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SENSITIVITY OF PIPING SEISMIC RESPONSES TO INPUT FACTORS

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SENSITIVITY OF PIPING SEISMIC RESPONSES TO INPUT FACTORS

ABSTRACT

This report summarizes the sensitivity of peak dynamic seismic responses to input parameters. The responses have been modeled and calculated for the Zion Unit 1 plant as part of a seismic probabilistic risk assessment (PRA) performed by the U.S. NRC Seismic Safety Margins Research Program (SSMRP). The SSMRP was supported by the U.S. NRC Office of Nuclear Regulatory Research.

Two sensitivity topics motivated the study. The first is the sensitivity of piping response to the mean value of piping damping. The second is the sensitivity of all the responses to the earthquake and model input parameters including soil, structure and piping parameters; this information is required for another study, the sensitivity of the plant system response (in terms of risk) to these dynamic input parameters and to other input factors.

We evaluate the response sensitivities by performing a linear regression analysis (LRA) of the computer code SMACS. With SMACS we have a detailed model of the Zion plant and of the important dynamic processes in the soil, structures and piping systems.

The qualitative results change with the location of the individual response. Different responses are in locations where the many potential influences have different effectiveness. The results give an overview of the complexity of the seismic dynamic response of a plant. Within the diversity trends are evident in the influences of the input variables on the responses.

EXECUTIVE SUMMARY

This report summarizes our study of the sensitivity of calculated peak seismic dynamic responses such as acceleration and moment to input parameters such as damping and frequency. These responses were modeled and calculated for the Zion Unit 1 plant as part of the probabilistic risk assessment (PRA) performed by the U.S. NRC Seismic Safety Margins Research Program (SSMRP) and reported in "Application of the SSMRP Methodology to the Seismic Risk at the Zion Nuclear Power Plant," by M.P. Bohn et al, NUREG/CR-3428, UCRL-53483 (1983). The computer code SMACS developed under the SSMRP was used to perform the response calculations. The present sensitivity study builds upon these response results. The SSMRP was supported by the U.S. NRC Office of Nuclear Regulatory Research.

Two sensitivity topics motivated our study. In the first topic we studied the sensitivity of piping response to the mean value of piping damping. We studied damping sensitivity for 20 piping systems and for stiff and flexible support conditions. In the second topic we studied the sensitivity of structural and piping response to all earthquake and model input parameters (that is, not just damping) and identified important parameters. These results are required for another study: the sensitivity of seismic risk to these as well as other input parameters such as fragilities. The seismic risk sensitivity study is published as a separate report but the results from both response sensitivity topics are summarized in this report.

We are interested in the sensitivities because the inputs to the response calculations can change as a result of research or by changes we make to equipment and structures. Which input parameters have an important effect on the response and which do not? In the SSMRP the inputs have a random variability represented by a probability distribution. What is the effect of a change in the mean or variance of an input? Answers to questions of this type can be quite helpful in allocating research resources and in focussing efforts in safety and seismic PRA reviews. Our sensitivity analysis results can be used to answer these questions. We show how to do this for response in this report and for risk in a separate report.

We estimate the response sensitivities using linear regression analysis (LRA). A detailed model of the Zion plant and of the important dynamic processes is contained in the computer code SMACS. We have a data base of SMACS inputs and outputs from previous calculations. We perform a LRA on this data base to estimate the sensitivities. This provides us with average sensitivities: sensitivity of a response to an input given variability in all the other inputs.

Our LRA of the SMACS data base was successful: the residual variance is small--on the order of the input spectral variance. Where the total variation of the response is high the LRA model

explains most of the variance. LRA thus provides a simple description of the functional behavior of the complex SMACS computer model. This description is approximate but serves as an adequate overview. Subsequent effort may then concentrate on seeking the physical reasons for the main aspects of the complex seismic dynamic response of a plant.

One noteworthy conclusion, but not a striking one, is that the qualitative results change with the location of the individual response. This is especially the case for piping systems. This is an indication of the complexity of the seismic dynamic response of a plant. Different responses are in plant locations where the many potential influences have different effectiveness.

The soil damping has an influence on virtually all of the responses. This occurs because of the soil damping's influence on the soil surface acceleration. Previous work in the SSMRP analyzed the specific site's effect on the relationship between the bedrock seismic acceleration and the soil surface (free field) acceleration. The present study shows that the variability in the soil peak ground acceleration (PGA) is mainly due to the variability in the soil damping. Variability in the soil stiffness, by contrast, has little effect on the PGA, but it does have a substantial effect on the variability of the low frequency spectral response. Because of the soil damping's influence on the soil surface acceleration, it is not surprising that our separate risk sensitivity study showed that soil damping was the most important seismic risk related parameter.

Piping damping has variable importance ranging from none up to a modest degree. The degree of importance varies between piping systems and at locations within a piping system. At response locations where piping damping is important, piping frequency is important as well.

The largest coefficients of piping damping in the LRAs of piping responses were about -0.4 to -0.5. A coefficient of -0.5 for the logarithmic damping variable in the LRA model has the following meaning in terms of the linear input damping and response variables. If the median of the probability distribution of the piping damping random variable is increased by 100 percent (say from 0.02 of critical to 0.04 of critical) then the median of the response distribution is decreased by only 29 percent.

The largest coefficients of piping frequency in the LRAs are about -1.4. A coefficient of -1.4 for the logarithmic frequency variable in the LRA has the following meaning in terms of the linear input and response variables. If the median of the piping frequency variable's distribution is decreased by only 22% (that is, the nominal values of the fundamental and higher mode frequencies are decreased by 22%) then the median of the response distribution is decreased by 29 percent.

At some other response locations, neither piping variable is important, eg., at a valve near an anchor. At still other locations both have an importance intermediate between the highest values of zero.

Differences between piping systems have a noticeable effect on characteristics of the responses. Flexible piping systems, as contrasted to more rigid piping systems, have in general a higher variability in their responses, and have a greater number of response locations where the piping frequency and damping are important for those responses. Piping systems supported on or connecting to major equipment have in general a high variability in their responses. The major equipment items examined were the steam generator and the pressurizer, which are in themselves rather flexibly supported. A higher variability in responses usually brings a higher probability of component failure given an earthquake.

The LRAs helped identify the reason for the large variability of some piping moment responses and these responses' high sensitivity to piping frequency. In this case the reason was an unintended artifact from the way SMACS models the random variability of inputs. The variability of piping frequency was modeled as arising from variability in piping stiffness rather than from variability in piping mass or other characteristics. This caused a larger than intended variability in the piping pseudostatic moment, i.e., the moment from relative displacement of supports. This modeling feature could easily be adjusted in a future version of SMACS. The variability in piping acceleration responses is not affected by this modeling choice.

There are numerous piping examples where the soil, structure, or piping variables have a large influence on a piping response. For some of the piping responses many of the potentially influential inputs have a large influence. Heavy equipment modeled with the structure model, e.g., the pressurizer and steam generators, has a large influence on piping attached to the equipment.

A ranking of the input variables was based on a measure using the largest influence of the variable on any piping response combined with the estimated random variability of that variable. A comparable measure was estimated for the bedrock seismic input. Then a rank ordering was developed by combining the two input variables of each input area--seismic input, soil, structures, major equipment, and piping.

The resulting importance measures for each input area are fairly close, recognizing the uncertainty band in estimation. There is a close tie for maximum contribution from three input areas--soil, major equipment (where applicable), and piping. Seismic input ranks a close fourth, and structures fifth but still significant in contributions to some piping response variances.

In a limited study of the effect of support stiffness, we find that a modeling change from very high values of support stiffness to more realistic values reduces the piping system modal frequencies by as much as 10 percent. This change is expected to increase some responses by up to 15 percent. These changes are small compared to the total variability present.

Future attention should be focused on frequency variability in piping and in heavy equipment to which piping is attached. First, the SSMP's estimates of frequency variability should be validated. Second, it may be worthwhile to develop methods that accommodate a larger piping frequency variability, for use in piping design and in design-checking stress analysis.

The linear regression model can be used as a substitute for the SMACS model in doing propagation of uncertainty and in studies of sensitivity to input uncertainties. In such studies numerous calculations of uncertainty propagation must be carried out with different assumptions on the input uncertainties. The substitute model will speed up calculations and, thus, allow larger samples and more tests of more input assumptions. A cautionary note is the possibility of introducing a new modeling uncertainty.

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1. INTRODUCTION

We address two sensitivity topics in the dynamic response of structures and equipment to earthquakes in this report. We do this by using linear regression analysis to develop simpler models of the response, based on a detailed model embodied in the computer code SMACS.

Two sensitivity topics motivated this study. The first topic is the sensitivity of piping response to the mean value of piping damping, and how this sensitivity may differ for different piping systems, e.g., flexible or fairly stiff as a result of the support placement design. The second topic is the sensitivity of all the responses to the earthquake and model inputs. This topic is a required part of a larger topic, the sensitivity of the total plant system response (in terms of risk or of probability of release of radioactive material); this latter question is covered in another report¹².

The larger context of these sensitivity questions is the seismic risk at a nuclear power plant. The Seismic Safety Margins Research Program (SSMRP) addresses this issue. The SSMRP is a U.S. NRC funded multiyear program conducted by Lawrence Livermore National Laboratory (LLNL). It has developed a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of an earthquake-induced radioactive release from a commercial nuclear power plant. The analysis procedure is based on a state-of-the-art evaluation of the current seismic analysis and design process and explicitly accounts for uncertainties inherent in such a process.

The SMACS code (Seismic Methodology Analysis Chain with Statistics)¹⁰ computes the dynamic response of structures and equipment; see Figs. 1-1 and 1-2. It has two levels. Its core is a deterministic calculation of the response to a specific input. The model includes process models--for local site effect, soil-structure interaction, structural dynamics, and multiply supported subsystem dynamics--and input models of a specific site, structures, and piping systems. On an outer level, the code models the fact that the input earthquake and model parameters are variable and, hence, the responses are variable. The SMACS outer level represents key input parameters as random variables with specified probability distributions. It calculates the

Figure 1-1. SMACS calculates the dynamic response of structures and equipment to an earthquake. SMACS models the local site effect, soil-structure interaction, structural response and subsystem response. SMACS models random variability by statistical procedures.

Figure 1-2. The SMACS code (Seismic Methodology Analysis Chain with Statistics) has a deterministic calculational model at its core, and a statistical model to represent the variability of inputs and outputs. The inputs and outputs of SMACS are probability distributions of random variables. The inputs are described by means and variances (and covariances if necessary). The outputs are described by the means, variances and covariances of the responses or by a sample of vector responses.

distribution of response by repeated sampling from the inputs and calculating through the inner loop. To answer sensitivity questions, we desire simple approximate models of the more complex SMACS model at both its inner and outer levels.

Using linear regression analysis, we develop a simple model of the SMACS inner level; see Fig. 1-3 and Section 2 below. We then analytically develop a simple model for the SMACS outer level based on the inner level model; see Fig. 1-4. This development and the application to the two sensitivity questions are the subjects of this report.

Linear regression operates on an input-output data sample. Conveniently, we have a sample of the SMACS inner level input and output generated by its outer level to compute response distributions. Thus, the analysis of variance for this sample of responses has some special interest, in addition to the use of the sample in evaluating the parameters of the simpler models.

1.1 OUTLINE

In Section 2 we review the principles of linear regression analysis (LRA) and develop the equations for our application. These equations are simpler than in a general case due to properties of the input distributions.

Our LRA is done on a detailed model of the dynamic response, embodied in the computer code SMACS. In Section 3, we briefly review the SMACS computation methods. We then present the Zion plant models and model parameters which were inputs to the SMACS calculations. These models and calculations are the same as in Ref. 11.

In Section 4 we present two LRA examples. The first example is the peak and spectral acceleration responses at the site soil surface. This example is simple in that the response can be modeled as a function of only two input variables. The second example is the acceleration at a piping valve. This example illustrates the complexity realized in some cases. This response is a function of ten input variables and shows a significant dependence on six of these ten variables.

Figure 1-3. The linear regression analysis (LRA) treats the SMACS core as a "black box." By examining a set of input-output pairs the LRA produces an "explicit box" which models the behavior of the black box as closely as possible. See text, Equation II.

Figure 1-4. The product of the LRA can be used as the inner box of a statistical model to generate an explicit outer box which parallels the SMACS outer box. Given a specification of the input distributions and given an explicit inner box, the output distribution is in principle determined. The output distribution is evaluated by the method of propagation of moments.

In Section 5 we present an overview of the results for all the response locations evaluated in the dynamic response calculations. We point out the diversity of responses at different locations, and the characteristics and trends observable within this diversity. We examine the piping responses and their dependence on piping damping and frequency variables. We do LRAs of additional input-output data sets to further analyze the influence of piping damping.

In Section 6 we regroup the piping response results. We examine how the characteristics of the ensemble of responses depend on properties of the piping system. System properties distinguished among different piping systems are (1) stiff versus flexible piping systems, and (2) nature of supporting base, e.g., on one concrete base, on two structures, or on large equipment plus structures.

In Section 7 we examine the influence of modeled stiffness of piping supports. In Section 8 we develop a measure to rank the input variables by their importance to piping response values. Section 9 draws together the conclusions and recommendations.

2. LINEAR REGRESSION ANALYSIS

In this Section we review some applications of linear regression analysis (LRA) in Section 2.1, state what LRA is, (Section 2.2), adapt our problem data to a form to make effective use of LRA (Section 2.3), and outline the development of the results we need (Sections 2.3-2.6).

In adapting SMACS inputs and outputs, we take their logarithms and then shift the inputs to zero mean values. Thus, we treat an output Y , which is the logarithm of the SMACS response, and inputs X_i which are logarithms of the SMACS inputs. In these terms, the results we develop are:

- (1) a linear regression model for Y as a function of the X_i
  - (2) sensitivity of Y to X_i
  - (3) analysis of variance of Y for our sample
  - (4) a model of the output mean $\bar{Y}$ and variance ($\text{Var } Y$) as functions of $\bar{X}_i$ and $\text{Var } X_i$
  - (5) sensitivity of $\bar{Y}$ and $\text{Var } Y$ to $\bar{X}_i$ and $\text{Var } X_i$, based on the model in (4).
- In our application the X_i are independent normally distributed random variables. Hence for items (4) and (5) we need only the first two moments $\bar{X}$ and $\text{Var } X_i$ of the input variables.

In later Sections we will develop numerical results for items (1), (2), and (3). The corresponding numerical results for (4) and (5) are closely related as we will see in the equations below in this section. We will express numerical results for items (4) or (5) only for a few responses with special interest.

2.1 PREVIOUS APPLICATIONS

Linear regression analysis¹ has frequently been used to model the input-output relationships of more complex mathematical models,²⁻⁷ a use analogous to its more traditional use in modeling the input-output relationships of experimental or field data (e.g., Ref. 8).

Marshall et al.⁶ applied linear regression analysis to the RELAP code, a thermal-hydraulic code which they were using to compute the cladding temperature of an electric heating rod in an experiment. They analyzed

temperature at a given time as a function of the logarithms of input variables, using linear and quadratic terms, to get a linear regression model. To compute the variance of output temperature for given variances of the input variables, they used an outer level with Monte Carlo sampling and calculating through their linear regression model.

Lucia et al.⁷ examined the inelastic response of piping in an earthquake. They used a response calculation method involving an inelastic response spectrum and the piping modal vibrations. They developed a linear regression model of this calculation method. Then to compute the variance of output piping response for given variances of the input variables, they used a similar sampling approach to that of Marshall et al.

An algebraic equation is an alternative to sampling for analysis of the propagation of variance. For the case of an arbitrary second order model (i.e., including terms for $X_i X_j$) and input and output distributions described by their first four moments, the algebraic equations can be lengthy.¹⁸ The model we arrive at below has only one second order term and has normal distributions for inputs, leading to shorter algebraic equations for the moments of the output distribution.

2.2 LINEAR REGRESSION BASICS

Linear regression analysis is a well established methodology. We include a brief review here for ready reference. We use matrix algebra and concepts of vector spaces. We have a functional relationship (unknown) between inputs X_i and an output Y :

$$Y = g(X_1, X_2, \dots, X_M) + e \quad (1)$$

where g is a deterministic, but unknown function and e is a random variable with mean zero, representing the effect of unknown variables plus any random influence on the output Y .

We wish to model this relationship with a model $\hat{Y}$:

$$\hat{Y} = \sum_{j=1}^P \beta_j Z_j(X_i) \quad , \quad (2)$$

where the Z_j are functions of the X_i and β_j are coefficients to be determined (see Fig. 1-3).

$$Y = \hat{Y} + \xi \quad , \quad (3)$$

where ξ is the residual, due to the random error e plus any systematic lack of fit between $\hat{Y}$ and Y . Note that $\hat{Y}$ is a linear function of the β_j .

As information about the functional relationship, we have a sample of N input-output pairs

$$\{Y_k; X_{k1} \dots X_{ki} \dots X_{kM}\} \quad \text{for } k = 1, 2, \dots, N \quad .$$

We estimate the coefficients β_j to get an estimator $\hat{Y} = \sum \beta_j Z_j$ that minimizes some function of the residuals ξ_k over the sample.^{1,3} We minimize the sum of squares:

$$SSE = \sum_{k=1}^N \xi_k^2 = \underline{\xi}^T \cdot \underline{\xi} \quad , \quad (4)$$

where $\underline{\xi}$ is the vector of residuals and T indicates the transpose of a vector or matrix.

The least-sum-of-squares criterion is selected because it leads to a mathematically convenient solution for the coefficients $\underline{b}$. The elements of $\underline{b}$ are linear functions of the observed outputs $Y_1, Y_2, \dots, Y_N$, and provide unbiased estimates of the elements of $\underline{\beta}$ which have the minimum variances (among any linear functions of the Y s which provide unbiased estimates).¹³ If the residuals ξ_k are independent random variables and have identical normal distributions, then $\underline{b}$ found by the least-squares criterion on $\underline{\xi}$ is also the maximum likelihood estimator of $\underline{\beta}$.¹⁴

For any b_j , when minimizing

$$\underline{\underline{E}}^T \cdot \underline{\underline{E}} = (\underline{\underline{Y}} - \hat{\underline{\underline{Y}}})^T \cdot (\underline{\underline{Y}} - \hat{\underline{\underline{Y}}}) \quad , \quad (5)$$

we will have

$$\frac{\partial(\underline{\underline{E}}^T \cdot \underline{\underline{E}})}{\partial b_j} = 0 \quad . \quad (6)$$

This gives

$$\underline{\underline{Z}}_j^T \cdot \underline{\underline{E}} = 0 \quad \text{for } j = 1, 2, \dots, P \quad (7)$$

where the vectors are over the number of members in the sample. That is, $\underline{\underline{E}}$ is orthogonal to each input $\underline{\underline{Z}}_j$. Substituting with $\underline{\underline{E}} = \underline{\underline{Y}} - \hat{\underline{\underline{Y}}} = \underline{\underline{Y}} - \underline{\underline{Z}}\underline{\underline{b}}$ we have P equations in the P unknowns b_j . These can be solved with matrix algebra.¹

Finally we have

$$\begin{aligned} \underline{\underline{Y}} &= \hat{\underline{\underline{Y}}} + \underline{\underline{E}} \\ &= \sum_{j=1}^P b_j \underline{\underline{Z}}_j + \underline{\underline{E}} \quad . \end{aligned} \quad (8)$$

The b_j are estimates of β_j based on the sample $\{\underline{\underline{Y}}; \underline{\underline{X}}_i\}$. The $\underline{\underline{Z}}_j$ form a P-dimensional subspace. $\hat{\underline{\underline{Y}}}$ is the projection of $\underline{\underline{Y}}$ on this subspace, and $\underline{\underline{E}}$ is orthogonal to this subspace.

2.3 OUR APPLICATION

We can adapt our input and output variables to make more effective use of LRA. For example, we can take logarithms or other one-to-one functional transformations of each variable, before we try a linear fit as per Equation 2.

By "effective use of LRA" we mean the following. The LRA will use all of the supplied input-output data in estimating the coefficients β_j of Equation 2. We wish to set up the form of the model $\hat{\underline{\underline{Y}}}$ in Equation 2 so that the fit to the data will be fairly good (i.e., have a low unexplained variance; see Section 2.5) and so that there will not be an appreciable systematic lack of fit over the domain of the supplied input data.

Our problem has the primary input variables V_i which represents the peak ground acceleration (PGA) of the free field input earthquake, frequency multipliers for a structure or piping system, and damping multipliers for the soil, a structure, or a piping system. The full list of input variables is discussed in Section 3.2 below. The output is the response R , either acceleration or piping moment at a specific location in the plant.

We take logarithms of our input V_i and output R before doing the LRA. We do this for two reasons. First, for at least some of our input variables V_i we expect that the response is proportional to a power of the input. For example, we expect that response will be proportional to the input ground acceleration. We can convert a power-law function to a linear function of the form of Equation 2 by taking logarithms. The second reason is that the V_i and R are always positive or absolute values. To be compatible with linear analysis we need input and output variables which don't have bounds on their domains. Logarithms of our original variable will satisfy this. The effectiveness of the logarithmic transformations in leading to a good LRA fit is only a trial assumption to be checked in the results. Plots of residuals versus input variables for typical results (Section 4) show no identifiable trends of systematic lack-of-fit.

Hence for applications of LRA, the output is

$$Y = \ln R$$

The inputs are transformed in two steps: taking logarithms and shifting means:

$$X_i = \ln V_i - \overline{\ln V_i}$$

Then X_i has a mean of zero. This linear shift of $\ln V_i$ by $\overline{\ln V_i}$ is equivalent to normalizing V_i to V_i/V_{i0} where $V_{i0} = \exp(\overline{\ln V_i})$.

Now we can apply the LRA model of Eqs. (2) and (3). The Z_j of Eq. (2), functions of these X_i , will include a constant term, linear terms, and for

piping responses also a term X_{fp}^2 , where X_{fp} is the variable transformed from the piping system frequency multiplier. In summary, for a response we use the model

$$Y = b_0 + \sum_j b_j X_j + b_{fp}^2 X_{fp}^2 \quad (9)$$

b_0 is the nominal value of the output Y , that is, the value when all the inputs X_j are at their average values.

Note that we have two notations for subscripts. The first notation has subscript j representing a number, when we enumerate the variables X_j and their coefficients by b_j . The second notation has symbols as subscripts. For example, b_{D_I} is the coefficient of the term X_{D_I} , where subscript D_I identifies the variable as that for the damping of the containment internal structure. See Table 3.4 for the list of variables in our application and their symbols. For subsystem (piping system) variables, in the notation X_{fp} and X_{dp} the sub-subscript p means "piping" and refers to whatever piping system has as influence on that response. Most piping responses are dependent on the variables of only one piping system. b_{fp} is the coefficient of X_{fp} and b_{fp}^2 is the coefficient of $(X_{fp})^2$. (In Sections 5 and following we will omit X and write f_p to refer to the logarithmic variable X_{fp} .)

Since we have the full SMACS model, we know that the responses depend only on subsets of the input variables. For example, the structural responses depend on the PGA and the soil and structural variables, but not on any piping variables. The full list which limits the possible dependences is given in Table 3-7 in Section 3.

2.4 SENSITIVITY

As the sensitivities of the response to the inputs we use the coefficients b_j , which are the partial derivatives of the model $\hat{Y}$

$$\left. \frac{\partial \hat{Y}}{\partial X_j} \right|_0 = b_j \quad (10)$$

Since these b_j come from the linear model developed over the full sample of input-output data, they represent the sensitivity to an input averaged over the sample range of the other input variables.

2.5 ANALYSIS OF VARIANCE

We are interested in how much of the variance of the sample $\underline{Y}$ is explained by the model $\hat{\underline{Y}}$. We denote the sample mean by the scalar $\bar{Y}$ and the sample variance by $\text{Var } Y$:

$$\text{Var } Y = \frac{1}{N-1} \sum_{k=1}^N (Y_k - \bar{Y})^2 = (\underline{Y}^T \cdot \underline{Y} - \bar{Y}^2)/(N-1) \quad (11)$$

For convenience in interpreting the following analysis of variance, here we will shift all the values in the sample $\{Y_k\}$ by their mean, to get a zero mean sample. Then, when we do a regression analysis, we will get a new $\{\hat{Y}_k\}$, where the coefficients b_j are all the same as previously except for the constant. The mean of $\{\hat{Y}_k\}$ will also be zero, since $\{Y_k\}$ and $\{\xi_k\}$ now have zero means. Then, the variance will be the sum of squares divided by the number of degrees of freedom.

The analysis of the sum of squares is given in Table 2-1. In general,

$$\underline{Y}^T \cdot \underline{Y} = \hat{\underline{Y}}^T \cdot \underline{Y} + \underline{\xi} \cdot \underline{Y} \quad (12)$$

With the residual-sum-of-squares minimization criterion, $\underline{\xi}$ is orthogonal to $\hat{\underline{Y}}$. Hence, Eq. (12) simplifies to

$$\underline{Y}^T \cdot \underline{Y} = \hat{\underline{Y}}^T \cdot \hat{\underline{Y}} + \underline{\xi}^T \cdot \underline{\xi} \quad (13)$$

That is, the sum of squares of the estimator $\hat{\underline{Y}}$ is always somewhat less than the original total sum of squares of $\underline{Y}$, by an amount equal to the sum of squares of the residuals $\underline{\xi}$.

Table 2-1. Analysis of sum of squares.

SOURCE	SOURCE VECTOR	SUM OF SQUARES	DEGREES OF FREEDOM
Total	$\underline{Y}$	$\underline{Y}^T \bullet \underline{Y}$	N
Regression Model	$\hat{\underline{Y}}$	$\hat{\underline{Y}}^T \bullet \underline{Y} = \hat{\underline{Y}}^T \bullet \hat{\underline{Y}}$	P
Residual	$\underline{\xi}$	$\underline{\xi}^T \bullet \underline{\xi} = \underline{Y}^T \bullet \underline{Y} - \hat{\underline{Y}}^T \bullet \underline{Y}$	N-P

2.6 PROPAGATION OF VARIANCES

A common problem in engineering and science arises in a situation where we have a deterministic model relating inputs to an output. We may believe the model to be quite accurate; however, our inputs are uncertain, either because of their inherent randomness or our limited knowledge. Accordingly, we treat these inputs as random variables. The output is then a random variable whose variance arises from the variances of the inputs. That is, from a function

$$Y = f_1(\dots X_i \dots) \quad (14)$$

there naturally arises a corresponding function

$$\text{Var } Y = f_3(\dots \mu_i \dots \text{Var } X_i \dots) \quad (15)$$

where μ_i is the mean of X_i . In the general case higher moments and cross moments of the inputs are required in f_3 . See for example Ref. 18. In our case with independent normally distributed variables X_i , the first two moments are sufficient. For completeness, we consider also the mean

$$\mu_Y = f_2(\dots \mu_i \dots \text{Var } X_i \dots) \quad (16)$$

The first question is, given the function f_1 in Eq. (14), and given variances $\text{Var } X_i$, then what is $\text{Var } Y$? That is, how do we evaluate f_3 in Eq. (15) for one set of input values? Further questions, developed in some applications, relate to mapping out more information on the function f_3 . For example, if the inputs $\text{Var } X_i$ change, then how much does the output $\text{Var } Y$ change? And which inputs $\text{Var } X_i$ are most important in determining the value of $\text{Var } Y$?

The substance of the first question is called propagation of variance or propagation of error. There are several methods to get an approximate answer. One method uses sampling of inputs, calculation of Eq. (14) for each member of the input sample, and then computing the sample variance of the output values.^{9,10,16} The input sample may be selected by stratified random

sampling,^{9,10} Monte Carlo sampling, or systematic sampling.¹⁶ In the SSMRP we used Latin hypercube sampling, one stratified random sampling method. A second method involves finding a simpler model to approximate $f_1(\dots X_i \dots)$, and then performing the above sampling method, using the simpler model to compute the sample of outputs.^{6,7} Linear regression analysis is one way to develop the simpler model; it requires a certain number of calculations of the full model, but fewer than in the later calculation of variance by sampling. A third approach does not use sample propagation, but uses an analytical formula to relate the moments of the output probability distribution to the moments of the input distributions.^{17,18} This requires the partial derivatives of f_1 [Eq. (14)] with respect to the inputs X_i . Up to second order, fourth moment approximations have been developed.¹⁸ The partial derivatives constitute a simpler model of $f_1(\dots X_i \dots)$, i.e., a Taylor series expansion or a response surface approximation. The partial derivatives may be evaluated numerically either by evaluating $f_1(\dots X_i \dots)$ at selected input values X_i and $X_i + \Delta X_i$, or by evaluating $f_1(\dots X_i \dots)$ on a larger sample of inputs and doing a linear regression analysis. We follow this last approach--developing partial derivatives using a sample, and then propagating moments from the input distributions as in Ref. 18.

We then evaluate the models of μ_Y and $\text{Var } Y$ as functions of μ_i and $\text{Var } X_i$, implied in Eqs. (15) and (16), by using the approximation to our f_1 given in Eq. (9). (Refer to Fig. 1-4. Equation (9) is the model in the inner box. Using that and the input distributions, the output distributions are evaluated.) We estimate the coefficients b_i using a data set which has $\mu_i = 0$. We are interested in how μ_Y and $\text{Var } Y$ depend on inputs μ_i and $\text{Var } X_i$ which may be different from the earlier values. The following model has a range of validity only over small changes of μ_i and $\text{Var } X_i$, small enough so that the values of X_i which would be sampled from the modified probability distribution of X_i mostly lie within the domain of the original data set used to estimate the coefficients b_i .

The mean μ_Y (expected value) and the variance $\text{Var } Y$ are then

$$\mu_Y = b_0 + \sum_i b_i \mu_i + b_f \left(\mu_f^2 + \text{Var } X_{fp} \right) \quad (17)$$

$$\text{Var } Y = \sum_i C_{Yi} + \text{Var } \xi \quad (18a)$$

where C_{Yi} , the summand depending on the distribution of variable X_i , is:

. for $i \neq f_p$:

$$C_{Yi} = b_i^2 \text{Var } X_i \quad (18b)$$

. for $i = f_p$:

$$C_{Yi} = (b_{f_p} + 2 b_{f_p}^2 \mu_{f_p})^2 \text{Var } X_{f_p} + 2(b_{f_p}^2)^2 (\text{Var } X_{f_p})^2 \quad (18c)$$

In reaching Equation 15 we made use of a property of the normal distribution of the X_i . In Equation 18c we use further properties of the normal distribution: odd central moments are equal to zero and the fourth central moment δ_{f_p} is equal to

$$\delta_{f_p} = 3(\text{Var } X_{f_p})^2 .$$

We can use the model of μ_Y and $\text{Var } Y$ as given in Eqs. (17) and (18) to determine the partial derivatives with respect to μ_i and $\text{Var } X_i$. For example, for $i \neq f_p$, where we have only a linear term, we find

$$\frac{\partial \mu_Y}{\partial \mu_i} = b_i , \quad (19)$$

where b_i is the same b_i as in Eq. (9). We will use this result in Section 6.2 when examining the sensitivity of a piping response (single value or mean) to the piping damping (input value or mean, respectively). Also for $i \neq f_p$, we find

$$\frac{\partial \text{Var } Y}{\partial \text{Var } X_i} = b_i^2 \quad (20)$$

These partial derivatives are used in a separate study examining how $P[\text{release}]$, the probability of radioactive release, is sensitive to μ_i and $\text{Var } X_i$ ¹². The program SEISIM¹⁹ computes $P[\text{release}]$, which depends on the response distribution statistics μ_Y and $\text{Var } Y$ as well as on fragility statistics and on other information. $P[\text{release}]$ is thus sensitive to μ_Y and $\text{Var } Y$, which are in turn sensitive to μ_i and $\text{Var } X_i$. The chain rule can be used to evaluate the sensitivity of $P[\text{release}]$ to μ_i and $\text{Var } X_i$.

3. MODELS AND METHOD OF DYNAMIC ANALYSIS

The methods and models we used are the same as those used in the SSMRP on-line calculations.¹⁰ We describe these methods and model here very briefly.

3.1 RESPONSE COMPUTATION METHODS

The amplitude and frequency content of earthquake motions at the site are influenced by the soil column at the site (110 feet at the Zion site). To take this influence into account, first the earthquake motions are those predicted for a rock site. Assuming vertically propagating waves, this motion then determines the rock motion at a depth of 110 feet (which is essentially the same as at the rock surface, since, at the relevant frequencies, 110 feet is much shorter than one wavelength in the rock). Then this rock motion at depth is propagated up through the soil column to the site surface.

The earthquake motion is further modified by the presence of massive structures. The continuum linear analysis method, in combination with a substructure approach, is used in the soil-structure interaction and structural response parts of our analysis.¹⁰ The computation relies on the computer code CLASSI. The process starts with the calculation of the modal characteristics of fixed-base structures and the calculation of foundation impedance and scattering matrices. Modal superposition can then be used to calculate the dynamic response at any point within the structure. For piping systems, a modal time-history analysis with multisupport input motions was used.¹⁵ For example, for the auxiliary feed water system model inside containment, each of the analyses used 45 different support input motions.

3.2 DYNAMIC ANALYSIS MODELS

The Zion Nuclear Power Plant, north of Chicago, Illinois, (Fig. 3-1) was the subject of this study. The containment building and auxiliary building were included in the soil-structure interaction. The containment building (Fig. 3-2) comprises two separate structures on a common base mat--a prestressed containment shell and a concrete internal structure, which

Figure 3-1. Site plan of the Zion nuclear power plant.

Figure 3-2. Cross section of the containment building at Zion, showing the approximate extent of embedment.

supports a four loop PWR nuclear steam supply system (NSSS). The model for the containment building, which includes these two structures and the NSSS, is a finite element model with 3937 equations. The auxiliary building is approximately symmetrical about a plane dividing units 1 and 2; the half-structure finite element model has 3888 equations. The portion of the model on one side of the plane of symmetry is shown in Fig. 3-3.

The soil medium was represented by three horizontal layers over a relatively stiff half space. The upper two layers have nominal shear-wave velocities of less than 900 ft/s. These two layers constitute the total embedment depth of 36 feet. The third layer, 75 feet thick, has a shear-wave velocity of 2,390 ft/s. The soil was assumed to be viscoelastic. The bedrock has a shear-wave velocity of 9,000 ft/s.

Twenty piping systems were examined, see Table 3-1. In general, the piping systems were multiply supported on one or more structures and attached to major equipment, such as the steam generators or pressurizer (which were included in the containment internal structure model). For piping in the crib house, the structure motion was taken to be the same as the free-field surface motion. Some of the piping system characteristics are listed in Table 3-2. One piping system is illustrated in Fig. 3-4.

The responses calculated are peak and spectral accelerations (at the free-field soil surface, the containment foundation, and at various locations in the three structures), accelerations of piping valves, and moments of pipes in piping runs. The latter are maxima over the moments calculated at a number of points in a piping run. The response types and locations are listed in Table 3-3.

There is a variability in future earthquakes and in the soil, structure and piping properties. We represent this variability by using a sample of earthquake time histories (at the rock outcrop surface) and by treating key parameters in the soil, structure, and piping models as random variables. The seismic hazard curve is discretized into six intervals. A sample of time histories is generated for each interval. The key variables and their coefficients of variation (CV) are listed in Tables 3-4 and 3-5. Their

Figure 3-3. Finite element model of a portion of the auxiliary building.

Table 3-1. Structures and piping systems in the dynamic analysis.

STRUCTURES	
1	Containment shell, Unit 1
2	Containment internal structure, Unit 1
3	Auxiliary-fuel-turbine building (AFT)
4	Containment shell, Unit 2
5	Containment internal structure, Unit 2
SUBSYSTEMS (Piping Systems)	
1	Charging water pump discharge
2	Pressurizer relief lines
3	AFW inside containment (to steam generator 1A)
4	AFW outside containment
5	SW pump discharge
6	SW strainer
7	SW to AFW pump
8	RHR pump discharge
9	RHR pump suction
10	RHR/SI 1
11	RHR/SI 2
12	Charging water discharge--boron injection tank to containment
13-14	RCL including branch lines
15	Feedwater and AFW, SG-1B to containment penetrations
16	Feedwater and AFW, SG-1C to containment penetrations
17	Feedwater and AFW, SG-1D to containment penetrations
18	SG-1A steam to containment penetration P5
19	Steam outside containment from P5 to safety valve manifold, aux. main steam
20	Steam to turbine driven AFW pump 1A
21	Main steam from SG-1A and SG-1D to containment penetration

Table 3-2. Important dynamic characteristics for the 20 piping models.

NO.	DESCRIPTION	FUNDAMENTAL FREQUENCY (Hz)	NO. OF MODES CONSIDERED	STRUCTURES TO WHICH ATTACHED	NO. OF SUPPORT MOTIONS
1	Charging pump discharge	3.2	87	1,3	35
2	Pressurizer relief lines	3.5	34	2	28
3	AFW SG-1A to containment	2.9	36	1,2	45
4	AFW outside containment	3.2	93	1,3	47
5	SW pump discharge	12.9	20	CrH ^a	3
6	SW strainer	16.0	7	CrH	3
7	SW to AFW pump	2.0	57	3	44
8	RHR pump discharge	9.8	10	3	10
9	RHR pump suction	4.3	32	1,2,3	33
10	RHR and SI-1	3.9	18	2,3	21
11	RHR and SI-2	2.7	115	1,3	49
12	Boron inj. tank to containment	9.1	8	1,3	14
13-14	RCL and branch lines	1.4	130	2	127
15	AFW SG-1B to containment	3.5	50	1,2	57
16	AFW SG-1C to containment	2.2	35	1,2	51
17	AFW SG-1D to containment	2.1	45	1,2	51
18	SG-1A steam to containment	9.7	9	1,2	21
19	SG-1A steam outside containment	5.0	12	1,3	24
20	Steam to turbine AFW pump 1A	5.4	23	1,2,3	32
21	Main steam 1A and 1D	2.9	50	1,2,3	58

^a CrH = crib house

Figure 3-4. Model of the auxiliary feedwater piping system inside containment to steam generator 1A.

Table 3-3. Response numbers, types, and locations.

RESPONSE NUMBERS	LOCATION OR SUBSYSTEM NUMBER	TYPE
1-4	Soil free-field	Acceleration
5-8	Foundation no. 1	Acceleration
9	Structure 1 (Containment Shell)	Acceleration
10-16	Structure 2 (Containment Internal)	Acceleration
17-52	Structure 3 (AFT Building)	Acceleration
53-70	1	Acceleration
71-77	2	Acceleration
78	3	Acceleration
79-103	4	Acceleration
104-111	5	Acceleration
112-117	6	Acceleration
118-130	7	Acceleration
131-139	8	Acceleration
140-147	9	Acceleration
148-149	10	Acceleration
150-170	11	Acceleration
171-172	12	Acceleration
173-189	13	Acceleration
190	15	Acceleration
191	16	Acceleration
192	17	Acceleration
193-194	19	Acceleration
195-196	20	Acceleration
197-200	21	Acceleration
201-214	1	Moment
215-220	2	Moment
221	3, 4	Moment
222	3	Moment
223-233	4	Moment
234-235	5	Moment
237, 239	5	Moment
236, 238	5, 6	Moment
240-244	6	Moment
245-268	7	Moment
269-271	8	Moment
273-271	8	Moment
272	8, 10, 11	Moment
275-280	9	Moment
281	10	Moment
282-302	11	Moment
303-306	12	Moment
307-324	13	Moment
325-326	15	Moment
327-328	16	Moment
329-330	17	Moment
331	18, 19	Moment
332	19, 20, 21	Moment
333	21	Moment

Table 3-4. Key input variables. Variables 37-40 for RCL piping were set equal to variables 5 and 6 for the containment internal structure.

NO.	SYMBOL	VARIABLE
1	G_S	Soil shear stiffness
2	D_S	Soil damping
3	F_C	Frequency, structure 1
4	D_C	Damping, structure 1
5	F_I	Frequency, structure 2
6	D_I	Damping, structure 2
7	F_A	Frequency, structure 3
8	D_A	Damping, structure 3
9	F_4	Frequency, structure 4
10	D_4	Damping, structure 4
11	F_5	Frequency, structure 5
12	D_5	Damping, structure 5
13	f_1	Frequency, subsystem 1
14	d_1	Damping, subsystem 1
15	f_2	Frequency, subsystem 2
16	d_2	Damping, subsystem 2
.	.	.
.	.	.
.	.	.
53	f_{21}	Frequency, subsystem 21
54	d_{21}	Damping, subsystem 21
55	PGA	Free field (soil) PGA

Table 3-5. Coefficients of variation (CV) for key input variables.

Variables(s)	CV
G_{soil}	0.40
D_{soil}	0.50
$F_{structures}$	0.25
$D_{structures}$	0.35
f_{piping}	0.25
d_{piping}	0.35

probability distributions are assumed to be lognormal. The median values of excitation-sensitive parameters, such as soil shear modulus and damping, and subsystem and structural damping, change with each acceleration range; these are listed in Table 3-6. The structural and piping system nominal frequencies were computed by a SAP4 mode shapes run, keeping all modes up to 33 Hz. Each structure and piping system has two variables, frequency and damping. The frequencies for all modes in a system are considered to vary by the same amount, and a similar assumption is made for the damping values for all modes.

One kind of uncertainty is not included, namely uncertainty arising from limited knowledge of the true distributions of variables and limitations in our modeling of the structures, etc., and of the dynamic processes. This kind of (modeling) uncertainty is treated elsewhere.

The piping systems, with the exception of the RCL primary loop, were not included in the structure models. Hence, the structures' dynamic response behavior in SMACS is not dependent on the piping system parameters. Also, each piping system response does not depend on other piping system parameters. The RCL primary loop was included in the internal structure model. For piping analysis, the same loop with a more detailed model, and with branch lines included, was used. In the variation of parameters to be considered below, the internal structure and RCL piping parameters were kept consistent.

Using the above models and input characterizations, several series of SMACS runs have been done in the SSMRP¹¹, which provide input-output sample data bases for linear regression analyses.

For our analyses, we use a series of SMACS runs for six earthquake intervals, including the local site effect and incorporating random variability. There were 30 input-output calculations in each earthquake interval. In 3 structures and 20 piping systems, 333 response locations were calculated. (There are 1,160 more localized responses from which the 333 responses are aggregated. A structural response is the maximum of responses in the X, Y, and Z directions. A piping moment response is the maximum of responses at locations along a pipe run, usually one connected segment between

Table 3-6. Earthquake intervals and nominal (median) values of variables. Frequency nominal values do not change with earthquake interval. Soil values listed are those for layer 3.

EARTHQUAKE INTERVAL	ROCK PGA RANGE ^a	NOMINAL G _{SOIL}	NOMINAL D _{SOIL}	NOMINAL D _{STRUCTURE}	NOMINAL D _{STRUCTURE}	NOMINAL D _{STRUCTURE}	NOMINAL D _{PIPING}
NO.	(g)	(10 ⁶ psf)		(Containment Shell)	(Internal Structure)	(AFT Complex)	
1	0.06-0.10	8.70	0.043	0.020	0.020	0.020	0.020
2	0.10-0.20	8.35	0.049	0.030	0.022	0.036	0.024
3	0.20-0.32	7.54	0.062	0.040	0.024	0.052	0.028
4	0.32-0.42	6.85	0.072	0.050	0.026	0.068	0.032
5	0.42-0.53	6.51	0.076	0.060	0.028	0.084	0.036
6	0.53-0.69	5.83	0.084	0.070	0.030	0.100	0.040

^a At the Zion site the soil surface PGA averages roughly twice the rock PGA, but depends on the soil damping as well. The Zion design PGA of 0.17g is thus in earthquake interval no. 1 near its upper end. The probability of exceedance of this PGA value is estimated at 5×10^{-4} per year (Ref. 11, Section 3.3.2).

valves or equipment.) A separate linear regression analysis was done for each of the 333 responses. The input variables used in the analysis of each response are listed in Table 3-7, as based on the possible dependences noted two paragraphs above.

Table 3-7. Input variables used in the linear regression analyses. "PGA" refers to Response 1, the PGA at the soil surface.

RESPONSE NO.	INPUT VARIABLES
2-4	PGA, 1,2
5-52	PGA, 1-8 ^{a,b}
53-172, 190-306, 325-333	PGA, 1-8, ^{a,b} plus two for each applicable subsystem from Table 3-1
173-189, 307-324	PGA, 1-8 ^{a,b} (No. 5 and 6 serve as the piping variables for the RCL Piping)

^a For variable numbers refer to Table 3-4.

^b Preliminary analyses also had structure variables 9 to 12, for the containment structures of Unit 2. These variables were found to have no significant effect on the responses (of Unit 1) and were omitted in the final analyses.

4. LINEAR REGRESSION EXAMPLES

We develop two examples in this section in some detail to illustrate the methods and results. In later sections, we turn to overviews of large sets of results and insights on linkages to physical features of the plant and piping design.

The first example is the peak and spectral acceleration responses at the site soil surface (free field). Each response is analyzed as a function of only two input variables. By repeating these analyses for different earthquake intervals we can also explore how much the LRA results change with the average earthquake amplitude. The soil free field acceleration has a great importance to the plant response since all the structures and equipment are shaken by this same earthquake motion.

The second example is the response at a piping valve. This response was chosen because it has a high response variance and because it shows a significant dependence on six input variables from the soil, the two containment structures, and the piping system.

4.1 FREE FIELD ACCELERATION AT SOIL SURFACE

The free-field earthquake peak and spectral responses at the site depend on the rock outcrop earthquake motion and on the soil shear stiffness G_S and soil material damping D_S (see Section 3). We have SMACS computations of the peak acceleration and the spectral accelerations at 4, 8, and 16 Hz.

We do a linear regression analysis of each of these four responses as a function of G_S and D_S for one earthquake interval from Table 3-6. We should also include some parameters from the rock outcrop earthquake, but we will examine instead how much of the soil earthquake variation we can explain without it.^a The rock peak acceleration is limited to a small range of

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^a We are not sure, whether the rock peak acceleration or its spectral acceleration at, say, 8 Hz would be more relevant to explaining the soil peak acceleration, since the soil column amplifies certain frequency content in the

variation by definition of the earthquake intervals.

For our earthquake interval 4, Fig. 4-1 shows the cumulative distribution of the soil PGA for the 30 earthquakes in the sample. The PGA responses are sorted from lowest to highest and are matched fairly closely by a lognormal distribution. A linear regression analysis of this sample of PGA as a function of the input G_S and D_S values yields

$$\begin{aligned}\hat{Y} = \ln \text{PGA} &= 3.15 - 0.36 (\ln D_S - \ln D_{S0}) + \xi, \\ &= 3.15 - 0.36 \ln (D_S/D_{S0}) + \xi\end{aligned}\quad (21)$$

with essentially a zero coefficient value for the stiffness G_S term. Figure 4-2 shows the result of this regression analysis. The solid line is the regression prediction

$$\hat{Y} = 3.15 - 0.36 \ln (D_S/D_{S0}) \quad , \quad (22)$$

as a function of $\ln (D_S/D_{S0})$. The plotted points are the observed sample responses, each plotted over its input value of the abscissa $\ln (D_S/D_{S0})$. The differences between the points and the line are the residuals ξ .

The mean-centered sum of squares of (a) the sample of responses, (b) the fitted $\hat{Y}$ at the same input values, and (c) the residuals, are given in Table 4-1. The fitted approximation $\hat{Y}$ accounts for 66 percent of the full response of sum of squares. This statistic is called the percentage of explained variation.

Next, applying the procedure to another response, the 4 Hz spectral acceleration on the soil, we show the cumulative histogram of the data in Fig. 4-3. This set of data has a higher variance than that of Fig. 4-1. Applying the linear regression analysis, we find

base rock motion. The rock acceleration data are in a different data base format not readily accessible to our regression program. Time and budget did not permit us to investigate this interesting question.

Figure 4-1. Cumulative probability distribution of the response: peak ground acceleration (PGA) at the soil surface, for earthquake interval 4. The points are the sample of responses; the dashed curve is a lognormal cumulative probability distribution function fitted to the sample data.

PRIMARY INPUT SOIL DAMPING
RESPONSE 1.

Figure 4-2. Dependence of the PGA at the soil surface on soil damping as determined by a linear regression analysis. See text, Equation 22.

Table 4-1. Analysis of variance for response no. 1, the soil peak ground acceleration. See Eq. (21) and Fig. 4-2.

	SUM OF SQUARES	PERCENT OF SUM OF SQUARES
Sample	1.18	100
Model	0.78	66
Residual	0.40	34

Figure 4-3. Cumulative probability distribution of the 4 Hz spectral acceleration at the soil surface for earthquake interval 4.

$$\hat{Y} = 4.08 + 0.42 \ln(GS/GS0) - 0.36 \ln(DS/DS0) + \xi \quad (23)$$

Figure 4-4 (a) and (b) show the result of this regression analysis, plotting the effect of one input variable at a time. In terms of Eq. (18), the solid line plots $b_0 + \sum b_i Z_i$ for the Z_i which depend on one X_j (here we have only one Z_i per X_j), and the plotted points are from the influence of that one variable plus the observed residuals $\xi = Y - \hat{Y}$. In other words, the line represents

$$\hat{Y}(X) = \sum_{m=j} b_m Z_m(X) \quad (24)$$

and the plotted points are based on the observed sample with the same subtraction

$$Y(X) - \sum_{m=j} b_m Z_m(X) \quad \text{at } X = \text{input values.} \quad (25)$$

The range of the vertical axis covers the range of the observed outputs Y plus a 5 percent margin. From such a set of plots we can observe (a) how much of the total range of the output is explained by any one variable, (b) how large the residuals are, and (c) whether there are any systematic trends as a function of one variable (e.g., a quadratic curvature) that are not in the model Y .

For this case, the explained variation is down to 46 percent. There is greater variation with the soil properties than was the case for the soil PGA, but even greater unexplained variation, perhaps due to variations at a lower frequency range in the rock time histories.

The medians and ranges in the sample are summarized in Table 4-2. Median response and standard deviation progressively increase going from PGA on rock to PGA on soil to the spectral response of a 4 Hz oscillator based on the soil.

Figure 4-4. Dependence of the soil 4 Hz spectral response on (a) soil stiffness, (b) soil damping. The range of the vertical axis covers the full range of the sample of responses. The solid curve (text, Equation 24), shows how much the response varies with the one variable of the horizontal axis. The data points (text, Equation 25) show the dependence on the one variable plus the residual variation; dependence on other variables has been subtracted out according to the regression analysis.

Table 4-2. Medians, sample ranges and standard deviation values for rock PGA and two soil surface responses.

	MIN. (g)	MEDIAN (g)	MAX.(g)	STANDARD DEVIATION ^a
PGA rock	0.32	0.35	≤ 0.42	~ 0.07
PGA soil	0.50	0.73	1.19	0.20
4 Hz soil	0.98	1.84	3.45	0.28

^aSquare root of the variance (Fig. 4-6) of the logarithmic input or response.

4.2 EXTENSION TO OTHER EARTHQUAKE INTERVALS

We extend the analysis to each of the six earthquake intervals, and to the 8 Hz and 16 Hz spectral responses on the soil surface. We are particularly interested in whether the coefficients b_i (slopes in the response surface) change with earthquake interval. This is possible, since the median values of the input G_S and D_S change with earthquake intensity, so we are looking at somewhat different areas of the response surface.

The results are shown in Figs. 4-5 to 4-8. (The error bars are the 10 percent to 90 percent confidence intervals on the determination of the coefficients.) The percentage of explained variation is lower at the lower earthquake intervals, probably because the earthquake acceleration intervals are wider in proportion to their mean values, and we are not including that acceleration as an input in the regression. There seems to be a change to more negative values in the coefficient of damping with acceleration level. The coefficient of stiffness is zero or positive; there is not any obvious trend of change with acceleration level.

Later, we will combine the input-output samples from several earthquake intervals to get a larger sample for a regression analysis. This reduces the statistical sampling errors, but introduces some averaging in the results. With several intervals, we then have by choice a larger range of input rock accelerations. We must allow for this in the regression analysis; we do this by including the soil-surface PGA as an input variable to the regression analysis. This will mask some of the influence from soil damping, since, as we saw above, the soil PGA is correlated with the damping.

4.3 A VALVE ACCELERATION IN THE PRESSURIZER PIPING

We consider Response No. 75, acceleration of a valve in the pressurizer piping. We select this as the first piping valve example because it has one of the larger R^2 s and because many of the inputs show a significant influence on this response. The pressurizer piping is multiply supported on the internal structure and the pressurizer. The input variables considered are the two variables each for the soil, the three structures of Unit 1, and the pressurizer piping.

Figure 4-5. Results of regression analyses of responses at the soil surface. Percent of response variance explained. (a) Spectral acceleration response at 4 Hz. (b) Spectral acceleration response at 8 Hz. (c) Spectral acceleration response at 16 Hz. (d) Peak acceleration response (i.e., PGA).

Figure 4-6. Results of regression analyses of responses at the soil surface. Variance of response. (a)-(d) as in Figure 4-5.

(a) Free field, 4Hz
(response 2)

(b) Free field, 8 Hz
(response 3)

(c) Free field, 16 Hz
(response 4)

(d) Free field, PGA
(response 1)

Figure 4-7. Results of regression analyses of responses at the soil surface. Coefficient b_{G_s} of soil stiffness variable. The error bars are the 90 percent confidence lower bound and the 90 percent confidence upper bounds on b_{G_s} . (a)-(d) as in Figure 4-5.

Figure 4-8. Results of regression analyses of responses at the soil surface. Coefficient b_{D_s} of soil damping variable. The error bars are the 90 percent confidence lower bound and the 90 percent confidence upper bound on b_{D_s} . (a)-(d) as in Figure 4-5.

Figure 4-9 shows the cumulative distribution of this valve's response for the 30 earthquakes in the sample for earthquake interval 4. A linear regression analysis of this sample as a function of the inputs yields the results given in Tables 4-3 and 4-4. We can extract from Table 4-4 the linear model:

$$\begin{aligned}\hat{Y} = & 4.07 + 0.24 \ln(GS/GS_0) - 0.27 \ln(DS/DS_0) \\ & - 0.14 \ln(D_C/D_{C0}) - 0.25 \ln(F_I/F_{I0}) \\ & - 0.17 \ln(f_p/f_{p0}) - 0.02 \ln^2(f_p/f_{p0}) - 0.13 \ln(d_p/d_{p0}) + \xi, \quad (26)\end{aligned}$$

and essentially zero coefficient values for the other input terms. The coefficient of the term $\ln^2(f_p/f_{p0})$ is not significantly distant from zero, but we include it because we have a term linear in $\ln(f_p/f_{p0})$. (Figure 4-10 (d) shows the slight curvature.) From Table 4-3, we see that the linear model $\hat{Y}$ explains 84 percent of the full response's sum of squares. Plots of the regression fit as a function of each of the seven most important input terms as ranked by the F test¹ (six input variables since f_p is in two terms) are presented in Fig. 4-10 (a)-(f). The data conventions are as for Fig. 4-4 above.

Several features of the results for valve Response No. 75 are worth noting:

1. There is a strong dependence on the two soil parameters. This may arise through the local site effect and SSI. The coefficients of the soil parameters here (Response 75) are comparable to those seen for Responses 1-4, the free field soil acceleration (Figs. 4-7 and 4-8 above), where only the local site effect is applicable. Further discussion of the soil parameters' influence is in Section 5.
2. There is a dependence on the containment shell damping. Since the piping is not attached to the shell, this influence can enter only via the SSI effect on the common base mat of the two structures.

Figure 4-9. Cumulative probability distribution of Response No. 75, the peak acceleration of a valve in the pressurizer piping, for earthquake interval 4.

Table 4-3. Analysis of variance for response no. 75, a valve in the pressurizer piping, for earthquake interval 4. See Eq. (26) and Fig. 4-10.

	SUM OF SQUARES	PERCENT OF SUM OF SQUARES
Sample	8.19	100
Model	7.25	88
Residual	0.94	12

Table 4-4. Estimated coefficients b_j from the linear regression analysis for response no.75.

VARIABLE NUMBER	VARIABLE SYMBOL ^a	COEFFICIENT VALUE	90% CONFIDENCE LOWER BOUND ON COEFFICIENT	90% CONFIDENCE UPPER BOUND ON COEFFICIENT
1	G_S	0.24	0.15	0.33
2	D_S	-0.27	-0.35	-0.20
3	F_C	0.03	-0.07	0.13
4	D_C	-0.14	-0.22	-0.05
5	F_I	-0.25	-0.33	-0.17
6	D_I	-0.06	-0.14	0.01
7	F_A	-0.01	-0.11	0.09
8	D_A	-0.01	-0.09	0.07
15	f_2	-0.17	-0.25	-0.10
(15) ²	$(f_2)^2$	-0.02	-0.08	0.03
16	d_2	-0.13	-0.21	-0.06
Intercept		4.07	3.99	4.15

^aThe subscript 2 on f_2 and d_2 refers to piping system no 2. See Table 3-4.

Figure 4-10. Results of regression analysis of Response No. 75 for earthquake interval 4. Illustrated are dependence of the response on (a) soil damping, (b) frequency of the containment internal structure, (c) soil stiffness, (d) frequency of the pressurizer piping system, (e) damping of the pressurizer piping system, (f) damping of the containment shell structure. The plotting conventions are as in Figure 4-4.

3. There is a dependence on the containment internal structure's frequency. The internal structure model includes the pressurizer. The structure both provides the motion of valves mounted near anchors or supports, and puts energy into the vibratory modes of the piping system.
4. There is a dependence on the piping system's frequency and damping parameters.

No single response location is "typical." Hence, we turn next to an overview of all the responses calculated.

5. OVERVIEW OF RESPONSES

We wish to examine the trends, characteristics, and diversity in the functional dependence of the various responses on the inputs.

We combine the data of earthquake intervals 3, 4, and 5 to form a data base with 90 input-output pairs for LRAs. With more data the uncertainty intervals in the estimates of the coefficients will be reduced. However, we get some averaging effect, losing some resolution on how the coefficients change with earthquake intensity (Section 4.2). We must add an input variable related to input earthquake intensity (not needed in the analysis of Section 4), since we now deliberately sample over a wide range of earthquakes. We use the soil free-field PGA (Response No. 1) for this input variable.

The responses exhibit diversity, as one would expect from their different locations and structural properties. Within this diversity trends are evident in the influences of the individual input variables on the responses. We do LRAs of two additional input-output data sets to further analyze the influence of piping damping and frequency variables.

5.1 OVERVIEW OF RESPONSE BEHAVIOR

The variances of each of the Responses No. 2 through 333 are presented in Fig. 5-1 (a). The responses were identified in Table 3-3. There is a trend to larger variances as we go from structural responses to piping acceleration responses to piping moment responses. The "larger" comparison holds both in the average and when taking the largest single value in each group as the basis for comparison. Those components with either large median or large variance have a higher probability of failure given an earthquake. Hence, a criterion for comparing seriousness of effects is better based on the magnitude of the larger variances in each group rather than on average variance.

A large number of responses have small variances, comparable in size to the variances of the soil surface earthquake (Responses 2-4 plotted, and Response 1 not plotted, which has a variance nearly equal to that of Response 4).

Considering all 332 responses, the linear regression model is fairly "successful" to the extent evidenced in Fig. 5-1. Where the response variance is high, the linear model can (for most responses) explain most of that variance. The unexplained variance is on the order of, or not much greater than, the spectral variation not included in the model. The spectral variance can be seen in the input soil time histories. Note that Fig. 5-1 presents the results of 332 separate linear regression analyses, one for each response except Response 1. The input variables used in each analysis are listed in Table 3-7.

The estimated coefficients are presented in Figs. 5-2 through 5-14 for all 332 analyses. Several technical points done for streamlined data handling will be mentioned first.

- (1) All three structures for Unit 1 were used as inputs to all foundation, structure, and piping response analyses. As noted in Section 3.2, some structures may have a strong influence on responses, and others only a secondary influence. (For piping systems 5 and 6, Responses 104-117 and 234-244, the structures are known not to be included in the SMACS model, so their variables have no influence. Inclusion of these variables in the linear regression analysis yields essentially zero coefficients.)
- (2) The "piping frequency variable" and "piping damping variable" in Figs. 5-12 to 5-14 are one each per piping system, but a different one for each different piping system. Several piping runs (six piping moment responses, see Table 3-3) extend over more than one piping system. The one system having the most effect on the piping run's response is used for the piping variable in Figs. 5-12 through 5-14.

5.2 INTERCEPTS--RESPONSES FOR NOMINAL INPUT VALUES

The intercepts from each regression analysis are shown in Fig. 5-2. The intercept is the estimated response when all the inputs are at their median values (including median PGA; and averaging over other characteristics of the earthquake time histories). The response is the natural logarithm of acceleration in ft/s^2 , or of moment in ft-lb . All piping moments have been converted by proportional factors to an equivalent moment in a 6 inch diameter

Figure 5-1. Results for 332 linear regression analyses (LRAs), for responses 2-333, for the combined data of earthquake intervals 3-5. (a) Total variance of the responses, (b) residual variance, (c) percent explained variance.

Figure 5-2. Intercept of the (logarithmic) response, from the LRAs of the responses as in Figure 5-1. The intercept value is the logarithm of acceleration in ft/s^2 or of moment in ft-lb .

Figure 5-3. Coefficient b_a of the PGA variable. The L²As are of the responses as in Figure 5-1. The error bars show the 90 percent confidence lower and upper bounds on b_a .

Figure 5-4. Coefficient b_g of the soil stiffness variable.

Figure 5-5. Coefficient b_{D_s} of the soil damping variable.

Figure 5-6. Coefficient b_{F_C} of the variable F_C for frequency of the containment shell structure.

Figure 5-7. Coefficient b_{D_C} of the variable D_C for damping of the containment shell structure.

Figure 5-8. Coefficient b_{F_1} of the variable F_1 for frequency of the containment internal structure.

Figure 5-9. Coefficient b_{D_1} of the variable D_1 for damping of the containment internal structure.

Figure 5-10. Coefficient b_{F_A} of the variable F_A for frequency of the auxiliary building.

Figure 5-11. Coefficient b_{D_A} of the variable D_A for damping of the auxiliary building.

Figure 5-12. Coefficient b_p of the respective piping frequency variable applicable for each piping response.

Figure 5-13. Coefficient b_{p2} of the term with $(f_p)^2$, piping frequency variable squared.

Figure 5-14. Coefficient b_{dp} of the respective piping damping variable applicable for each piping response.

standard straight pipe. The proportional factors are based on the median fragility of each piping element's component type and cross section.

For the earthquakes in intervals 3, 4, and 5 combined, the median PGA on the soil is ($\ln = 3.11$; $\text{PGA} = 0.69 \text{ g}$), or 4.1 times the design safe shutdown earthquake (SSE). We emphasize as did Ref. 11 that to study the probability of plant system failure, rare earthquakes above the SSE must be included. For earthquakes below the SSE, the conditional probability of plant failure is very low. For progressively higher earthquakes the conditional probability of plant failure increases but the probability of occurrence of such earthquakes decreases.

The soil free-field spectral response at 4 Hz is exceeded by only three or four of the acceleration responses (no. 5-200), and then at most by 45 percent. This is summarized in Table 5-1. Thus, the potential amplification of acceleration motion, when going from free-field to structural floor motion to heavy equipment to light equipment and piping, is found not to occur, at least in the nominal values. This happy result is due to plant design, which avoided resonance between building and piping frequencies, and rejected potential valve locations where their vibration would be too high. Many piping variances, however, are higher than for the free-field. Thus at, say, the upper 10 percent or 3 percent confidence level, many more of the piping valve accelerations might exceed the corresponding value for the free-field spectral response. Thus it is not the means but the variances which bring in most of the probability of component failure.

The piping moment responses intercepts in Fig. 5-2 cover a wider range than do the accelerations. Despite the high earthquake intensity, only one of these nominal values exceeds the median of the piping fragility curve. This is summarized in Table 5-2. For all those whose nominal value (and often median value as well) is below the fragility median, a higher variance causes a higher probability of failure.

Table 5-1. Values of intercept for accelerations, for earthquake intervals 3, 4, and 5.

	LOG VALUE ^a	ACCELERATION (g)
Soil free-field PGA	3.11	0.69
Soil free-field, 4 Hz	4.04	1.76
Largest acceleration response	4.41	2.55
Median of piping valve fragility	5.36	6.61

^aLogarithm of acceleration in ft/s².

Table 5-2. Values of intercept for piping moments, for earthquake intervals 3, 4, and 5.

	LOG VALUE	MOMENT (ft-lb)
Median of responses (approx.)	8.9	7300
Second largest response	12.06	172800
Largest response	13.43	680100
Median of piping element Fragility	12.22	203300

5.3. INFLUENCE FROM INDIVIDUAL INPUT VARIABLES

The significant features in the response dependence on each input variable is discussed in this section and the next.

5.3.1 Peak Ground Acceleration

The dependence on earthquake PGA has a coefficient slightly less than 1.0 (averaging 0.8 to 0.85). A coefficient $b = 1$ in our log-log model would correspond to an exponent $b = 1$ in the model

$$R \sim (PGA)^b$$

Possible reasons for the coefficient being lower than 1.0 are (1) changing spectral shape with increasing earthquake intensity at the site and (2) other input variables partially correlated with the PGA variable (see Section 4.1).

5.3.2 Soil Variables

The response dependence on the two soil variables can arise through the local site effect (LSE), and through the SSI, both of which may vary with frequency. Among the structural responses, the containment shell's ring girder response and responses in the auxiliary building at 4 Hz have coefficients of soil stiffness greater than 0.5. This is due to both LSE and SSI. The coefficient of soil damping does not show a similar change, but it does show a significant change (from its usual value) for pressurizer piping responses.

A major influence of the soil damping variable is masked since we use soil-surface PGA as an input variable. Figure 5-15 shows the coefficient of soil damping, b_D , for the case analyzed in Section 4, with no PGA variable and using data from earthquake interval 4 only. Here b_D averages -0.3 and is significantly below zero (even with the larger error bars due to a smaller input-output data sample).

Figure 5-15. Coefficient b_{D_s} of the soil damping variable, for all responses, no. 1-333, for the data of earthquake interval 4 analyzed as in Section 4.1. The average of the values is to be contrasted with that for b_{D_s} in Figure 5-5.

5.3.3 Structure Variables

The effect of structure variables is now examined. As noted in Table 3-2, each piping system is supported on only one or two structures. A containment penetration anchor allows separation of larger piping networks into vibrationally separated systems. The other structures can have an influence on the structures supporting the piping, through a common foundation or structure-structure interaction.

Where there is a possible direct influence, the coefficients are often small. This depends on the location of the piping (e.g., near foundation, elevated, near a flexible wall element, etc.). The most striking exceptions to the otherwise small coefficients will now be summarized.

The internal structure coefficients (Figs. 5-7 and 5-8) show a striking influence on two piping systems. The structure model includes major equipment, whose support is flexible compared to the stiff concrete structure. The pressurizer motion has a strong influence on the pressurizer relief piping (Responses No. 71-77 and 215-220). The main RCL motion has a strong influence on its own responses and on its branch line response. Since the main RCL is in both the internal structure model and in the RCL piping model, the internal structure frequency variation serves as the RCL piping frequency variation also.

The largest coefficients of containment shell frequency for any piping responses are apparent in Fig. 5-5. There are:

- (1) Responses No. 53-55, three valves in piping system no. 1, the CW pump discharge piping. This is in the auxiliary building and anchored to a containment penetration. The three valves' accelerations are strongly influenced both the containment shell frequency variable and by their piping system variable.
- (2) Response No. 222, a piping moment in piping system no. 3, the AFW inside containment. This response is the peak moment in the 16-inch line between the steam generator and the containment penetration, and is controlled by the pseudostatic moment (i.e., by relative anchor displacement). The containment shell frequency variable may influence

the relative anchor displacement directly (at the penetration) or indirectly (at the steam generator). But this Response has a near-zero coefficient for internal structure frequency (i.e., steam generator). Thus, the influence of the shell on the pseudostatic moment is probably direct.

The auxiliary building frequency influences only a few of the piping responses that it might influence. This selectiveness presumably depends on elevation within the building and also on location near a more flexible wall panel. The most noticeable influence on piping (see Fig. 5-10) is on Responses 53-55 (valves in piping system no. 1, charging water pump discharge) and Responses 245-268 (moments in piping system no. 7, service water to AFW pump). The largest single coefficient is for Response No. 257; this is a moment response dominated by differential support displacement. (Responses No. 17-52 in Fig. 5-10 are structural responses in the auxiliary building.)

5.4 INFLUENCE FROM PIPING VARIABLES

5.4.1 Influence of Piping Frequency

The coefficients for piping frequency in Fig. 5-12 show a wide range, with different outer limits for acceleration and moment types of responses. Figures 5-16 through 5-18 are cross plots for all the valve acceleration responses (No. 53-200), plotting the piping frequency linear-term coefficient versus the piping frequency quadratic term (Fig. 5-16), the piping damping term (Fig. 5-17), the total variance (Fig. 5-18), and the intercept (Fig. 5-19). Figures 5-20 through 5-22 are similar cross plots for the piping moment responses (No. 201-333). Figure 5-19 shows the intercepts for both moments and accelerations, well separated (they have different units). Figure 5-23 shows the same data as in Fig. 5-20, with error bars (the 10-90 percent confidence limits on the determination of the coefficient values plotted) added.

Some regularities are apparent in Fig. 5-20 (and to a lesser extent in Fig. 5-16). The two coefficients plotted in these figures determine the response dependence on piping frequency.

Figure 5-16. Cross plot of coefficient $b_{f_p^2}$ of the term with $(f_p)^2$ versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping valve acceleration response, no. 53-200.

Figure 5-17. Cross plot of coefficient b_{d_p} of term d_p versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping valve acceleration response, no. 53-200.

Figure 5-18. Cross plot of variance versus coefficient b_p of term f_p ; one data point for each regression analysis of a piping valve acceleration response, no. 53-200.

Figure 5-19. Cross plot of intercept versus coefficient b_p of term f_p ; one data point for each regression analysis of a piping valve acceleration response, no. 53-200 (plot symbol 0) and of a piping moment response, no. 201-333 (plot symbol 2).

Figure 5-20. Cross plot of coefficient $b_{f_p^2}$ of the term with $(f_p)^2$ versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping moment response, no. 201-333.

Figure 5-21. Cross plot of coefficient b_{d_p} of term d_p versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping moment response, no. 201-333.

Figure 5-22. Cross plot of variance versus coefficient b_p of term f_p ; one data point for each regression analysis of a piping moment response, no. 201-333.

Figure 5-23. The same data as in Figure 5-20 with error bars added indicating the 90 percent confidence lower and upper bounds on the coefficient values.

Selected valve acceleration responses are shown in Fig. 5-24 (a)-(f) to illustrate the range of response dependences on frequency encountered at different valve locations. For a limited range of frequency variation, we might expect such a curve for one valve to look like a portion of a response spectrum (such as in Fig. 5-25). When the frequency is shifted upward, all the piping modes ultimately shift into the upper flat region of the response spectrum. When the frequency is shifted downward, higher-frequency modes move down into the amplified region of the response spectrum. Different valves have different starting points, depending on their location in the pipe and thus on their modal participation factors. While the sample of responses for each valve is fitted fairly well in its range by a quadratic function, we expect that in a greatly extended range of frequency shifts, the response function would look like Fig. 5-25 rather than continuing the same quadratic trend. Thus, a caution in linear response analysis is illustrated, i.e., extrapolation of a fit beyond the range of the data is not supported.

Selected piping moment responses are shown in Fig. 5-26 (a)-(f) to illustrate the range of response dependences on frequency for these moment responses. Toward the high-frequency end, the shape is linearly upward with a slope of 2, rather than constant as for the acceleration responses.

This slope results in a high variance for the response. The reason for this high slope of moment responses is explored in the next subsection.

5.4.2 Contributions of Two Terms to the Piping Response

We recall^{10,15} that the motion of the piping is a sum of two motions--(1) the vibratory motion of the pipe, fixed at various support points, and (2) the motion of the pipe equilibrium position, as controlled by the motions of the supports. For the accelerations at locations on the pipe, this sum is

$$\{\ddot{x}_1\} = [\hat{\phi}]\{\ddot{q}\} + [P]\{\ddot{x}_2\} \quad , \quad (27)$$

where

Figure 5-24. Dependence of piping valve acceleration responses on the piping frequency variable, as determined by the linear regression analyses. (a)-(f) six responses selected to illustrate the range of the acceleration response dependences on piping frequency. The plotting conventions are as in Figure 4-4.

Figure 5-25. Mean acceleration response of a single-degree-of-freedom subsystem on the containment foundation as a function of subsystem frequency, at three damping values (from SSMRP Phase 1 data, without local site effect).

Figure 5-26. Dependence of piping moment responses on the piping frequency variable, as determined by the linear regression analyses. (a)-(f) six responses selected to illustrate the range of the moment response dependences on piping frequency.

$\{q\}$ = vector of modal coordinates

$\{x_2\}$ = vector of support displacements

$[\hat{\phi}]$ = (truncated) mode shapes matrix

$[P]$ = matrix giving the pseudostatic (equilibrium) displacement of the pipe for a given set of support displacements $\{x_2\}$

" = indicates second derivative with respect to time.

Only the first term in Eq. (27) depends on the piping modal frequencies and damping. For the case of input motion at all supports, the second term equals that input acceleration. (A similar two-term equation is used in computing an acceleration response spectrum.)

For a force or moment at a piping location in piping member m , the sum is

$$\{F_M\} = [K_{1m}]\{q\} + [K_{2m}]\{x_2\} \quad (28)$$

where

$$[K_{1m}] = [k_{1m}][\hat{\phi}] \quad ,$$

$$[K_{2m}] = [k_{1m}][P] + [k_{2m}] \quad ,$$

where $[k_{1m}]$ is the stiffness matrix for piping member m in terms of the piping displacements $\{x_1\}$, and $[k_{2m}]$ is the additional stiffness matrix for piping member m , if the member boundary includes some of the support coordinates $\{x_2\}$.

As in Eq. (27), the first term in Eq. (28) depends on the piping modal vibration displacement. The second term depends on the support displacements; this force and moment will be zero for uniform displacement, but nonzero when the pipe supports have relative displacements.

The variations in piping frequency in our model were associated with variation in the piping system stiffness. (Mass or stiffness variation, or

both, might have been chosen to produce a net variation in piping frequencies with no change in mode shapes.) Thus, stiffness varies here as the square of frequency. Recall, for a simple oscillator:

$$(2\pi)^2 f^2 = k/M \quad . \quad (29)$$

The first moment term in Eq. (28) decreases with increasing frequency. The second term increases as f^2 (because $[K_{2m}]$ increases as f^2), eventually dominating the first term in controlling moment.

A SMACS run²², saving the peak values of the two separate terms as well as the sum in Eqs. (27) and (28), illustrates the dependence on f_p as just described. This run had 90 members in the sample, used earthquake level 2 only, and had the same input parameter distributions as the preceding runs.

We plot regression analysis results for two responses in the AFW inside containment. Figure 5-27 shows the result for the 3 inch valve acceleration in the X direction. Figure 5-28 shows the result for a pipe moment at an elbow in the 16 inch pipe, near the steam generator nozzle. The base acceleration term (or pseudostatic moment term, respectively) has the dependence on f_p as described, and tends to dominate in the sum when f_p has a high multiplier.

The ensemble of responses also illustrates the dependence on f_p . Figure 5-29 shows the coefficients for all accelerations calculated (X, Y, and Z accelerations at many nodal points on the pipe) for piping systems no. 3 and 10. The coefficient b_f for the base-motion term is always about zero. The coefficient b_f for the dynamic term is always negative, and the coefficient b_f for the total (sum of the two terms) usually falls in between the two individual-term groups of result data. Similarly, Fig. 5-30 shows the coefficients for the moments calculated at all response locations (i.e., at individual components rather than after combining responses over a piping run). Again, the coefficients for the total usually fall in between the two individual-term groups of results, and in a few cases, may be virtually coincident with those for one of the individual terms.

(a)

(b)

(c)

Figure 5-27. Dependence of the two terms contributing to a piping valve acceleration response, on piping frequency. Response is x-directional acceleration at a valve in piping system 3. (a) dependence of the dynamic term; (b) dependence of the support-motion term; (c) dependence of the sum.

(a)

(b)

(c)

Figure 5-28. Dependence of the two terms contributing to a piping moment response, on piping frequency. (a) dependence of the dynamic term; (b) dependence of the pseudostatic term; (c) dependence of the sum.

(a)

(b)

(c)

Figure 5-29. Cross plot of coefficient b_{d_p} of term d_p versus coefficient b_{f_p} of term f_p ; from regression analyses of piping valve acceleration responses. The responses are x, y, and z-directional accelerations. (a) analysis of dynamic term only; (b) analysis of support-motion term only; (c) analysis of sum.

(a)

(b)

(c)

Figure 5-30. Cross plot of coefficient b_{d_p} of term d_p versus coefficient b_{f_p} of term f_p ; from regression analyses of piping moment responses. The responses are resultant moments at individual locations in the pipe runs, rather than maxima over a pipe run as in the moment data presented previously. (a) analysis of dynamic term only; (b) analysis of pseudostatic term only; (c) analysis of sum.

Thus the contribution of two terms to the moment response, and the variation in piping stiffness, explain the increasing response moments as piping frequency increases in Fig. 5-26, and explains the maximum slope value of 2 (slope in Fig. 5-26, coefficient in Figs. 5-12 and 5-20) associated with the exponent value of 2 in Eq. (29). This slope is an artifact of the modeling assumptions rather than a desired result. The moment response variance is higher than we would expect. In modeling the input random variability we assigned all the variability to a few key input variables. We could easily modify this assumption in a future version of SMACS.

The piping acceleration variances, on the other hand, appear reasonable. Numerically, the acceleration response is unchanged whether we put the frequency variability into mass or stiffness or into a combination of both.

5.4.3 Influence of Piping Damping

Figure 5-18 for the valve acceleration responses shows that for some valves, the two piping variables have zero influence on the piping response (zero coefficients plotted). For some other valves, the piping variables are important--coefficients of about -1.0 to -1.5 for the frequency linear term and about -0.4 for the damping term in the linear regression model. Other valves show a piping importance with smaller coefficients, filling in a continuum between the extremes. There seems to be a relation between the two coefficients--when piping frequency is important, then damping is also, but to a smaller degree (coefficient only one-third as large).

The range of coefficient values can be explained from Eq. (27). When the second term dominates (stiff piping), then the response is constant with changing frequency (zero coefficient). Damping also has zero effect, since it influences only the first term. On the other hand, when the first term in Eq. (27) becomes dominant (flexible piping), then the piping frequency and damping have a large influence. The largest coefficients in Fig. 5-18 for these extended multi-mode piping systems are comparable to those one would derive for a single degree-of-freedom oscillator's peak response as its frequency or damping varies (slopes in Fig. 5-25, the response spectrum).

For piping moment responses as well, the varied influence of piping damping is seen in Fig. 5-21. In Eq. (28) as in (27), only the first term is affected by the piping modal damping. When the second term dominates, damping has zero effect (and frequency has a coefficient of about 2). When the first term dominates, damping and frequency have a large influence, comparable to the case of acceleration responses.

5.4.4 Damping Importance Changed by a Frequency Change

The discussion of Eqs. (27) as in (28) above and the related set of responses in Figs. 5-24 and 5-26 have indicated that piping damping is more important for response locations associated with more flexible piping vibration, and less important or unimportant at locations associated with stiff response. For the same reasons, the importance of damping is expected to change at a fixed response location, as the frequency changes. Looking at any one of the responses in Fig. 5-26, when the frequency is high enough (to the right in the figure) that the pseudostatic response dominates, then the coefficient for damping should be zero. In the same figure, when the frequency is low enough (to the left) that the modal motion dominates, then the damping should be important, i.e., should have a nonzero negative coefficient.

Two investigations explored the above expectation. The first gave only an indication but not a statistically strong conclusion; the second was more supportive.

The first method to look for the above effect is to add a new term to the linear regression model:

$$b_{fd} \{ \ln f \cdot \ln d \} ,$$

where f and d are the piping system parameters. The total influence of the piping damping is then in the sum of two terms which equal

$$\{ b_d + b_{fd} \ln f \} \cdot \ln d .$$

The effective coefficient on the left changes with frequency if b_{fd} is nonzero. A new analysis of the same input-output data was carried out. The computed results for b_{fd} were about zero at some response locations. There were many positive results, as expected (see Fig. 5-31 (a)). Most of the b_{fd} values are greater than zero--not significantly so when considered singly but perhaps significantly when taken together. Since the input values for $(\ln f \cdot \ln d)$ were clustered about zero (because of the distributions of $\ln f$ and $\ln d$), the resolving power of the input sample for such a possible cross term is low (see Fig. 5-31 (b)). Hence, even the positive results were not conclusively so.

A second method to look for the effect is to shift the median value of the piping frequency distribution to a high or low value, get a new SMACS input-output sample, do a linear regression analysis using a linear term in $(\ln d)$, and then examine whether the coefficient of $(\ln d)$ has changed as compared to the base case of no shift in the median value of frequency.

Two such median shifts and SMACS runs were carried out in another part of the SSMRP. The median of piping damping and of soil and structure parameter distributions were also shifted (see Table 5-2). The same median shifts applied to 19 piping systems (i.e., all but the RCL piping). Each case had 40 members of the input-output sample. A linear regression of each case (for the first 12 piping systems) yields results shown in Figs. 5-32 through 5-35. The piping systems' responses are shown in Figs. 5-17 and 5-21 for the base case. It is apparent, comparing the figures, that on the whole the coefficients of damping are larger (negative) in Case 1, and smaller (nearer to zero) in Case 2. There is some random scatter due to the smaller input-output sample size, 40 vs. 60 earlier. This result lends support to the expected effect described in the earlier part of this subsection, that a change in piping frequency will often change the importance of piping damping.

Figure 5-31(a). Cross plot of coefficient b of term $f_p * d_p$ versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping valve acceleration response, no. 53-200. The 90 percent confidence lower and upper bounds on the coefficient b of the term $f_p * d_p$ are typically ± 0.25 .

Figure 5-31(b). Dependence of piping valve acceleration response on the term $f_p \cdot d_p$ for one valve in piping system no. 2, the pressurizer piping.

Figure 5-32. Cross plot of coefficient b_{d_p} of term d_p versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping valve acceleration response, no. 53-200; for case 1, with a negative shift of the median of f_p .

Figure 5-33. Cross plot of coefficient b_{d_p} of term d_p versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping valve acceleration response, no. 53-200; for case 2, with a positive shift of the median of f_p .

Figure 5-34. Cross plot of coefficient b_{d_p} of term d_p versus coefficient b_{f_p} of term f_p ; one data point for each regression analysis of a piping moment response, no. 201-333; for case 1, with a negative shift of the median of f_p .

Figure 5-35. Cross plot of coefficient b_{d_p} of term d_p versus coefficient f_p of term f_p ; one data point for each regression analysis of a piping moment response, no. 201-333; for case 2, with a positive shift of the median of f_p .

6. RESPONSES OF SELECTED PIPING SYSTEMS

We now examine how the main features of the piping responses depend on the properties of the piping system. The system properties we distinguish are:

- a) stiff versus flexible piping
- b) nature of supporting base, i.e., piping supported on one rigid base, on two structures, or on large equipment plus structures.

To do this examination, we group selected piping systems into three groups with distinguishable properties.

6.1 PIPING SYSTEMS EXAMINED

6.1.1 Group 1 -- Piping in the Crib House

The service water (SW) piping is examined--piping models no. 5 and 6, the SW pump discharge and SW strainer discharge (Figs. 6-1 and 6-2).¹⁵

The noteworthy features of this piping are:

- (i) Uniform (3-D) input motion at all supports; the soil free-field motion is used as input.
- (ii) Large diameter pipes, 24-inch to 48-inch.
- (iii) Fairly stiff configuration; the nominal first-mode frequencies are 12.9 and 16.0 Hz (see Table 3-2).

6.1.2 Group 2 -- Selected Piping in the Auxiliary Building

The piping model examined is no. 11, the RHR and SI-2 (Fig. 6-3).

The noteworthy features of this piping are:

- (i) Multisupport input motions, from two structures. The piping location is mainly at low elevations in the auxiliary building, with two pipes running to containment penetrations at higher elevation.
- (ii) Medium diameter pipes, 8-inch to 10-inch.

Figure 6-1. Model of the service water (SW) pump discharge piping configuration.

Figure 6-2. Model of the service water (SW) strainer discharge piping configuration.

Figure 6-3. Model of the residual heat removal (RHR) and safety injection (SI-2) piping configuration.

- (iii) Flexible configuration; the nominal first-mode frequency is 2.7 Hz.

6.1.3 Selected Piping in the Containment Internal Structure

The piping models examined are no. 2, the pressurizer relief piping (Fig. 6-4), and no. 3, the AFW from a steam generator to the containment (Fig. 3-4).

The noteworthy features of this piping are:

- (i) Multisupport input motions. The piping is attached in part to heavy equipment which may vibrate much more than the concrete internal structure. The pressurizer relief piping is attached to the top of the pressurizer and at relatively high elevations in the internal structure. The AFW piping has a 16-inch line attached to the steam generator, the internal structure, and a containment shell penetration; and a 3-inch line attached to the 16-inch line, the internal structure, and a containment penetration at low elevation.
- (ii) Medium to small diameter pipes; 3-inch and 16-inch in the AFW, and 3-inch to 12-inch in the pressurizer piping system.
- (iii) Flexible configuration; the nominal first-mode frequencies are 3.5 and 2.9 Hz.

6.2 PIPING RESPONSE ANALYSIS

The results of the linear regression analysis of the valve and piping moment responses for the piping of groups (1), (2), and (3) above are presented in Figs. 6-5 through 6-8. These data are the same as in Section 5, Figs. 5-1 and following, but highlighting only one group of pipes at a time. The figures show respectively the total variance, the intercept, the coefficient b_p of the piping frequency linear term, and the coefficient b_{dp} of the piping damping term. Each figure shows the three piping groups.

Figure 6-4. Model of the pressurizer relief piping configuration.

Figure 6-5. Variances of the responses; same data as in Figure 5-1. Parts (a), (b), and (c) highlight results for piping groups 1, 2, and 3.

(a) (Group 1)

(b) (Group 2)

(c) (Group 3)

Figure 6-6. Intercepts of the responses; same data as in Figure 5-2. Parts (a), (b), and (c) highlight results for piping groups 1, 2, and 3.

Figure 6-7. Coefficient b_p of the variable f_p for frequency of the piping system; same data as in Figure 5-12. Parts (a), (b), and (c) highlight results for piping groups 1, 2, and 3.

Figure 6-8. Coefficient b_D of the variable d_p for damping of the piping system; same data as in Figure 5-14. Parts (a), (b), and (c) highlight results for piping groups 1, 2, and 3.

6.2.1 Variances

Comparing the response variances, Fig. 6-5, with all the variances in Fig. 5-1, we note that:

- o for piping group (1), all the variances are relatively small;
- o for piping group (2), the variances are small to medium, plus two relatively large variances; and
- o for piping group (3), the variances are medium to large.

The small variances in piping group (1) are associated with the layout and properties:

- o No intervening structures or heavy equipment between the soil motion and the piping supports. If present, such structures could modify the input motion and increase its variability.
- o Relatively stiff piping. High stiffness means that acceleration responses will be determined mainly by the peak input acceleration. For the moment responses, the piping frequencies will be mostly well above the amplified frequency range of the soil free-field input motion, and therefore not very sensitive to shifts of the frequencies in the input motion.
- o No relative anchor motion. If present, anchor motion produces a pseudostatic moment whose amplitude is sensitive to shifts in piping stiffness.

The medium variances in piping group (2) are associated with its greater flexibility and with the possibility for SSI and auxiliary building motion to modify and vary the seismic input motion.

The two large variances in piping group (2) are associated with the two responses which have b_{fp} large (Fig. 6-7 (b)). These two responses are dominated by pseudostatic moments, sensitive to piping stiffness. (Thus, b_{fp} is nearly 2.0). These two responses are located at the two containment-penetration anchors.

The relatively large variances in piping group (3) are associated with one or more of the following properties (in varying proportions from one response location to another):

- o The piping is attached to flexibly-supported equipment (pressurizer or steam generator) which can provide large and variable input motion.
- o The pressurizer piping is also attached to relatively high elevations in the internal structure.
- o A large variability is introduced by the SSI (evidenced by the influence of the containment shell and soil parameters). The SSI modifies the translational motion and produces substantial rocking of the foundation.
- o The piping is flexible.

Thus flexible piping has greater response variance. Piping with diverse support bases also has greater response variance. There is actually some correlation between support base type and flexibility arising from the design process to limit stresses from differential support displacement. A higher response variance contributes to a higher probability of component failure.

6.2.2 Intercepts

The intercepts are shown in Fig. 6-6. In piping group (1), the third through fourteenth valve acceleration responses all have nearly the same intercept value (as well as the same variance). These valve response accelerations are all nearly the same as the input PGA. The moment intercepts in group 1 are all relatively small. As mentioned above, the piping mode frequencies are well above the amplified frequency range of the input ground motion. Also, there is no pseudostatic moment.

For piping groups (2) and (3), the response intercepts cover a wide range similar to the range for the complete set of responses.

6.2.3 Damping

In each of the three selected piping groups, the importance of damping changes from one response location to another; see Fig. 6-8.

Piping group (1). For many valves the piping damping is of no importance (coefficient b_{dp} is zero). For the first two valves, damping is of some

importance (coefficient b_{dp} is nonzero). There the piping frequency is of some importance also.

For piping group (1) moment responses, damping is of some importance, with b_{dp} values mostly about -0.1 to -0.2.

Piping groups (2) and (3). The coefficients of piping damping, b_{dp} , cover a wider range, from about zero to about -0.4 for acceleration responses and to about -0.5 for moment responses. When $b_{dp} = 0$, then the damping is of no importance to that response. When $b_{dp} = -0.5$, then damping is of some importance (see example below). Other responses have b_{dp} values filling in the range of values from 0 to -0.5, and thus, filling in a gradation of quantitative importance of damping to those responses.

The average b_{dp} for piping group (3) is less than that for piping group (2), and the largest value of b_{dp} ($b_{dp} = -0.35$) is less than that for piping group (2). Both piping groups are rather flexible. The key difference is that the pseudostatic term in the total moment response plays a relatively greater role in piping group (3). This is evidenced by the coefficients of piping frequency, b_{fp} in Fig. 6-7(c), being around +1.0 or greater in six of the seven piping-run moment responses. In the pressurizer piping, the source of the large pseudostatic moment is the relative motion between the flexibly-supported pressurizer and the concrete internal structure. In the AFW system, the steam generator plays a similar role.

A coefficient $b_{dp} = 0.5$ for the logarithmic variable has the following meaning in terms of the linear input damping and response values.

If the damping is increased by 100 percent (say from 0.02 of critical to 0.04 of critical), then the response will be decreased by only 29 percent.

Earlier we incorporated the random variability of the input variables and the responses by modeling them as random variables (Fig. 1-2). Just as a response value is sensitive to its input values, similarly the response distribution, described by a distribution type and parameters, is sensitive to the parameters of the input distributions (Fig. 1-4). The sensitivity turns out to be expressed by the same coefficients b_i , in particular for damping by

b_{d_p} (see Equations 19 and 20).

The example above with $b_{d_p} = -0.5$ has the following meaning in terms of the distributions of the linear input damping variable and response variable. Recall that these random variables have lognormal distributions (in the case of response, only approximately lognormal). Thus for the linear random variable it is convenient to examine their medians. This is because the median of the linear variable is linked to the median of the corresponding distribution of the logarithm of the variable. For the logarithm, the median equals the mean because the distribution is symmetric. Using this linkage of concepts and using Equation 19 to get a linkage of both sensitivities to the same coefficient b_{d_p} , we get the conclusion for the example -- if the median of the damping distribution is increased by 100 percent (say from 0.02 to 0.04), then the median of the response distribution is decreased by 29 percent.

In summary, piping damping has variable importance ranging from none up to a certain modest degree. The degree of importance varies between piping systems and at locations within a piping system. The physical reasons for this variation are judged to include at least these factors: (1) piping flexibility due to layout design, (2) response location and modal participation, and (3) competition from the base acceleration or the pseudostatic moment. At response locations where piping damping is important, piping frequency is important as well.

7. INFLUENCE OF SUPPORT STIFFNESS

The effect of using realistic support stiffness values, as contrasted to very stiff values often used by default, was examined in one piping system, the AFW inside containment.

It has often been assumed in the past that the supports are much more rigid than the pipe, and that, therefore, very rigid support values and the actual support values would give nearly the same results in the piping stress analysis.

Generally a change in the piping model to less rigid support stiffness values (realistic) decreases the overall piping system stiffness (perhaps by only a very small amount). Such a change may have different effects on the two constituent parts of the total piping moment (Section 5.4.2). The pseudostatic moment is decreased, since the applied displacements remain the same. The dynamic moment often increases. The lower stiffness in part of the piping system means that some or all of the modal frequencies are shifted to lower values. Over much of the frequency range of interest, such a shift increases the response (see the response spectrum in Fig. 5-25). There are changes in the mode shapes as well; it is not possible to generalize about these changes and their effects on force distribution throughout the piping system and on modal participation factors.

Support stiffnesses were evaluated for rigid hangers, lateral supports, and hydraulic snubbers. The stiffnesses of rigid hangers and lateral supports were estimated from the support design drawings, and the stiffness of hydraulic snubbers was estimated.

For the AFW piping, the frequencies for the first 30 modes are shown in Fig. 7-1. As expected, the frequency values for the best-estimate stiffness case are the same or lower. The mode shapes are not always comparable from case to case, probably due in part to mixing of nearby (in frequency) modes when the proportions in the support stiffness are changed.

The first five modal frequencies are nearly unchanged. The higher frequencies show (roughly) a trend to greater changes. This is to be expected. The higher modes are "stiffer," considering that $\omega^2 = k/m$, or that

Figure 7-1. Frequencies for the first 30 modes for the AFW piping inside containment, for two modeling inputs for support stiffness—very rigid and best-estimate values. The very rigid supports produce higher system frequencies, ranging from negligible increase for the lowest modes to about a 10 percent increase for some of the higher modes.

the higher modes involve shape changes over shorter lengths of the pipe. As the modal stiffness gets larger, the (fixed) support stiffness gets smaller in proportion, eventually small enough so that it will have a noticeable effect on the combined stiffness.

The small changes in frequencies will lead to only small changes in responses; Eq. (9) and the results of Chapter 5 are a guide to this conclusion. The higher modal frequencies in Fig. 7-1 (say the twelfth mode and up) show decreases of roughly 10 percent in frequency. Since the coefficients b_f in Fig. 5-17 range from zero to as large as about -1.4, we might expect an increase in acceleration response as large as +14 percent at some response points in the pipe. For piping moments dominated by the dynamic term, a similar expectation would apply. The pseudostatic moment, by contrast, is generated by a long-range deflection shape in the pipe, comparable or longer in size scale to the lowest few mode shapes. These latter have virtually unchanged frequencies in Fig. 7-1. Thus, we may expect that the decrease in the pseudostatic moment will be vanishingly small, at least for most piping configurations where long distances or flexibility are built in between major displaced support points.

A recent study²⁰ examined the related question of how much the piping response would change if one support in a piping system changed in stiffness. The base case was best-estimate support stiffnesses as estimated before detailed design of the supports. The study found, similar to our Fig. 7-1, that the higher modal frequencies were shifted down if the stiffness of all supports was shifted down to form a new base case. Upon varying one support, the variation of piping moment or support load was found to be relatively smaller if the base case was stiffer or if the one support was shifted to a stiffer value, and relatively larger if the base case was more flexible and the one support was shifted to a less stiff value.

Another study²¹ examined the variation in stiffness of in-line pipe anchors built up of structural steel. Piping results using diagonal stiffness matrices for the anchor with various stiffness constants (and always with rotational stiffnesses greater) were compared against results using a 6 x 6

stiffness matrix of the anchor. Support stiffness constants were varied over seven orders of magnitude. The modal frequencies and the response spectrum used were not stated, but a piping force and a piping displacement each varied up to about a factor of two above and below the nominal. The main conclusion of the study was that the best diagonal approximation to the anchor stiffness matrix was orders of magnitude less stiff than the default values used in many piping computer programs, a difference large enough to have a noticeable influence on the responses.

The change in response for our own test case of the AFW, estimated to be up to 10 percent change, is small compared to other systematic uncertainties present. This conclusion might change for other examples, however, dependent on pipe diameter, support spacing, and support design. A modal frequencies calculation using order-of-magnitude estimates of support stiffnesses, compared to a calculation with very high stiffnesses, can give a quick and rough indication of the size of response changes.

8. RANKING OF INPUT VARIABLES

We wish to have a relative ranking of the input variables' importance as based on some relevant criterion. The "bottom line" output value is risk due to overall plant system failure given an earthquake. A ranking based on the risk's sensitivity to the input variables' PDF parameters is presented in another report.¹² Here we note that the piping responses can be influenced by any of the input variables. We will base the ranking on the contribution of an input variable's variance to the variance of a piping response.

The contribution to variance and several alternate possible choices for ranking all are tied to the same LRA coefficients b_i . One possible choice might be the change achieved in response when a variable changes by one standard deviation from its mean value:

$$\Delta Y = b_i \cdot \Delta X_i = b_i \cdot \sigma_i$$

using sensitivity b_i from Equation 19 and $\sigma_i^2 = \text{Var } X_i$. A related choice, which we will use, is the contribution of one input variable to $\text{Var } Y$. From Equation 18, that contribution is the term

$$C_{Yi} = (b_i \sigma_i)^2$$

A third choice might be to use the sensitivity of $\text{Var } Y$ to changes in $\text{Var } X_i$. This also has b_i^2 ; see Equation 20.

The ranking of input variables might be based on how many responses they make a significantly non-zero contribution C_{Yi} to, or on the average C_{Yi} , or on the maximum C_{Yi} over the set of piping responses. Component failure given an earthquake usually has a low probability. This probability is increased if the response variable has a large variance, which in turn could arise if one or several of the input variables contributes a large term to the variance. Hence for an importance ranking criterion we settle on the largest value of the term C_{Yi} rather than taking an average over many piping component responses which may be far below the failure level.

Table 8-1 lists (1) the variables contributing to the piping response variance along with (2) their maximum coefficients for any piping response (at the 90 percent confidence level, which is depicted by the error bars in Figs. 5-3 through 5-15), and σ_1 the standard deviation (SD) of the logarithm (calculated from the CVs in Table 3-5). Major equipment was included in the internal structure model, but we list it separately since its influence on attached piping is much greater. For the structure frequency's maximum coefficient, two isolated large values associated with pseudostatic moments were not counted. The SD of the rock input PGA is estimated from the minimum variance in Fig. 5-1(a), after subtracting the contribution from soil damping.

The last column in Table 8-1, listing $|b_i| \times \sigma_1$, is a measure of the maximum contribution of an input variance to a response's total variance (which is made up by the sum of squares of such contributions). A second contribution from seismic input is attributable to spectral variability (estimated from the residual variances in Fig. 5-1(b), after subtracting the contribution from soil stiffness). The uncertainties given for the numbers in each column are minimal estimates. For $|b_i|$ they are based on the sampling statistics and the extent of responses modeled; for σ_1 they are based on the roundoff error in Table 3-5.

We next combine (by SRSS) the contributions to response variance from the two input variables of each "input area," i.e., seismic input motion, soil, structure, major equipment, and piping. (In the case of piping moment maximum, there is only one piping variable, the frequency. In coincidence with that maximum, the piping damping has zero influence.)

The resulting contributions from each input area, listed in Table 8-2, are fairly close, recognizing the uncertainty in estimation. There is a close tie for maximum contribution from three input areas--soil, major equipment (where applicable), and piping. Seismic input ranks a close fourth, and structures fifth but still significant in contributions to some piping response variances.

Table 8-1. Maximum contribution of each input variable to the standard deviation of any piping response. This measure was chosen as a basis for ranking the input variables. The coefficient b_i are from the LRAs of the piping responses. The σ_i are the standard deviations of the logarithmic input variables used in the LRAs. The errors in these values are estimated and apply as percentages to all values in a column.

VARIABLE	$ b_i $	σ_i	$ b_i \times \sigma_i$
G_{soil}	0.8 ($\pm 5\%$)	0.39 ($\pm 15\%$)	0.31 ($\pm 22\%$)
D_{soil}	0.5	0.47	0.24
F_{struc}	0.6	0.25	0.15
D_{struc}	0.15	0.34	0.051
F_{equip}	1.5	0.25	0.38
D_{equip}	0.10	0.34	0.034
f_p (for accelerations)	1.3	0.25	0.33
f_p (for moments)	2.0	0.25	0.50
d_p	0.4	0.34	0.14
Rock PGA	1.0	0.2	0.2
Rock spectral variability	--	--	0.15

Table 8-2. Maximum contribution of each input area to the standard deviation of piping responses. By combining the maximum contribution from the two input variables of an input area, from Table 8-1, we get a measure which can be used in an importance ranking of the input areas. The rankings are close when we consider the percent error in evaluating the ranking measure.

INPUT AREA	CONTRIBUTION ^a
Seismic Input	0.25 (±25%)
Soil	0.39
Structures	0.16
Equipment	0.38
Piping (for accelerations)	0.36
Piping (for moments)	0.50

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^a SRSS of $|b_i| \times \sigma_i$ values from Table 8-1

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

Linear regression analysis (LRA) provides a means to describe, in approximate but simple terms, the functional behavior of a complicated function or computer model. LRA provides a quick overview and comparison within a large set of response functions. Subsequent effort may then concentrate on seeking the physical reasons for the main aspects of the functional behavior.

The linear regression analyses were fairly successful, in the sense evidenced in Fig. 5-1. The residual variance is small, on the order of the input spectral variation not included in the model. Where the response total variance is high, the linear regression model explains most of that variance.

One noteworthy conclusion, but not a suprising one, is that the qualitative results change with the location of the individual response. This can be seen in the total variances (Fig. 5-1) and in the coefficients of the respective linear regression models (Figs. 5-3 through 5-14). Different responses are in locations where the many potential influences have different effectiveness.

The soil damping has an influence on virtually all of the responses, seen in Fig. 5-15. This occurs because of the soil damping's influence on the soil surface acceleration; see Fig. 4-8. Previous work in the SSMRP¹¹ analyzed the specific site's effect on the relationship between the bedrock seismic acceleration and the soil surface (free field) acceleration. That analysis covered surface acceleration amplitude, spectral characteristics, and net variability. The present study shows that the variability in the soil PGA is mainly due to the variability in the soil damping. Variability in the soil stiffness, by contrast, has little effect on the PGA, but it does have a substantial effect on the variability of the low frequency spectral response.

Piping damping has variable importance ranging from none up to a modest degree. The degree of importance varies between piping systems and at locations within a piping system. At response locations where piping damping is important, piping frequency is important as well.

The largest coefficients of piping damping in the LRAs of piping responses were about -0.4 to -0.5. A coefficient of -0.5 for the logarithmic damping variable in the LRA model has the following meaning in terms of the linear input damping and response variables. If the median of the probability distribution of the piping damping random variable is increased by 100 percent (say from 0.02 of critical to 0.04 of critical) then the median of the response distribution is decreased by only 29 percent.

The largest coefficients of piping frequency in the LRAs are about -1.4. A coefficient of -1.4 for the logarithmic frequency variable in the LRA has the following meaning in terms of the linear input and response variables. If the median of the piping frequency variable's distribution is decreased by only 22% (that is, the nominal values of the fundamental and higher mode frequencies are decreased by 22%) then the median of the response distribution is decreased by 29 percent.

Differences between piping systems have a noticeable effect on characteristics of the responses. Flexible piping systems, as contrasted to more rigid piping systems, have in general a higher variability in their responses, and have a greater number of response locations where the piping frequency and damping are important for those responses. Piping systems supported on or connecting to major equipment have in general a high variability in their responses. The major equipment items examined were the steam generator and the pressurizer, which are in themselves rather flexibly supported. A higher variability in responses usually brings a higher probability of component failure given an earthquake.

The LRAs helped identify the reason for the large variability of some piping moment responses and these responses' high sensitivity to piping frequency. In this case the reason was an unintended artifact from the way SMACS models the random variability of inputs. The variability of piping frequency was modeled as arising from variability in piping stiffness rather than from variability in piping mass or other characteristics. This caused a larger than intended variability in the piping pseudostatic moment, i.e., the moment from relative displacement of supports. This modeling feature could

easily be adjusted in a future version of SMACS. The variability in piping acceleration responses is not affected by this modeling choice.

There are numerous piping examples where the soil, structure, or piping variables have a large influence on a piping response. For some of the piping responses many of the potentially influential inputs have a large influence. Heavy equipment modeled with the structure model, e.g., the pressurizer and steam generators, has a large influence on piping attached to the equipment.

A rank ordering of the input variables was based on a measure using the largest influence of the variable on any piping response combined with the estimated random variability of that variable. A comparable measure was estimated for the seismic input bedrock acceleration and spectral variability (within a single earthquake acceleration interval). Then a rank ordering was developed for each input area--seismic input, soil, structures, major equipment, and piping-- by combining the importance measures of the two input variables of each input area.

The resulting contributions from each input area, listed in Table 8-2, are fairly close, recognizing the uncertainty band in estimation. There is a close tie for maximum contribution from three input areas--soil, major equipment (where applicable), and piping. Seismic input ranks a close fourth, and structures fifth but still significant in contributions to some piping response variances.

9.2 RECOMMENDATIONS

More attention should be focused on frequency variability in piping and major equipment, which may cause large variability in piping response. First, our estimate of the frequency variability should be tested experimentally. This may be done by (1) comparing modal frequency identification tests against the frequencies calculated based on as-built drawings, for piping systems, steam generators, pressurizers, etc., (2) looking at tests under random motion to see how closely the frequencies can be identified, and (3) testing under different conditions of input motion, e.g., direction, amplitude, location, and waveform, to see whether the modal frequencies change. Second, if the

present study is confirmed, methods to design piping systems to be less sensitive to piping frequency variability should be developed. Third, analysis methods accounting for piping frequency variability should be developed for routine use in confirming a piping system design's acceptability.

The strong variability of pseudostatic moment with frequency or stiffness is an artifact of the way SMACS models the random uncertainty of input variables and conditions. The pseudostatic moment variability should be reduced in a future SMACS model to be less than the typical variability of the dynamic moments. This may be considered a fine tuning of SMACS modeling of uncertainty. The piping fragility function as well might be provided with two alternatives for failures from either the vibratory motion (a primary load) or the pseudostatic moment (a secondary load, i.e., one which can be relieved by some inelastic yielding of the pipe).

The linear regression model can be used as a substitute for the SMACS model in doing propagation of uncertainty and in studies of sensitivity to input uncertainties. In such studies numerous calculations of uncertainty propagation must be carried out with different assumptions on the input uncertainties. The substitute model will speed up calculations and, thus, allow larger samples and more tests of more input assumptions. A cautionary note is the possibility of introducing a new modeling uncertainty.

The linear regression model of the SMACS combined responses is fairly accurate, to the extent displayed earlier. The SMACS combined responses are maxima over a number of moment locations or of acceleration components. Thus, these quantities screen out the less important small responses. But a model built up of combinations of LRAs of the more detailed responses would be even more accurate. For the purpose of isolating key physical influences on the responses, also, linear regression analysis of the detailed local responses will be more helpful.

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