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Evaluation of Seismic Fragility of Structures - A Case Study

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ABSTRACT : The present paper attempts to evaluate the seismic fragility for a typical water retaining structure. The structure in question is analysed for two cases : (i) empty tank and (ii) tank filled with water. Variation in damping, response spectral shape and allowable stress has been considered. Based on this limited study the seismic fragility of the structure is developed as families of conditional failure probability curves plotted against peak ground acceleration at two different locations.

INTRODUCTION

The safety of a nuclear power plant (NPP) depends on a number of factors – intrinsic and external to the plant. Seismic ground motion is an important consideration in evaluating the safety of the plant or, alternatively, the risk associated with it. The various uncertainties and randomness associated with the occurrence of earthquakes and the consequences of their effects on the NPP components and structures call for a probabilistic risk assessment (PRA). The elements of probabilistic seismic risk analysis (PSRA) can be identified as analyses of : (i) seismic hazard at the site, (ii) response of plant systems and structures, (iii) component fragilities and (iv) the consequences of various accident processes. Items (ii) and (iii) are intrinsically related to each other.

The present study is concerned with the response of a typical water retaining structure to seismic excitation and evaluation of component fragilities. Here it may be noted that in the response analysis, the response of the structure for a specified seismic input is calculated while in the fragility evaluation, the conditional probabilities of component failure for different values of the response parameters are estimated. Here again, the response of interest could be spectral acceleration, forces and displacements at selected structural locations.

SEISMIC FRAGILITY

A convenient way of quantifying the seismic fragility of a component is to determine the conditional probability of its failure for the given value of a ground motion parameter, e.g., the peak ground acceleration (PGA). The component failure can either be functional failure or brittle or ductile failure. The major steps involved in developing seismic fragilities for PSRA are (i) selection of structure/ component, (ii) identification of failure mode and (iii) evaluation of ground acceleration capacity for each chosen component through a structural response analysis considering the uncertainties associated with it. These uncertainties include variability in damping, response spectral shape, allowable stress for components, soil-structure interaction, structural material properties, inelastic energy absorption characteristics of structure, modelling assumptions, modal combination, spatial combination and variation in method of analysis etc. However, the present case study considers the uncertainties due to variation in damping, response spectral shape and allowable stress for the components.

FRAGILITY MODEL

The seismic capacity (in terms of PGA) of a given structure depends on a number of factors related to the basic ground motion, soil-structure interaction, structural modelling, method of evaluation of dynamic response and material properties etc. In the estimation of fragility parameters, it is convenient to evolve an intermediate random variable called factor of safety on ground acceleration capacity (PGA for failure) above the design basis PGA. This factor of safety (F) is defined as [1].

$$A = F.A_{design} \tag{1}$$

Here (A) is the PGA for failure and (A_{design}) is the design basis PGA; usually it is the PGA value associated with the SSE. (F) is a random variable and is the product of all the factors, which account for the uncertainties associated with the structural response and generally has a log – normal distribution [2]. Hence, (A) in equation (1) is also a random variable following the same frequency distribution, as does (F). It may be noted that the variability of (A) or (F) is due to random variation as well as due to uncertainties due to lack of complete accurate knowledge. Thus, it is evident that the failure frequency at a given PGA can not be predicted with absolute certainty but rather only with an associated probability of exceedence (or probability of non – exceedence).

The probability (P) that the failure frequency (p_f) exceeds (p_f') for a ground acceleration (a) is given by [2].

$$P\left[p_f \rangle p_f' / a\right] = \phi\left[\frac{\ln\left(\dfrac{a}{\bar{A}\exp\left[\beta_R \phi^{-1}\left(p_f'\right)\right]}\right)}{\beta_U}\right] \tag{2}$$

Alternatively, the frequency of failure (p_f') at a non – exceedence probability (Q) can be expressed as [2].

$$p_f = \phi\left[\frac{\ln\left(\frac{a}{\bar{A}}\right) + \beta_U \phi^{-1}(Q)}{\beta_R}\right] \tag{3}$$

$$Q = 1 - P \tag{4}$$

Where [Q] is the non exceedency probability of failure frequency.

a = Given peak ground acceleration level.
$\bar{A}$ = Median value of PGA to cause component failure.
$\phi(\ )$ = Standard Gaussian cumulative distribution function.
β_R, β_U = Logarithmic standard deviation of (a) due to random variability and uncertainty respectively.

The median value of ($\bar{A}$) and its logarithmic standard deviation are related to those of (F) through Eq. (1).

A CASE STUDY

A case study was carried out to evaluate the seismic fragility for the water retaining structure. The structure in question is spherical in shape enclosing a hollow cylindrical shaft inside and filled with water (up to the height of cylindrical shaft) and supported by a hollow conical wall on an embedded raft foundation. For simplicity the structure is modelled as an assembly of 3-D beam elements based on the finite element method as shown in Fig. 1. The filled up soil around the conical wall has been represented by spring and dashpot model derived from linear elastic half space theory [3] and accordingly the soil springs have been modelled at appropriate nodes as shown in Fig. 1. The hydrodynamic effect of the water has been modelled as per reference [4] and accordingly the calculated horizontal masses (impulsive mass and convective mass of water and its respective spring stiffness) and vertical mass of water are attached at appropriate nodes. Response spectrum method of analysis was adopted in which modal combination was carried out by CQC method while spatial combination for horizontal and vertical ground motions was carried out by SRSS method. Finite element program COSMOS/M [5] has been used for all the analysis purposes.

The nominal values of material damping, allowable stresses, grade of concrete, shear wave velocity of side soil are presented in Table-1. The normalised ground motion response spectra used in the analysis is presented in Fig. 2.

The structure was analysed with the tank (i) empty and (ii) filled with water conditions and the PGA to failure was determined for two different locations (i.e. node 9 for element 8 and node 20 for element 19 as shown in Fig. 1). These two elements were chosen because of the maximum stress experienced by them due to given ground motion. Parametric studies were made by varying the damping, the allowable stress and the normalised ground motion response spectral values about their nominal values making change only in one variable at a time. The results of this study are then used to determine seismic safety factor (i.e. the ratio of the PGA for failure to design basis PGA) and its variability (i.e. its mean value and standard deviation) with each of the parameters mentioned above. The variabilities due to individual factors are then combined to determine the overall standard deviation of the seismic safety factor for the structure at the two different locations as mentioned above. Here, it may be noted that the overall standard deviation of the seismic safety factor for the structure is the SRSS combination of the standard deviations of the individual parameter considered in the analysis.

The results are presented in Tables – 2,3,4 and 5. The mean value of the PGA for failure and its standard deviation for variation are also given in the Tables for various parameters considered in the analysis. From these Tables it is seen that the PGA for failure is quite sensitive to the variation of material properties and the normalised ground motion response spectral values.

In this simple case study only three parameters have been varied. Based on this limited case study the seismic fragility of the structure in question has been evaluated at two different locations and is shown in Fig. 3,4,5 and 6.

CONCLUSIONS

Based on this limited case study following conclusions can be drawn :

1. Fragility development accounts for the uncertainties and randomness in the response of the structures.
2. Fragility evaluation for structures at critical locations identified as dominant risk contributors provides better confidence in PRA studies.
3. By carrying out extensive experimental and analysis work to ascertain the variation in different parameters such as damping, material strength etc., which may affect the seismic response of the structure, the fragility evaluation may be carried out in a more realistic manner.

REFERENCES

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2. Kennedy, R. P. et. al., *Nuclear Engineering and Design*, 1980, pp. 315-338.
3. ASCE, ASCE Standards 4-86, 1995, Washington.
4. USAEC, United States Atomic Energy Commission, 1963, Washington.
5. COSMOS/M, Finite Element Analysis System, S. R. A. C., 1995, Los Angeles.

Table –1 : Relevant Input Data (Nominal Values)

(1) Material Damping = 7 %
(2) Grade of Concrete :
Elements 1 to 18 = M20
Elements 19 to 30 = M35
Elements 31 to 45 = M20
(3) Allowable Stress (MPa) :
Elements 1 to 18 = 8.00
Elements 19 to 30 = 14.0
Elements 31 to 45 = 8.00
(4) Shear Wave Velocity of Side Soil = 700 m/sec.

Table – 2 : Influence of Damping on PGA(g) for Failure (Response Spectral Shape and Allowable Stress held at Nominal Values) (Element No. 19 With Tank Full Case)

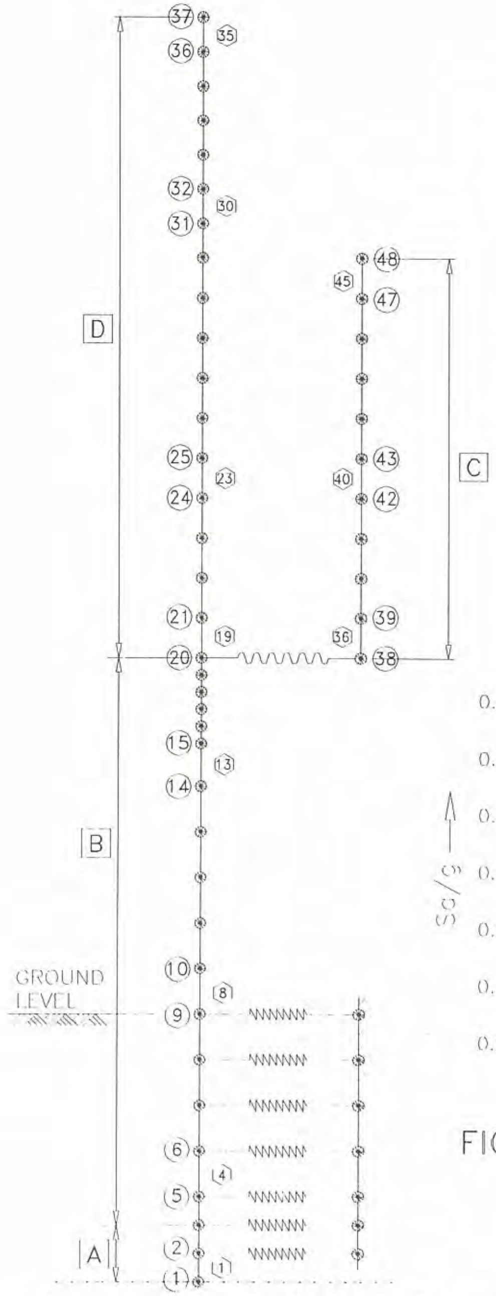
ξ(%) →	5	6	7	8	9	10	PGA_M(g)	PGA_S(g)
PGA_F(g)	0.5479	0.5682	0.5904	0.6042	0.6163	0.6314	0.5931	0.0283
PGA_N(g)	0.9238	0.9580	1.0000	1.0187	1.0391	1.0646	1.0007	0.0476
PGA_L(g)	-0.0793	-0.0429	0.0000	0.0185	0.0384	0.0626	-0.0005	0.0481

Table-3 : Influence of Spectral Shape on PGA(g) for Failure (Material Damping and Allowable Stress held at Nominal Values) (Element No. 19 With Tank Full Case)

'a' →	M+2.5σ	M+2.0σ	M+1.0σ	M	M-0.25σ	M-0.5σ	PGA_M(g)	PGA_S(g)
PGA_F(g)	0.4830	0.5132	0.5904	0.6838	0.7134	0.7451	0.6215	0.0996
PGA_N(g)	0.8181	0.8692	1.0000	1.1582	1.2083	1.2620	1.0526	0.1687
PGA_L(g)	-0.2008	-0.1402	0.0000	0.1469	0.1892	0.2327	0.0380	0.1647

Table-4 : Influence of Allowable Stress on PGA(g) for Failure (Material Damping and Response Spectral Shape held at Nominal Values) (Element No. 19 With Tank Full Case)

Sa(Mpa)→	11.90	12.60	14.00	14.70	15.40	16.10	PGA_M(g)	PGA_S(g)
PGA_F(g)	0.5019	0.5314	0.5904	0.6199	0.6495	0.6790	0.5954	0.0624
PGA_N(g)	0.8500	0.9000	1.0000	1.0500	1.1000	1.1500	1.0083	0.1058
PGA_L(g)	-0.1625	-0.1054	0.0000	0.0488	0.0953	0.1398	0.0027	0.1068



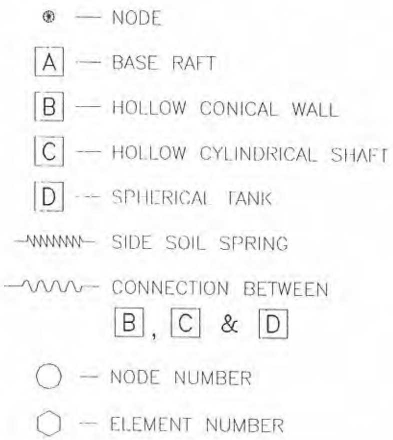


FIG.1: FINITE ELEMENT MODEL OF STRUCTURE

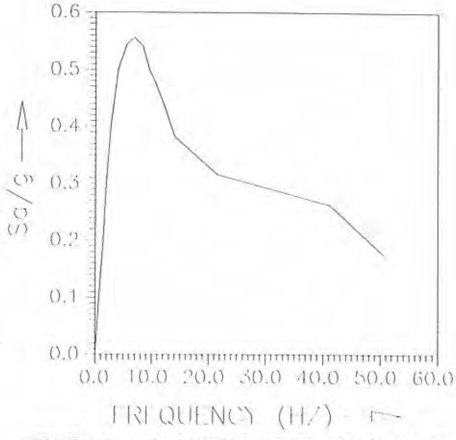


FIG.2: INPUT RESPONSE SPECTRUM

Table-5: Influence of Damping, Spectral Shape and Allowable Stress on PGA(g) for failure

Element No.		Damping (ξ)		Spectral shape (a)		Allowable stress (Sa)	
		Case-1	Case-2	Case-1	Case-2	Case-1	Case-2
8	PGA$_M$(g)	-0.0028	0.0001	-0.0045	0.0131	0.0027	0.0027
	PGAs(g)	0.0237	0.0329	0.0732	0.1066	0.1068	0.1068
19	PGA$_M$(g)	-0.1176	-0.00045	-0.0917	0.0380	0.0027	0.0027
	PGAs(g)	0.1953	0.0481	0.2357	0.1647	0.1068	0.1068

PGA$_F$(g) = PGA Value for Failure.
PGA$_N$(g) = PGA value normalised with respect to nominal value.
PGA$_L$(g) = Natural Log value of PGA$_N$(g).
PGA$_M$(g) = Mean value of PGA(g).
PGA$_S$(g) = Standard deviation for PGA(g).
Case-1 = Tank empty condition.
Case-2 = Tank filled with water condition.
ξ = Material damping (%).
a = Response spectral shape factor.
Sa = Allowable stress (MPa).

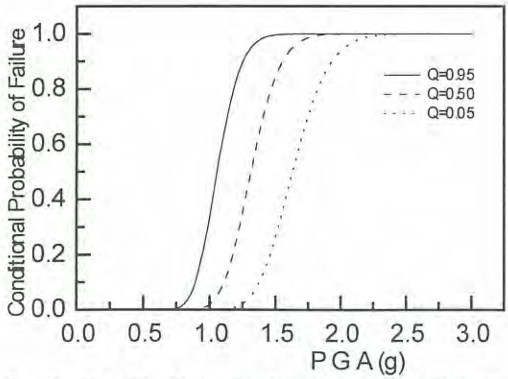


Fig. 3 : Fragility Curve for the Element no. 8, case-1

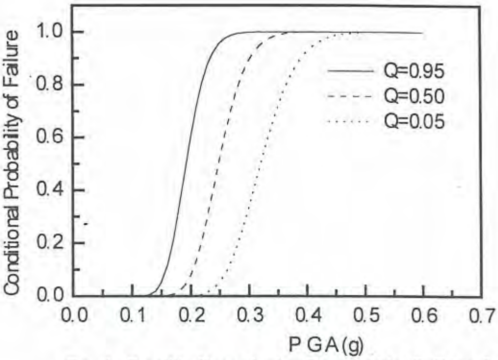


Fig. 4 : Fragility Curve for the Element No. 8, Case-2

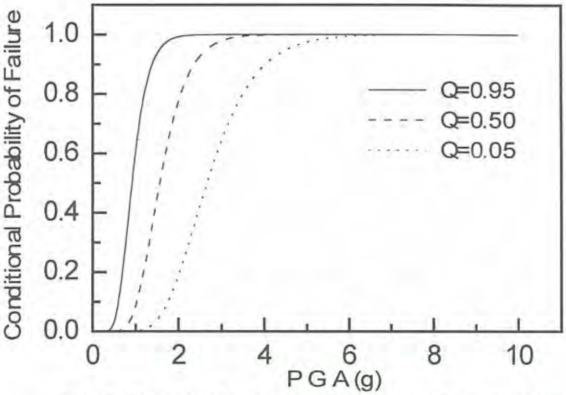


Fig. 5: Fragility Curve for the Element No. 19, Case-1

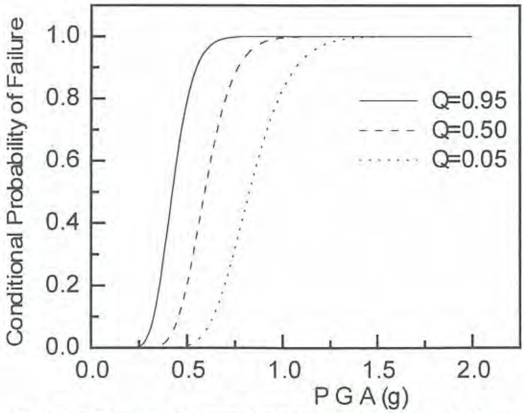


Fig. 6 : Fragility Curve for the Elment No. 19, Case-2