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Statistical Correlation of Observed Ground Motion with Low-Rise Building Damage: Project RULISON

September 1971

JOHN A. BLUME & ASSOCIATES RESEARCH DIVISION

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STATISTICAL CORRELATION OF OBSERVED GROUND MOTION WITH LOW-RISE BUILDING DAMAGE PROJECT RULISON

by

I. Farhoomand

and

R. E. Scholl

John A. Blume & Associates

Research Division

San Francisco, California

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STATISTICAL CORRELATION OF OBSERVED GROUND MOTION WITH LOW-RISE BUILDING DAMAGE PROJECT RULISON

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ABSTRACT

A statistical study is conducted using the observed ground motion and structure damage data obtained from Project *RULISON*. The statistical analysis leads to identifying the ground motion characterization which best represents the damage potential of ground motion for low-rise buildings. A statistical model for predicting damage is presented. This model relates ground motion intensity to three damage prediction parameters: number of complaints, percentage of buildings damaged, and damage repair cost. A simple procedure for the application of the model to practical cases is discussed. The vector of the two horizontal components of response spectrum acceleration was determined to best represent the damage potential of ground motion for low-rise buildings.

I. INTRODUCTION

Project RULISON was a joint experiment sponsored by Austral Oil Company Incorporated, Houston, Texas, the U.S. Atomic Energy Commission, and the Department of the Interior, with the Program Management provided by CER Geonuclear Corporation of Las Vegas, Nevada, under contract to Austral. Its purpose was to study the economic and technical feasibility of using underground nuclear explosions to stimulate production of natural gas from the low-productivity, gas-bearing Mesaverde Formation in the RULISON field. The nuclear explosive for Project RULISON was detonated successfully at approximately 3:00 PM Mountain Daylight Time, September 10, 1969, at a depth of approximately 8425 ft below ground level and was completely contained. Preliminary results indicate that the RULISON device behaved about as expected, i.e., with a yield of approximately 40 kilotons.

John A. Blume & Associates Research Division (JABARD) conducts structural response and damage investigations for the Atomic Energy Commission's Nevada Operations Office (Office of Effects Evaluation) to determine the effects of dynamic ground motion on a wide variety of structures. The effort described herein is directed toward studying the relationships between dynamic ground motion and low-rise building damage which were observed for the RULISON event. This and additional data will ultimately be utilized to improve methods for predicting damage to low-rise buildings caused by dynamic ground motion.

A. Background

Prediction of damage to low-rise buildings subjected to ground motion is a step toward improving design and construction practice to provide better resistance against ground motion disturbances. It is also a necessary step in evaluating the potential damage and hazard to human life for projects requiring the use of an underground nuclear device.

The following three procedures have been developed for establishing the relationship between structure damage and dynamic ground motions:

- Theoretical
- Empirical
- Mixed Theoretical-Empirical

Many investigators have studied the response-damage relationship for various classes of structures, and several methods have been suggested for estimating one or more of the three necessary damage prediction parameters -- number of complaints filed, percentage of buildings damaged, and damage repair cost. Steinbrugge, McClure, and Snow[1] suggested a method for predicting the probable damage repair cost of residential buildings. Blume[2] laid out a more general scheme to evaluate probabilistically the cost of damage repair of any type of building.

Along with the development of these methods, many investigators demonstrated relations between the intensity of ground motion and observed building damage. Duvall and Fogelson,[3] after a series of tests with high explosives, stated that a peak particle velocity of 5 cm/sec can be considered the threshold of damage. For residential buildings located on firm soil, Cauthen[4] established 10 cm/sec peak particle velocity as the threshold for plaster cracking. However, recent underground nuclear detonations revealed that peak particle velocity is not a reliable parameter for a ground motion damageability criterion. Nadolski[5] demonstrated that Pseudo-Absolute Acceleration (PSAA) obtained from response spectrum curves might be a convenient parameter which relates ground motion to damage for low-rise buildings. Rizer[6] used this concept to present a curve relating PSAA to percentage of buildings damaged and to number of complaints but failed to relate it to damage repair cost. To predict damage repair cost, he suggests multiplying the number of credible damage claims by $400, which is an estimate of the average cost for RULISON claims.

B. Purpose and Scope

Until recently, reliable ground motion - damage data was not available for developing a simple and adequate statistical model for damage prediction. The RULISON event provided, probably, the first opportunity to obtain the appropriate data. This report is the first of two reports which utilize the RULISON ground motion - damage data to study the influence of various structure, soil, and ground motion characteristics on damage prediction parameters. Other descriptions of the characteristics of the event, the damage done to low-rise buildings, and the process of data acquisition and related preliminary investigations can be found elsewhere.[7,8] Here, the collected data is appropriately processed, a statistical study is conducted, and a statistical model for predicting the necessary damage parameters is presented. The scope of this first study is limited to the analysis of damage to overall structural systems. Damage done to components of buildings will be the subject of a later report.

In Chapter II, preparation of data is discussed briefly. Based on the statistical analysis performed in Chapter III, a procedure for predicting the required damage factors is presented in Chapter IV. The application of the procedure is demonstrated by an example in Chapter V. Finally, Chapter VI presents some remarks about the limitations of the procedure and about the possible continuation of the study.

II. DATA

To conduct a statistical analysis correlating damage with ground motion, three types of information are required:

- Ground motion data
- Structure inventory data
- Damage survey data

The specific data used in this study are discussed in this chapter.

There are approximately 2500 residential and commercial buildings (excluding outbuildings) for which structure inventory and damage survey data are available from Project RULISON. Because there were only a limited number of seismometers available to record ground motion for the shot, it was impossible to attempt to approximate the motion at all the rural locations. However, there are five major towns in the area located at varying distances from ground zero for which structure inventory, damage survey, and ground motion data are available. These towns are: Collbran, DeBeque, Grand Valley, Rifle, and Silt. The combined structure population of these five towns (1469 buildings) constitutes slightly more than half the total for the area inventoried. The locations of these towns with respect to GZ are shown in Figure 1. Considering these facts the rural areas were excluded from this study.

A. Ground Motion Data

Several velocity records were obtained at various locations encompassing a fairly large geographical area around ground zero.(9) However, for the reasons stated, only the records obtained in the above five towns are considered in this study. Figures 2 and 3 are two samples of the velocity records. The response spectrum curves and digitized ground motion records used in this study were obtained from Environmental Research

Corporation (ERC). A general summary of observed ground motion for the RULISON event is shown in the ERC report.(10)

The ground motion record for the town of Silt showed that only the radial component was recorded. In examining the response spectra and peak motion values for the five towns, it can be seen that the radial component is nearly always of greater intensity than the transverse component; thus it was considered to be of value for this study. The ground motion measurement for the town of Collbran was incomplete in that only the first 3 seconds of motion were recorded. However, after examining and comparing all the records from the five towns, it was concluded that for the period range considered in this report the response spectra from these 3-second recordings were reasonably reliable. Reliable peak intensity analysis of the Collbran recording is not available. As indicated in the ERC report,(10) there were multiple ground motion recording stations for the towns of DeBeque and Rifle. In view of such factors as soil conditions and locations of seismometers with respect to building population distribution, the recordings selected for use in this study were DeBeque #1 for DeBeque and the average of Rifle Church and Rifle Hill for Rifle.

B. Structure Data

The structure inventories of the five towns described above were performed in view of this planned statistical research study. Therefore, it is most probable that more detailed information was obtained than is necessary for damage prediction purposes.

An example of the structure inventory form used for the five towns is shown in Figure 4. All buildings (residential, commercial, and institutional) within JABARD defined geographical limits of the five towns were inventoried. For residential locations, detached buildings such as garages and sheds were not counted as separate buildings.

C. Damage Data

For this study, the following definitions are used:

Complaint: any complaint made concerning property damage whether or not formalized as a claim (limited to types of damage described below).

Credible Damage: any of the above described complaints which were defined as credible by JABARD or GAB (General Adjustment Bureau) investigators.

In all, there were 455 damage complaints filed for the RULISON event. Approximately half of this total (220) are included in this study. These 220 complaints involved damage to 200 buildings, and 200 is the number used in this analysis. Most of the remaining complaints were received from rural areas, but those unrelated to structures were excluded from this study on the basis of damage type. The types of complaints and credible damage included in this study are:

- Chimney -- including fireplace
- Interior wall
- Exterior wall
- Foundation
- Window
- Household items

Of approximately 325 filed claims for the RULISON event which were acknowledged as credible damage, 164 buildings included in this study were involved.

D. Preprocessing of Data

The structure inventory data and damage data were transformed into computer form to be used in the statistical study. For each structure, both types of data were punched on a computer card. Figure 5 shows the format used for the arrangement of the information on a computer card.

III. STATISTICAL ANALYSIS

This chapter first describes idealizations of the parameters which influence damage. Second, the parameters essential to the evaluation of complaint investigation and damage repair costs (damage prediction parameters) are described. A comprehensive statistical study is then performed using the RULISON data. Finally, on the basis of this statistical investigation the observed correlation of various ground motion characterizations with low-rise building damage is summarized.

A. Idealizations and Definitions

1. Structure Idealization

In studying the damage to buildings caused by ground motion it is essential to consider the phenomenon of dynamic-structure response. In considering this phenomenon it is clear that the relationship between the structure and ground motion frequencies is very significant in relating the motion amplitudes of the two. Observed data presently available show that the fundamental periods for most one- and two-story buildings fall in the range of 0.05 to 0.2 seconds. The particular period of a building is influenced by such parameters as:

- Frame Type
- Dimensions
- Age
- Condition
- Soil Conditions
- Fenestration

Of the 1469 residential, commercial, and institutional buildings considered in this study, 95 percent (1394) fall in the period band of 0.05 to 0.2 seconds.

The structures considered in this study are idealized using two levels of approximation. One approximation considers all the structures as a single class having a period range of 0.05 to 0.2 seconds. The second approximation categorizes the structures as two classes. In the two-class approximation, all buildings with fundamental periods between 0.05 and 0.1 seconds (inclusive) fall in Class 1, and buildings with fundamental periods in the range of 0.1 to 0.2 seconds fall in Class 2 (see Table 1).

2. Adjusted Building Values

The most convenient and reliable expression of the relationship between damage cost and ground motion is dollar exposure, that is, the value of structures which might be affected because of their proximity to damaging ground motion.

Several possible methods for obtaining dollar exposure can be identified. For this study, values of individual structures were determined both from tax assessment records and by on-site estimate. Other potential methods are described in References 1 and 11.

After reviewing and comparing the dollar values obtained by the two methods described above, it was concluded that both were reliable in some respects but neither was completely reliable. Although in the five towns most buildings were assessed, the tax assessment was not complete. A major factor which makes the assessed values unreliable is that they do not in all cases reflect the effect of inflation on the market values of the structures. This is inconsistent with the damage repair cost which includes inflation and local fluctuation of prices. The estimated values, which were obtained for all buildings, include local and national fluctuation of prices. However, because of human error one expects to see a scatter about the true value, especially if estimates are made at prescribed price intervals. To obtain the most probable values one must adjust the estimated values so that they yield better correlation with the assessed values.

For the RULISON project the values were estimated at price intervals of $5,000. Since it is more probable that newer buildings have more accurate assessed values, an adequately large sample of homes up to ten years old was selected for adjusting the estimated values. For each $5,000 increment of estimated building value, the mean value of the probability density function of the associated assessed value is selected as the most probable building value. Figure 6 shows the probability density curve of assessed values for all new buildings with estimated values of $15,000. The estimated values and the corresponding adjusted values for all buildings in this study are given in Table 2.

3. Ground Motion Characterizations

As described in the introduction, several different characterizations of ground motion have been used to predict structure damage; there are many others which might be utilized. The statistical study conducted here will be limited to peak intensity and response spectrum characterizations.

Response spectrum curves are very well known and widely used in the ground motion analysis of structural systems. In this investigation, vector response spectrum as well as response spectrum curves are used. The vector response spectrum is defined as the response spectrum of the vector ground motion. Since the vector ground motion may be defined for every two components as well as all components of a seismogram, four independent vector response spectrum curves may be defined.

The 5% damped response spectrum curves and the vector response spectrum curves of the two horizontal components are shown in Figures 7 through 9. Table 3 summarizes the peak values of the ground motion records for each town, and the average 5% damped spectrum values of each class of buildings for the five towns are recorded in Table 4.

4. Damage Prediction Parameters

The following three parameters adequately describe various aspects of damage to low-rise buildings.

Damage Ratio (DR) is defined by:

$$DR = \frac{\text{Number of Damaged Buildings}}{\text{Total Number of Buildings}} \times 100$$

Complaint Ratio (CR) is defined by:

$$CR = \frac{\text{Number of Complaints}}{\text{Total Number of Buildings}} \times 100$$

Damage Cost Factor (DCF) is defined by:

$$DCF = \frac{\text{Damage Repair Cost of Buildings}}{\text{Value of Buildings}} \times 100$$

It is interesting to note that the effect of inflation and local fluctuation of construction cost on DCF should be negligible. Table 5 contains information regarding the number of damaged buildings, number of complaints, and damage repair cost of buildings, as well as the magnitudes of CR, DR, and DCF for each class of buildings of each town. In the same table the corresponding values of the average damage cost are included. This parameter is defined as:

$$\frac{\text{Damage Repair Cost of Buildings}}{\text{Number of Damaged Buildings}}$$

B. Correlation Studies

In the previous section three damage prediction parameters were defined. In this section various ground motion characterizations are correlated with the damage prediction parameters to identify the one which yields the best correlation.

The first step is to find whether ground motion velocity peak value or acceleration peak value yields a better correlation with damage. Figures 10 and 11 demonstrate two samples of the scatter of peak values versus DR. A quantitative measure of scatter of the data from the line of the best fit is the standard deviation of sample points with respect to that line. In order to be consistent, all the standard devations are evaluated for DR. The data points shown in Figures 10 through 16 are identified by the first letters of each of the five towns and then by subscripts to distinguish the two building classes.

A summary of the results is given in Table 6. It is observed that no definite conclusion can be made as to whether peak velocity or peak acceleration is a better indicator of damage potential of ground motion.

The next step is to find whether response spectrum or peak value yields a better correlation with damage. Figures 12 and 13 show the lines of best fit for the average response spectrum values plotted against DR. On the same figures the straight lines for the peak values versus DR are presented. The standard of deviations of the data for the spectrum values are recorded in Table 6. The table shows that correlation of spectrum values with damage data results in smaller standard of deviations for the radial and transverse acceleration components of ground motion. Therefore, the spectrum values appear to be a slightly better indicator of damage potential of ground motion than peak values. This conclusion agrees with the fact that peak values do not reflect all the characteristics of ground motion, i.e., amplitude, frequency, and duration; spectrum values reflect amplitude, frequency, and some information pertaining to duration. The fact that the standard deviations for the response spectrum characterizations (Table 7) are only slightly less than those for peak ground motion (Table 6) is not too surprising for this particular event. Inspection of the response spectra for the five towns (Figures 6 through 9) shows that the peak amplitudes for both S_a and S_v occur at periods of about 0.2 seconds or less. Thus the high amplitude ground motion periods for these recording stations are approximately coincident with the low-rise building periods.

Figures 14 and 15 show that the scatter of sample points which employs pseudo absolute acceleration (PSAA) is less than the one which uses pseudo relative velocity response spectrum (PSRV). Investigation of Table 6 asserts this conclusion also. Therefore, it may be said that the PSAA is more representative of the damage potential of ground motions.

Now the question is which component of PSAA yields the best damage criterion for ground motion disturbances. The answer may be determined by correlating various components of PSAA with DR. A qualitative comparison of Figures 12 through 15 or a quantitative investigation of the standard deviation of the scattered data (Table 6) reveals that the vector response spectrum values (V_a) which are computed from the two horizontal components of the seismograms are the best indicators of the damage potential of ground motions.

C. Statistical Observations

Observations based on the above correlation studies for RULISON data are:

- The response spectrum values give a slightly better correlation with damage than peak values of ground motion.

- The PSAA data yield better correlation with damage than PSRV data.

- V_a yields better correlation with damage than any other ground motion characterization.

One expects the same observations if the other damage prediction parameters are used. It is interesting to note that the uncertainty of sample data for CR is higher than for DR and DCF. Figure 16 demonstrates scatter of data for CR and DR. It is observed that the sample points of CR are more spread than those of DR. Table 7 compares the values of the standard deviations of various data samples. It should be also pointed out that for every level of ground motion, in Figure 16, the complaint ratio is higher than the damage ratio. This is due to the fact that many complaints made by people are not credible. Clearly, there are human elements which affect the number of complaints.

Inspection of Tables 4 and 5 reveals that average damage cost does not correlate well with ground motion. It is also observed that the coefficient of variation of the data ($C_V = 0.51$) is not small enough to consider this parameter constant. Therefore, the average damage cost is not an appropriate damage parameter to be used in predicting the damage to low-rise buildings.

IV. DEVELOPMENT OF STATISTICAL MODEL

This chapter is devoted to the development of a systematic procedure for predicting damage to low-rise buildings based on the observed RULISON data. In the analyses described in the previous chapter, two distinct building classes are differentiated by period: 0.05 to 0.1 seconds and 0.1 to 0.2 seconds. Examination of Figure 15 shows that there is not a very significant difference between the acceleration regression lines for Class 1 and Class 2. Considering the errors included in other parameters in this study, the error introduced by using the average regression line is probably insignificant. Therefore, for the statistical model developed in this chapter, all buildings are assumed to be in a single class having a period band of 0.05 to 0.2 seconds.

In the previous chapter it was demonstrated that V_a yields better correlation with damage than any other ground motion characterization. However, a method of predicting V_a has not yet been developed. Therefore, two models are presented here. The first model relates each damage prediction parameter to V_a and the second one relates each damage prediction parameter to the horizontal component of PSAA (S_a) which shows higher intensity.

A general relationship between ground motion and damage might be expressed by:

$$A = \overline{A} \cdot e \qquad (1.a)$$

$$\overline{A} = aB^{\beta} \qquad (1.b)$$

where A is a damage parameter, B is a ground motion parameter, and a and β are two constants which are computed from the observed data. In Equation 1.a, e is the uncertainty about the mean value ($\overline{A}$). In general, e is a function of the uncertainty of ground motion, damage evaluation, and structure idealization parameters.

Equations 1.a and 1.b are quite general in the sense that they are applicable to each class of buildings as well as to all buildings regardless of their class. A may be either DR, CR, or DCF; B may be assumed to be the desired ground motion characterization.

Equations 1.a and 1.b have the following form in the logarithmic domain (base 10):

$$Y = \overline{Y} + E \tag{2.a}$$

$$\overline{Y} = \alpha + \beta X \tag{2.b}$$

where:

$$\begin{aligned} Y &= \log A \\ X &= \log B \\ E &= \log e \\ \alpha &= \log a \end{aligned} \tag{3}$$

Equation 2.b is a linear equation. To evaluate α and β a linear regression analysis is performed on the data in the logarithmic domain. Then α and β are the intercept and the slope of the straight line of best fit. E is assumed to be normally distributed with zero mean. The expression(11) for estimating Y_j at a particular point, say X_j, is:

$$Y_j = \overline{Y}_j \pm S_{y/x}\, t_{(\rho/2;n-2)} \sqrt{\frac{1}{m} + \frac{1}{n} + \frac{\left(X_j - \overline{X}\right)^2}{D}} \tag{4}$$

$$D = \sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2$$

in which:

$\overline{X}$ = the mean value of X.

n = the number of sample points.

$S_{y/x}$ = the estimated standard deviation of sample points, in Y direction, with respect to the line of best fit.

$t_{(\rho/2;n-2)}$ = the value of t distribution with n-2 degrees of freedom and confidence interval of $1-\rho$.

m = the number of buildings in the sample space.

In Equation 4 all variables, except X_j, on the right side of the equation are constant for the model. Therefore, given X_j the corresponding value for Y_j is evaluated. The damage parameter is evaluated from the following equation:

$$A = 10^{Y_j} \tag{5}$$

A. V_a - Damage Prediction Model

Figures 17 through 19 show the graphical models for predicting the three damage parameters. Regression analysis yields the following empirical equations for the single class approximation.

$$\overline{CR} = (57.6 \pm 20.8)\ V_a^{(1.01\pm0.16)} \tag{6.a}$$

$$\overline{DR} = (47.5 \pm 7.1)\ V_a^{(1.08\pm0.07)} \tag{6.b}$$

$$0.063g < V_a < 0.93g$$

$$\overline{DCF} = (1.45 \pm 0.26)\ V_a^{(1.28\pm0.10)} \tag{6.c}$$

Equation 4 has the following forms:

$$Y_{CR} = \log \overline{CR} \pm \log E_{CR} \tag{7.a}$$

$$Y_{DR} = \log \overline{DR} \pm \log E_{DR} \tag{7.b}$$

$$Y_{DCF} = \log \overline{DCF} \pm \log E_{DCF} \tag{7.c}$$

where:

$$\log E_{CR} = 0.185\, t_{(\rho/2;8)} \sqrt{0.1 + (\log V_a + 0.73)^2/1.43}$$

$$\log E_{DR} = 0.083\, t_{(\rho/2;8)} \sqrt{0.1 + (\log V_a + 0.73)^2/1.43}$$

$$\log E_{DCF} = 0.082\, t_{(\rho/2;6)} \sqrt{0.125 + (\log V_a + 0.63)^2/1.00}$$

Finally, Equation 5 yields:

$$CR = 10^{Y_{CR}} \tag{8.a}$$

$$DR = 10^{Y_{DR}} \tag{8.b}$$

$$DCF = 10^{Y_{DCF}} \tag{8.c}$$

It is interesting to note that the error terms for DR and DCF have narrower band width than that of CR.

B. S_a - Damage Prediction Model

Regression analysis similar to that of the first model is performed to define a model which relates the more intensive horizontal component of PSAA to damage. Figures 20 through 22 present the graphical model for predicting damage using S_a. Regression analysis yields the following empirical equations for the average damage for the single class approximation.

$$\overline{CR} = (63.0 \pm 26.2)\, S_a^{(0.986 \pm 0.17)} \tag{9.a}$$

$$\overline{DR} = (52.4 \pm 12.1)\, S_a^{(1.05 \pm 0.10)} \tag{9.b}$$

$$0.063g < S_a < 0.93g$$

$$\overline{DCF} = (1.52 \pm 0.53)\, S_a^{(1.17 \pm 0.16)} \tag{9.c}$$

Equation 4 has the following forms:

$$Y_{CR} = \log \overline{CR} \pm \log E_{CR} \tag{10.a}$$

$$Y_{DR} = \log \overline{DR} \pm \log E_{DR} \tag{10.b}$$

$$Y_{DCF} = \log \overline{DCF} \pm \log E_{DCF} \tag{10.c}$$

where:

$$\log E_{CR} = 0.206\ t_{(\rho/2;8)} \sqrt{0.1 + (\log S_a + 0.79)^2/1.45}$$

$$\log E_{DR} = 0.123\ t_{(\rho/2;8)} \sqrt{0.1 + (\log S_a + 0.79)^2/1.45}$$

$$\log E_{DCF} = 0.148\ t_{(\rho/2;6)} \sqrt{0.125 + (\log S_a + 0.7)^2/1.14}$$

The predicted values are obtained from Equation 5.

Equations 6.a through 6.c and 7.a through 7.c and Equations 9.a through 9.c and 10.a through 10.c are the two statistical models. They can be used to estimate the damage potential of the predicted ground motion. Figures 17 through 19 and Figures 20 through 22 can also be used for this purpose.

It should be mentioned that the statistical models presented here were determined from a limited number of sample points. In the future these models will be continually improved as more and more data are collected. Also, because of limitation of data the expressions and diagrams may be more reliably used for $0.063g < V_a < 0.93g$ or $0.063g < S_a < 0.93g$.

The next chapter contains a procedure for predicting the damage potential of ground motions using the models developed in this chapter.

V. APPLICATIONS

Prediction of the expected damage to low-rise buildings in an area subjected to ground motion is an important step toward modifying the present design and construction practice for this category of structures. Modifications and recommendations will, in turn, result in controlling the damage potential of ground motions for low-rise buildings. Damage prediction serves an immediate need also. The application of nuclear explosives in peaceful missions is increasing. Before projects are carried out, the probability of property damage must be thoroughly investigated; and the potential hazard to human life must be determined.

In the previous chapter two statistical models for predicting damage to low-rise structures were presented. In this chapter a procedure for a quick damage prediction is described. The potential application of the procedure is demonstrated by some examples. The procedures described below are similar to those given by Blume[2] but differ markedly in the definition of the damage prediction parameters.

A. Procedure for Damage Prediction

A damage prediction should indicate:

- Percentage of buildings damaged (DB)
- Damage cost (DC)
- Number of complaints (C)

The models discussed in Chapter IV provide this information.

Suppose that a damage prediction is required for area "A". Area A may be comprised of N subareas A_i ($i = 1,2,\ldots,N$). Each subarea (A_i) may have n_i low-rise buildings with different periods in the range of 0.05 to 0.2 seconds (see Figure 23).

Furthermore, assume that the mean values of the response spectrum curves of the ground motion for each subarea i are known ($\overline{R}_i$, i = 1,2,...,N). Then from the appropriate model presented in the previous chapter the corresponding DCF_i, DR_i, and CR_i may be obtained for each subarea i.

In order to evaluate percent of damaged buildings, damage cost and number of complaints in area A, the market value (p_i) and number of buildings (n_i) in each subarea i must be known. In this case the three damage parameters can be computed for area A from:

$$DR = \sum_i DR_i/NB \qquad (11.a)$$

$$DC = \sum_i DCF_i \; p_i \qquad i = 1,2,...,N \qquad (11.b)$$

$$C = \sum_i CR_i \; n_i \qquad (11.c)$$

where:

$$NB = \sum_i n_i \qquad (11.d)$$

The following steps summarize the procedure for predicting damage to low-rise buildings for a defined area A.

- Divide A into appropriate subareas (A_i) for which ground motion is known.
- The period band of all low-rise buildings in area A_i is assumed to be in the range of 0.05 to 0.2 seconds.

- Count the buildings in each subarea i. This yields the magnitude of n_i.

- Determine the total market value p_i of buildings in each subarea.

- Obtain the average value of the 5% damped response spectrum curve in each subarea. The average value of the spectrum curve between periods "a" and "b" is:

$$\overline{R_i} = \frac{\int_a^b R\,dp}{b - a} \tag{13}$$

in which R is the spectrum value, $\overline{R}$ is the average of R, and dp is the differential of the period. For the single class approximation which is considered in this investigation:

$$a = 0.05, \quad b = 0.2$$

- Use Figures 17, 18, and 19, or 20, 21, and 22 -- whichever are appropriate -- to compute the mean values of DCF_i, CR_i, and DR_i. Equations 7.a through 7.c or 10.a through 10.c yield the upper and lower bounds of the above parameters.

- Obtain the final result by application of Equations 11.a through 11.d.

It should be noted that the soil conditions of the site have an important influence on the magnitude of R. A column of soft soil amplifies ground motion many times. Therefore, the value of R must be adjusted for the difference in soil condition of the area and the ground motion station.

B. Example

To further clarify the procedure outlined in the previous section the following example is presented:

Consider an area which consists of three towns A, B, and C. Estimate the expected average, the upper and lower bound of the percentage of buildings damaged, the number of complaints, and the damage repair cost if the area is subjected to a ground motion. Assume that Figure 24 presents the 5% damped response spectrum curves for the three towns. The curves have been adjusted for the geological difference between each town and the ground motion station. Assume building periods may fall between 0.05 and 0.2 seconds.

Solution

Step 1. Since reliable ground motion data are available for the three towns, the area is divided into three subareas. Each subarea contains one town.

Step 2. The period band of the building class is 0.05 to 0.2 seconds.

Steps 3. and 4. Table 8 yields the appropriate information. In this case the inventory is conducted neglecting the classification of the buildings.

Step 5. From Figure 24 the average values of S_a for the period band of 0.05 to 0.2 seconds are evaluated. Table 8 contains the summary of computations.

Step 6. Information obtained from Equations 9.a through 9.c and 10.a through 10.c are arranged in Table 9.

Step 7. The upper and lower bounds of the estimate are calculated by the application of Equations 11.a through 11.d. The result is shown in Table 10.

VI. CONCLUSIONS AND RECOMMENDATIONS

A statistical study was conducted on the data obtained from the RULISON event. It was demonstrated that, for the RULISON data, vector response spectrum values (V_a) obtained from the two horizontal components of a ground motion yield the best correlation with the damage prediction parameters. Two statistical models were developed. The first model relates V_a to the three parameters essential to the evaluation of complaint investigation and repair costs for low-rise building damage resulting from underground nuclear detonations. These three parameters are: number of complaints, percentage of buildings damaged, and damage repair cost. The second model relates the more intensive horizontal component of the response spectrum acceleration S_a to the damage prediction parameters. On the basis of these models a procedure for predicting the damage potential of ground motions was presented.

The statistical models presented in this report will be improved as more empirical data are collected. In the future, the availability of more data will provide an adequate basis for establishing damage thresholds for various classes of buildings, as well as for determining the probability of damage to buildings subjected to a prescribed ground motion intensity. This information can then be included in the more general SMM procedure(2). An immediate potential extension of this study is the statistical analysis of the RULISON data concentrating on the individual components of buildings.

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APPENDIX A

FIGURES

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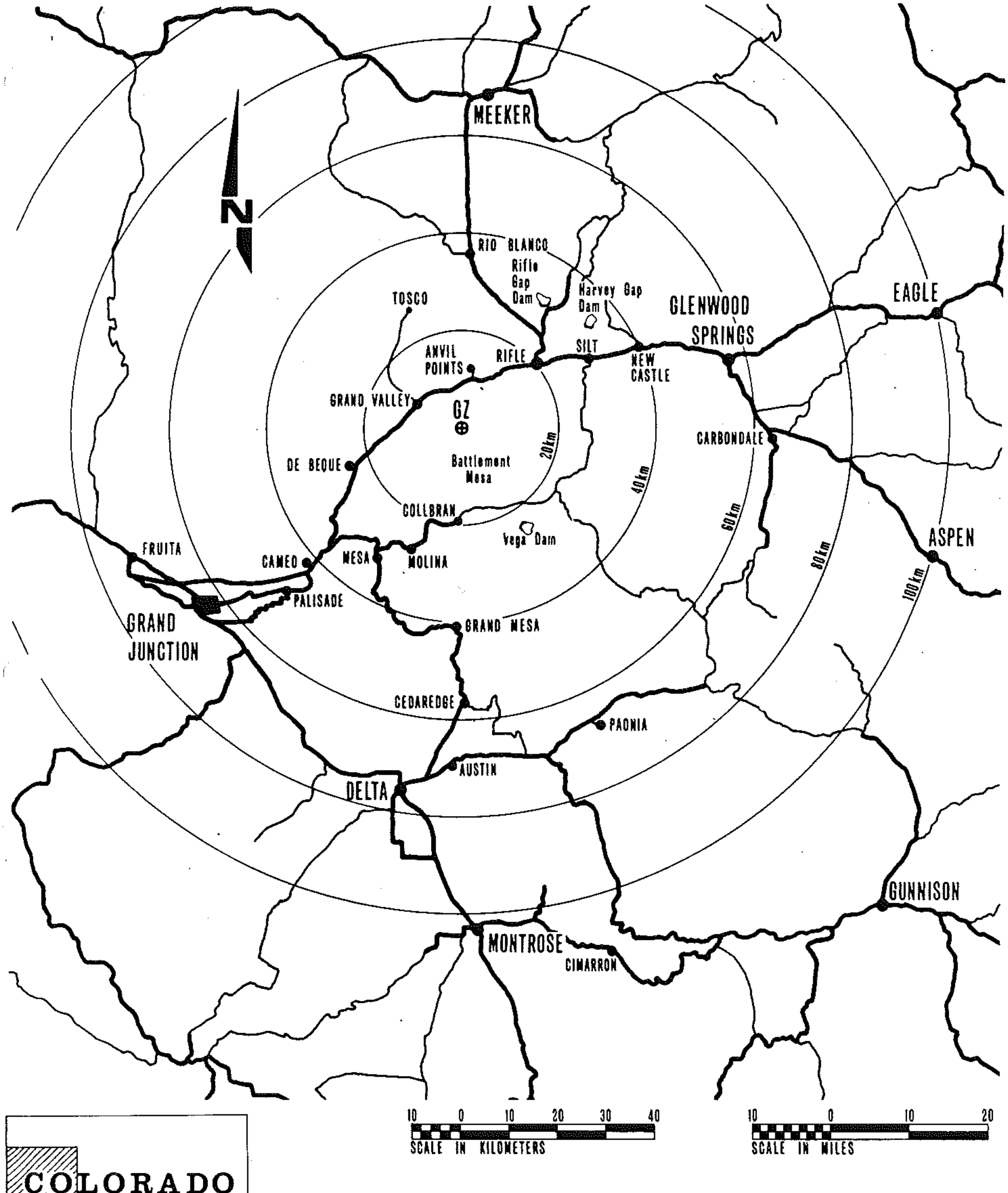

PROJECT RULISON
General Area Map

Figure 1

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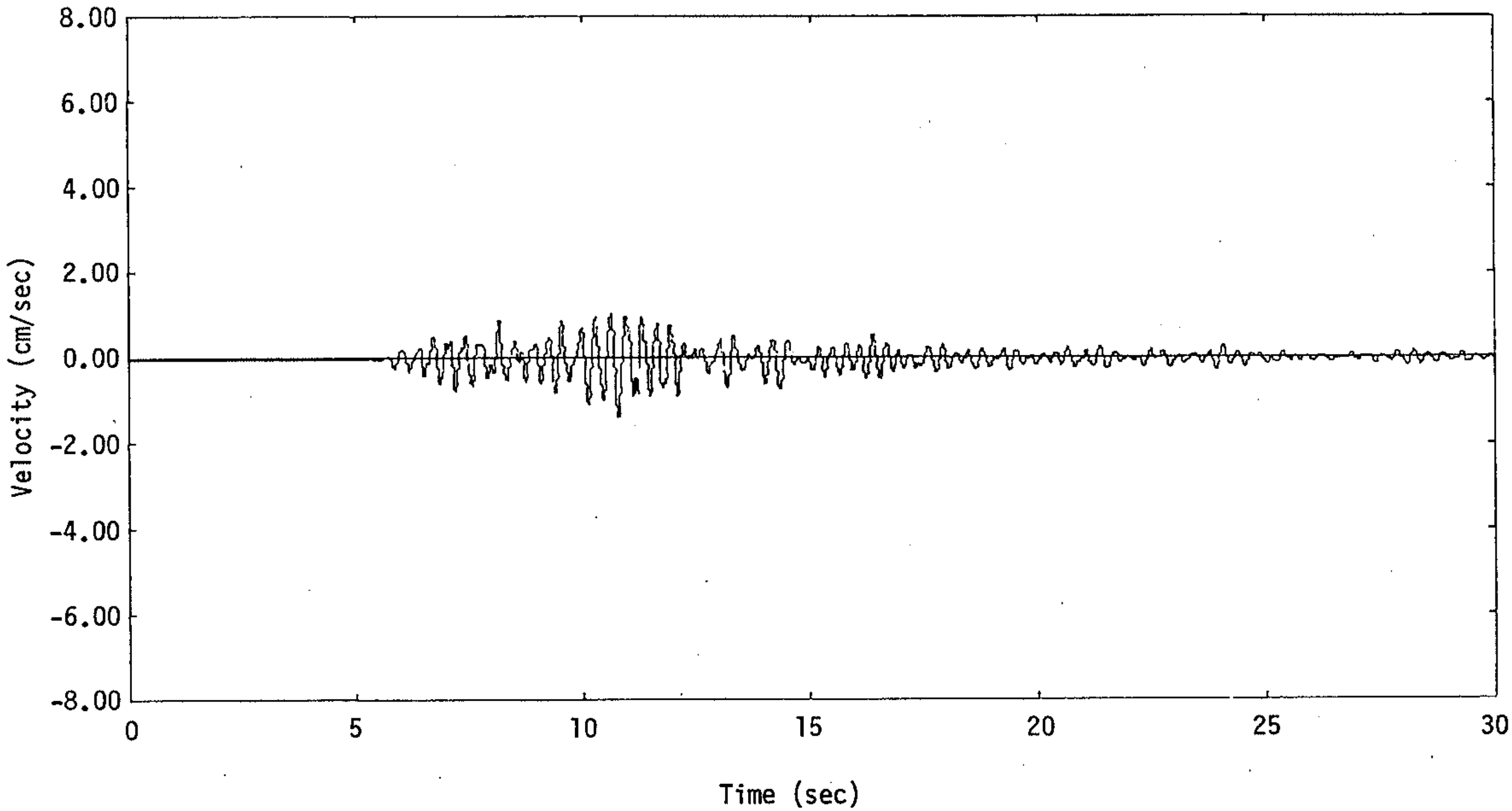

FIGURE 2 VELOCITY RECORD OF RADIAL COMPONENT OF GROUND MOTION: SILT

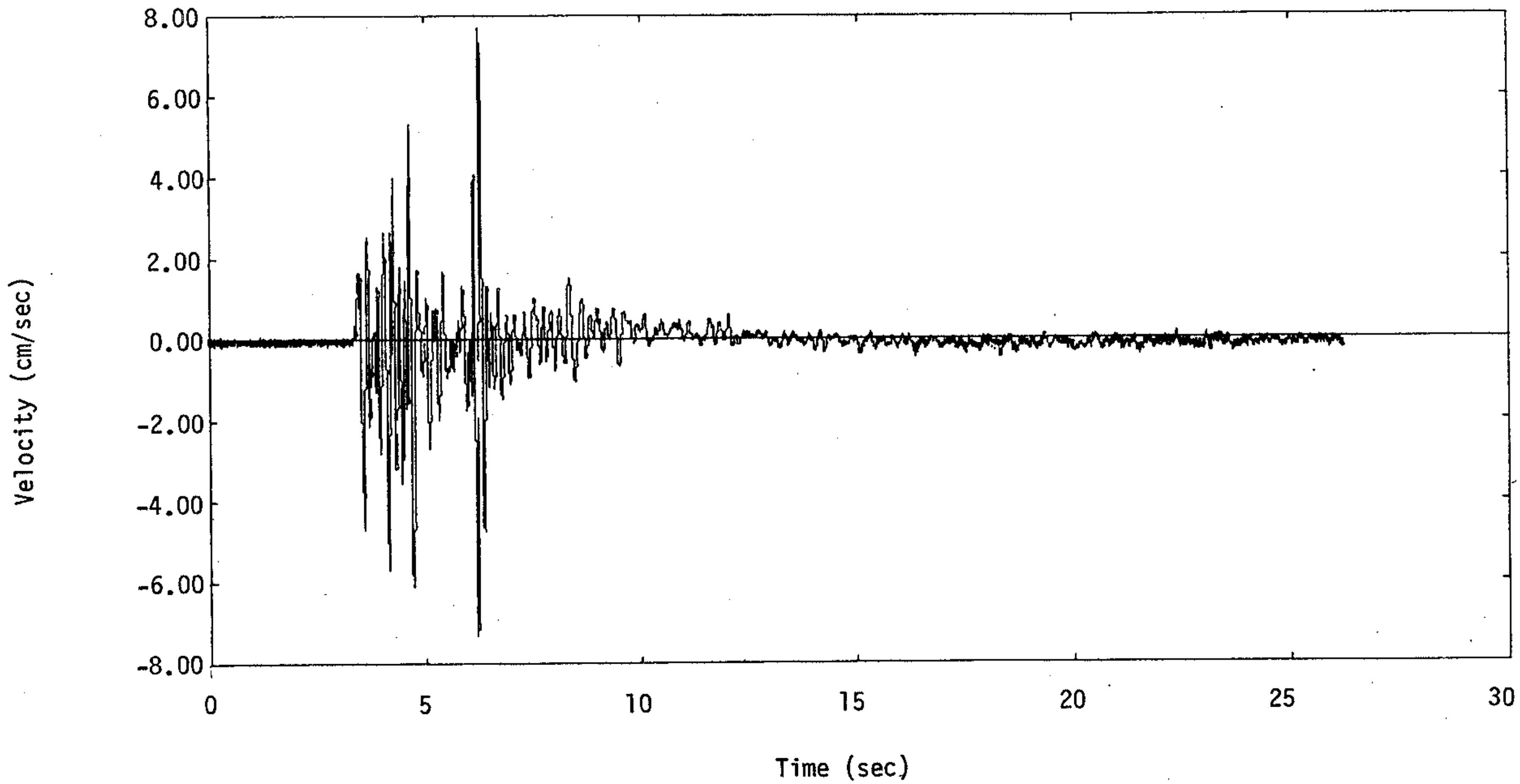

FIGURE 3 VELOCITY RECORD OF RADIAL COMPONENT OF GROUND MOTION: GRAND VALLEY

Building Location Data

City: ______________________ Address: ______________________

Location No.: ______________________ Owner: ______________________

Building Classification Data

Occupancy: ☐ Residential ☐ Commercial ☐ Institutional

Frame Type: ☐ Wood ☐ Adobe ☐ Log ☐ Masonry ☐ Metal

Exterior Walls: (Siding) ☐ Wood ☐ Brick ☐ Concrete Block ☐ Metal ☐ Cement Asbestos ☐ Adobe ☐ Log ☐ Stone ☐ Other: __________

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

Foundation Type: ☐ Wall Masonry Stone ☐ Mudsill ☐ Pier Masonry Timber

Chimney Type: ☐ Brick ☐ Stone ☐ Ceramic ☐ Metal Flue ☐ Capped Brick ☐ Capped Stone ☐ Capped Ceramic ☐ None

Height of Chimney Above Roof (Feet) ______________________

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

FIGURE 4 STRUCTURE INVENTORY FORM

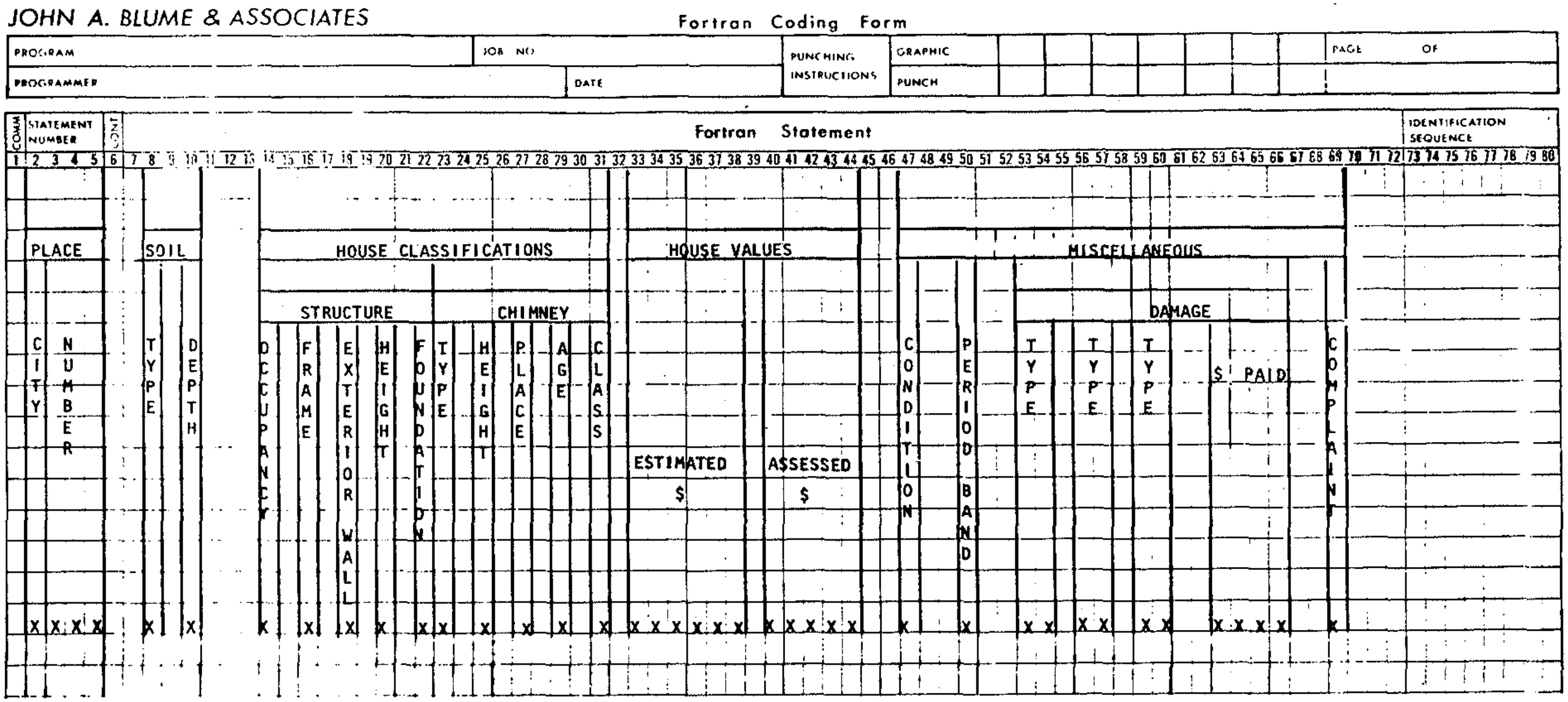

FIGURE 5 FORMAT OF COMPUTER CARD FOR STATISTICAL ANALYSIS

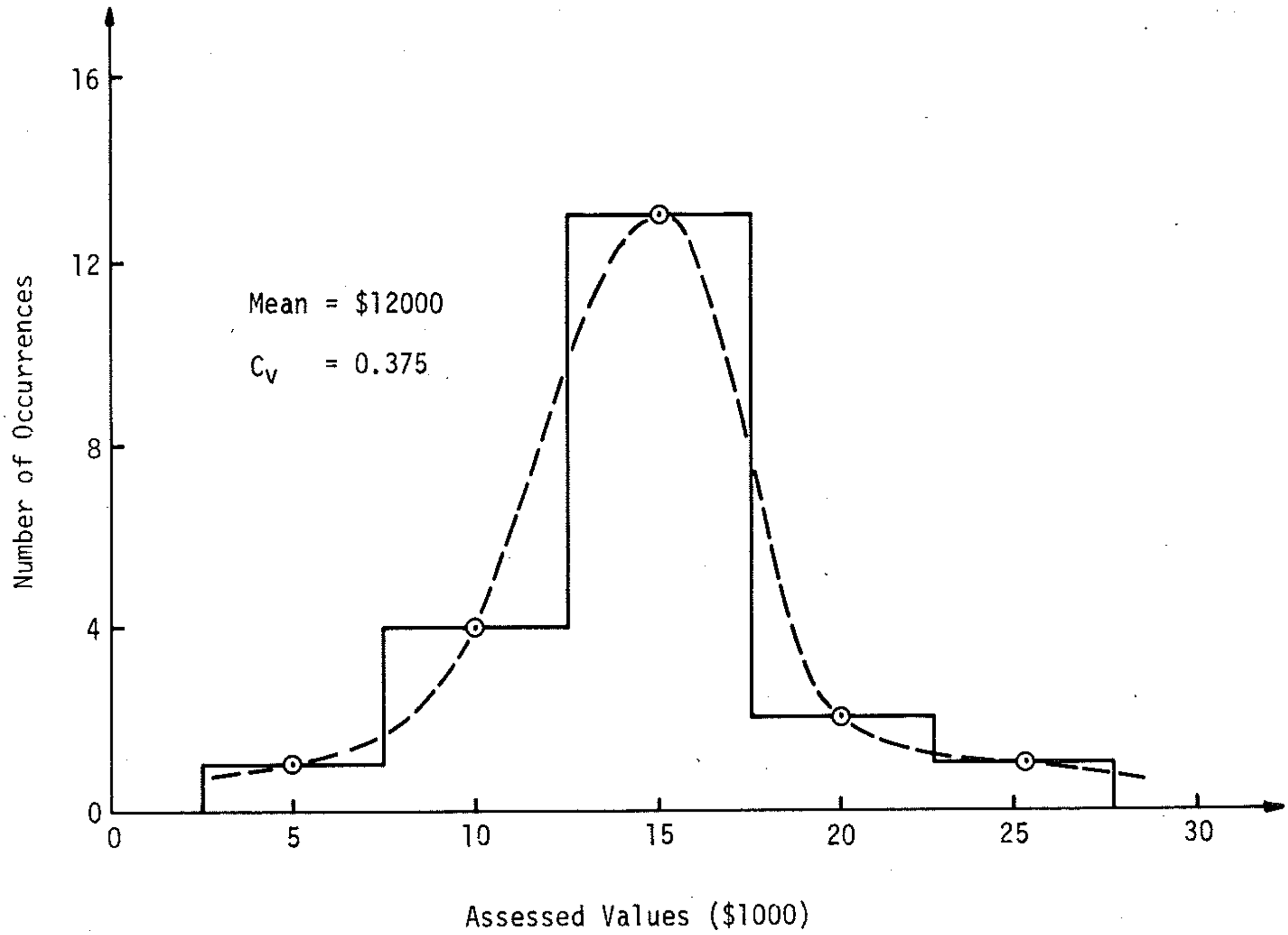

FIGURE 6 PROBABILITY DENSITY CURVE FOR $15000 ESTIMATED VALUE HOMES

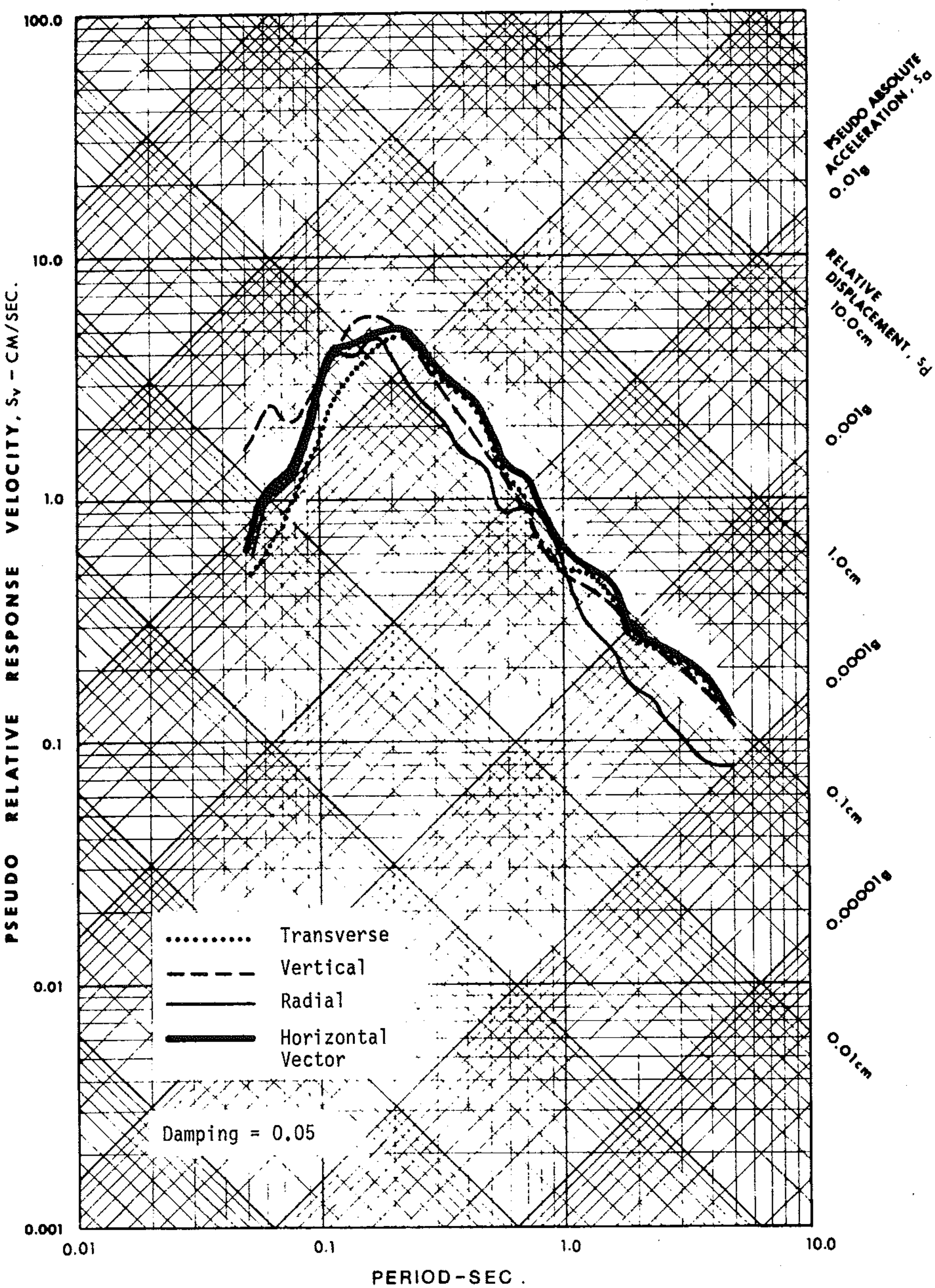

FIGURE 7 RESPONSE SPECTRA: RULISON De Beque #1

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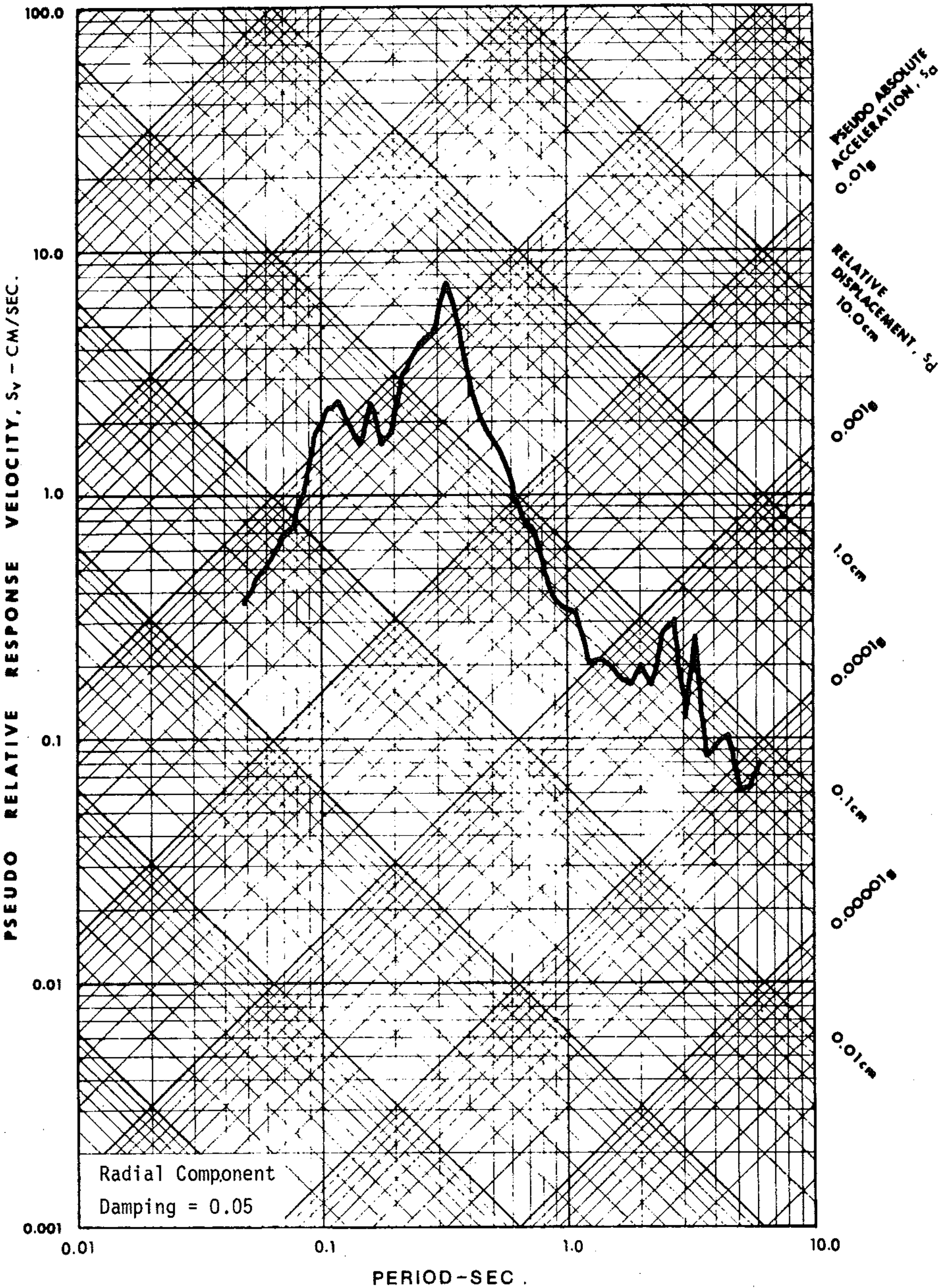

FIGURE 7.a RESPONSE SPECTRA: RULISON Silt

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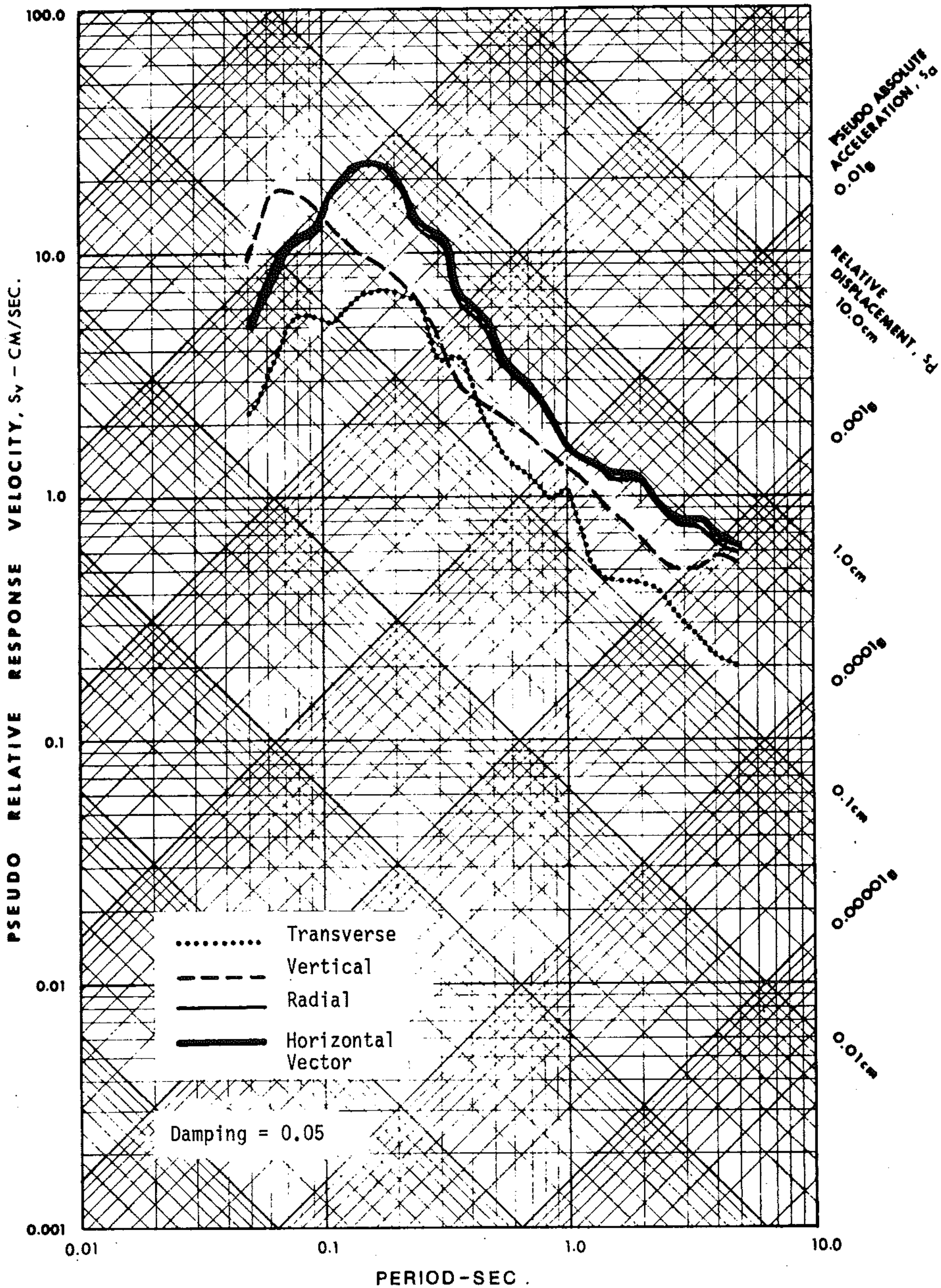

FIGURE 8 RESPONSE SPECTRA: RULISON Grand Valley

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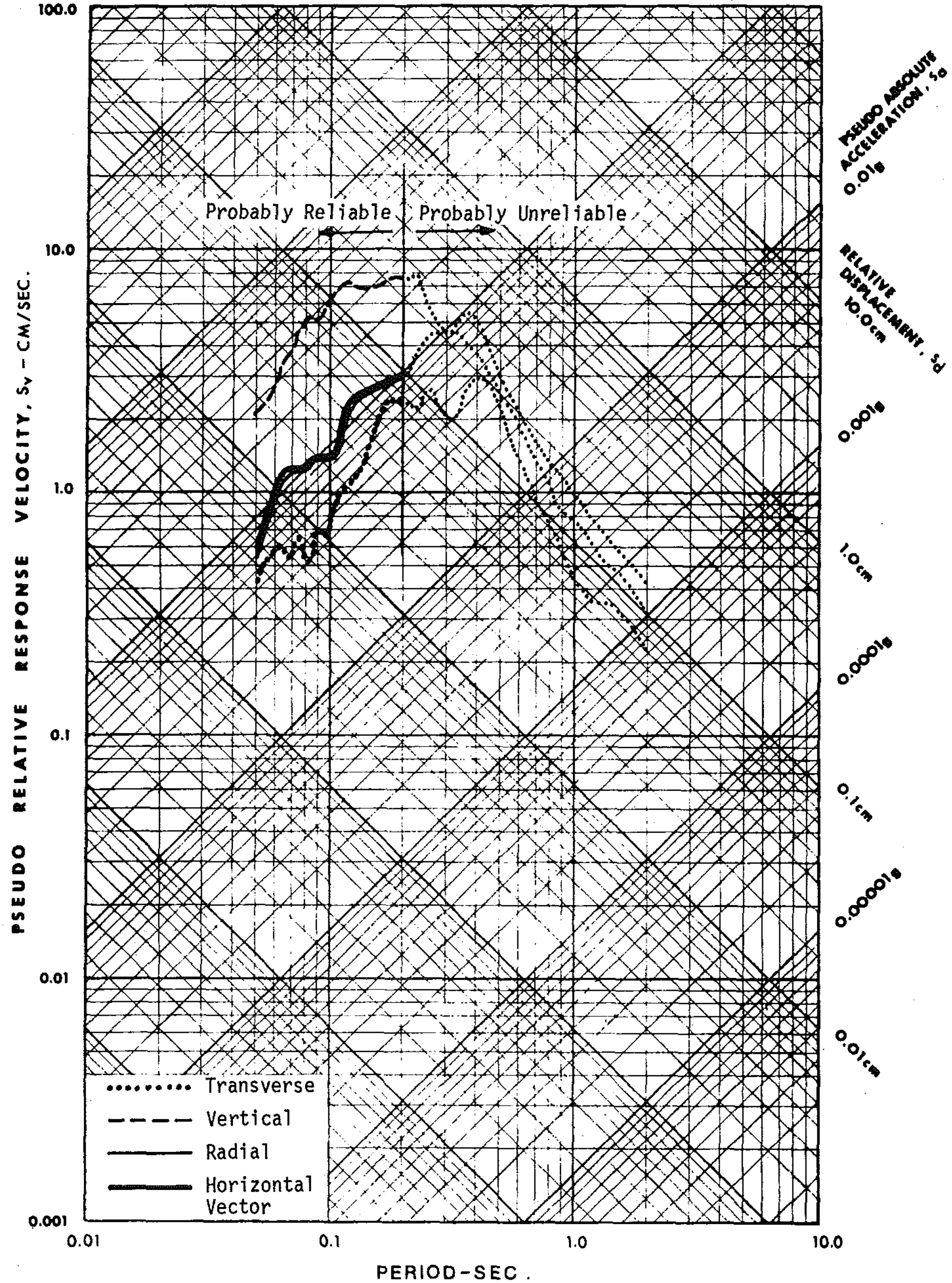

FIGURE 8.a RESPONSE SPECTRA: RULISON Collbran

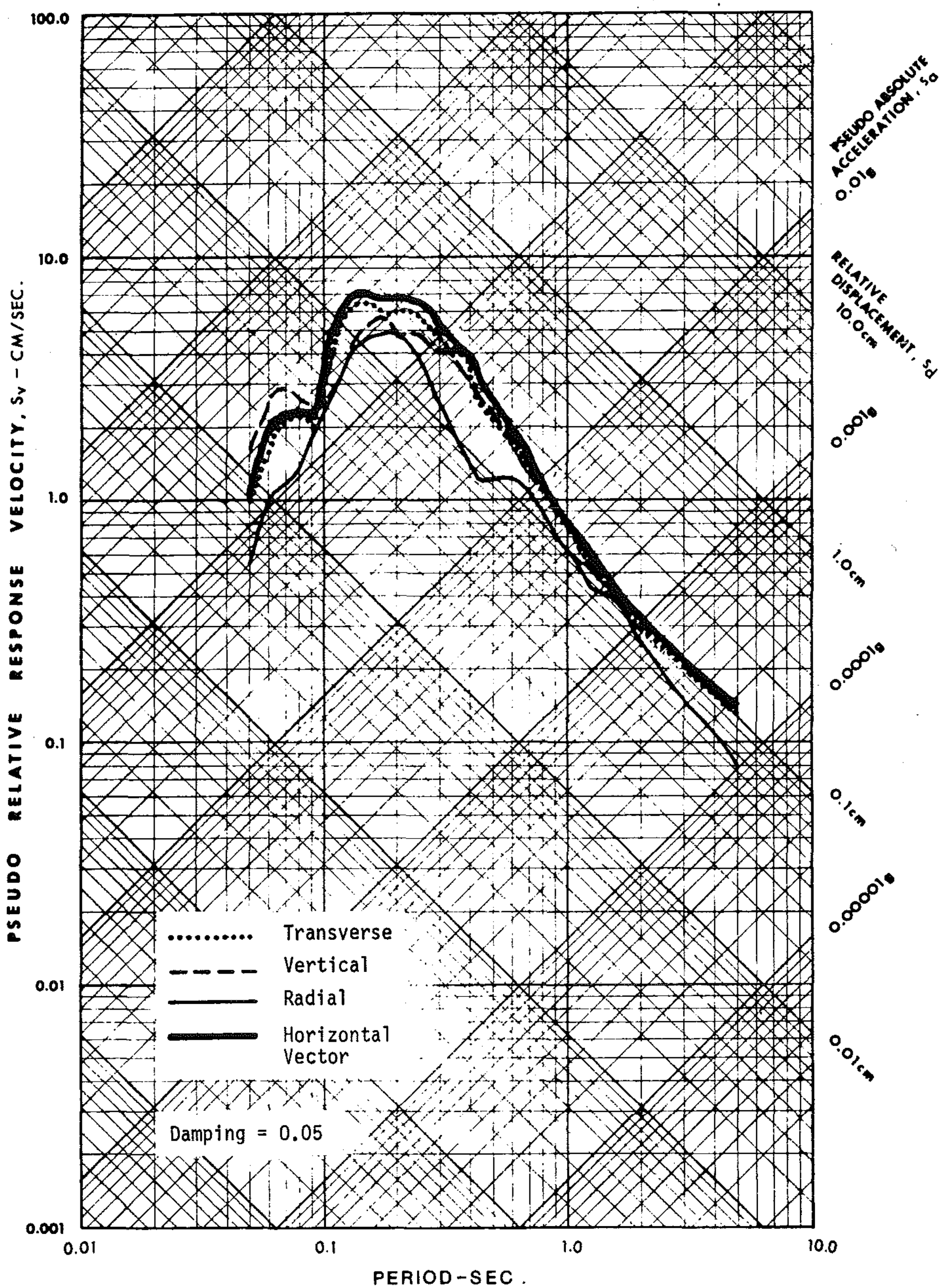

FIGURE 9 RESPONSE SPECTRA: RULISON Rifle Church

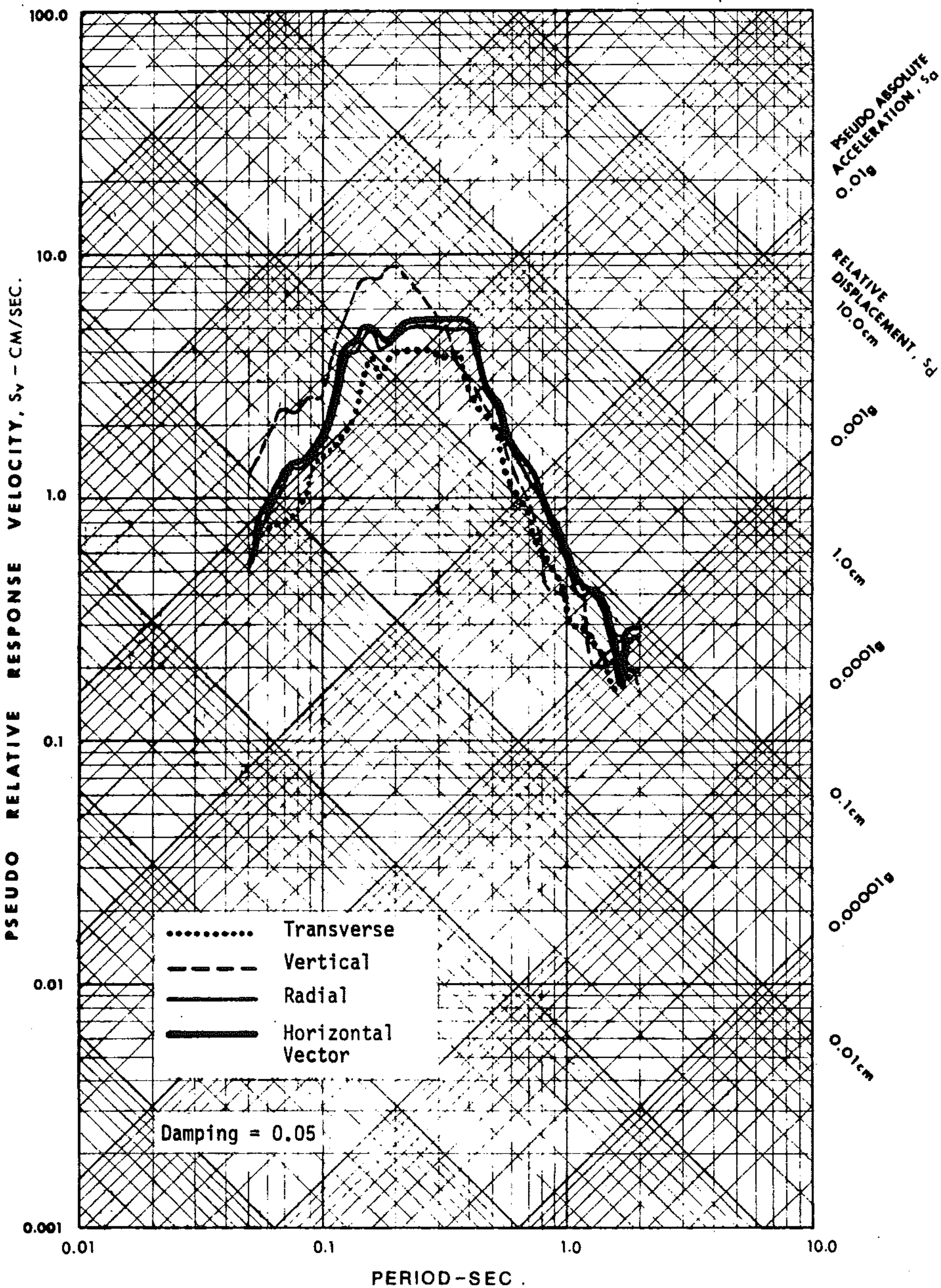

FIGURE 9.a RESPONSE SPECTRA: RULISON Rifle Hill

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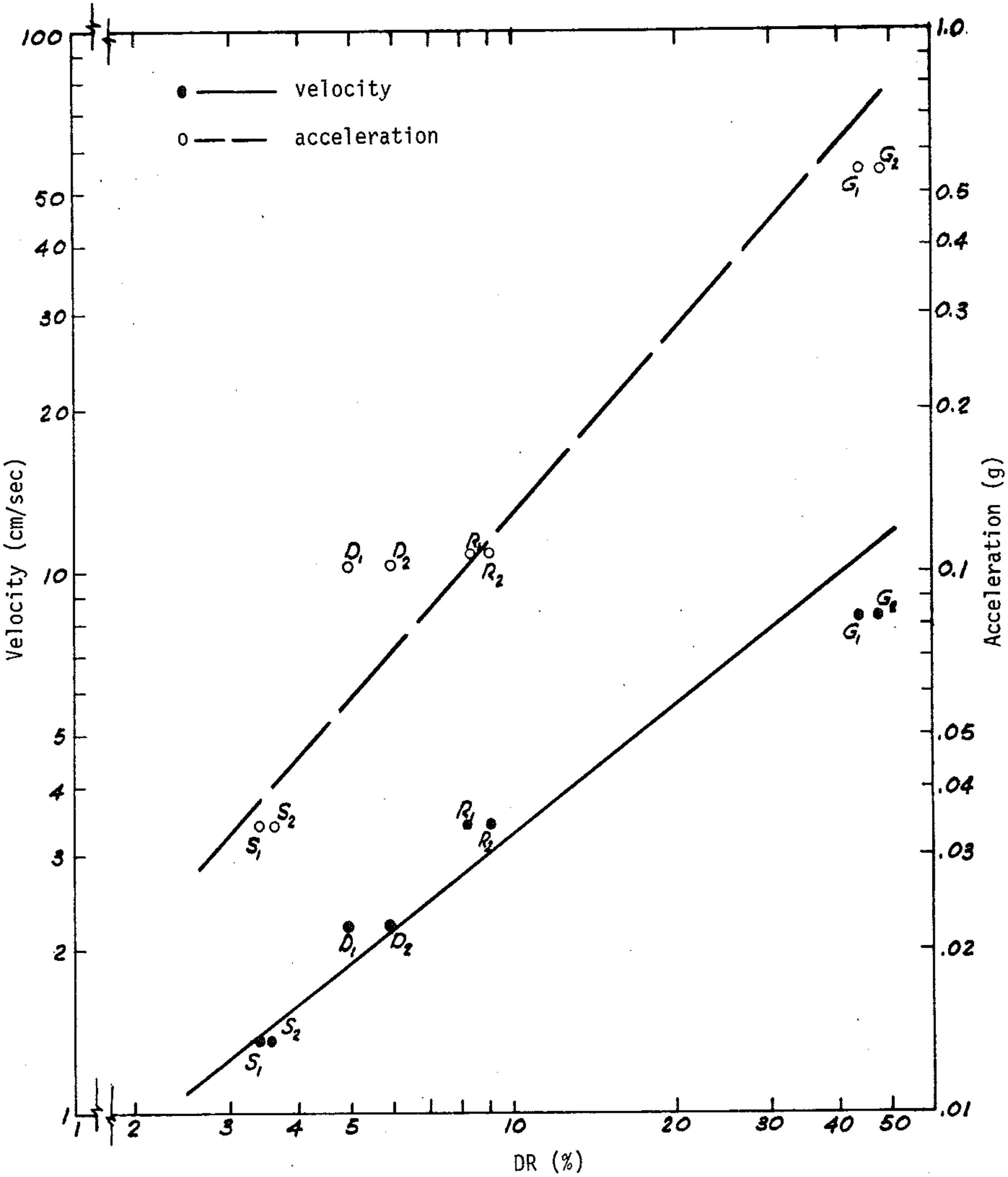

FIGURE 10 VECTOR GROUND MOTION PEAK vs. DAMAGE RATIO

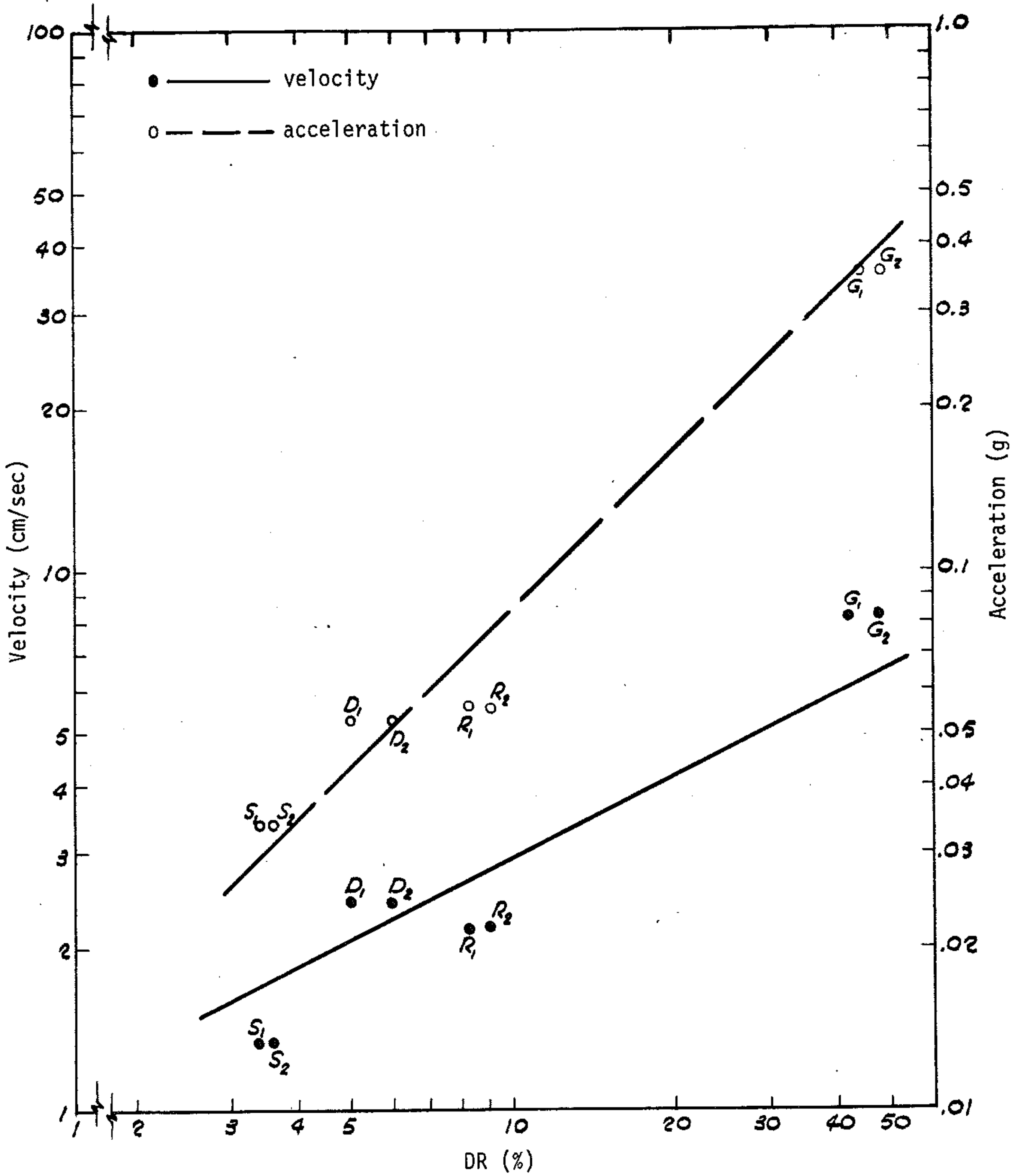

FIGURE 11 RADIAL GROUND MOTION PEAK vs. DAMAGE RATIO

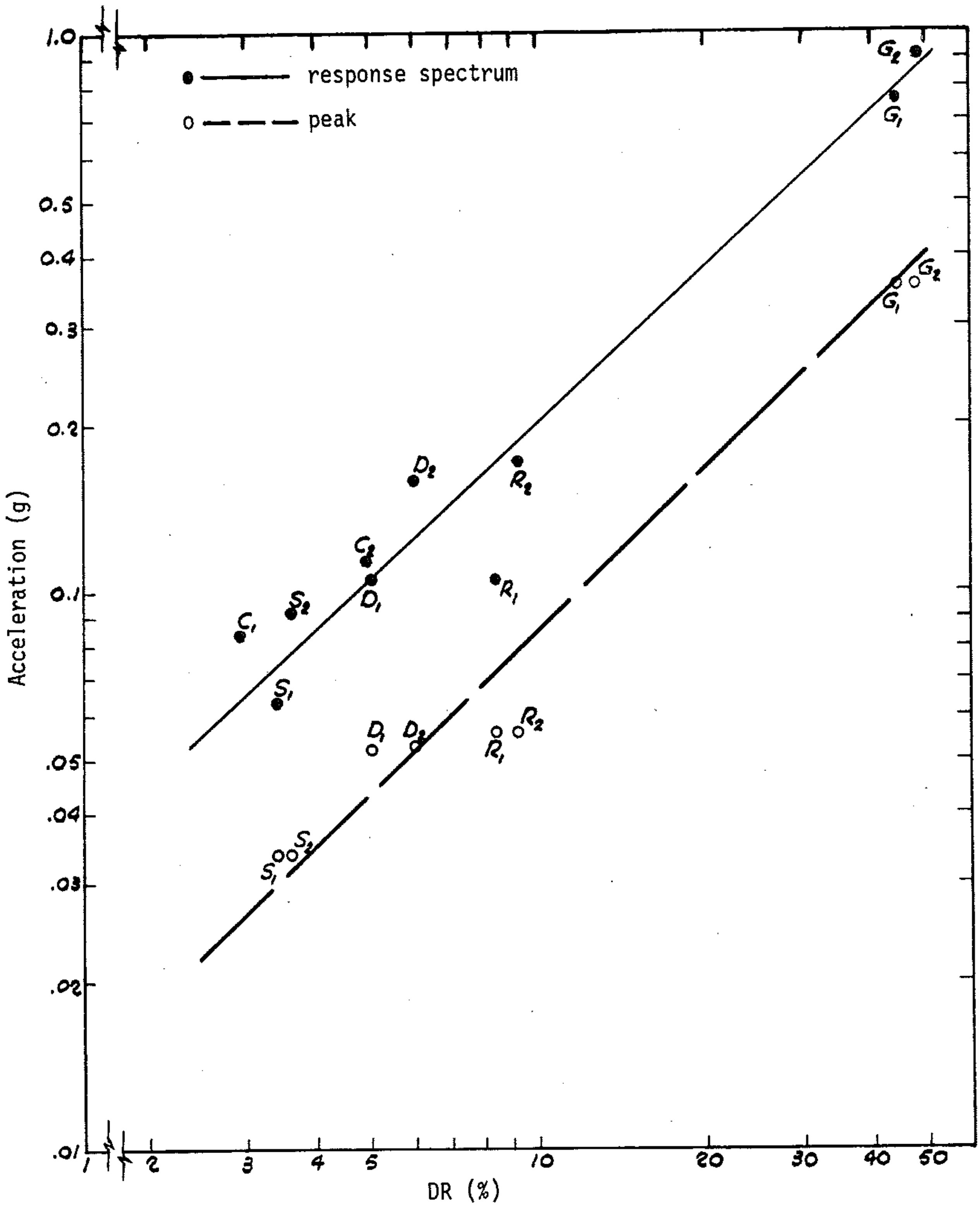

FIGURE 12 RADIAL RESPONSE SPECTRUM AND PEAK VALUES vs. DAMAGE RATIO

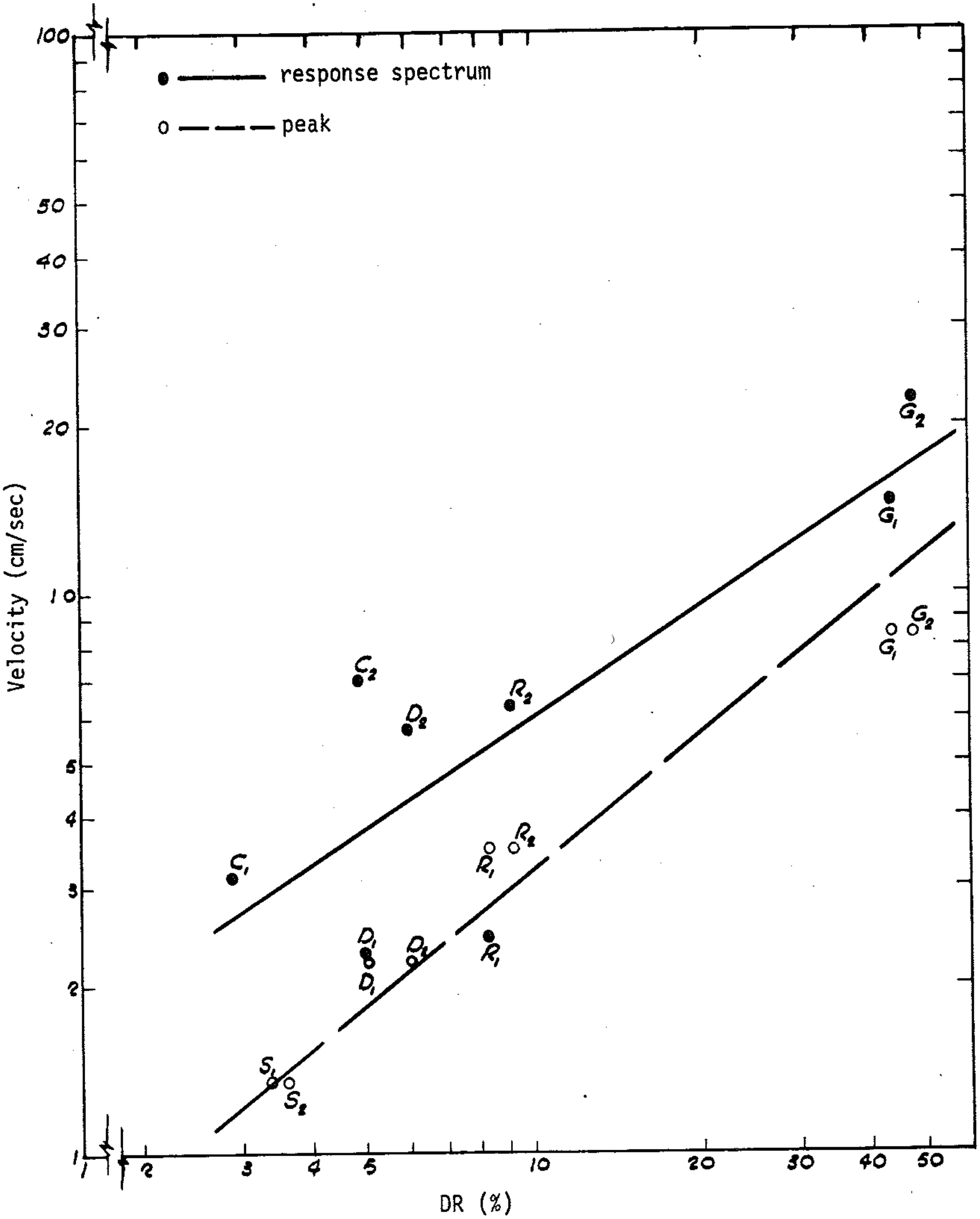

FIGURE 13 VECTOR RESPONSE SPECTRUM AND PEAK VALUES (ALL COMPONENTS) vs. DAMAGE RATIO

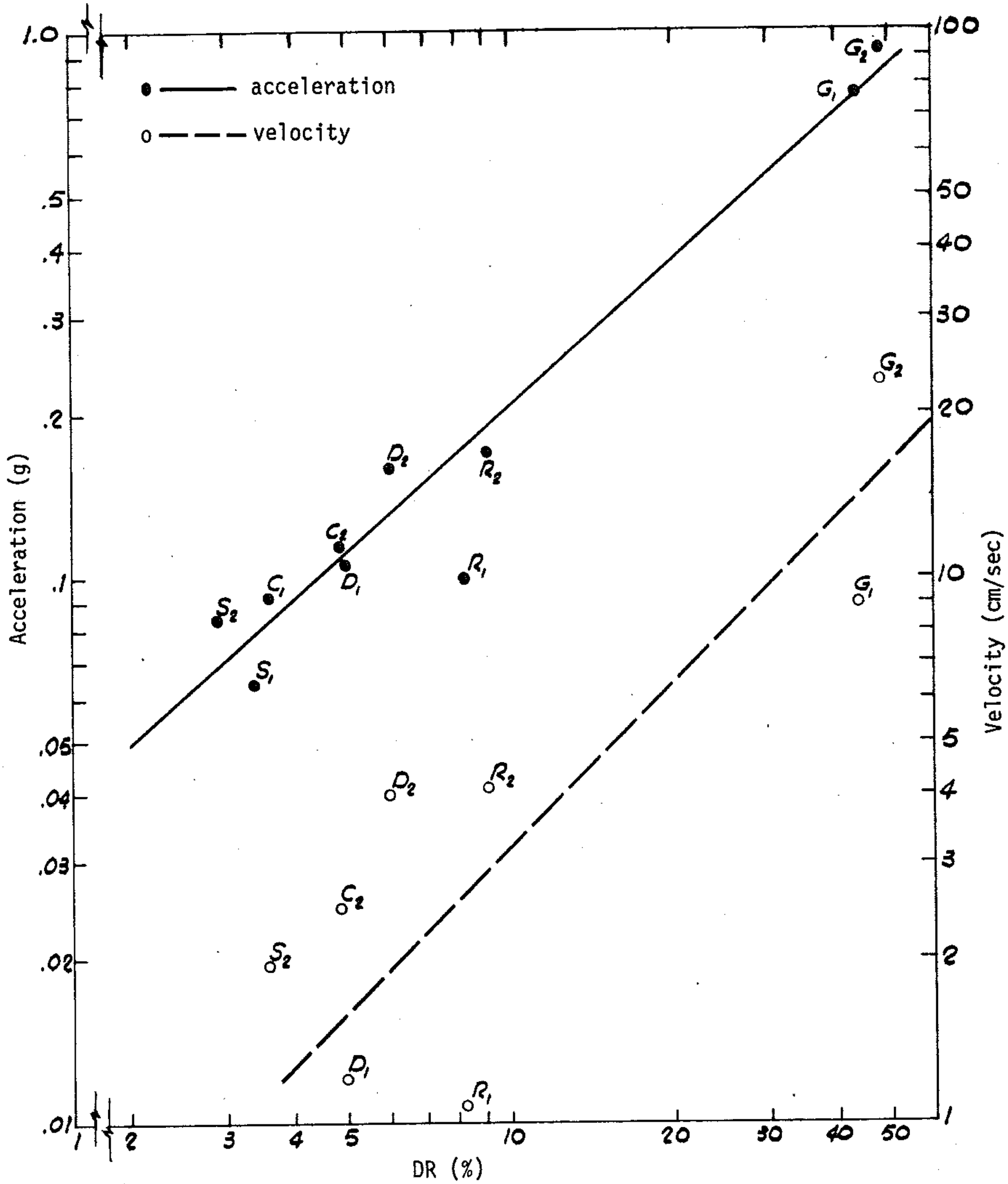

FIGURE 14 RADIAL RESPONSE SPECTRUM VALUES vs. DAMAGE RATIO

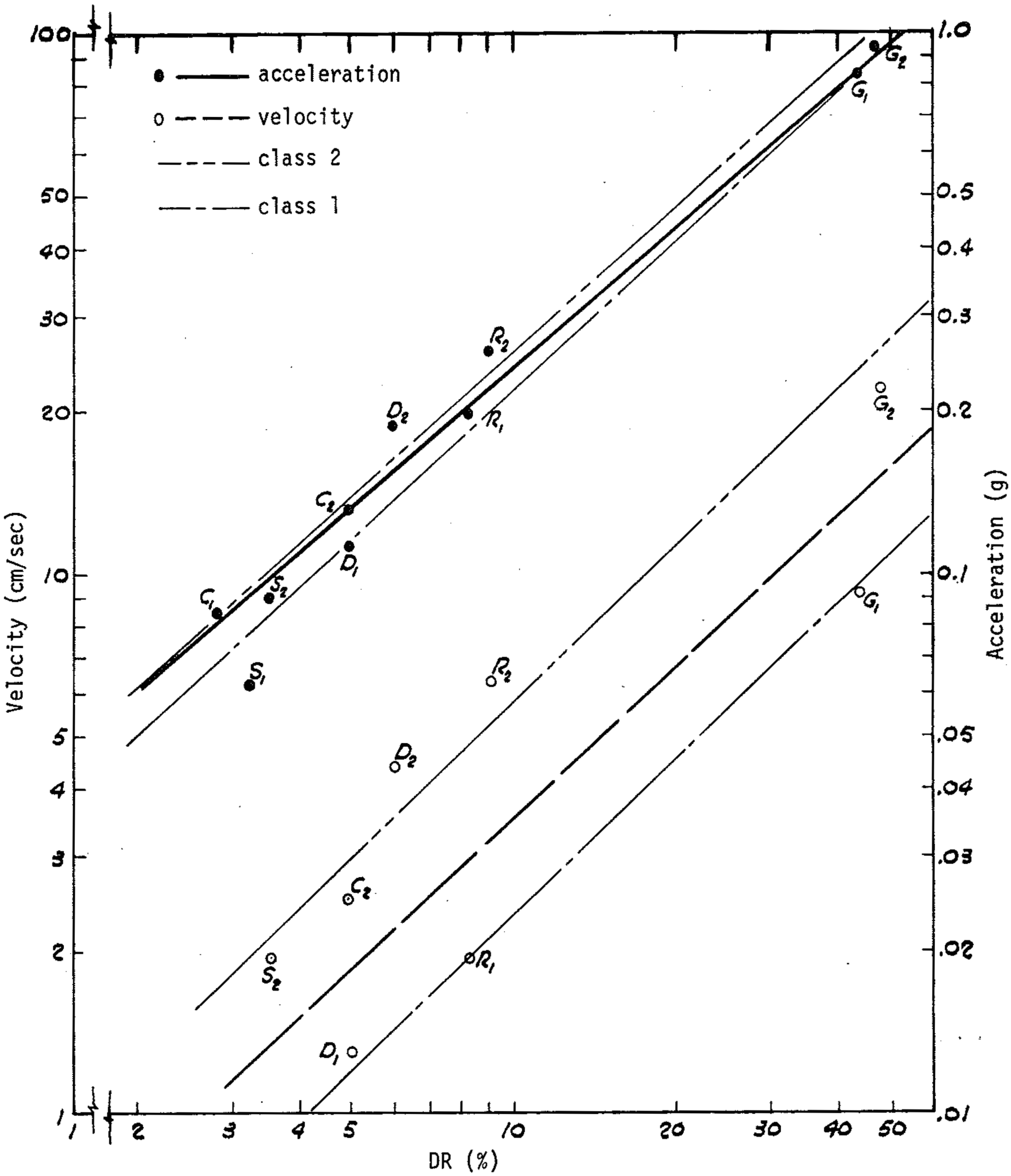

FIGURE 15 VECTOR RESPONSE SPECTRUM (HORIZONTAL COMPONENTS) VALUES vs. DAMAGE RATIO

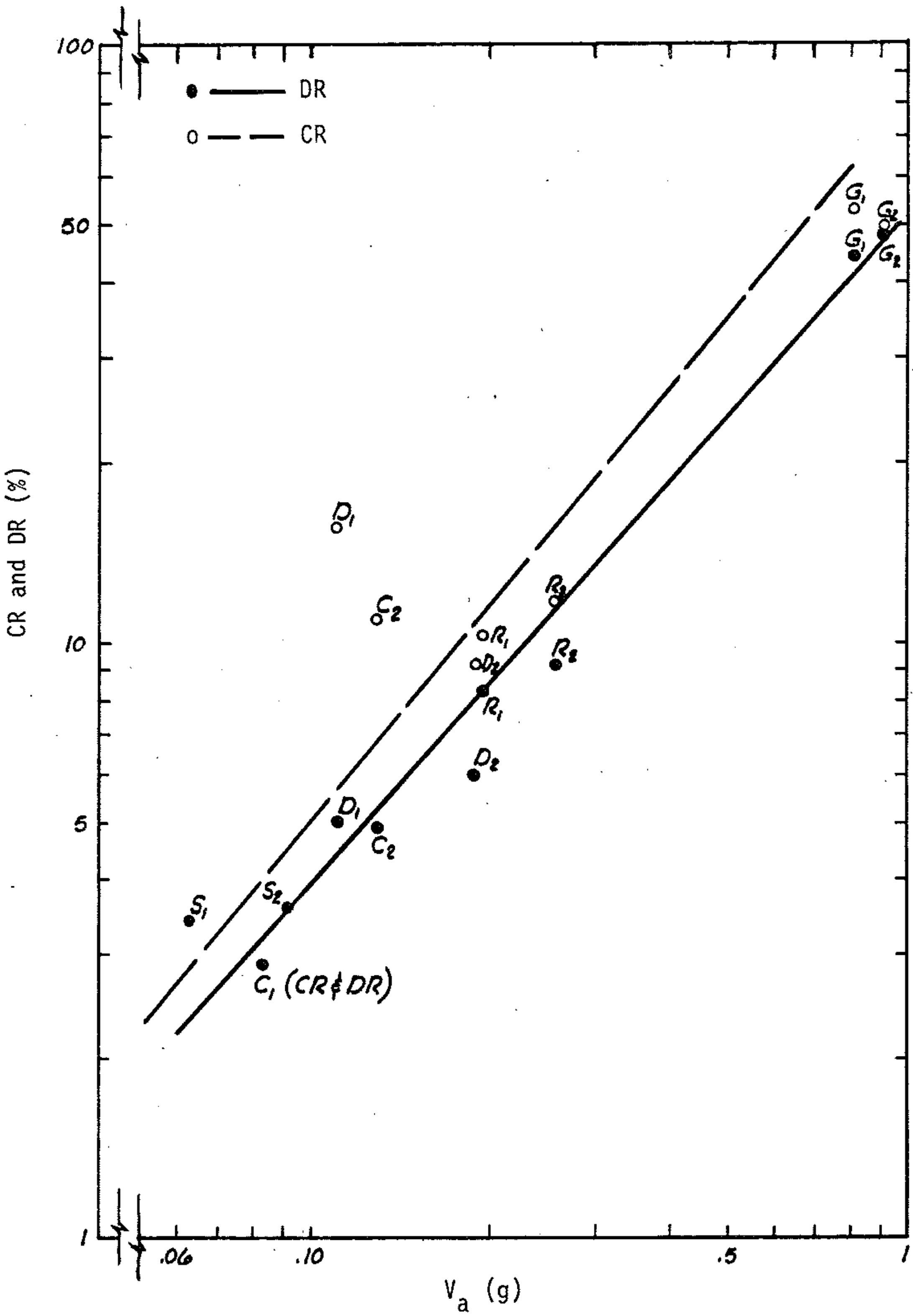

FIGURE 16 DAMAGE RATIO & COMPLAINT RATIO

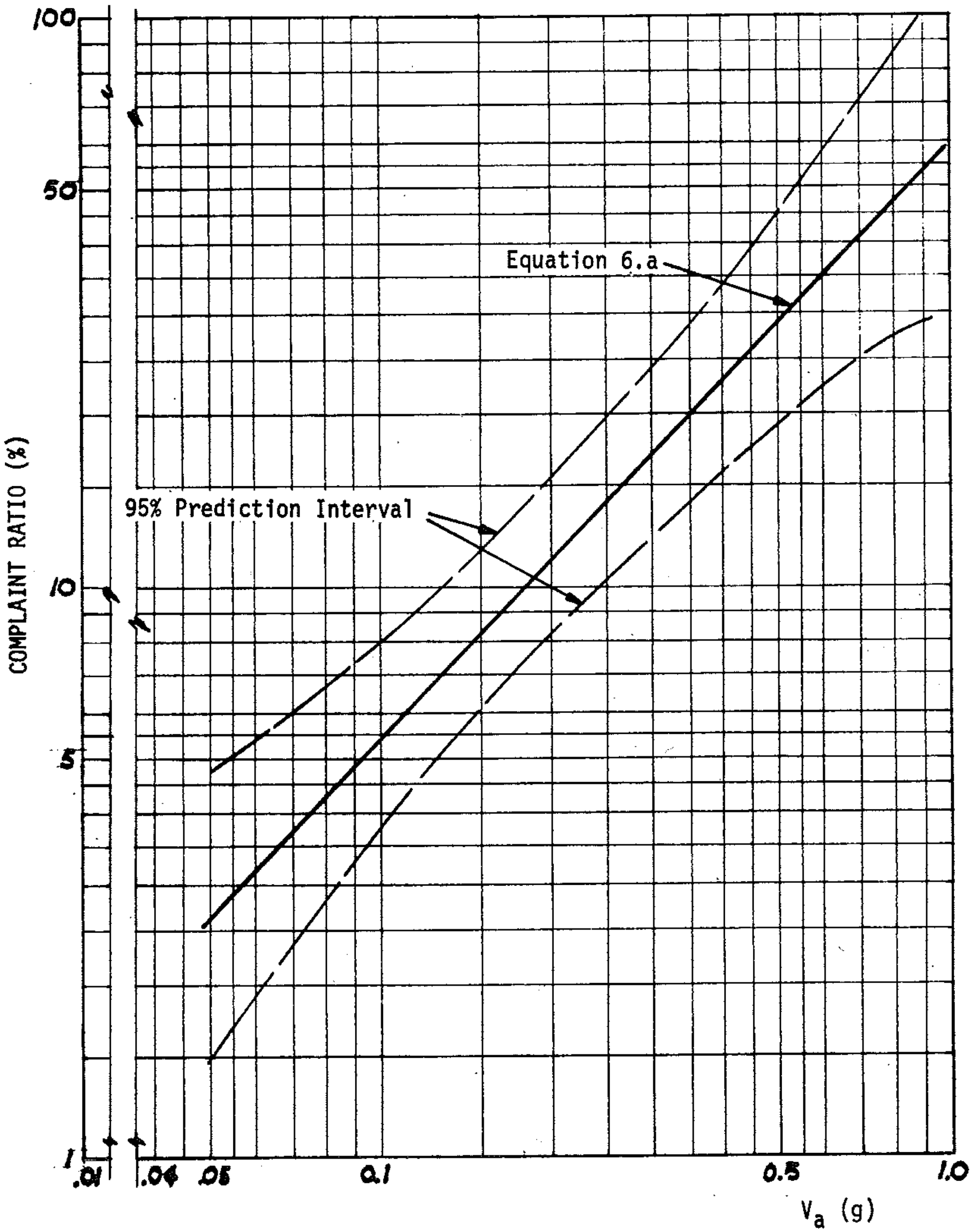

FIGURE 17 COMPLAINT RATIO VS. V_a

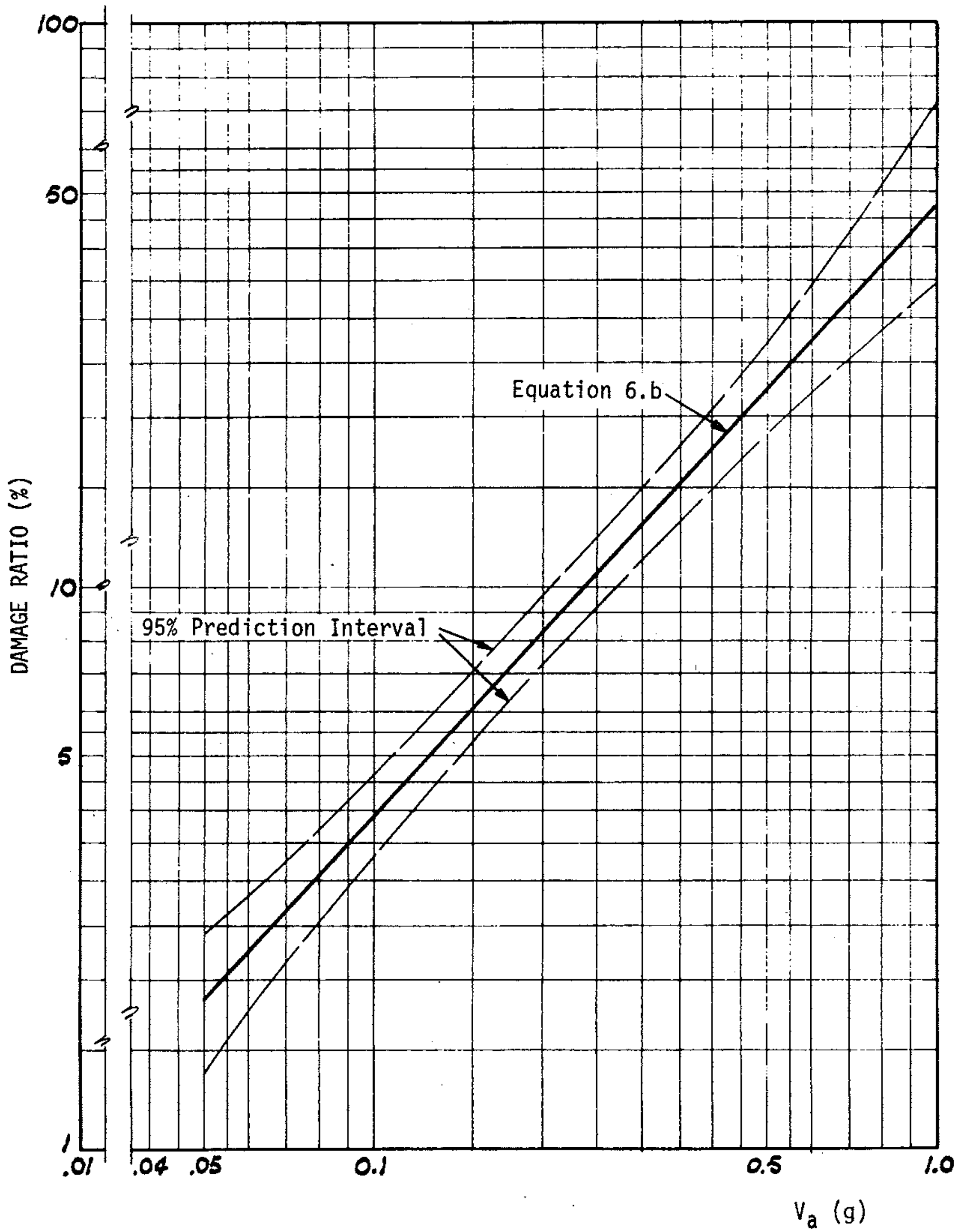

FIGURE 18 DAMAGE RATIO VS. V_a

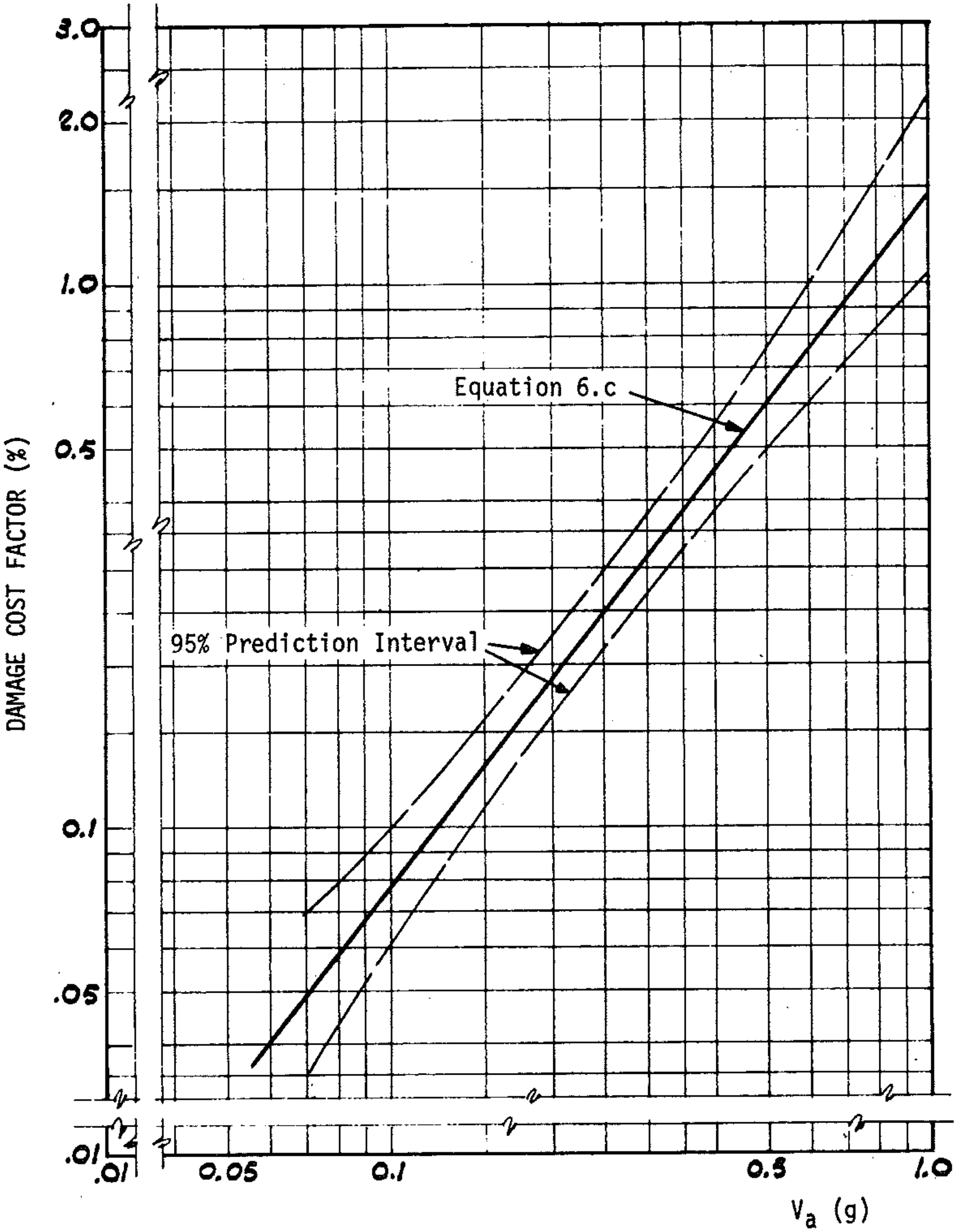

FIGURE 19 DAMAGE COST FACTOR VS. V_a

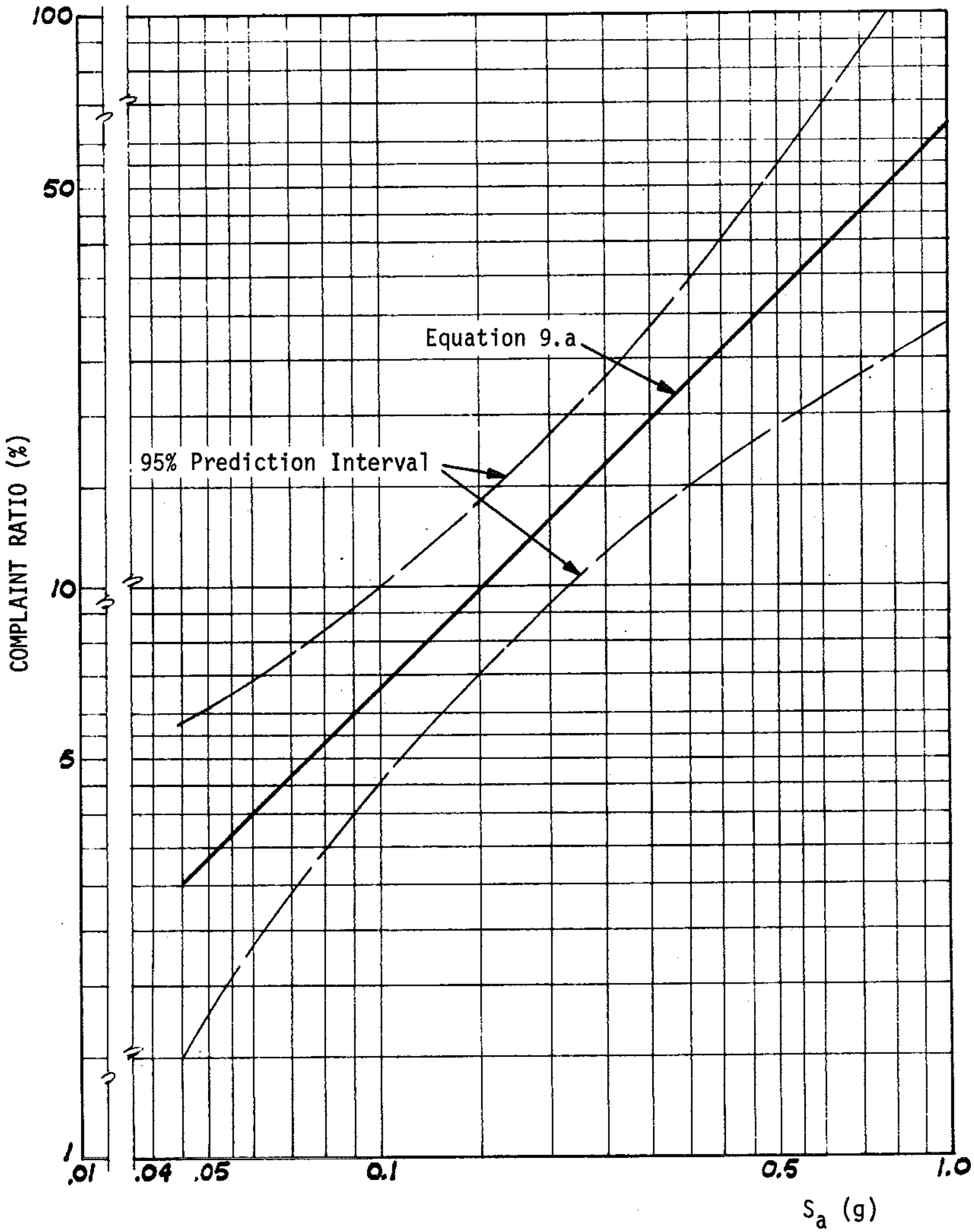

FIGURE 20 COMPLAINT RATIO VS. S_a

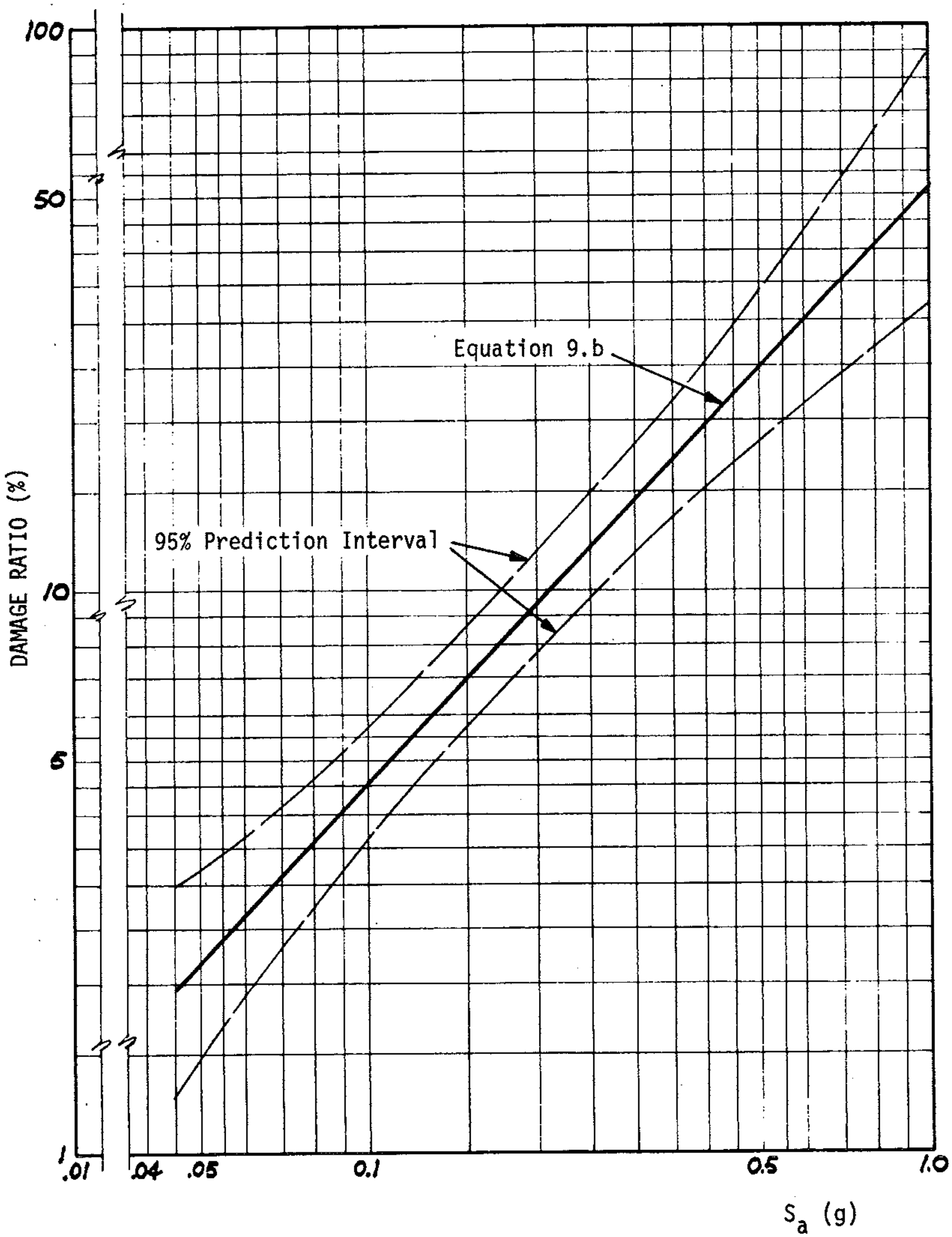

FIGURE 21 DAMAGE RATIO VS. S_a

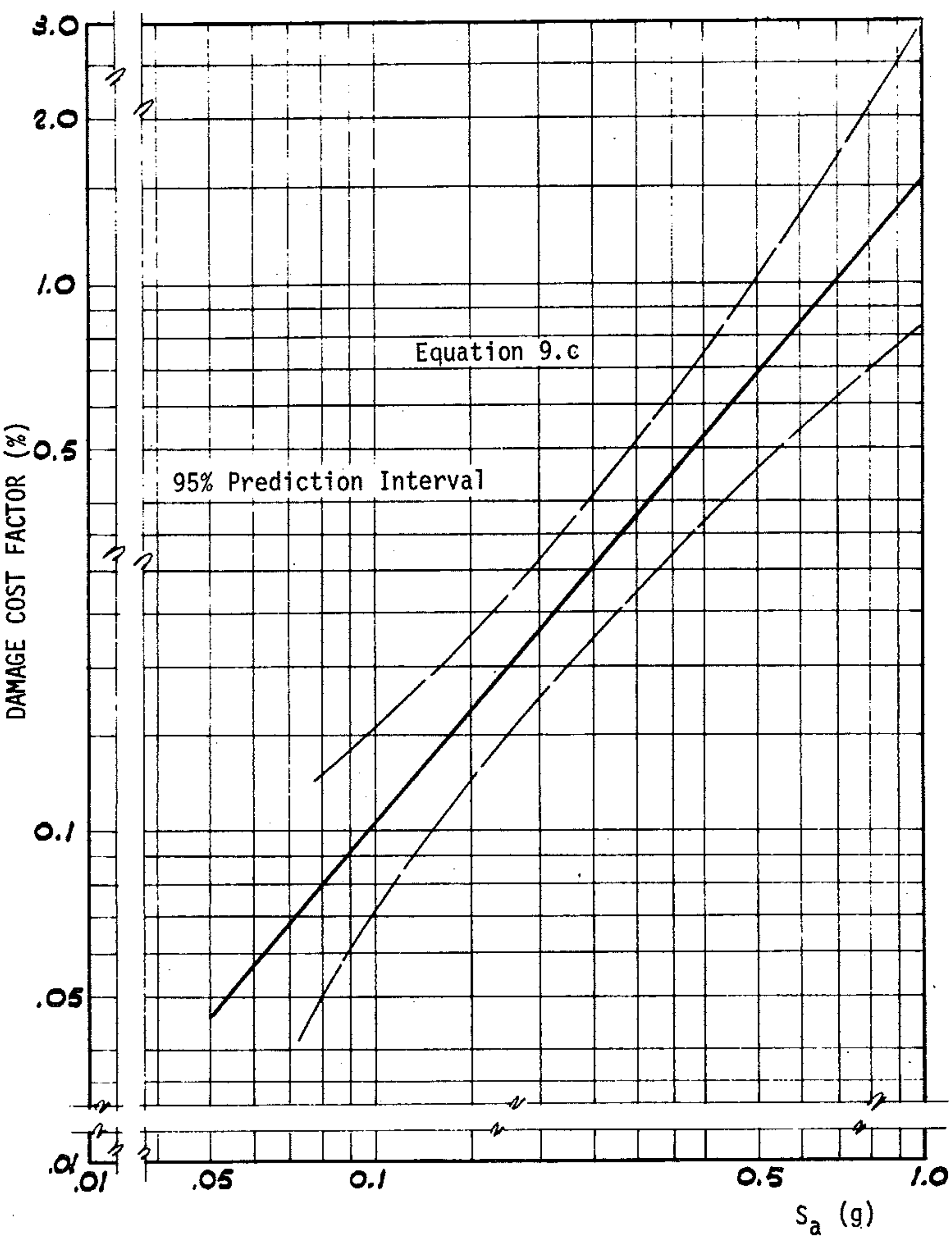

FIGURE 22 DAMAGE COST FACTOR VS. S_a

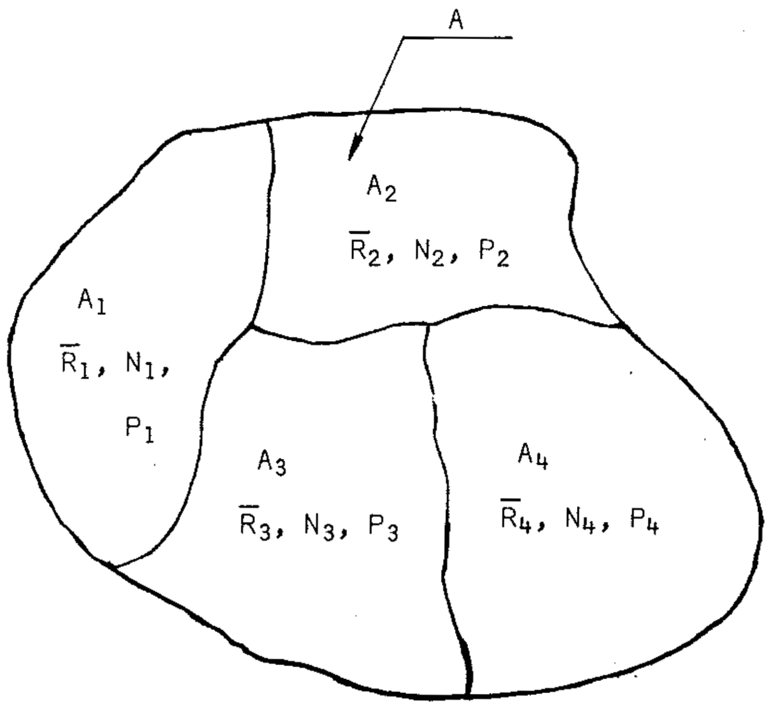

FIGURE 23 VARIOUS CHARACTERISTICS OF AREA "A"

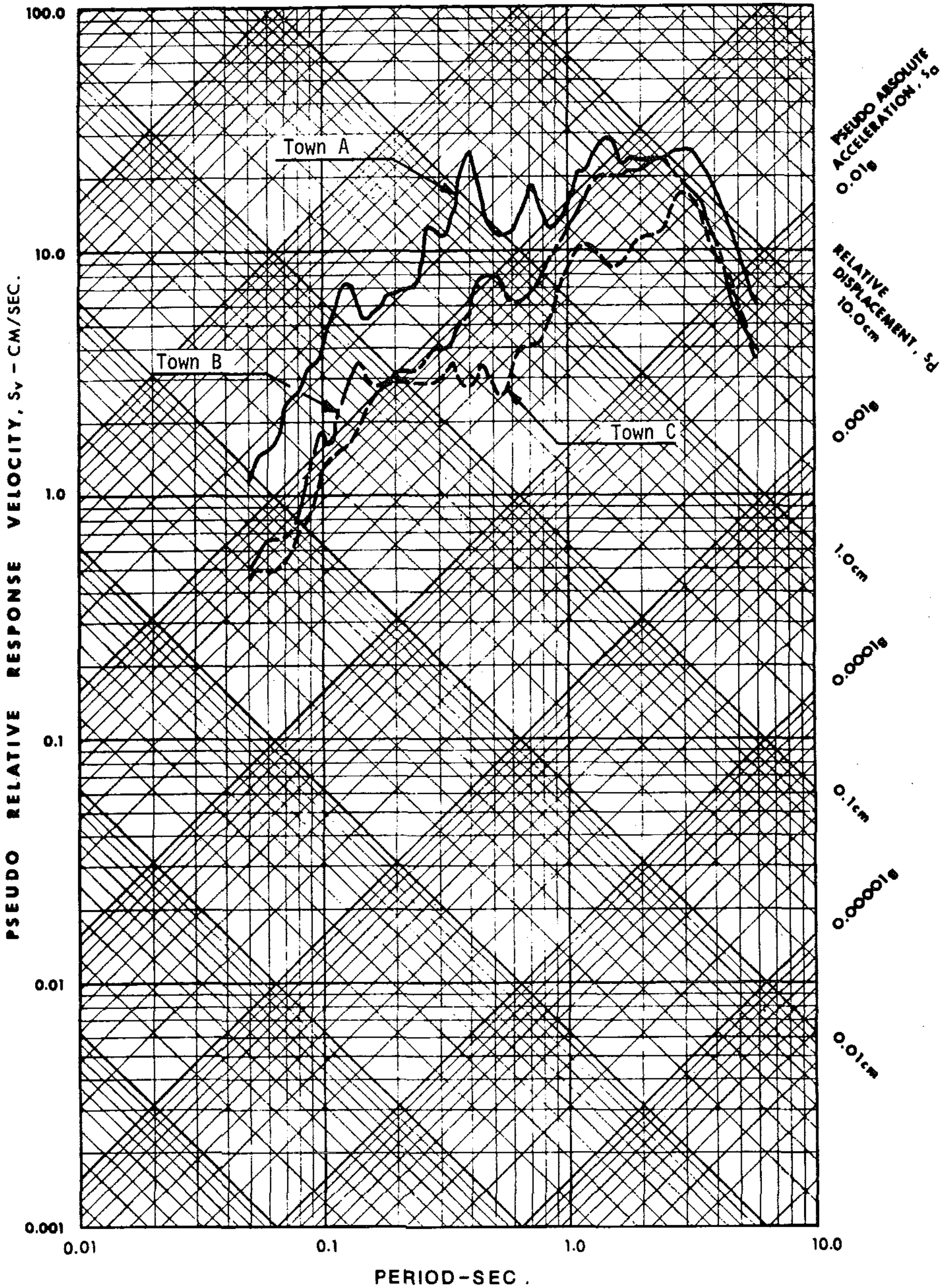

FIGURE 24 RADIAL COMPONENT: RESPONSE SPECTRUM CURVES FOR TOWNS A, B AND C

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APPENDIX B

TABLES

TABLE 1 DISTRIBUTION OF BUILDINGS INCLUDED IN STUDY

CITY	NUMBER OF BUILDINGS		
	TOTAL	CLASS 1	CLASS 2
Collbran	139	37	102
De Beque	105	39	66
Grand Valley	164	87	77
Rifle	818	543	275
Silt	168	57	111

TABLE 2 BUILDING VALUES IN RULISON AREA

Estimated (E)	Adjusted	Coeff. of Variation
<7500	$\frac{E}{2}$	
7500 - 12500	8500	0.367
12500 - 17500	12000	0.375
17500 - 22500	13500	0.376
22500 - 32500	17000	0.242
32500 - 37500	24500	0.184
>37500	$\frac{E}{2}$ +7000	

TABLE 3 PEAK VALUES OF GROUND MOTION RECORD FOR RULISON AREA

CITY	RADIAL		TRANSVERSE		VERTICAL		VECTOR	
	Vel. (cm/sec)	Acc. (g)	Vel.	Acc.	Vel.	Acc.	Vel.	Acc.
Collbran	NOT RELIABLE							
De Beque	1.34	0.053	1.73	0.047	2.07	0.097	2.20	0.102
Grand Valley	8.14	0.358	3.3	0.136	7.34	0.531	8.27	0.55
Rifle *	2.2	0.056	1.95	0.06	3.28	0.109	3.45	0.117
Silt	1.34	0.034					1.34	0.034

*Average of Church & Hill Stations in Rifle

TABLE 4

AVERAGE RESPONSE SPECTRUM VALUES FOR RULISON AREA

Average Response Spectrum		Collbran		De Beque		Grand Valley		Rifle		Silt	
		Class 1	Class 2	Class 1	Class 2	Class 1	Class 2	Class 1	Class 2	Class 1	Class 2
Radial	Vel. $\frac{cm}{sec}$	0.87	2.51	1.2	4.	9.	22.1	1.15	4.19	0.7	1.93
	Acc. (g)	0.084	0.115	0.106	0.158	0.77	0.93	0.099	0.17	0.063	0.092
Transverse	Vel. $\frac{cm}{sec}$	0.5	1.69	0.84	3.48	4.15	6.49	1.5	2.		
	Acc. (g)	0.051	0.068	0.073	0.104	0.35	0.27	0.138	0.2		
Vertical	Vel. $\frac{cm}{sec}$	3.1	7.02	2.1	5.	14.2	9.79	2.23	4.51		
	Acc. (g)	0.295	0.3	0.2	0.238	1.3	0.43	0.208	0.191		
Vector All Components	Vel. $\frac{cm}{sec}$	3.1	7.02	2.27	5.75	14.4	22.1	2.41	6.32		
	Acc. (g)	0.295	0.3	0.213	0.246	1.3	0.93	0.227	0.27		
Vector Horizontal Components	Vel. $\frac{cm}{sec}$	0.87	2.51	1.3	4.4	9.2	22.1	1.96	6.29	0.7*	1.93*
	Acc. (g)	0.084	0.13	0.112	0.187	0.82	0.93	0.197	0.26	0.063	0.092

*Assumed

TABLE 5

DAMAGE DATA FOR RULISON AREA

DAMAGE DATA	COLLBRAN		DE BEQUE		GRAND VALLEY		RIFLE		SILT	
	Class 1	Class 2	Class 1	Class 2	Class 1	Class 2	Class 1	Class 2	Class 1	Class 2
Total No. Buildings	37	102	39	66	87	77	543	275	57	111
Complaints	1	11	6	6	46	37	55	32	2	4
Credible Damage	1	5	2	4	39	37	45	25	2	4
Total Cost $	---*	1168	290	1105	13656	5469	15873	7864	65	535
CR %	2.88	10.8	15.4	9.1	54	48	10.1	11.6	3.4	3.6
DR %	2.88	4.9	5	6	44.2	48	8.3	9.1	3.4	3.6
DCF %	---	0.12	0.085	0.224	1.33	1.13	0.18	0.209	---	0.059
Average Damage Cost $	---	234	145	276	350	149	353	315	33	134

* $1823 paid for damage to an ornamental interior wall; claim was excluded from analysis because of the extreme bias it causes.

TABLE 6

STANDARD DEVIATIONS OF DAMAGE RATIO

WITH RESPECT TO SINGLE-STRUCTURE CLASS

LINE OF BEST FIT

Component of Motion	Standard Deviation for Damage Ratio (%)			
	Peak Values		Average Response Spectrum	
	Vel.	Acc.	Vel.	Acc.
Radial	1.3	1.4	1.5	1.3
Transverse	1.55	1.3	1.7	1.2
Vertical	1.25	1.3	2.0	2.0
Vector (All Comp.)	1.4	1.2	1.8	1.6
Vector (Horiz. Comp.)	---	---	1.5	1.1

TABLE 7

STANDARD DEVIATIONS OF DAMAGE

RATIO AND COMPLAINT RATIO WITH RESPECT

TO SINGLE-STRUCTURE CLASS LINE OF BEST FIT

COMPONENT OF RESPONSE SPECTRUM	STANDARD DEVIATION FOR DAMAGE PREDICTION PARAMETERS (%)					
	DR		CR		DCF	
	Vel.	Acc.	Vel.	Acc.	Vel.	Acc.
Radial	1.5	1.3	1.7	1.5	1.7	1.35
Transverse	1.7	1.2	1.8	1.55	1.7	1.3
Vertical	2.0	2.0	2.0	2.0	2.2	2.1
Vector (all components)	1.8	1.6	1.9	1.8	1.8	1.4
Vector (horizontal components)	1.5	1.1	1.65	1.5	1.6	1.1

TABLE 8

INVENTORY AND GROUND MOTION DATA FOR TOWNS A, B, AND C

City	Number of Buildings	Building Values ($1,000,000)	Response Spectrum (S_a)
A	400	5.5	0.25
B	250	2.9	0.1
C	1050	16.5	0.07

TABLE 9

MEAN VALUES AND ERROR VALUES FOR DAMAGE PARAMETERS

Town	S_a	$\overline{CR}$	$\overline{DR}$	$\overline{DCF}$	E_{CR}	E_{DR}	E_{DCF}
A	0.25	16.0	12.2	0.302	1.87	1.25	1.31
B	0.1	6.40	4.66	0.103	1.92	1.29	1.41
C	0.07	4.60	3.25	0.068	2.35	1.36	1.5

TABLE 10

FINAL RESULTS OF EXAMPLE

Damage Parameter	Upper Bound	Average	Lower Bound
Number of Complaints	264	128	63
Damage Ratio (%)	7.2	5.6	4.3
Damage Repair Cost ($)	42760	30817	22192

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