Sensitivity of Seismic Risk Estimates to Design and Construction Errors

M. K. Ravindra
EQE Engineering, Inc., Costa Mesa, CA USA
B. Ellingwood
Johns Hopkins University, Baltimore, MD USA

INTRODUCTION

The subject of gross design and construction errors has been addressed in the general context of structural reliability (Ellingwood, 1987; Ditlevsen, 1983; Lind, 1983; Nowak and Carr, 1985). Questions have been raised concerning the potential impact of gross design errors on risk estimates and insights obtained from seismic PRA studies of nuclear power plants (e.g., Ravindra, 1985, 1988; Gonzalez-Cuesta and Okrent, 1986). In PRA studies, seismic fragilities of structures and equipment generally are estimated by extrapolating the SSE design analysis to failure levels, taking into account safety margins and uncertainties. If design/construction errors affect a component, the component fragility family may be shifted to the left, increasing the conditional probability of failure at a given peak ground acceleration (see Figure 1). There is some concern that the results and insights gained from existing seismic PRA studies, conducted assuming error-free plant systems and components, would have been different if gross design/construction errors had been considered.

In a seismic PRA, the seismic capacity of a plant is evaluated in its assumed existing condition. Any benefits of quality assurance and quality control in reducing the likelihood of gross error have been already accounted for in its design. The as-built condition of structures and equipment may not be verified beyond a review of drawings and a cursory inspection for any obvious visible deviations, and design/construction errors may be present. Two broad classes of gross errors have been identified (Ravindra, 1988) as random error and systematic error. An example of a random error would be the use of regular bolts for equipment anchorage when the specification calls for high-strength bolts. An example of a systematic error might be the use of incorrect soil properties in a soil-structure interaction analysis, which would affect the calculated responses at several different component locations in the plant. The occurrence of such gross errors and their effects in seismic risk estimates must be assessed primarily using sensitivity studies and engineering judgment.

SENSITIVITY STUDIES

The risk-impact of a gross error may be assessed by postulating a specific error (i.e., type and magnitude) based on the significance of the failure mode and calculating the resulting change in the seismic risk (i.e., frequencies of core damage). In performing the sensitivity studies, certain gross errors are postulated in critical components of the plants to assess the significance of errors on the accident sequence frequencies. There is no evidence to believe that such errors do exist in the plant. The objective is simply to judge the potential significance of gross errors. Three sets of studies were performed: sensitivity to gross random errors in critical components, sensitivity to simultaneous occurrence of errors in different components and sensitivity to systematic errors.

MILLSTONE ACCIDENT SEQUENCES

The seismic fragilities of critical structures and equipment in Millstone Unit 3 have been reproduced from Budnitz et al (1985) in Table 1. Four important seismic-induced damage states have been identified for Millstone 3:

TE = Transient (caused by loss of offsite power) with failure of on-site emergency power or RCS heat removal.

AE = Large LOCA with failure of safety injection and containment quench sprays.

SE = Small LOCA or ATWS with failure of safety injection and containment quench sprays.

V3 = LOCA with containment bypass.

The Boolean expressions are given for these plant damage states as:

TE = 1 * [(3 + 5 + 7 + 12 + 20 + 31 + 35 + R19) + {(17 + R5) * 4 }]

AE = (3 + 4 + 5 + 7 + 12 + 20 + 31 + 35 + R19) * (15 + 30 + 32)

SE = (3 + 4 + 5 + 7 + 12 + 20 + 31 + 35 + R19) * (6 + 9 + 16)

V3 = 27 + 29

where the numbers represent failure of the corresponding component given in Table 1 and, R5 and R19 are random (nonseismic) failures of the auxiliary feedwater system and the on-site emergency power system respectively. Core melt is taken to be the union of these plant damage states.

For this study, we have assumed that the impact of a gross error can be appropriately represented by a reduction in the median capacity of the component. The β values have not been altered from those estimated assuming error-free condition.

RANDOM ERRORS IN SINGLE COMPONENTS

Errors that affect a single component are postulated and the remaining components are assumed error-free. As an example, the calculated median capacity of the reactor internals (No. 6, Table 1) is 0.99g. The failure mode is the bending of the upper support plate resulting in excessive distortion of the core geometry preventing control rod insertion. A gross error is postulated in the structural analysis for SSE or in fabrication of the reactor internals that leads to a reduction in the median capacity of 10%, 20%, or 50%. Table 2 summarizes the impact of such errors on the median and 95 percent accident sequence frequencies calculated using the site-specific seismic hazard curves. A review of the results in Table 2 (and other examples) reveals that the random errors causing a reduction in the median capacities of components generally does not increase the frequencies of accident sequences by more than a factor of 5. The containment crane wall fragility is an exception, wherein a reduction of the median capacity by 50% would increase the V3 sequence frequency by a factor of 12. However, the rate of occurrence of errors leading to such a large reduction in the capacity is so small that the increase in accident frequency is negligible.

RANDOM ERRORS SIMULTANEOUSLY OCCURRING IN DIFFERENT COMPONENTS

The potential for errors occurring in several components cannot be ruled out. Sensitivity studies that take into account errors in multiple components simultaneously were performed to establish the significance of joint occurrence of errors. As an example, gross errors that reduce the median capacities of components 3, 4, 5, 6, and 15 by 25% were postulated. The sources of errors in these components were assumed to occur independently (i.e., poor quality concrete, improper anchorage, welding failures, etc.). Table 3 shows the impact of this set of gross errors on the frequencies of accident sequences. Simultaneous reductions in capacities of a group of components caused by random gross errors result in increases of accident frequencies by not more than a factor of 3 at 95% confidence level.

SYSTEMATIC ERRORS IN STRUCTURAL COMPONENTS

To evaluate the potential significance of systematic errors, the median capacities of all structural elements (i.e., components 3, 7, 12, 20 and 27) were assumed to be reduced by 25% as a result of gross errors such as poor concrete placement, wrong grade of steel or error in the ground motion input. Table 4 shows the influence of these postulated errors on the frequencies of accident sequences. The maximum increase in the accident frequencies caused by these systematic errors is less than a factor of 3 at the 95% confidence level.

CONCLUSIONS

The significance of gross design/construction errors was evaluated in terms of their impact on seismic risk of nuclear power plants. Random errors affecting single components or groups of components and systematic errors of given magnitude were considered by reducing the median fragilities of selected components. The effect of such errors in increasing accident sequence frequency was estimated. The results of this sensitivity study indicate that plausible reductions in seismic fragilities that occur as a result of errors of the type considered apparently have a negligible effect on the seismic risk of nuclear plants.

REFERENCES

Budnitz R.J. et al., "An Approach to the Quantification of Seismic Margins in Nuclear Power Plants", *NUREG/CR-4334*, *UCID-20444*, August 1985

Ditlevsen, O. "Fundamental Postulate in Structural Safety." *Journal of Engineering Mechanics* (ASCE) 109, no. 4., pp. 1096-1102. August 1983.

Ellingwood, B. "Design and Construction Error Effects on Structural Reliability", *Journal of Structural Engineering*, ASCE, Vol. 113, No.2, February 1987, pp 409-422.

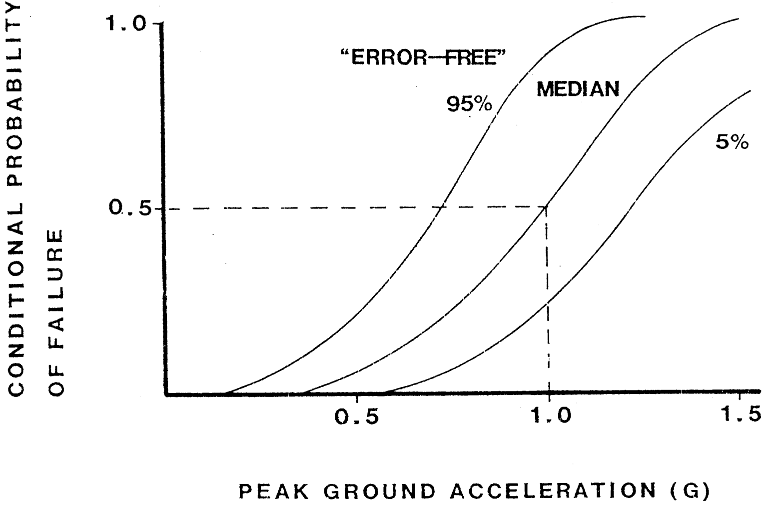
Gonzalez Cuesta, M. and D. Okrent. "A Method for Quantification of Nuclear Reactor Seismic Risk Due to Design and Construction Errors Based on Deficiencies Identified in the Past", *Nuclear Engineering and Design*, Vol. 96, 1986.

Lind, N. C. "Models of Human Error in Structural Reliability." *Structural Safety* 1, no. 3, pp. 167-175. April 1983.

Nowak, A. S. and R. I. Carr. "Sensitivity Analysis for Structural Errors." *Journal of Structural Engineering* 111, no. 8, pp. 1734-1746. August 1985.

Ravindra, M.K. "Treatment of Gross Errors in Nuclear Plant Risk Studies - A Suggested Approach." In *Structural Safety and Reliability - Proceedings of ICOSSAR '85*. Edited by I. Konishi, A. H-S. Ang, and M. Shinozuka. Kobe, Japan, May 1985.

Ravindra, M.K., "Gross Design and Construction Errors, and Seismic Risk Studies", *Nuclear Engineering and Design*, 110 (1988) pp 255-263.



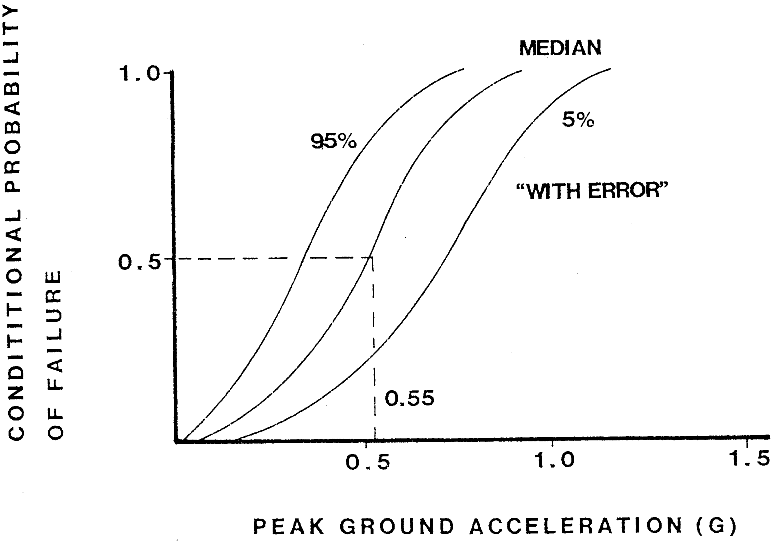


Table 1
Fragilities of Key Structures and Equipment

No.	Equipment	A_m (g)	β_R	β_U
1	Loss of Offsite Power	0.20	0.20	0.20
3	Emergency Gen. Enclosure Bldg.	0.88	0.20	0.46
4	Refueling Water Storage Tank	0.88	0.30	0.36
5	Emergency Diesel Generator	0.91	0.24	0.43
6	Reactor Vessel Core Geometry Distortion	0.99	0.31	0.33
7	Control Building	1.00	0.24	0.33
9	Control Rod Drive System	1.00	0.30	0.38
12	Service Water Pumphouse	1.30	0.24	0.49
15	Reactor Coolant System Piping	1.59	0.48	0.51
17	Demineralized Water Storage Tank	1.60	0.25	0.43
20	Engineered Safeguard Features Building	1.70	0.23	0.43
27	Containment Crane Wall	2.20	0.39	0.38
29	Steam Generator Tubes Rupture	2.28	0.44	0.48
30	Reactor Vessel	2.35	0.48	0.44
31	Service Water System Pumps	2.40	0.31	0.53
32	Reactor Coolant Pumps	2.68	0.43	0.47
35	Cable Trays	2.70	0.48	0.42

Table 2
Annual Accident Sequence Frequency (x 10^{-6}) vs. Random Error in Reactor Vessel Core Geometry Distortion

Sequence	Median				95% Confidence			
	BC[a]	10%[b]	20%[c]	50%[d]	BC	10%	20%	50%
SE	0.24[a]	0.30	0.38	1.17	6.22	7.02	8.13	13.76

a: Base Case.
b,c,d: Median capacities are decreased from the base case by the percentage shown.

Table 3

Sensitivity of Accident Sequence Frequency to Simultaneous Occurrence of Random Error in Components 3, 4, 5, 6, 15

Sequence	Mean		95% Confidence	
	BC[b]	25%[c]	BC	25%
TE	1.80[a]	3.87	20.78	38.79
AE	0.04	0.21	2.97	6.98
SE	0.24	0.93	6.22	12.16

[a] All entries in these tables are annual frequencies multiplied by 10^6.

[b] Base Case: Component median capacities given in Table 1.

[c] Sensitivity Study: Median capacities given in Table 1 are reduced by 25%.

Table 4

Sensitivity of Accident Sequence Frequency to Systematic Errors in All Structural Elements

Sequence	Median		95% Confidence	
	BC[b]	25%[c]	BC	25%
TE	1.80[a]	3.89	20.74	38.67
AE	0.04	0.05	2.97	4.17
SE	0.24	0.36	6.22	7.69
V3	0.004	0.03	0.84	2.67

[a] All entries in the table are annual frequencies multiplied by 10^6.

[b] Base Case: Structural Elements (3, 7, 12, 20, 27) Median Capacities as given in Table 1.

[c] Sensitivity Study: Median Capacities of Structural Elements reduced by 25% from those shown in Table 1.