Recommendations for the combination of seismic and hydrodynamic loads for probabilistic risk assessment

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1 INTRODUCTION

In the Risk Methods Integration and Evaluation Program (RMIEP) sponsored by the Nuclear Regulatory Commission, the seismic risk analysis methodology developed in the Seismic Safety Margins Research Program (SSMRP) is being applied to estimate the seismic risks from a boiling water reactor (BWR) plant. The LaSalle County Station with a Mark II containment was selected as the reference plant for this study. Since seismic events can potentially cause accident scenario initiating events, (e.g., LOCA, plant transient) which can result in hydrodynamic loads in the plant (e.g., safety/relief valve discharge, condensation oscillation) it is necessary to examine the combined effects of seismic loads with one or more hydrodynamic loads.

In this study, a critical look is taken at the potential for combination of seismic and hydrodynamic loads and the impact such combined loads have on the ability of critical structures and equipment to perform their necessary safety functions. It should be emphasized that the intent here is to examine the effect of hydrodynamic loads on the plant seismic risk, rather than a deterministic assessment of whether of not seismic loads caused by the Safe Shutdown Earthquake (SSE) should be combined with hydrodynamic loads for design purposes. The difference is significant since past probabilistic risk assessment (PRA) studies have shown that the dominant contribution to seismic risk comes from earthquake levels greater than twice the SSE indicating that large earthquakes must occur in order for there to be a significant probability of plant damage (Ravindra, et al, 1984). Thus, comparison of the stresses induced by the hydrodynamic loads and the stresses induced by the SSE is not valid for assessment of the impact of hydrodynamic loads in evaluating seismic risk. In order for the hydrodynamic loads to be significant, they must induce stresses comparable to those induced by earthquakes greater than twice the SSE.

In a probabilistic format, hydrodynamic loads must be considered when their inclusion has a non-trivial effect on the failure probability of a particular structure or equipment item for an earthquake of a specific maximum ground acceleration. For such cases, a probabilistic load combination methodology which accounts for the magnitude, frequency content, and time-phasing of the loads is used to determine the combined load effect. The results from this rigorous approach can be compared with those obtained using simplified rules such as SRSS.

2 HYDRODYNAMIC LOADS SCREENING CRITERIA

The hydrodynamic loads which can occur in a Mark II BWR are described in detail, in General Electric NEDO 21061 (1981). The hydrodynamic loads which may be induced by an earthquake (i.e., as a result of a plant transient or seismic LOCA) were examined as to the nature of the phenomena, the magnitude of the ensuing load and the occurrence time of the load. From this analysis, it was found that SRV and CO loads (induced by large LOCA) may have a significant impact on seismic fragilities. Details of the screening analysis can be found in Sues, et al. (1986). It should be noted that in the overall risk analysis the probability of a seismic induced large LOCA must be considered. If it is found that this is not a credible event, then CO loads need not be combined with seismic loads. In the next section, a probabilistic methodology for combining seismic and hydrodynamic loads is discussed.

3 PROBABILISTIC LOAD COMBINATION METHODOLOGY

Although the durations of the individual hydrodynamic events discussed may overlap, peak response from these events may not occur simultaneously. The combined response of a particular structure or equipment item is evaluated in this study using the procedure outlined by Winterstein (1980). In this approach, the response from each of the loads is characterized by its mean upcrossing rate function and its probability density function. The upcrossing rate function gives the rate at which the response is expected to exceed some specified level, and the probability density function (pdf) is a measure of what values the response is likely to take on at some point in time.

For the seismic and hydrodynamic loadings considered herein, the necessary load-input sample time histories are obtained either from test data (SRV time histories are available from the LaSalle County Station in-plant SRV test performed by Commonwealth Edison Company, Sargent & Lundy Engineers, and Wyle Laboratories) or, by analysis.

Since the loadings are non-stationary (i.e., intensity will vary with time) and since the response will include transient behavior, the upcrossing rate function and pdf of the individual responses will vary with time. Thus, the pdf and upcrossing rate functions are evaluated for specific time segments of the entire time history.

Consider now the two response time histories for a particular structure or equipment item shown in Figure 1. Given the upcrossing rate functions $\nu_{x_1}(z,t)$, $\nu_{x_2}(z,t)$, of the two response time histories, their respective pdf's, $f_{x_1}(x)$, $f_{x_2}(x)$ and the pdf of the of the time lag $f_{\varepsilon_{12}}$, the mean upcrossing rate function for the combined response can be calculated using the point crossing formula, as,

$$(1) \qquad \nu(z) = \frac{1}{T_1+T_2} \int_{\theta} f_{\theta_{12}}(\theta)d\theta \left\{ \int_0^{\theta} \nu_{x_1}(z,t)dt + \int_{\theta}^{T_1} \left[\nu_{x_1}(y,t)*f_{x_2}(z-y,t-\theta) + \nu_{x_2}(y,t-\theta)*f_{x_1}(z-y,t) \right] dt + \int_{T_1}^{T_2+\theta} \nu_{x_2}(z,t-\theta)dt \right\}$$

where $\nu_{x_i}(y,t_1)*f_{x_j}(z-y,t_2) = \int_{-\infty}^{\infty} \nu_{x_i}(y,t_1) f_{x_j}(z-y,t_2)dy$

With the upcrossing rate function of the combined responses obtained, the distribution of the maximum response can be obtained by assuming that the upcrossings of level z are governed by a Poisson process. Thus:

(2) $P(Z < z) = e^{-\nu(z)t}$

The Poisson process is used since for large values of z (corresponding to the higher percentiles) the events of upcrossing tend to be less frequent and can be taken as independent. For smaller values of z, the Poisson process assumption may give conservative results; however, it is the larger values of z corresponding to the larger non-exceedance probabilities which are of interest here.

In order to evaluate the effect of the hydrodynamic loads combining with the seismic load, it is only necessary to compare the upcrossing rate function of the combined response with that due to the seismic response alone. If there is no significant difference, then the hydrodynamic load may be neglected. If the hydrodynamic load does appear to be significant, then the combined expected maximum response can be calculated using the distribution of the maximum response (Eq. 2). The combined maximum response can then be compared to the maximum responses due to the individual loads for verification of simple load combination rules such as SRSS.

4 APPLICATION AND NUMERICAL STUDIES

The numerical studies were limited to consideration of SRV loads. At several critical locations sample SRV and seismic load time histories were obtained; from these time histories, response time histories for oscillators of various frequencies were calculated. The frequencies were selected so that the rigid, soft, and amplified regions of the response spectra for each load were represented. The upcrossing rate functions and pdf's were then evaluated for the response time histories and the point crossing formula (Eq. 1) then applied to obtain the combined response upcrossing function. The pdf's of the SRV time lag variable used in Equation 1 are shown in Figure 2. A complete discussion of the derivation of these distributions is given in Sues, et al (1986). The combined upcrossing rates were obtained for two different levels of earthquakes. Thus, a range of SRV and earthquake response levels were covered in order to determine the significance of SRV loads and test the applicability of any simple load combination rule.

Some typical results will be presented here. Table 1 shows the rate at which a 2.0 Hz oscillator would cross several acceleration levels for earthquake acting alone, SRV load acting alone and for both loads acting. The combined response upcrossing rate was calculated using the point crossing formula (Eq. 1).

Note that except for the very low response levels, the combined upcrossing rate is greater than the sum of the individual upcrossing rates. This is to be expected, and can be understood by examining the physical meaning of the point crossing formula (Eq. 1). For example,

consider the 0.77g upcrossing rate for the 2.0 Hz oscillator (Table 1). The rate at which the SRV response crosses ±0.77g is essentially zero; that is, we do not expect that the oscillator response would exceed ±0.77g due to SRV loading alone. The response due to the earthquake load, however, is expected to cross this level 0.19 times per second. If the earthquake response is at say, ±0.76g, there is a finite probability that the SRV response is ±0.01g so that the combined response crosses ±0.77g with some finite probability. The point crossing formula, as discussed earlier, considers all such combinations. Thus, the SRV response contributes to the combined upcrossing rate of ±0.77g even though the rate at which the SRV-alone response would cross this level is essentially zero.

From the upcrossing rate function, the distribution of the maximum response (Eq. 2) and the median maximum response may be estimated. Note that the estimates will tend to be conservative due to the Poisson process assumption used to obtain the probability distribution of the maximum response. Tables 2 and 3 show the median maximum responses for the cases studied, obtained using the earthquake, SRV and combined upcrossing rate functions. Also shown in the tables, are the absolute sum and square-root-of-the-sum-of-the-squares (SRSS) combinations of the earthquake and SRV median maximum responses. As can be seen from the tables, the absolute sum combination gives very conservative results as expected. The SRSS combination gives results slightly on the conservative side as compared with the median maximum obtained using the probabilistic load combination approach. This should be expected since the SRSS rule does not specifically account for the fact that the SRV load is a very short duration load. This greatly reduces the likelihood that the maximum SRV response will combine with the maximum earthquake response. The SRSS rule is most conservative when the maximum responses due to the two individual loads are close together. However, even for the most extreme cases (f = 2.8 Hz, Earthquake - Level 2), the SRSS combination exceeds the probabilistic level combination result by only 12 percent. For the cases in which the median maximum responses are farther apart, the SRSS rule and the probabilistic load combination results show little difference.

5 CONCLUSIONS

Based on the study conducted the following conclusions may be drawn:

1. The need for combining hydrodynamic load responses with the seismic response, in a PRA, depends on the relative magnitudes of the individual responses, the time-phasing of the loads, and on the conditional probability of hydrodynamic loads being induced by earthquakes. A careful screening study should be conducted in any BWR PRA to identify significant hydrodynamic loads.
2. Based on the screening performed for the LaSalle plant, it was found that only certain SRV load responses and, possibly, CO load responses need to be combined with seismic responses for the PRA.
3. The probabilistic load combinations study showed that the median of the combined maximum response may be obtained as the square-root-of-the-sum-of-the-squares (SRSS) of the median maximum responses of the individual loads. This approximation was found to be only slightly conservative.

It must be kept in mind that the conclusions drawn here are applicable only to seismic PRA studies and should not be construed as evidence for combining or not combining hydrodynamic loads with seismic loads for design purposes.

6 ACKNOWLEDGEMENT

The work reported herein was funded by the Lawrence Livermore National Laboratory. The authors are grateful for the helpful suggestions and comments of Dr. T-Y. Chuang formerly of LLNL.

7 REFERENCES

General Electric. 1981. "Mark II Containment Dynamic Forcing Functions Information Report," NEDO-21061, Revision 4, Class I.

Ravindra, M.K., Banon, H., Sues, R.H., Thrasher, R.D. 1984. "Sensitivity Studies of Seismic Risk Models," EPRI NP-3562, Project 2170-5, Electric Power Research Institute.

Sues, R.H., Ravindra, M.K., Putcha, C.S., Kincaid, R.H., "Combination of Seismic and Hydrodynamic Loads for the LaSalle County Station Probabilistic Risk Assessments," prepared for Lawrence Livermore National Lab, National Technical Systems NTS 12211.07, February 1986.

Winterstein, S.R., "Combined Dynamic Responses: Extremes and Fatigue Damage," MIT, Dept. of Civil Engineering, R80-46, December, 1980.

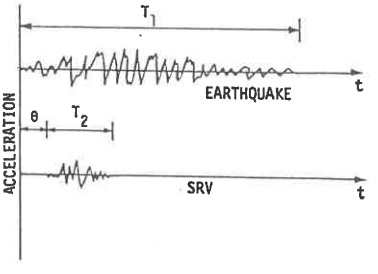
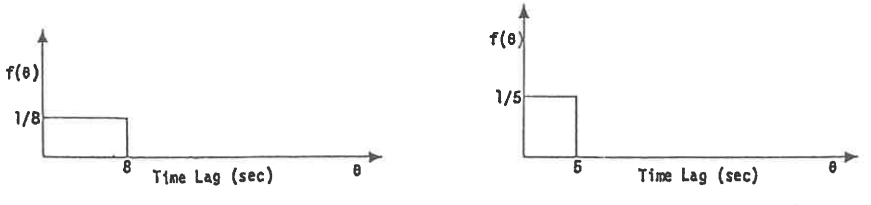


Figure 1. Conicidentally Acting Earthquake and SRV Responses.



a) Level 1 Earthquake b) Level 2 Earthquake

Figure 2. Distribution of the SRV Time Lag Random Variable, θ.

TABLE 1. UPCROSSING RATES FOR EARTHQUAKE LEVEL 2, SRV, AND COMBINED RESPONSE (OSCILLATOR FREQUENCY = 2Hz, DAMPING = 5%)

RESPONSE ACCELERATION LEVEL (G)	TIME AVERAGED (±) UPCROSSING RATES		
	EARTHQUAKE ALONE (SEC^{-1})	SRV ALONE (SEC^{-1})	COMBINED RESPONSE (SEC^{-1})
0.0	3.3	0.72	3.5
0.15	1.6	0.32	1.9
0.46	0.57	0.001	0.64
0.77	0.19	0.0	0.21
1.24	0.026	0.0	0.031

TABLE 2. COMPARISON OF SRSS AND ABSOLUTE SUM COMBINATION WITH PROBABILISTIC COMBINATION (EARTHQUAKE = LEVEL 1).

OSCILLATOR FREQUENCY (Hz)	EARTHQUAKE MEDIAN MAXIMUM RESPONSE (G)	SRV MEDIAN MAXIMUM RESPONSE (G)	ABSOLUTE SUM (G)	SRSS (G)	PROBABILISTIC COMBINATION MEDIAN MAXIMUM RESPONSE (G)
2.0	0.51	0.31	0.82	0.59	0.56
4.0	0.75	2.05	2.80	2.18	2.11
25.0	0.17	0.75	0.92	0.77	0.76

TABLE 3. COMPARISON OF SRSS AND ABSOLUTE SUM COMBINATION WITH PROBABILISTIC COMBINATION (EARTHQUAKE = LEVEL 2).

OSCILLATOR FREQUENCY (G)	EARTHQUAKE MEDIAN MAXIMUM RESPONSE (G)	SRV MEDIAN MAXIMUM RESPONSE (G)	ABSOLUTE SUM (G)	SRSS (G)	PROBABILISTIC COMBINATION MEDIAN MAXIMUM RESPONSE (G)
2.0	1.23	0.31	1.54	1.27	1.26
2.8	0.79	0.77	1.56	1.20	0.98
3.0	0.73	1.02	1.75	1.25	1.15
7.0	0.52	2.05	2.57	2.11	2.10