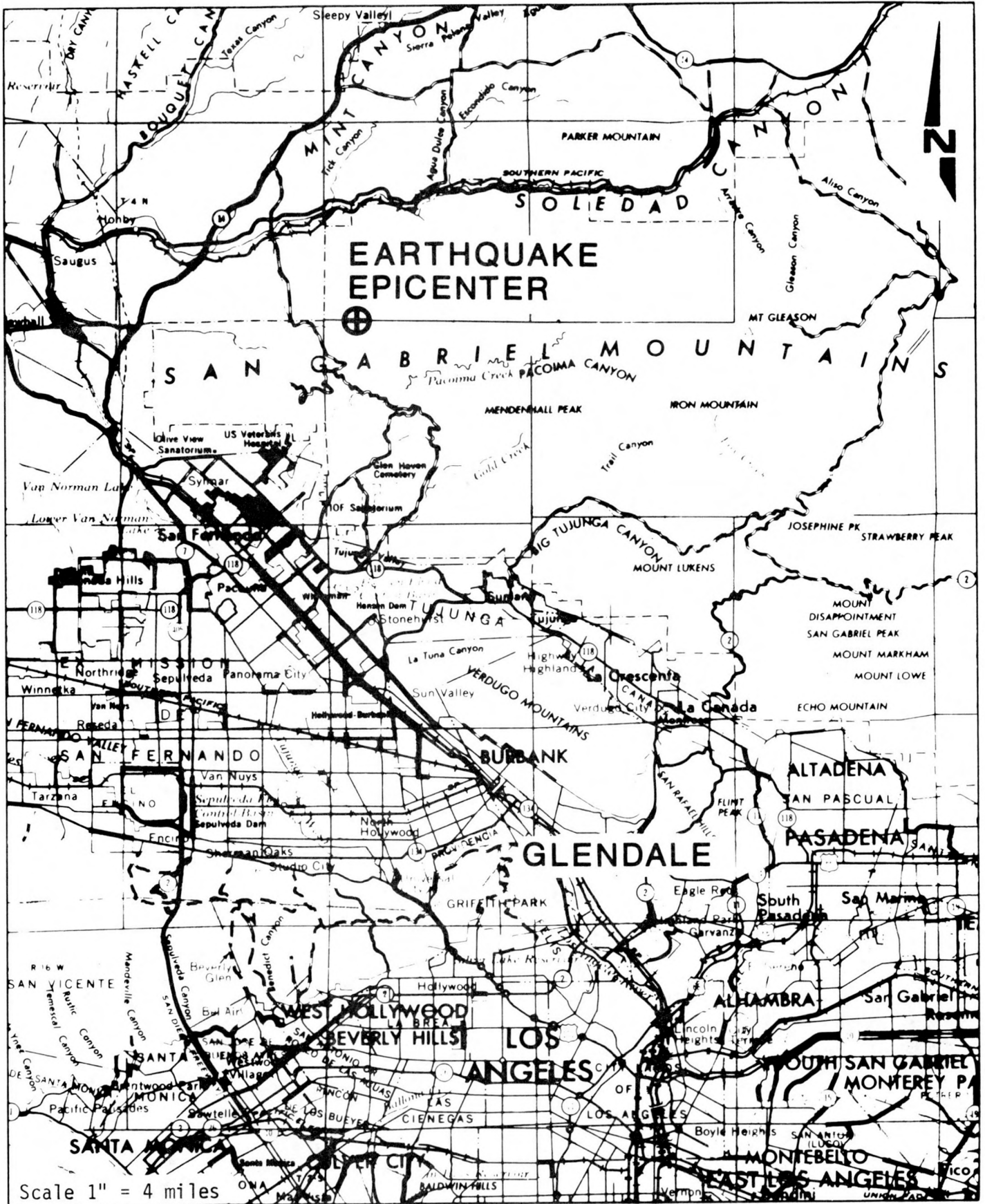


FIGURE 1 GREATER LOS ANGELES AREA MAP

II. DESCRIPTION OF DATA

In studying ground motion - damage relationships, three major variables must be considered: the types of structures involved, the character of the ground motion, and the nature of structure damage. This chapter describes these data as used in this study.

A. Study Locations

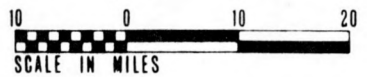
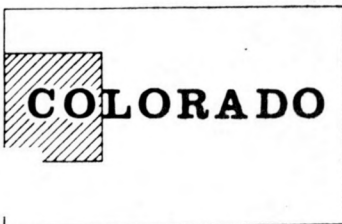
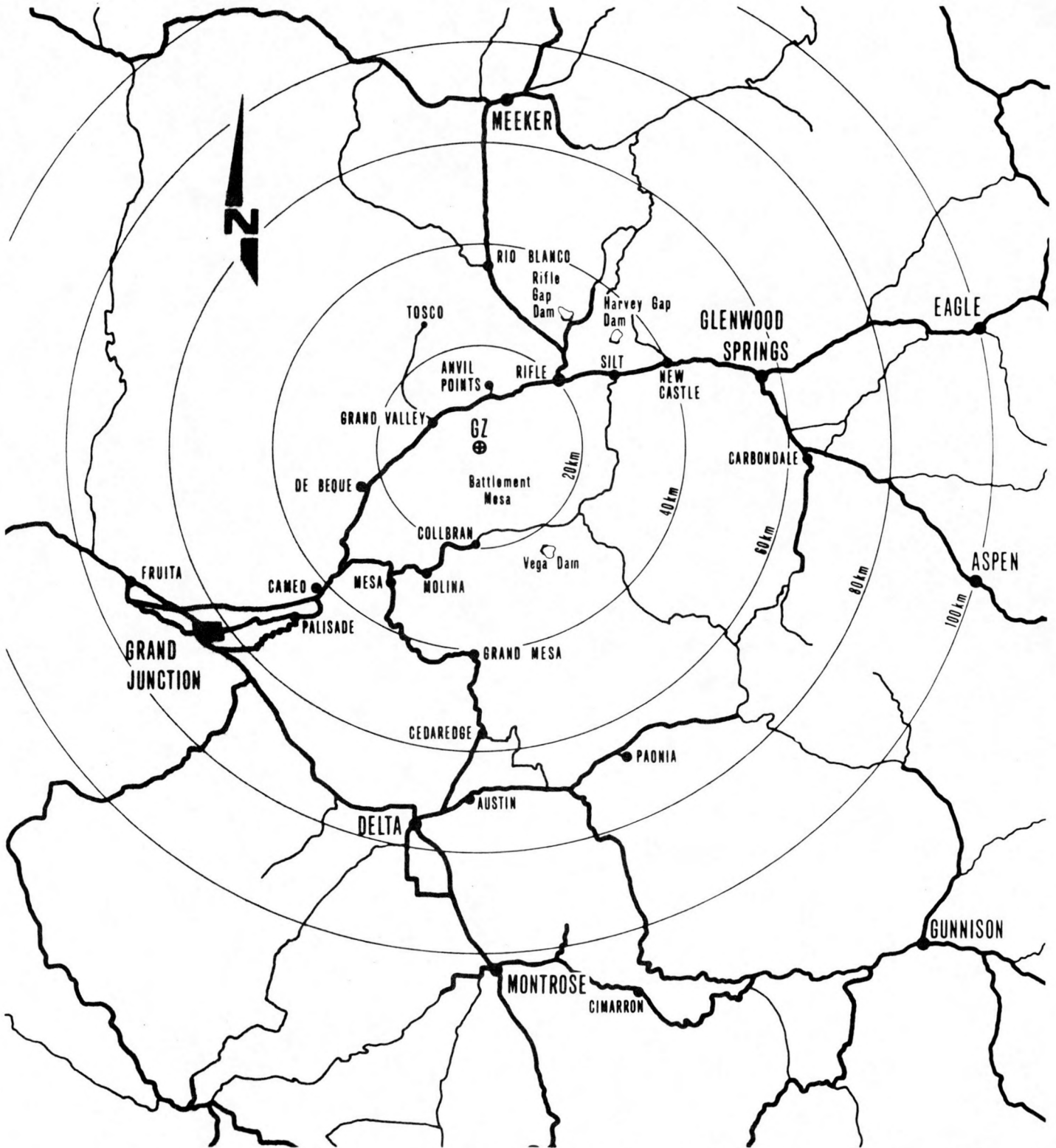
Figure 2 shows general cultural features within 100 kilometers of the explosive emplacement well, or Ground Zero (GZ) for Project RULISON. There are five towns in the area, located at varying distances from GZ, for which the structure inventory, damage survey, and ground motion data were available: Collbran, DeBeque, Grand Valley, Rifle, and Silt.

The stippled areas on the Glendale city map (Figure 3) indicate the two selected study areas for which structure inventory and damage data were acquired for the earthquake study. These two areas were selected as representative of damage to both hillside (Area 1) and flatland (Area 2) low-rise buildings in Glendale. In an early post-earthquake reconnaissance of the area, it was readily apparent that damage was more severe in the hillside area.

B. Structure Inventory Data

In all, 1043 low-rise buildings (residential, commercial, and institutional) within the boundaries of the two Glendale areas were included in that study. The combined structure population of the five towns included in the RULISON study was 1378 buildings.

In both the RULISON and the Glendale studies, structure inventory data were obtained by observations conducted from the street and recorded on forms similar to that in Figure 4. As specified in the inventory form, building values were obtained from property tax assessment records and from on-site estimates made during the



PROJECT RULISON General Area Map

Figure 2

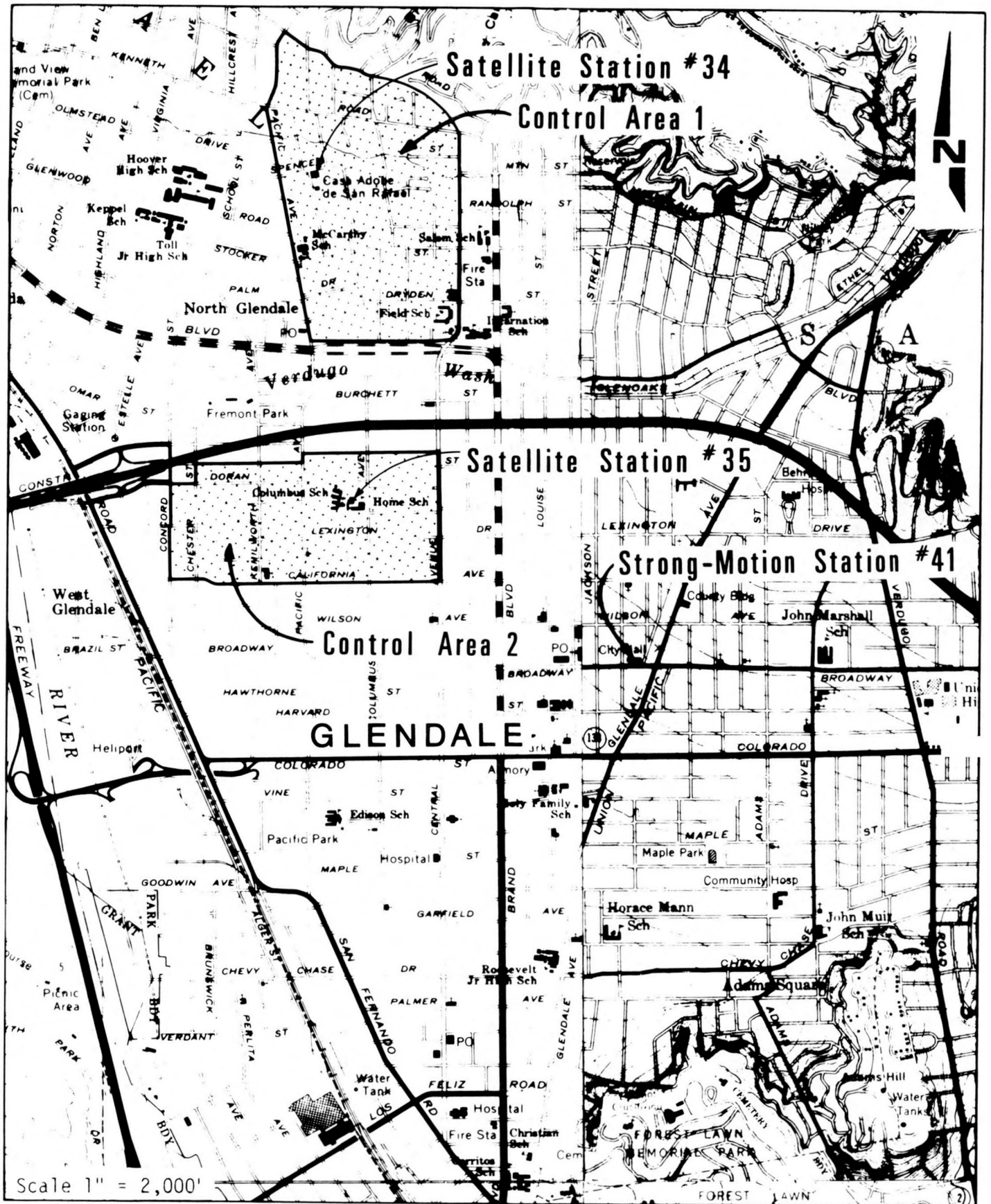


FIGURE 3 GLENDALE, CALIFORNIA, AREA MAP

Building Location Data

City: _____ Address: _____

Location No.: _____ Owner: _____

Building Classification Data

Occupancy: Residential Commercial Institutional

Frame Type: Wood Adobe Log

Masonry Metal

Direction of Major Axis: North East

Exterior Walls: Wood Brick Concrete Block
(Siding) Metal Cement Asbestos Adobe

Log Stone Other: _____

Building Height: 1 1-1/2 2 3 4
(Stories)

Aspect Ratio: H/Depth _____ H/Width _____

Foundation Type: Wall Masonry Concrete Mudsill Pier Masonry Timber

Chimney Type: Brick Stone Ceramic Plaster Coated Brick
 Capped Brick Capped Stone Capped Ceramic None

Height of Chimney Above Roof (Feet) _____

Chimney-Building Orientation: Major-Major Major-Minor

Chimney Location Center (Ridge) End Eave

Building Age (yrs) 0-5 5-10 10-20 20-40 Over 40

Building Classification No. _____

Building Value: Estimated \$ _____ Assessed \$ _____

Condition: Good Fair Poor

Soil Type: Hard Rock Alluvium

FIGURE 4 STRUCTURE INVENTORY FORM

structure inventories. Both values were obtained for all the structures involved in the RULISON study and were rigorously compared⁴ to arrive at a reasonable market value for improvements. For the Glendale study, similar adjustments were made to arrive at a reasonable market value, but tax assessment values were obtained for only 100 buildings. The number of buildings included in the two studies and general descriptions of their physical characteristics are given in Table 1.

C. Damage Data

For the earthquake study, damage data were obtained by a door-to-door survey. A sample of the form on which the data were recorded is given in Figure 5. RULISON damage data were obtained from the AEC's damage complaint and payment records. RULISON damages used in this study are those complaints that were acknowledged as credible by investigators. In both studies, damage was distinguished for the following building components:

- chimney -- including fireplace
- interior wall
- exterior wall
- foundation
- window
- other (building or household items)

D. Ground Motion Data

As stated above, five towns ranging from 10 to 30 kilometers from the RULISON emplacement well were included in that study. A summary of the ground motion data recorded for the RULISON event is given in Reference 7. Examples of ground motion recordings that are approximately representative of the maximum and minimum ground motion strengths included in the RULISON study are given in Figures 6 and 7, for the towns of Grand Valley and DeBeque, respectively. The respective response spectra calculated from these ground motion recordings are given in Figures 8 and 9.

TABLE 1
BUILDING DESCRIPTIONS

Location	Number of Buildings	Percent of Buildings by Construction Type and Height							Percent of Buildings by Use			Percent of Buildings by Age*				
		Wood Frame			Masonry			Other	Residential	Commercial	Insti-tutional	0-5 Years	5-10 Years	10-20 Years	20-40 Years	Over 40 Years
		1 & 1-1/2 Story	2 Story	3 or More Story	1 & 1-1/2 Story	2 Story	3 or More Story									
Collbran	139	65	9	0	9	4	0	13	78	18	4	2	9	11	33	45
DeBeque	105	66	8	0	14	1	0	11	79	16	5	<1	2	13	37	47
Grand Valley	154	61	5	0	17	2	0	15	78	18	4	<1	10	12	29	49
Rifle	812	63	5	0	19	5	0	8	83	15	2	2	16	20	27	35
Silt	168	63	4	0	12	<1	0	21	82	14	4	<1	11	21	26	41
Glendale Area 1	494	73	26	<1	<1	0	0	<1	≈100	<1	0	<1	4	8	18	69
Glendale Area 2	549	85	14	<1	<1	0	0	<1	99	<1	<1	<1	1	4	11	84

*Estimated

EARTHQUAKE DAMAGE STUDY

NAME _____

ADDRESS _____

1. Was there damage to your residence?

No

Yes

2. If you had damage, which of the following elements were affected:

Chimney

Interior

Exterior Wall

Foundation

Window

Other (Describe) _____

3. What percent of the total actual or estimated cost of repairs occurred in this element?

%

%

%

%

%

%

4. If you had interior wall damage, which of the following best describes the type of construction?

Drywall (Gypsum Board)

Lath and Plaster

Masonry

Other (Describe) _____

5. If you had damage, have repairs been made by or repair costs been estimated by a building contractor?

Yes

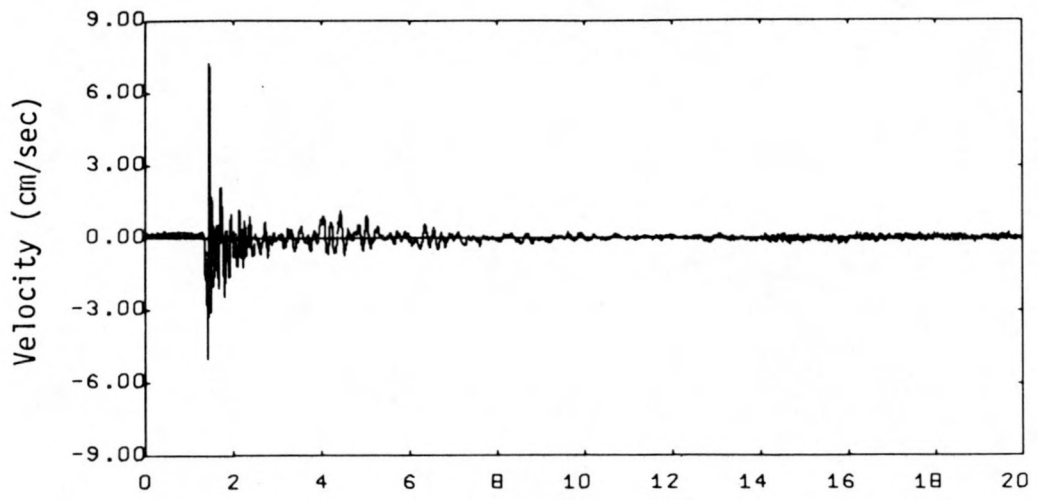
No

6. What is the actual or estimated cost of repairs?

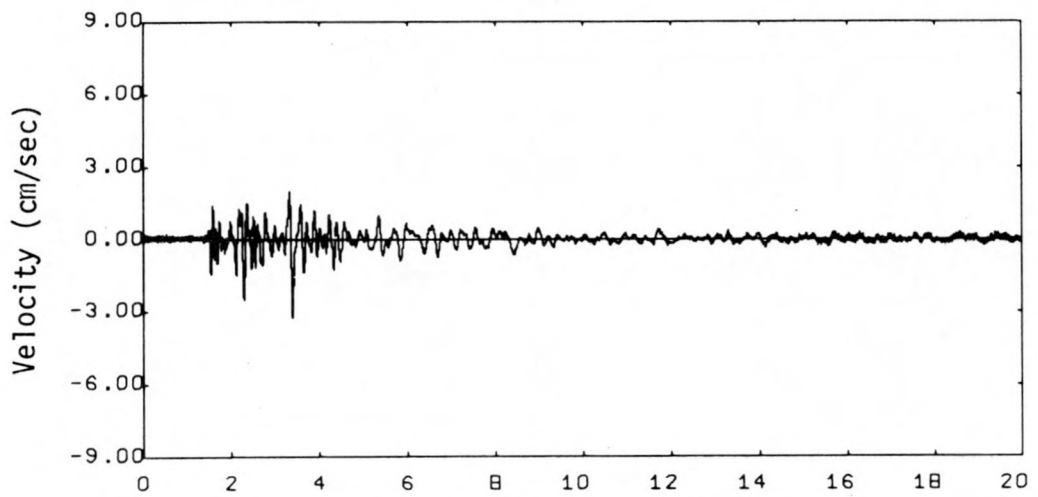
\$, . Contractor's

\$, . Resident's

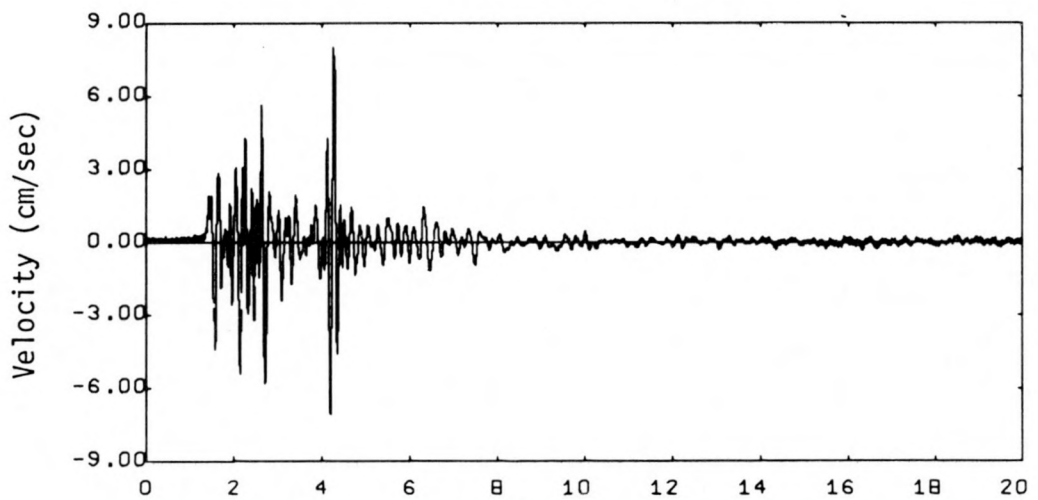
FIGURE 5 STRUCTURE DAMAGE SURVEY FORM



Vertical Component



Tangential Component



Radial Component

FIGURE 6 GROUND MOTION RECORDINGS
FOR THE RULISON UNE EVENT OF
SEPTEMBER 10, 1969: GRAND VALLEY STATION

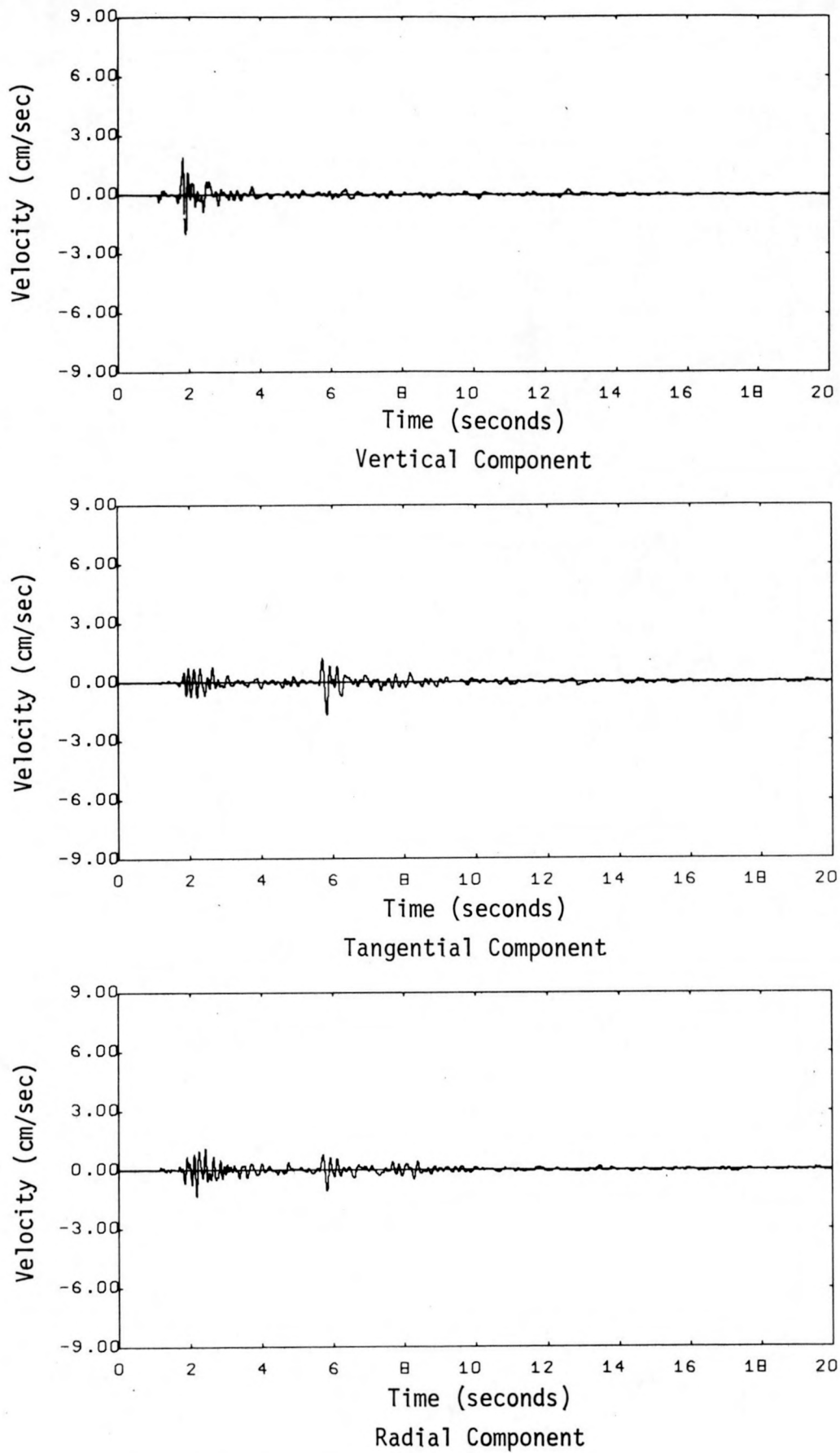


FIGURE 7 GROUND MOTION RECORDINGS
 FOR THE RULISON UNE EVENT OF
 SEPTEMBER 10, 1969: DEBEQUE NO. 1 STATION

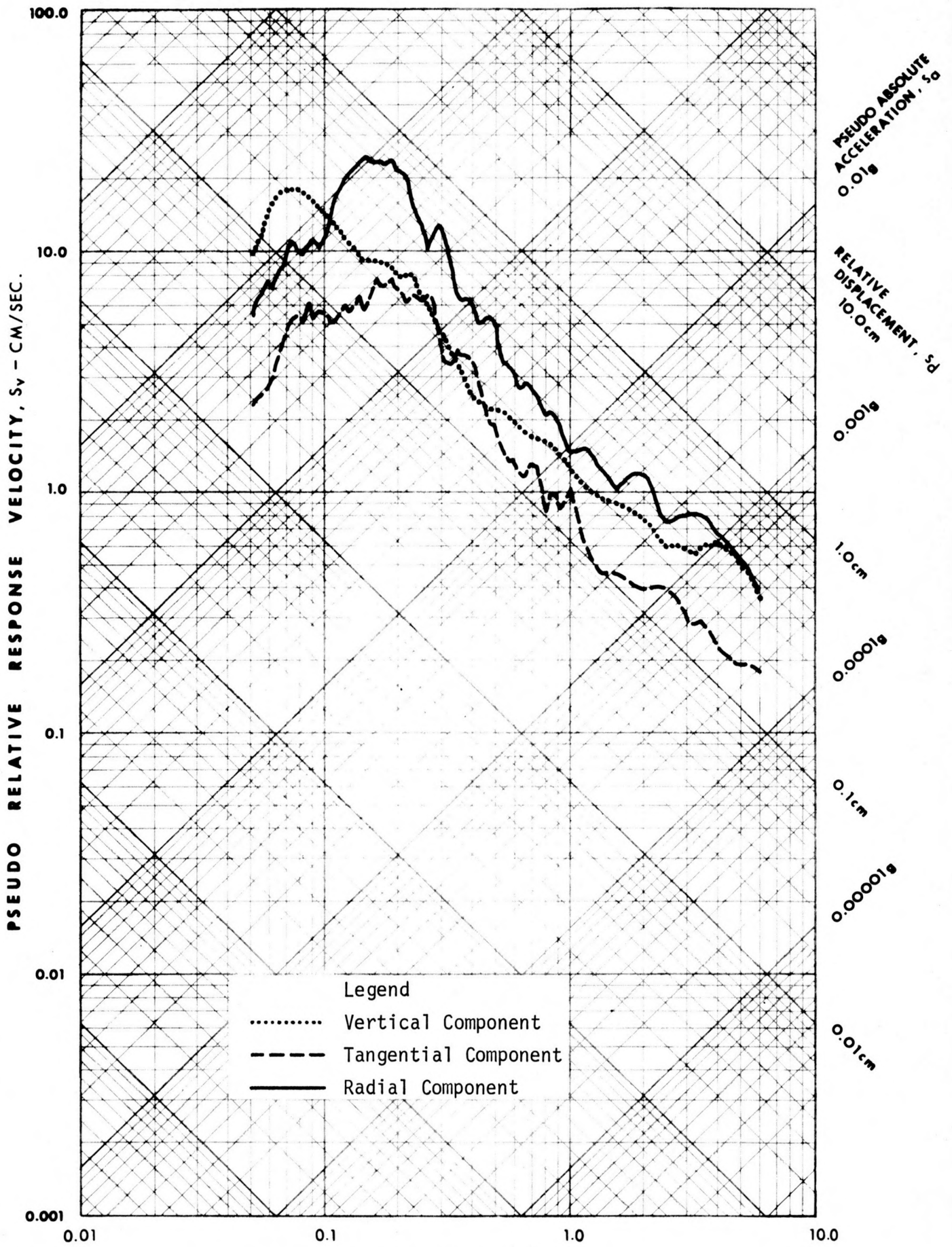


FIGURE 8 5%-DAMPED RESPONSE SPECTRUM CURVES
FOR THE RULISON UNE EVENT OF
SEPTEMBER 10, 1969: GRAND VALLEY STATION

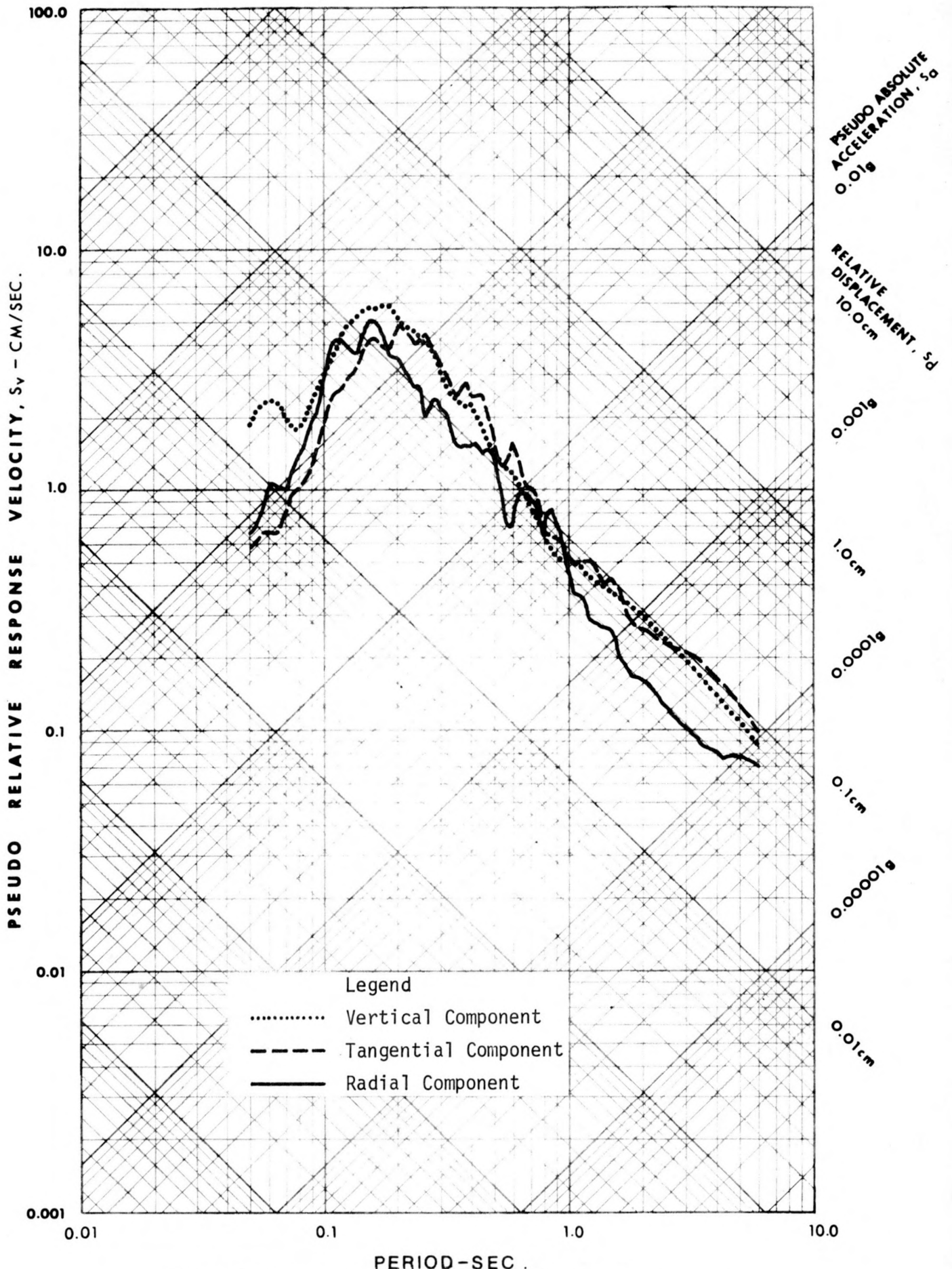


FIGURE 9 5%-DAMPED RESPONSE SPECTRUM CURVES
 FOR THE RULISON UNE EVENT OF
 SEPTEMBER 10, 1969: DEBEQUE NO. 1 STATION

In the Glendale area (Figure 3) there is one strong-motion seismograph station (No. 41) and it operated during the San Fernando earthquake. The recorded accelerograms and corresponding response spectra are given in Figures 10 and 11, respectively. Because of differences in local geology of various sections of Glendale, the ground motion and corresponding response spectrum exhibit significant variability within this rather small geographical area. Using recorded aftershock ground motions at satellite stations in the Glendale area (Figure 3), 5%-damped response spectra for these sites were analytically derived for the main shock.⁸ Figures 12 and 13 show the analytically derived median response spectrum curves for the two Glendale study areas included in this investigation. Assuming the spectral amplitudes to be lognormally distributed, the geometric standard error of estimate, n , for these derived spectra (not shown) was determined to be nearly constant for all periods and equals 1.5.⁸

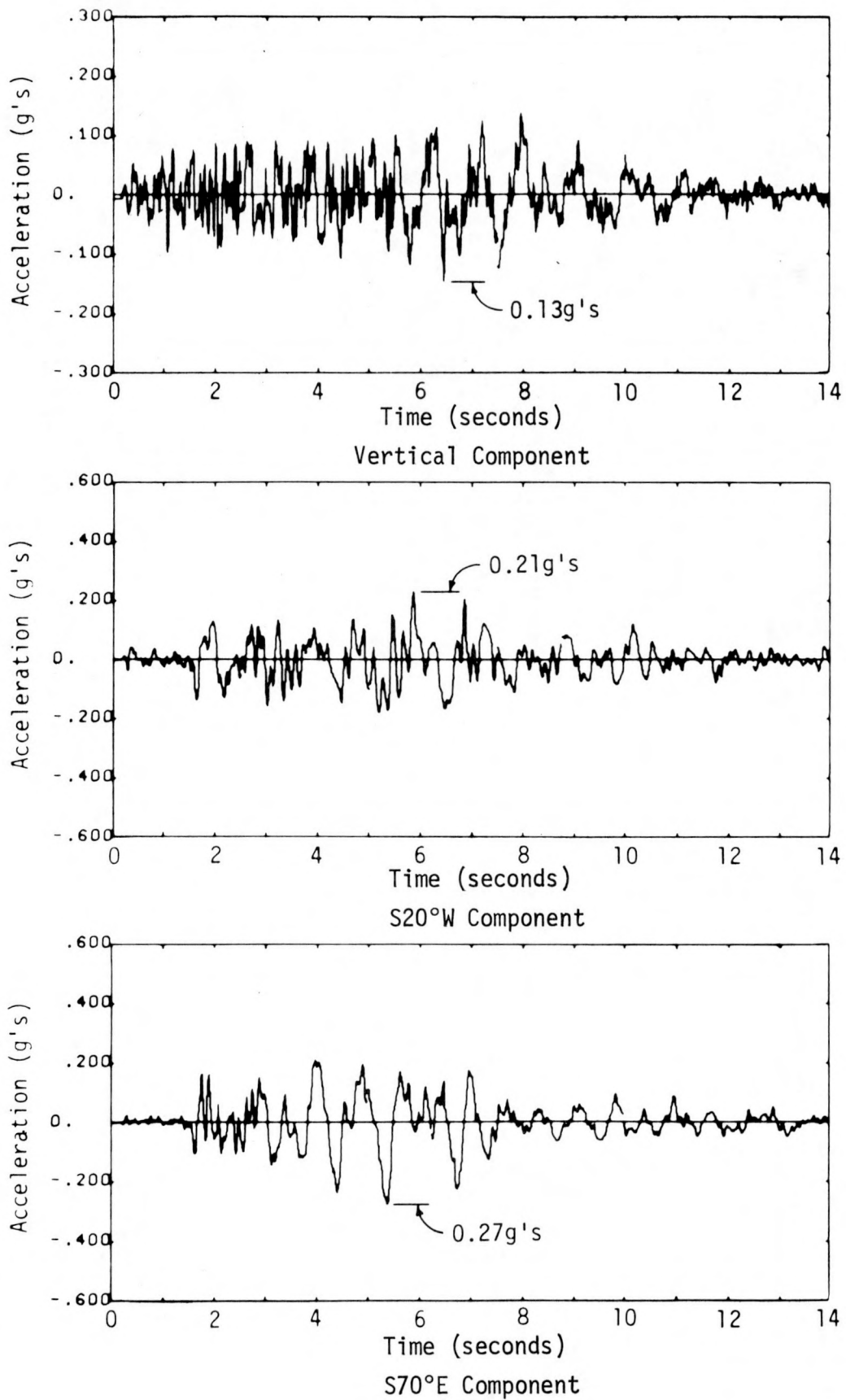


FIGURE 10 STRONG MOTION RECORDINGS FOR THE SAN FERNANDO EARTHQUAKE ON FEBRUARY 9, 1971, AT GLENDALE, CALIFORNIA, STATION NO. 41

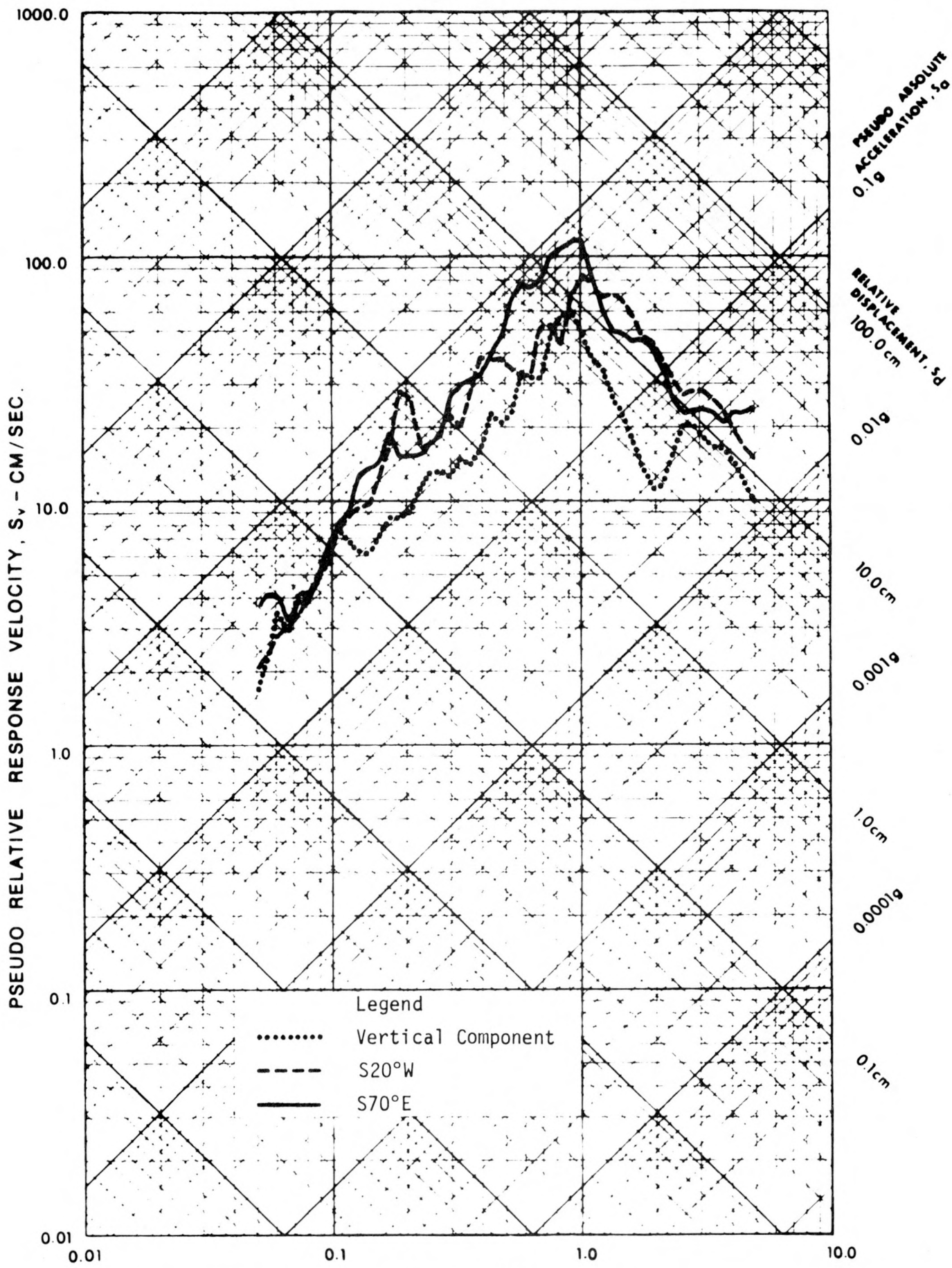


FIGURE 11 5%-DAMPED RESPONSE SPECTRUM CURVES FOR THE SAN FERNANDO EARTHQUAKE OF FEBRUARY 9, 1971, RECORDED AT GLENDALE, CALIFORNIA, STATION NO. 41

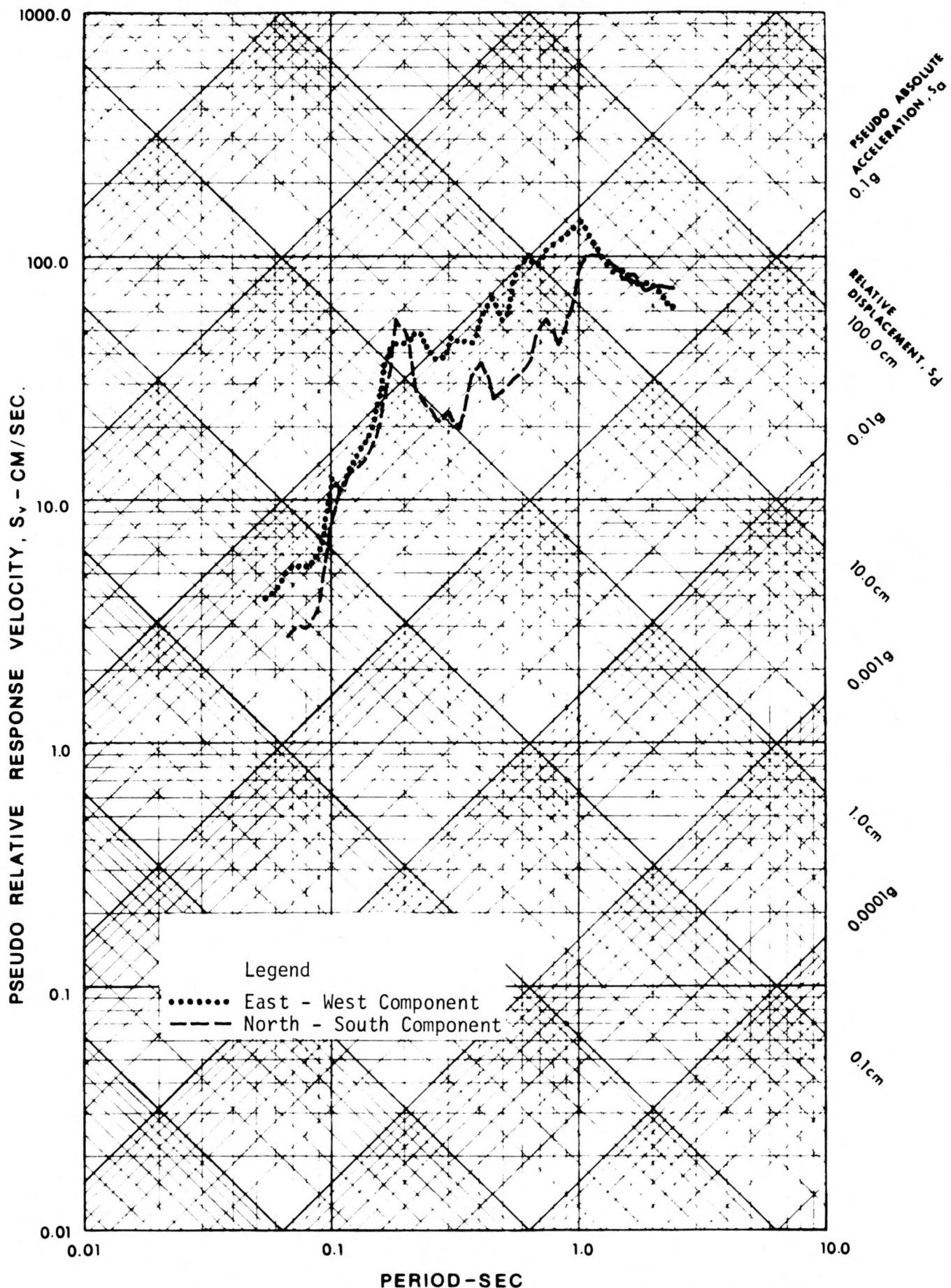


FIGURE 12 PREDICTED 5%-DAMPED RESPONSE SPECTRUM CURVES FOR THE SAN FERNANDO EARTHQUAKE ON FEBRUARY 9, 1971, AT GLENDALE AREA 1 (AFTER REFERENCE 8)

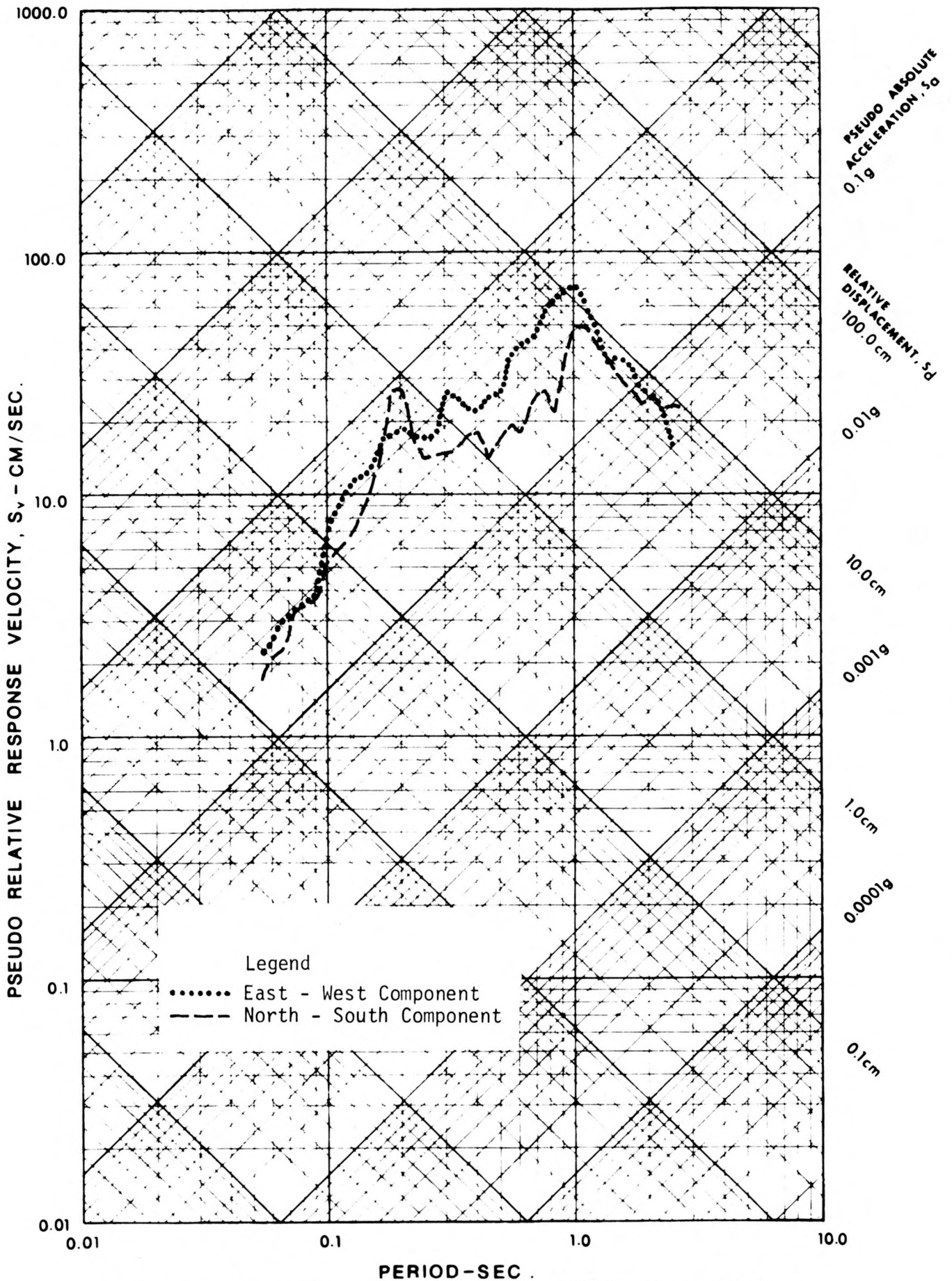


FIGURE 13 PREDICTED 5%-DAMPED RESPONSE SPECTRUM CURVES FOR THE SAN FERNANDO EARTHQUAKE ON FEBRUARY 9, 1971, AT GLENDALE AREA 2 (AFTER REFERENCE 8)

III. MOTION - DAMAGE CORRELATION METHODOLOGY

Effective correlation of ground motion and damage for low-rise buildings requires consideration of the way that ground motion affects structure response, i.e., dynamic response amplification, and the type and degree of damage caused. The methodology for incorporating these parameters into the motion - damage correlations performed are described below.

A. Damage Identification

The first step in conducting motion - damage correlations is to derive a description of damage that satisfies the user's needs. To this end, the AEC's principal ground motion effects-prediction requirements are the identification of the incidence and degree of damage. These can be effectively described with two variables: damage ratio (DR) and damage cost factor (DCF). These variables are defined as:

$$DR = \frac{\text{Number of Buildings Damaged}}{\text{Total Number of Buildings}}$$

$$DCF = \frac{\text{Damage Repair Cost}}{\text{Value of Buildings}}$$

These two nondimensional parameters are quite general and can be defined for a geographical area, or for various building classifications or types of construction, e.g., wood-frame buildings or two-story buildings. They can also be defined for various types of damage, e.g., chimney damage or interior wall damage.

B. Structure Idealization

Structures can be idealized in many ways. One may classify them in terms of their construction type, e.g., brick buildings or wood-frame buildings. More appropriately, structures may be idealized as multi-degree-of-freedom systems. For ground motion - damage correlation purposes, the former is inadequate because it does not

include consideration of the dynamic response behavior of structures, and the second is too sophisticated.

A very descriptive soil-structure system idealization involves fundamental mode vibration properties for the designated building construction types. This idealization is appealing because it includes consideration of the dynamic response behavior of structures and also allows for different motion - damage relationships for various building construction types. Although the fundamental mode generally does not represent total dynamic response, theoretical considerations indicate that a large percentage of the total is usually included in the fundamental mode.

Using the fundamental mode idealization, there are only three parameters that need be considered explicitly: period, mode shape, and damping. Theoretical and experimental studies⁹ indicate that the relative distribution of lateral distortions in a typical low-rise soil structure system -- reflected in mode shape -- can influence the manifestation of damage. However, because of the present lack of evidence to substantiate the importance of mode shape consideration and the additional effort required to include it in these studies, it was not considered. This, in essence, reduces the structure idealization used in these motion - damage correlation studies to that of a single-degree-of-freedom system, i.e., building period and damping. Test data^{10,11,12,13} show that the fundamental periods of one- and two-story buildings are in the range of 0.05 to 0.2 seconds, and that 5% equivalent viscous damping is a reasonable approximation.

C. Ground Motion Characterization

The recorded ground motion at a particular site can be characterized in many ways. Considering the nature of dynamic-structure response to ground motion and applicable damage criteria, it follows that the most important ground motion characteristics that influence structure damage are: motion amplitude, frequency

content, periodicity, and duration. Insofar as these characteristics influence structure damage, they are all, except duration, included in the response spectrum characterization. Ground motion duration is included to the extent that peak response is calculated but structure-response duration is not. The effect of response duration is discussed later in this report.

In the correlation study involving the low-rise building damage caused by the RULISON underground nuclear explosion, Scholl and Farhoomand⁴ concluded that the horizontal component envelope acceleration response spectrum, S_{ae} , was a very positive indicator of the damage potential of ground motion. This ground motion characterization is used in this report to compare motion - damage relationships for the two types of ground motion excitation. Horizontal component envelope spectra are obtained by simply superimposing the two individual horizontal component acceleration spectra and enveloping the two curves. 5%-damping was used to calculate the spectra because, as stated above, tests yield this as an approximate mean value for low-rise buildings. To arrive at a single-valued number characterizing the ground motion at a station, the S_{ae} spectrum was averaged over the period band of 0.05 to 0.2 seconds.

IV. MOTION - DAMAGE CORRELATION RESULTS AND DISCUSSION

Using the concepts of damage ratio and damage cost factor, damage statistics for the RULISON and Glendale study areas were calculated and are summarized in Table 2. All damage ratios shown in Table 2 were obtained by using the number of buildings in the corresponding location as the normalization factor, except for chimney damage ratios, which were obtained by dividing the number of damaged chimneys by the number of buildings with chimneys. Damage cost factors were calculated by dividing the total dollar damage in each distinct geographical area by the total market value of all the buildings in that area.

The distinction is made in Table 2 between overall damage including "other" damage and overall damage excluding reportings of only "other" damage. This was done because for RULISON very little damage fell into this category, while for Glendale there was a sizable amount. Nearly all the "other" damage reported for Glendale involved household items. It is noteworthy, therefore, that the overall damage excluding "other" damage includes nearly all the building damage.

Horizontal component envelope acceleration spectrum values (S_{ae}) pertinent to this study are given in Table 3. In addition, horizontal component envelope velocity spectrum values (S_{ve}) are included in the table for completeness.

A. Damage Ratio (Building Components)

Figure 14 shows overall and component damage versus spectral amplitude derived from RULISON data. The lines shown are the best-fit lines obtained from linear regressions in the log domain. The variation of damage ratio with spectral amplitude for overall and component damage derived from Glendale data is given in Figure 15.

Comparing Figures 14 and 15, it can be seen that the general trend of the relationships for both data sets is the same, but there are some discernible differences. Generally, for the same spectral

TABLE 2

DAMAGE RATIOS AND DAMAGE COST FACTORS

Location	Damage Ratio (%)								Damage Cost Factor (%)
	Overall		Chimney	Interior Wall	Exterior Wall	Foundation	Window	Other*	
	Including "Other"	Excluding "Other"							
Collbran	5.0	4.3	0	2.2	0.7	1.4	0	0.7	0.086
DeBeque	5.7	5.7	1.5	4.8	1.0	1.0	0	0	0.17
Grand Valley	50.0	48.1	43.0	26.0	12.3	10.4	0.6	5.8	1.35
Rifle	8.6	8.6	4.7	5.7	1.8	2.6	0.5	0.5	0.19
Silt	3.0	3.0	0.9	1.2	1.2	0	0	0	0.038
Glendale Area 1	66.6	58.3	41.5	47.8	17.8	3.2	5.9	28.3	2.09
Glendale Area 2	39.9	34.8	27.0	24.0	6.6	1.1	3.5	11.8	0.87

*Building or household items

TABLE 3
SPECTRAL AMPLITUDE VALUES

Location	Spectral Amplitudes*	
	S_{ae} (g)	S_{ve} (cm/sec)
Collbran	0.11	2.0
DeBeque	0.15	3.1
Grand Valley	0.88	17.7
Rifle	0.20	3.4
Silt	0.085	1.5
Glendale Area 1	0.97	21.8
Glendale Area 2	0.54	12.0
Station No. 41 (Strong-Motion Station)	0.57	12.5

*5%-damped horizontal component envelope response spectrum curves averaged over period band 0.05 to 0.2 seconds

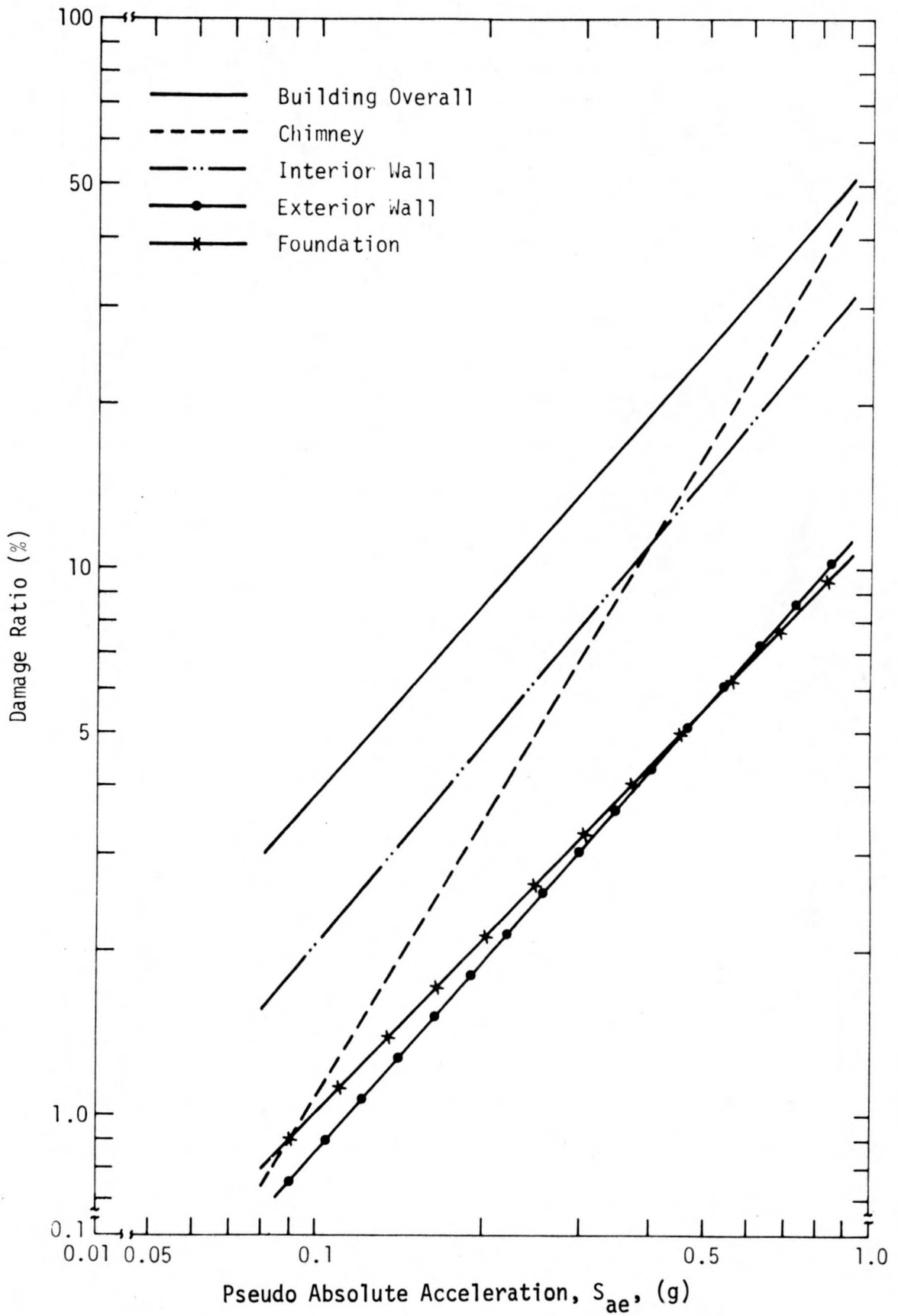


FIGURE 14 COMPONENT DAMAGE RATIO VERSUS SPECTRAL ACCELERATION (RULISON)

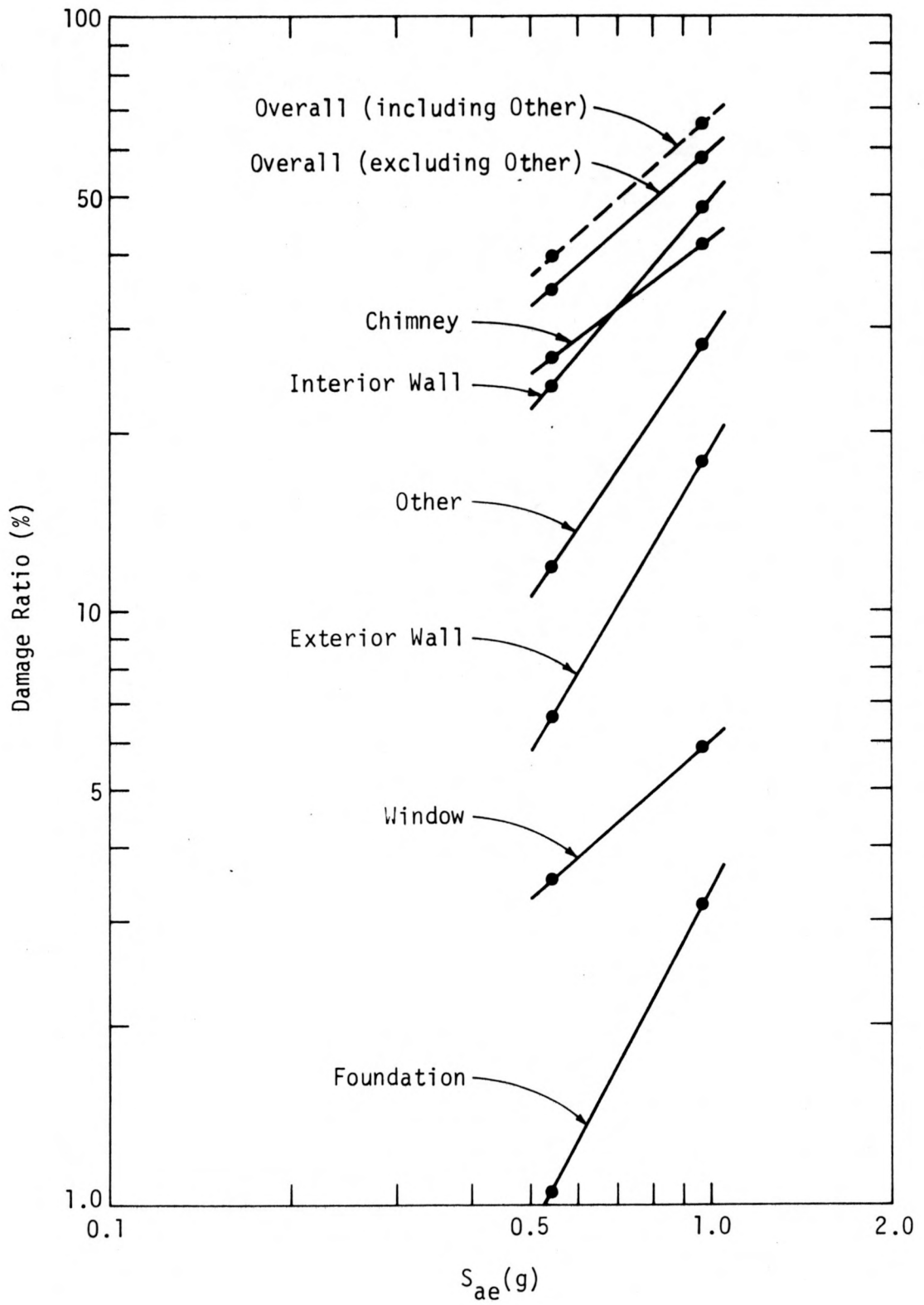


FIGURE 15 COMPONENT DAMAGE RATIO VERSUS SPECTRAL ACCELERATION (GLENDALE)

amplitude, more building components in the Glendale area sustained damage than in the RULISON area. Foundation damage is an exception. Inspection of both areas revealed that building foundations in the Glendale area are more substantial than in the RULISON area. Window and "other" curves are not shown in Figure 14 (for RULISON) because, as can be seen in Table 2, damage ratios for these categories are very small.

The difference in the number of building components damaged in the two sets suggests a need for a detailed study of differences in ground motions. This is discussed below.

B. Damage Ratio (Overall)

Figure 16 shows only the overall damage ratio variation with spectral amplitude. The solid diagonal line is the best-fit line obtained from a linear regression in the log domain using the five RULISON data points; the dashed diagonal lines represent the associated standard error of estimate. The five RULISON data points are also shown and are distinguished by the appropriate town name. Glendale damage ratios are shown in Figure 10 as bold dots. The Glendale overall damage ratios shown are those excluding "other" damage. These ratios represent the best comparison because very little household item damage appeared in the RULISON data. Comparing the two sets of data, it is seen that both of the Glendale mean value points lie above the RULISON mean line. Thus, for the same spectral acceleration, the earthquake caused slightly more damage than the underground nuclear explosion.

C. Damage Cost Factor

Figure 17 shows the variation of overall damage cost factor with spectral acceleration for the RULISON and Glendale data. The solid diagonal line is the line of best fit of the RULISON data points; the dashed lines indicate the associated standard error of estimate. Glendale damage cost factors are shown in the figure as bold dots.

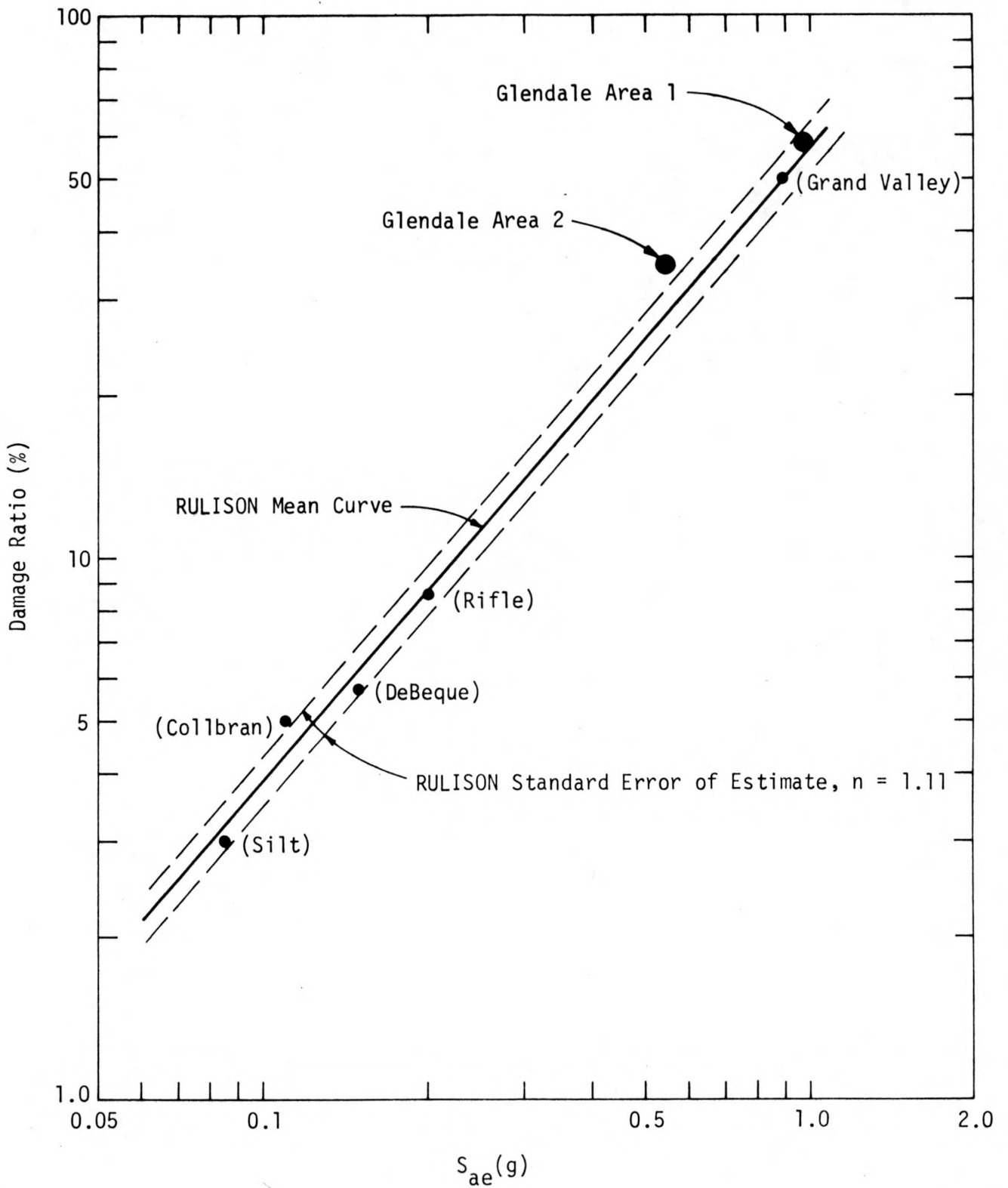


FIGURE 16 OVERALL DAMAGE RATIO VERSUS SPECTRAL ACCELERATION

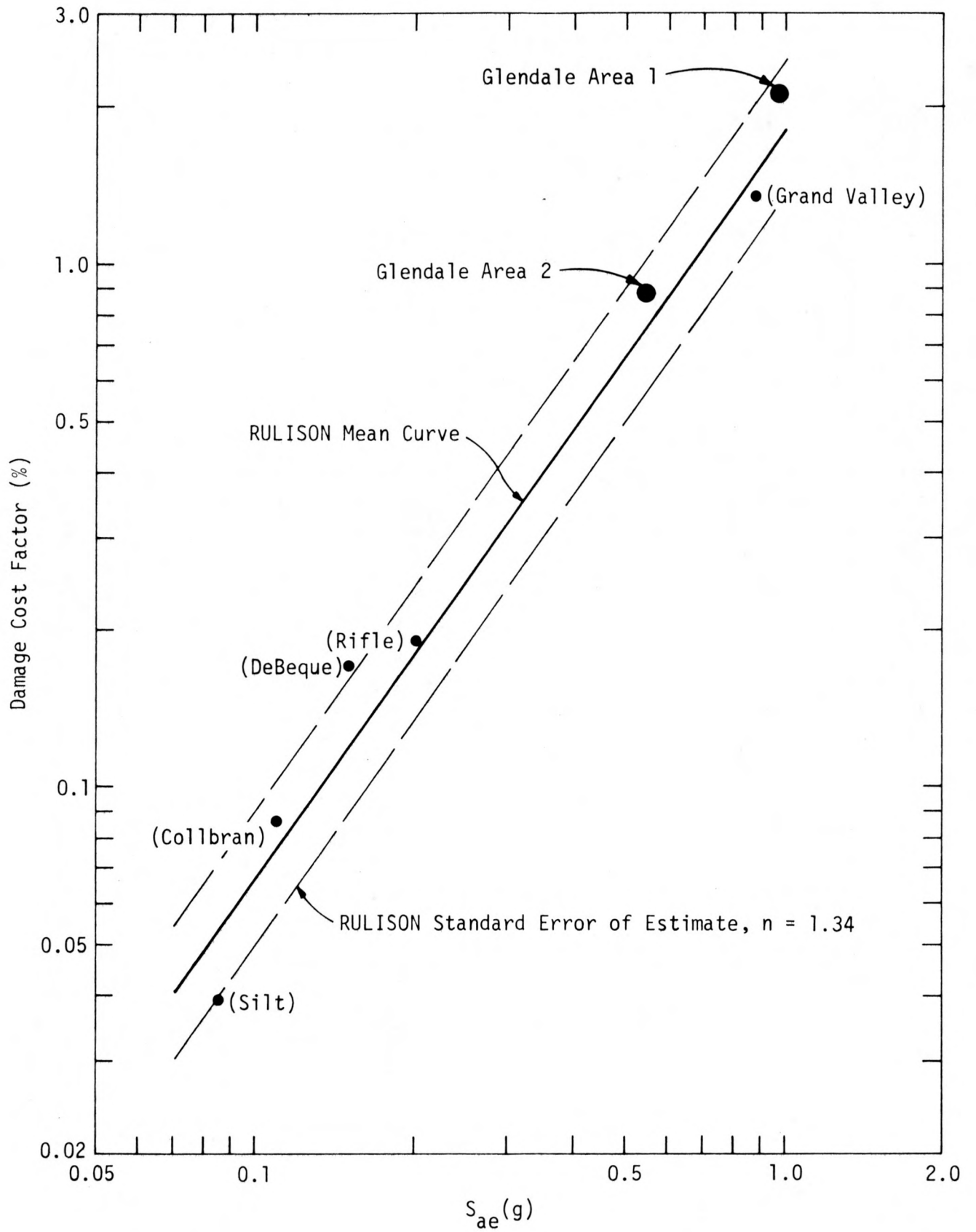


FIGURE 17 DAMAGE COST FACTOR VERSUS SPECTRAL ACCELERATION

The figure shows that the damage cost factor statistics derived from the earthquake compare reasonably well with those from the underground nuclear explosion, but for the same spectral acceleration, again, slightly more damage is indicated for the earthquake.

D. General Discussion

In addition to the quantitative comparison of damage presented so far, a few qualitative observations have been noted. As indicated, chimney damage ratios for the two types of ground motion compare very well. However, the degree of chimney damage caused by the earthquake was observed to be significantly more severe than that caused by the explosion.^{14,15} This, of course, would tend to cause the damage cost factor for the earthquake to be the greater of the two.

In a companion study of damage in Glendale, Nelson¹⁶ describes 23 commercial buildings in Glendale which were so severely damaged by the earthquake that they were condemned by the Glendale City Engineer. Most of these buildings were later demolished but a few were repaired. Other commercial buildings were of course damaged but less severely. The condemned buildings were generally old and of timber and masonry construction, which is vulnerable to severe damage during earthquakes. It is noteworthy that similar buildings in Grand Valley, Colorado, were not damaged so severely during the RULISON event. Because most of the condemned Glendale buildings were located in the commercial center area, the ground motion they were exposed to was most probably like that recorded at strong-motion station No. 41.

The difference in overall damage for the two sets of data is most probably attributable to differences in the ground motion characteristics of the two types of disturbances, and to the uncertainty of the analytically derived response spectra for the two Glendale study areas.

As stated previously, the standard error of estimate, n , for the analytically derived Glendale spectra is quite large and thus the spectral amplitudes for the two Glendale study areas could readily have been 50% higher than the derived median values, considering statistics only. However, the spectral amplitude for strong-motion station No. 41 ($S_{ae} = 0.57g$) and the analytically derived mean value for station No. 35 ($S_{ae} = 0.54g$), the observed similarity in damage, and the similarity of terrain and geology at these two sites indicate that a reasonable expected error for the spectral amplitudes of the two study areas is probably 10% to 20%. Thus, the uncertainty in the analytically derived median values provides a possible explanation for the discrepancies in damage for the two sets of data.

The most notable differences in the characteristics of ground motion for the two disturbances lie in response duration and peak ground displacement. The Response Envelope Spectrum (RES) used by Trifunac¹⁷ as a ground motion multiple filter can readily be used to study structure response duration.¹⁸ Figures 18 and 19 are examples of this three-dimensional ground motion characterization covering the period range of 0.05 to 0.2 seconds. Figure 18 represents the strongest horizontal component of ground motion recorded at Grand Valley, Colorado, and is exemplary of the underground nuclear explosion ground motion. Figure 19, representative of the strongest horizontal component of motion in Glendale Area 1, was analytically derived by scaling peaks of the response envelopes calculated from the station No. 41 record to those predicted for Area 1 for each of the discrete periods shown. Comparison of Figures 18 and 19 shows that the duration of response of the harmonics is longer for the Glendale seismogram than for the Grand Valley seismogram. This observation is readily quantified by comparing the number of consecutive cycles of harmonics with amplitudes exceeding certain levels in the two RES maps. To eliminate the effect of amplitude from this comparison, the Glendale RES was scaled down so that the envelope response spectrum peak amplitudes of both ground motions were identical. Table 4 summarizes the average number of consecutive half-cycles

TABLE 4
NUMBER OF HALF-CYCLES ABOVE
VARIOUS SPECTRAL INTENSITY LEVELS

Spectral Acceleration Level	Location	
	Grand Valley	Glendale
0.25 g	24	54
0.45 g	13	25
0.75 g	3	6
0.95 g	1	2

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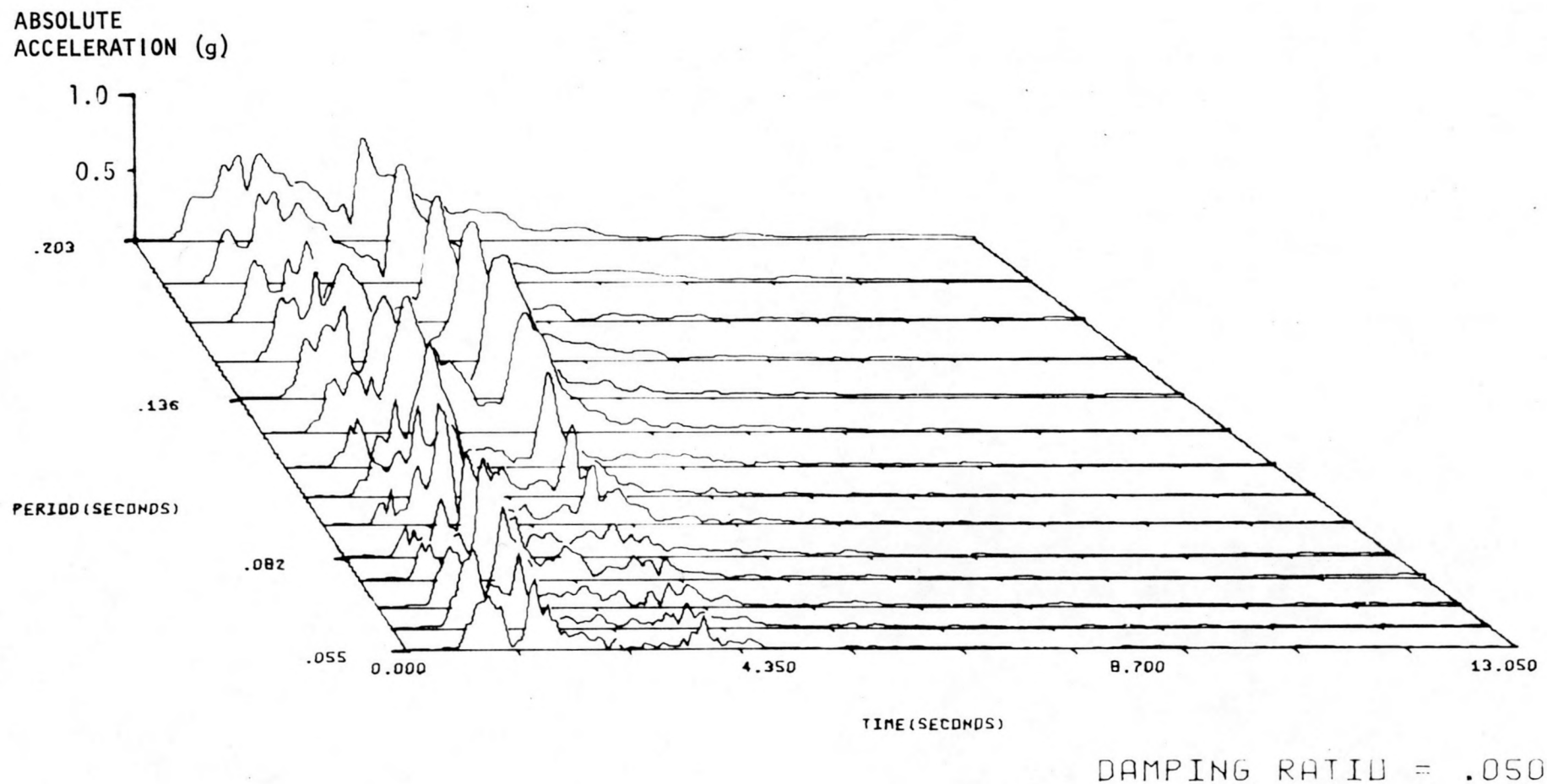


FIGURE 18 RESPONSE ENVELOPE SPECTRA (RES) PROFILES, RULISON GRAND VALLEY

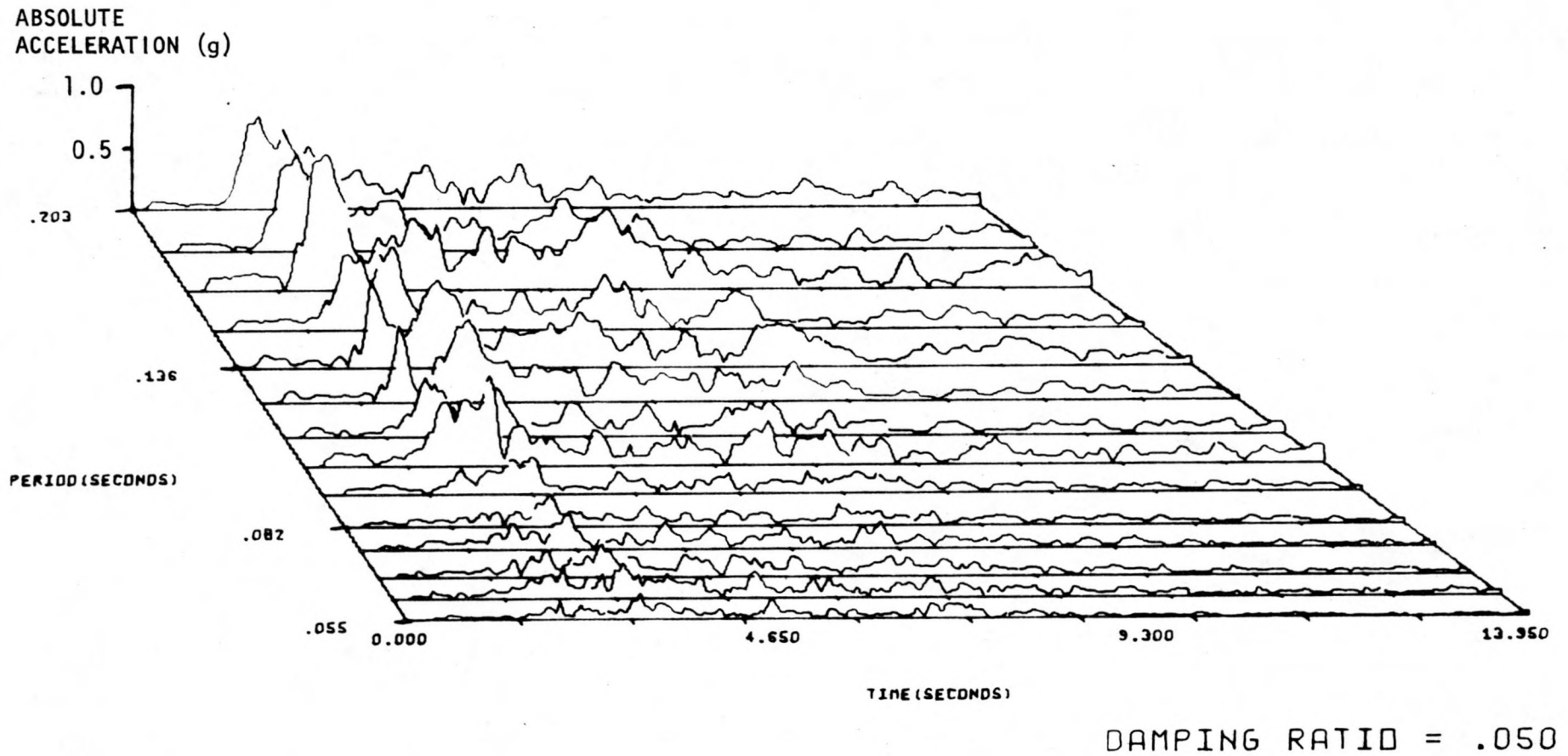


FIGURE 19 RESPONSE ENVELOPE SPECTRA (RES) PROFILES,
SAN FERNANDO EARTHQUAKE,
GLENDALE AREA 1, (E/W) PREDICTED

for four spectral acceleration levels: 0.25g, 0.45g, 0.75g, and 0.95g. The number of half-cycles shown is the average for the period band of 0.05 to 0.2 seconds. These values correspond roughly to damage sustained by 10%, 20%, 35%, and 45% of the buildings in the affected area (Figure 16). The table shows that the various harmonics of the Glendale RES map contain more consecutive half-cycles of response motion than those of Grand Valley, especially for relatively low amplitudes, such as 0.25g.

Comparison of the RULISON and Glendale ground motion records also reveals information concerning the interrelationships of acceleration, velocity, and displacement for the two types of motion. Table 5 shows peak ground motion values recorded at the Grand Valley station for the RULISON event and those recorded at strong-motion station No. 41 for the San Fernando earthquake. Comparison of peak ground motion values for the strongest horizontal component (radial for RULISON and S70°E for Glendale) indicates that while the accelerations are similar, the displacement for the earthquake is approximately 50 times that for the underground nuclear explosion. For a structural system responding within its strength limitations, it is theoretically clear that this difference in peak ground displacement (PGD) will have little effect. However, for a responding structural system that has suffered a strength failure, the magnitude of peak ground displacement that it is subjected to can have serious implications. For example, a masonry wall with a failure caused by high acceleration will probably only exhibit a crack if the accompanying PGD is small but may collapse if the PGD is large. The greater PGD is believed to be the primary cause of the more severe chimney damage and the catastrophic damage to the condemned commercial buildings in Glendale. The longer response duration for Glendale, however, undoubtedly also had some part in causing the more extensive damage there.

TABLE 5

COMPARISON OF RULISON AND GLENDALE PEAK GROUND MOTION VALUES

Type Motion	RULISON Grand Valley Station			Glendale Strong Motion Station 41		
	Radial	Tangential	Vertical	S70°E	S20°W	Vertical
Acceleration (g)	0.36	0.14	0.53	0.27	0.21	0.13
Velocity (cm/sec)	8.14	3.30	7.34	30.84	23.45	15.65
Displacement (cm)	0.22	0.097	0.16	11.10	5.29	5.62

V. SUMMARY AND CONCLUSIONS

Low-rise building motion - damage relationships derived from data collected for an earthquake were compared with those derived from an underground nuclear explosion. The ground motion was characterized by response spectrum acceleration intensity and damage was identified both in terms of frequency (damage ratio) and cost (damage cost factor).

Calculated damage cost factors (dollar damage/dollar value of buildings) involved in this study were in the range of 0.05% to 2.0%.

Comparison results indicate that for the same spectral amplitude, the earthquake caused slightly more damage than the underground nuclear explosion. This observation was investigated by comparing the duration of the two types of motion using Response Envelope Spectrum. This showed that the response motion was longer for the earthquake and a partial explanation for its higher damage ratio was provided. In addition, it was noted that peak ground displacement (PGD) was significantly greater for the earthquake than for the underground nuclear explosion. Considering overturning effects on laterally unstabilized objects, i.e., bric-a-brac or structures having failed lateral force-resisting elements, the large PGD must be the principal cause for some of the earthquake damage. Thus, the higher damage ratio for the earthquake was most probably caused by its longer duration and larger PGD.

Because of the generally good agreement between the earthquake and underground nuclear explosion damage statistics, the motion - damage relationships given herein are believed valid for other situations involving similar buildings and for which gross discontinuities in the ground surface are not caused by the seismic motion.

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