SENSITIVITY OF PEAK DYNAMIC RESPONSES TO INPUT FACTORS

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This paper was prepared for submittal to:
American Society of Civil Engineers,
Raleigh, North Carolina

June 1984

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We examine the sensitivity of calculated peak dynamic responses, such as acceleration and moment, to input parameters such as frequency and damping. These responses have been calculated for the Zion Unit 1 plant, using the SSMRP computer code SMACS, as part of the seismic probabilistic risk assessment performed by the Seismic Safety Margins Research Program (SSMRP), supported by the NRC Office of Nuclear Regulatory Research. We use linear regression analysis (LRA) to develop a simple model of the SMACS calculations. The sensitivities of the responses are the coefficients from the LRA. The LRA provides an approximate but simple overview of the complex response behavior. Heavy equipment such as the pressurizer and the steam generators has a large influence on the response of attached piping. Piping damping is sometimes important to the piping response, but in those cases piping frequency is usually more important. Variability in the inputs introduces correlations among the affected responses. The soil damping, through the local site effect, strongly affects all the plant responses.

Keywords: Earthquakes, Linear regression analysis, Nuclear electric power generation, Pipes, Probabilistic risk analysis, Sensitivity analysis, Statistical analysis, Structural engineering.

Introduction

This paper summarizes some of our results on the sensitivity of calculated peak dynamic responses, such as acceleration and moment, to input parameters such as frequency and damping. These responses have
been modeled and calculated for the Zion Unit 1 plant as part of the seismic probabilistic risk assessment (PRA) performed by the NRC Seismic Safety Margins Research Program (SSMRP). The computer code SMACS developed under the SSMRP was used to perform the response calculations. The SSMRP is supported by the NRC Office of Nuclear Regulatory Research.

Two sensitivity topics motivated our study: first, the sensitivity of piping response to the mean value of piping damping; and second, the sensitivity of seismic risk to all earthquake and model input parameters (to be published separately), which requires first the sensitivity of the responses to these input parameters. At the same time, the regression analysis allows us to see the main features of the performance of the SMACS model of the earthquake event, both on its deterministic and probabilistic levels.

We are interested in the sensitivities because the input parameter

![Site plan of the Zion nuclear power plant.](image)

Fig. 1. Site plan of the Zion nuclear power plant.
values can be changed through fabrication or field activities (presumably after some appropriate R&D). Our estimates of the input values can change as a result of measurement or research. Which input parameters have an important effect or the response and which do not? The input means and variances can affect the response means and variances and hence the seismic risk; which ones will actually have a large effect on the risk?

Method and Models

The SMACS code (Seismic Methodology Analysis Chair; with Statistics) (5) computes the dynamic response of structures and equipment. The SMACS models include both the plant-specific input models for the Zion Unit 1 plant (2) (Fig. 1) and the code’s algorithms for both the physical processes and the variability which is unavoidably present; see Figs. 2 and 3. To answer sensitivity questions, we desire simple approximate models of the more complex SMACS model at both its inner deterministic level and its outer probabilistic level.

Linear regression analysis (LRA) (3, 9) frequently has been used to model the input-output relationships of more complex mathematical models (1, 7, 8, 10) as well as of experimental or field data, e.g., Ref. (4). We use LRA to develop a simple model of the SMACS inner level; see Fig. 4. We have a data base of SMACS inputs and outputs from previous calculations (2). With this data base, the LRA provides us with average sensitivities: sensitivity of a response to an input given the variability in all the other inputs. We then analytically develop a simple model for the SMACS outer level based on the inner level model; see Fig. 5.

We anticipate that a power-law relationship may provide a fairly good approximation, over a fairly wide range of the inputs, to the structural dynamic response. We can convert a power-law function to a linear function by taking logarithms. Thus we can apply the linear regression analysis to the logarithm of response (log of acceleration or piping moment) as a function of the logarithms of the inputs. The equation we use is

\[ Y = a + \sum b_j X_j + b_p X_p^2 \]  

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Building and subsystem response

Free field acceleration
Bedrock acceleration
Basement acceleration

Fig. 2. SMACS (Seismic Methodology Analysis Chain with Statistics) calculates the dynamic response of structures and equipment to an earthquake. SMACS has computational models of the processes: local site effect, soil-structure interaction, structural response and subsystem response. SMACS models random variability with probability distributions.

Fig. 3. The SMACS code has a deterministic computational 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 their 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.
Fig. 4. 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.

\[ \hat{Y} = a + \sum b_j X_j + b_p X^2_p \]

Fig. 5. 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 determined. This output distribution is evaluated by the method of propagation of moments.
where the sum is over the set of converted input variables $X_j$. These include the piping variables of one piping system when $Y$ is a piping response, or in some cases the variables of two piping systems when a response is in a pipe run extending over two piping systems. We further include a term quadratic in $X_p$, log of piping frequency. Note that, as required for LRA, the function is linear in the coefficients $a, b_j$, and $b_p$.

Results

The linear regression analyses of the SMACS responses were fairly successful, as exhibited in Fig. 6. These LRAs used a data set with 90 input-output members, from three earthquake intervals having a range of 0.20 - 0.53g PGA at the rock surface outcrop. One relatively simple LRA is illustrated in Figs. 7 and 8. The response data are shown in Fig. 7 and are discussed in the following paragraph. There are two input variables and only one of them has a substantial influence on the response value, illustrated in Fig. 8.

Previous work in the SSMRP (2) showed the importance of the local site effect and found a variability in the magnitude of the effect. The present work identifies the source of that variability. The local site effect produces a larger peak ground acceleration (PGA) at the Zion site's soil surface than at an average site, basically because of the Zion site's configuration—a relatively shallow soil layer over a stiff bedrock. The present study shows that the variability in the soil-surface PGA (see Fig. 7), for a given rock-outcrop PGA, is mainly due to the variability in the soil damping (see Fig. 8). Variability in the soil stiffness, by contrast, has little effect on the PGA, although it does have a substantial effect on the variability of the low frequency spectral response. In fact both soil damping and soil stiffness have an effect. See Fig. 9 (a) and (b), where the first response in each figure is the soil PGA and the second response is the soil 4-Hz spectral acceleration. The variability in the parameters of the local site effect introduces positive correlations among almost all of the responses. Such correlations were found in the main set of SSMRP calculations.

Some results of the LRAs using the data from three earthquake
Fig. 6. Results for 332 linear regression analyses (LRAs), for responses 2-333, for the combined data from three earthquake intensity intervals (ranging from 0.20 - 0.53g PGA at the rock surface outcrop). (a) Total variance of the responses, (b) residual variance, (c) percent explained variance. The responses are grouped: no. 1-4 are in the soil free field, no. 5-52 are in structures, no. 53-200 are piping accelerations at valves, and no.201-333 are piping moments. The residual variances are small, on the order of the input spectral variation not included in the model. Where the response's total variance is high, the linear regression model explains most of that variance.
intervals (a data set with 90 input-output members), additional to the
results in Fig. 6, are shown in Fig. 10. The intercepts (coefficient $a$
in Eqn. (1)) are estimates of the responses when all inputs are at
their mean values. Coefficients $b_j$ of some of the terms linear in
the $X_j$ are also shown in Fig. 10.

Piping Responses

One easily observed conclusion, especially for the piping
responses, is that the qualitative results change with the location of
the individual response. Different responses are in locations within
the structures and piping where the many potential influences have
different effectiveness. In the following, generalizations apply in an
average sense or to those responses which have the larger variances

![Cumulative probability distribution of the peak ground acceleration (PGA) at the soil surface, given an earthquake in the interval (0.32 - 0.42g PGA at the rock surface outcrop). The points are the sample of responses; the dashed curve is a lognormal cumulative probability distribution function fitted to the sample data.](image)
within a group of responses.

The piping acceleration responses have larger variances than the free-field or structural response variances, and the piping moment responses have the largest variances. The larger variances can be explained in part because the piping responses have more input variables. Numerous piping examples are present where the soil, structure, or piping variables have a large influence on a piping response (i.e., large coefficient $b_j$ of that input variable $X_j$). For some of the piping responses many of the potentially influential inputs have a large influence. Heavy equipment modeled with the internal structure model, e.g., the pressurizer and steam generators, has a large influence on piping attached to the equipment (see coefficient $b_5$ of internal structure frequency in Fig. 10.e).

![Figure 8](image)

Fig. 8. Dependence of the PGA at the soil surface on soil damping as determined by a linear regression analysis. The range of the vertical axis covers the full range of the sample of responses. The solid curve shows how much the response varies with the one variable of the horizontal axis. The slope corresponds to the coefficient $b_0$ (see Fig. 9).
Fig. 9. (a) Coefficient $b_D$ of the soil damping variable, and (b) coefficient $b_g$ of the soil stiffness variable, for all responses no. 1-333, for the data of earthquake interval 4. The error bars show the 90%-confidence lower and upper bounds on $b$. 
Fig. 10. Further results from the LRAs as in Fig. 6. (a) Intercept, or equivalently the estimate of the response when all inputs have their mean values; (b) coefficient of the term linear in piping frequency (different piping variables for each piping system); (c) coefficient of the piping damping term; (d) coefficient of containment shell frequency; (e) coefficient of frequency of containment internal structure and major equipment; (f) coefficient of auxiliary-fuel-turbine building frequency.
Fig. 10, Continued.

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The nominal responses (Fig. 10.a) for accelerations are only a modest factor above the nominal value of the soil PGA. It is the variances, large in some cases, which give a possibility of higher responses at a correspondingly smaller probability of exceedence. Where the high variances are due to contributions from many input variables, there is an analogy with the compounding of safety factors in deterministic analysis of design adequacy. This analogy is only qualitative; the compounding produces an unknown degree of conservatism which may be, in some cases, very large (6).

The largest piping variances are for certain piping moments. These were found to be locations where the pseudostatic moment dominates the total moment response. SMACS associates frequency and stiffness variabilities. The estimated frequency variability produces a stiffness variability which has a large effect on the pseudostatic moment in the piping even when the relative displacement of the anchors of the pipe is not varied. We would expect instead to find less variability in the pseudostatic moment than in moments dominated by the dynamic vibration of the pipe, because the dynamic motion is more complex. This is an area where we might change the SMACS model to "fine tune" its modeling of the probabilistic aspects of the earthquake response. The model was developed with main emphasis on dynamic motion.

The effect of piping damping is best observed in the acceleration responses, which are not altered by whether we model frequency variation as arising from stiffness variation or mass variation or a combination. The largest negative coefficient of piping damping (Fig. 10.c) is about -0.4. In our log-log model, this means, for example, if we decrease damping by 33% of its value, say from 0.06 of critical to 0.04 of critical, then response will increase by 18% of its value. Where piping damping is important, however, then piping frequency is usually more important (see the correlation of the two coefficients, Fig. 11). The largest negative coefficient of piping frequency is about -1.2. In our log-log model, this means, for example, if we decrease frequency by 25% of its value, then response will increase by 41%. At some other response locations, neither piping variable is important; e.g., for the response at a valve near an anchor. At still other locations both have an importance intermediate between the highest values and zero.

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Conclusion

The LRAs of the SMACS calculated responses were successful in terms of small unexplained variance. LRA thus provides an approximate but simple and adequate overview of the functional behavior of the complex SMACS computer model. We can then examine the main features and their physical reasons. Many of the qualitative results change with the location of the individual response within the plant. Heavy equipment modeled with the internal structure model, e.g., the

Fig. 11. Cross plot of coefficient $b_d$ of piping damping versus coefficient $b_f$ of piping frequency; one point for each regression analysis of a piping valve acceleration, responses no. 53-200 in Fig. 10 (b) and (c). A significantly non-zero value of a coefficient indicates an influence of the corresponding coefficient on the response. Many of the data points are near (0,0). The others are clustered near a line running to approximately (-1.2, -0.4) indicating a correlation between the two coefficients.

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pressurizer and steam generators, has a large influence on the response of piping attached to the equipment. Piping damping is sometimes important in affecting the response, but in those cases piping frequency is usually more important. Variability in the inputs introduces correlations among the affected responses. The soil damping introduces variability in the local site effect, affecting all the plant responses and hence introducing correlations among all of these responses.

The LRA results allow development of the propagation of input probability distributions, following the scheme of Fig. 5. This will be published separately. The LRA model, once established based on a set of SMACS runs, may be used in place of the full SMACS model for variational studies. Others have used LRA models and statistical sampling to propagate input probability distributions (1,7,8).

The frequency variability in piping, and in heavy equipment which supports piping, should be addressed in future research. First, the SSMRP's estimates of frequency variability should be validated. Second, because of frequency's large influence on response, methods in fabrication and measurement should be developed to reduce the variability in piping and equipment frequency. Consideration should be given both to methods in design to accommodate frequency variability without it having such a large impact on response, and to new design-checking analysis methods which account for variability more realistically yet still retaining adequate conservatism.

The importance of future research in piping or other areas arises not simply from these areas' influences on responses, but more basically from their influence on risk. The evaluation of risk requires the combination of response, fragility and system information (11). As noted above, a parallel study within the SSMRP has analyzed the sensitivity of risk to the structural variables and other inputs; a separate report will be published.
Acknowledgements

This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

The author extends thanks to L. L. George for recommencing linear regression analysis and to Edna M. Carpenter for writing the first version of the linear regression analysis computer program.

References


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