Appropriation of probabilistic approaches to assess seismic risk in Nuclear Power Plants

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ABSTRACT

The fragility curve of components is a key point of seismic risk analysis and different approaches have been proposed to establish one. This paper describes briefly the "hybrid method" proposed by Kennedy, and then applied to the simplified model of nuclear power plant to assess the Core Damage Frequency (CDF). Furthermore, parametric studies have been performed to evaluate the parameter sensitivity on CDF. Finally, a working program focused on the appropriation of more or less simple/complex probabilistic methods intended to quantify seismic risk is presented.

INTRODUCTION

During recent years, the seismic risk analysis has received increasing attention. It has been observed that the seismic loading has simultaneous potential to damage several redundant components and systems of a nuclear power plant.

Since several decades, Seismic Probabilistic Risk assessment (SPRA) and Seismic Margin Assessment (SMA) studies have been performed on a large number of nuclear power plants. These studies have indicated that the seismic contribution to overall core damage frequency (CDF) and large-early release frequency (LERF) can be significant and occasionally can even be dominant. Since their introduction, the methodologies have been evolving. Recently, Kennedy [1] has proposed a simplified method combining both SMA and SPRA methodologies. This method is generally called "hybrid method". Indeed, it allows for determining the mean risk of seismic core damage even though fragilities are obtained from HCLPF (High Confidence Low Probability of Failure) capacities only, the latter resulting from SMA.

In this paper, the "hybrid method" is briefly described and then applied to the simplified model of a nuclear power plant. This allows for quantifying the mean seismic risk of core damage for this simplified model and for performing some parameter studies. In particular, the influence of different uncertainty levels, characterised by the composite logarithmic standard deviation β_C of capacity, and the contribution of the surrogate element on core damage frequency have been studied. Furthermore we have applied min/max method in order to examine the contributions of the individual components to the core damage. Finally, a working program destined for the appropriation of simple/complex methods to quantify seismic risk is presented. This program should finally allow for assessing the contribution of seismic risk relative to risk from other events for French nuclear power plants.

Description of the "hybrid method"

The "hybrid method" has been proposed by Kennedy [1], the term hybrid referring to a procedure which combines both features of SMA and SPRA. It involves the construction of a simplified system model using structures, systems and components (SSC) required for safe shutdown path in SMA and that are to be considered in SPRA.

The seismic fragility of SSCs is represented by fragility curves that are defined as a conditional probability of failure versus a given value of seismic excitation level (in general, peak ground acceleration or average spectral acceleration).

In common practice, the acceleration capacity A of SSC is supposed to be log-normally distributed. In SPRA methodologies, this choice is used since the lognormal model is mathematically easy to use and can be partly justified by the central limit theorem. This means that fragility curves can be defined by two parameters which are the median capacity Am and logarithmic root mean square β, yielding:

$$P_{f/a} = \Phi\left(\frac{\ln(a/A_m)}{\beta}\right) \quad (1)$$

where $\Phi()$ is the standard Gaussian cumulative distribution. In SPRA, one distinguishes generally "random" (intrinsic) uncertainty and "epistemic" uncertainty by introducing the two values β_R and β_U, respectively. This allows for obtaining confidence intervals with respect to a median fragility curve defined by A_m and β_R:

$$P_{f/a} = \Phi\left(\frac{\ln(a/A_m) + \beta_U \phi^{-1}(Q)}{\beta_R}\right) \quad (2)$$

where Q designates the degree confidence.

From the feedback experience of previous studies, Kennedy [1] has proposed to work with a mean fragility curve using the composite uncertainty β_C rather than β_R and βu to assess the mean seismic risk. This fragility curve is assessed from equation (1) with β_C value defined by the following relation:

$$\beta_C = \sqrt{\beta_U^2 + \beta_R^2} \quad (3)$$

In the "hybrid method", the median capacity A_m is derived from HCLPF values calculated in a SMA using a deterministic procedure called CDFM method and choosing representative values for β_C.

First of all, HCLPF values used in a seismic margin study are based on the assumption of 84% Non Exceedance Probability (NEP) earthquake structural response and, thus, have to be converted to median based HCLPF. The methodology proposed in reference [2] suggests to consider the HCLPF determined in the framework of SMA as $HCLPF_{84}$ and to proceed to the following conversion:

$$HCLPF_{50} = HCLPF_{84} * e^{-\beta_{RS}} \quad (4)$$

where β_{RS} is defined as the logarithmic standard deviation of the randomness in the earthquake spectral amplification PGA [3].

It can be shown that, for given $HCLPF_{50}$ and β_C values, the median value can be expressed by the formula:

$$A_m = HCLPF_{50} * \exp(+2{,}33 * \beta_C) \quad (5)$$

where $HCLPF_{50}$ corresponds to 1 % conditional probability of failure on the mean fragility curve and the value of β_C chosen is estimated by means of expert judgment. In general, it is supposed to take values in the range of 0,3 to 0,6.

By means of the Boolean equation of core damage, the fragility curves of SSC can be aggregated into a single fragility which represents the mean conditional core damage $F_{CD}(a)$. The last step consists in convolving the mean seismic hazard curve H(a) defined as a frequency of occurrence versus a seismic input parameter (peak ground acceleration or spectral acceleration) with the mean conditional core damage frequency $F_{CD}(a)$. This gives an estimate of the mean value of the seismic core damage frequency. Different numerical schemes such as a discrete or continuous form can be used to evaluate CDF.

The continuous integral form is given by:

$$CDF = -\int_0^{\infty} F_{CD}(a)\left[\frac{dH(a)}{da}\right]da \quad (6)$$

In discrete form, we can write:

$$CDF = -\sum_{i=1}^{M} F_{CD}(a_i) * \Delta h_i \quad (7)$$

where we have divided the range of acceleration values a in M intervals. These are the intervals which define the hazard curve H(a). Then, a_i is the average acceleration with respect to seismic interval i and Δh_i is the difference between the hazard values at the end and the beginning of this interval.

Application

The numerical applications are performed with a logical model and data given in EPRI [3]. The simplified system model of core damage CD considered in this study is shown in figure 1:

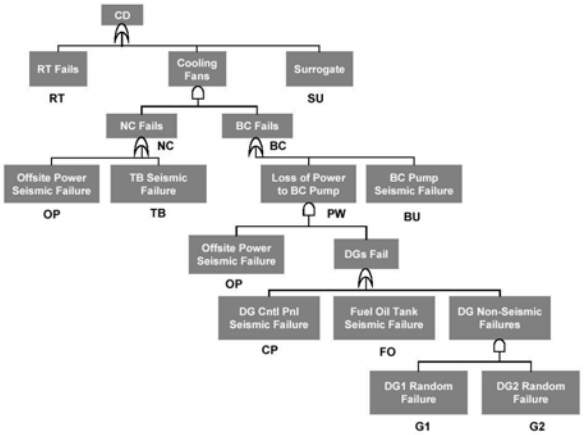

Fig. 1 Simplified plant logic model [3]

The core damage CD is given by the following Boolean equation:

$$CD = RT \cup SU \cup \{OP \cap [CP \cup FO \cup (G1 \cap G2) \cup BU]\} \cup (TB \cap BU)$$

Seismic capacity information for key components is given in table 1 in terms of HCLPF and median values:

Table 1. From [3]

Component	$HCLPF_{84}$ derived from	PGA $HCLPF_{84}$ in g	PGA $HCLPF_{50}$ in g	Median Capacity Am, g	β_C
SUrrogate Element (SU)	Screening to 0,8g	0,38	0,3	0,6	0,3
Offsite Power (OP)	Generic	No value	0,1	0,3	0,47
Control Panel (CP)	Test	0,35	0,27	0,74	0,43
Fuel Oil tank (FO)	Analysis	0,28	0,22	0,59	0,43
Turbine Building (TB)	Analysis	0,31	0,24	0,66	0,43
Backup Pump (BU)	Screening to 1,2g	0,57	0,45	0,9	0,3
Control rod insertion (RT)	Screening to 1,2g	0,57	0,45	0,9	0,3

The mean fragility curves, that have been determined from the data given in table 1, are presented in figure 2. The mean hazard curve used to assess the mean core damage frequency is shown in figure 3.

From fragility curves and mean PGA hazard, mean core damage frequency CDF has been assessed using both the discrete and continuous form. The CDF calculated are 2,85E-05/yr and 2,52E-05/yr respectively. The value obtained with the discrete form is more conservative, with a deviation of 13%. The latter could be reduced by increasing the seismic interval number. However, this discrepancy can be considered as acceptable in terms of mean seismic risk assessment.

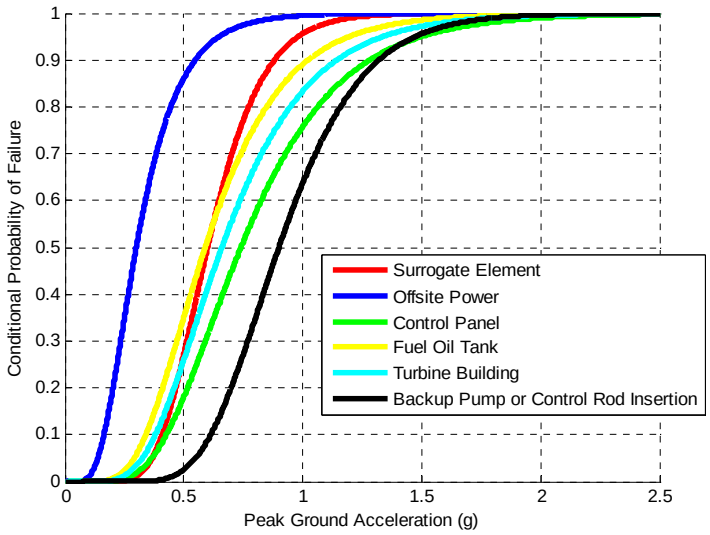

Fig. 2 Mean fragility curves

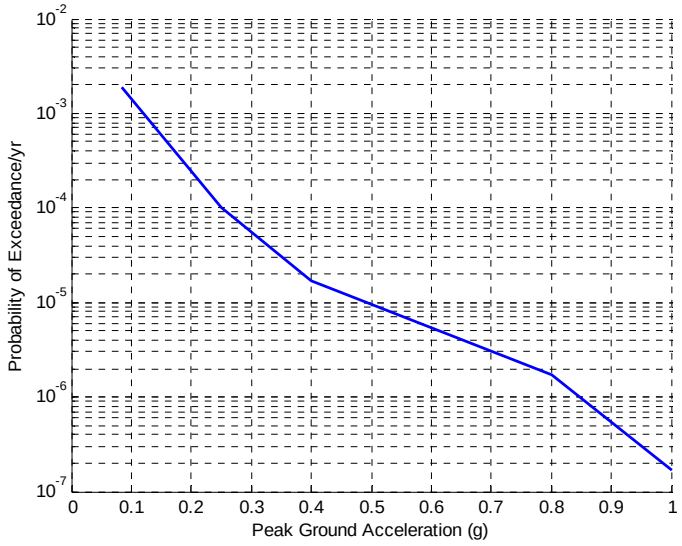

Fig. 3 Mean PGA Hazard curve

Parametric studies

First of all, the min/max method described by Kennedy [1] has been applied on the simplified model. The CDF is dominated by the fuel oil tank and the control panel as shown in figure 4. The core damage in terms of $HCLPF_{50}$ capacity is equal to 0,22g and the CDF would be about 2,22 E-05/yr by convolving FO (fuel oil tank) fragility curve with mean hazard curve. This is about 85% of the total calculated CDF. This result shows that FO is the most important contributor to final core damage. The analysis of the fragility curves shown, on figure 2, and the results of the min/max method, presented in figure 4, show that the components "backup pump and control insertion rod" have the weakest contribution.

Furthermore, the impact on core damage frequency of the choice of β_C values for the components FO and BU have been estimated. The results obtained with β_C values ranging from 0,2 to 0,6 are shown in figure 5.

As regards the most important contributor (FO), the core damage frequency decreases with increasing β_C by a ratio of 2 since, with this method, the HCLPF value is fixed while A_m increases with β_C. Clearly, CDF is sensitive to changes of β_C values relative to FO. On the other hand, we observe that CDF is not sensitive to changes of β_C values

related to BU. In consequence, it is important to know with accuracy the β_C values of important contributors to core damage frequency.

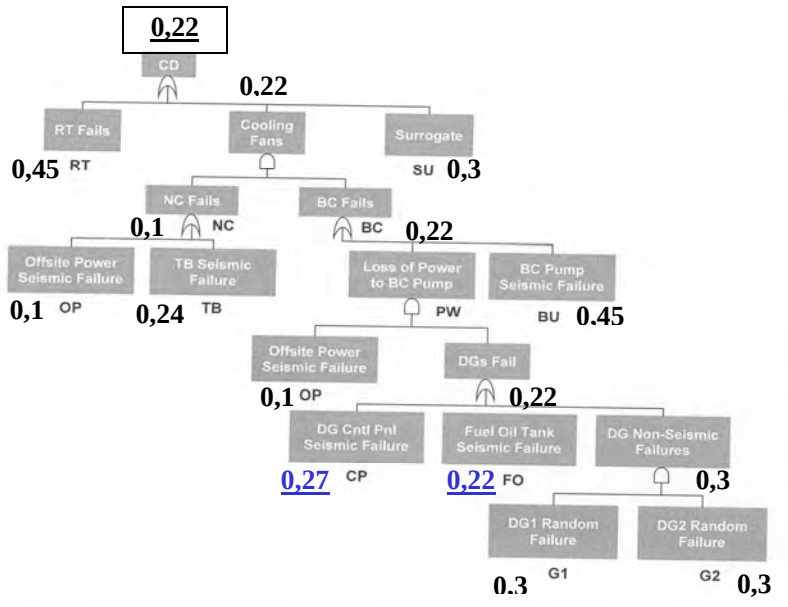

Fig. 4 Min/max method's result

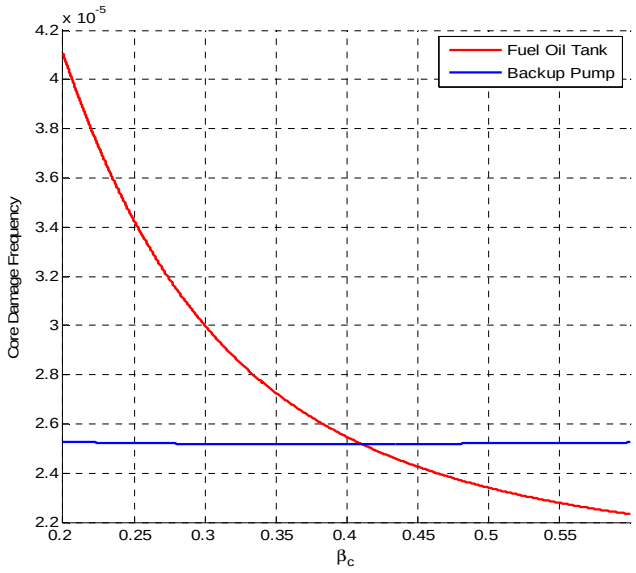

Fig. 5 Effect of β_C values on core damage frequency

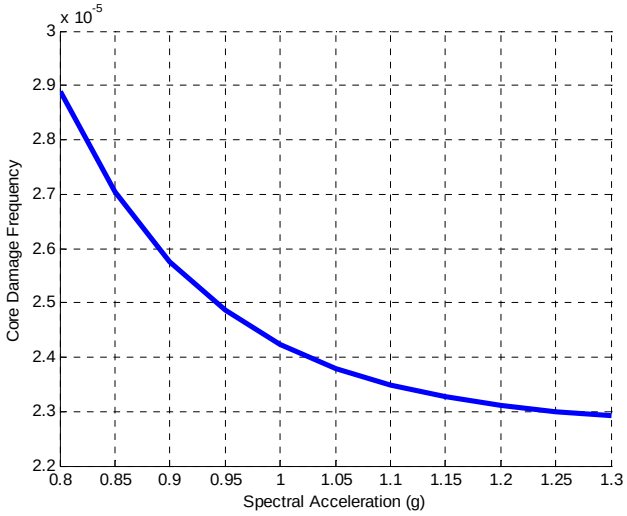

Fig. 6 Impact of screening level

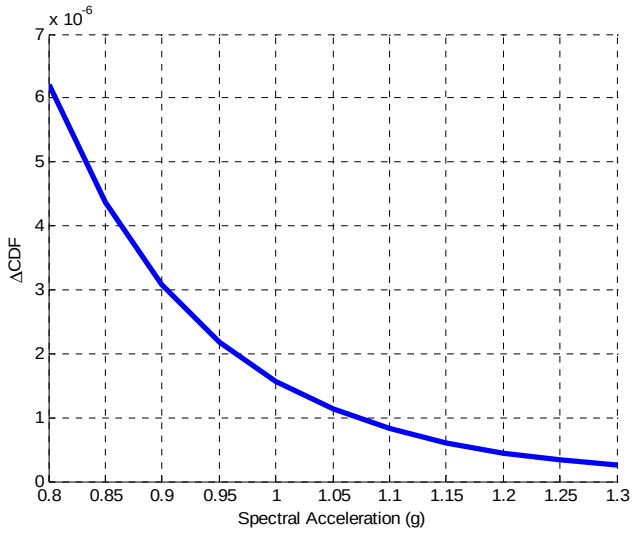

Fig. 7 ΔCDF versus spectral acceleration of screening level

In the simplified model, a surrogate element has been introduced to take into account the screened out components. The probability of failure of surrogate element has been estimated to be 1,3 E-05/yr with a screening level of 0,8g spectral acceleration while its contribution to the simplified logic model is about 20% of the total CDF.

Furthermore, the probability of failure of the surrogate element largely exceeds the criterion to be met in RG 1.174 [4], that is ΔCDF lower than 1.0E-06. When the screening level related to surrogate element is increased, then the core damage frequency decreases to 2,3E-05/yr. Indeed, the latter value corresponds to CDF without surrogate element (see figure 6) and the RG 1.174's criterion is met to a screening level of 1,07g spectral acceleration (see figure 7). When this criterion is not met, some screened out components should appear in the logic model in order to meet the RG 1.174.

Working program

In this paper, the "hybrid method" introduced by Kennedy [1] has been briefly described. We have applied this method to the simplified model of nuclear power plant response to a seismic event in order to obtain a core damage estimate.

In the framework of the "hybrid method", fragility curves are determined using only HCLPF capacities and generic β_C values. This makes their computation very easy but also attaches much importance to a single point on the fragility curve.

The next step will consists in additional sensitivity studies based on the simplified model. In particular, the question of correlation between component failures and the potential for no seismic random failures of equipment will be considered.

Finally, the working program will be focused on the appropriation of more or less simple/complex probabilistic methods intended to quantify seismic risk. With methodologies based on Monte Carlo scheme, it would be possible to propagate the random and epistemic uncertainties in order to evaluate their influence on CDF, to include the correlation effects between the failure modes and to "evaluate" the conservatisms of such methodology. On the other hand, it seems important to clearly define random and epistemic uncertainties since the delimitation of both can be somewhat blurred.

For active equipments, it is rather difficult to obtain a fragility curve because many data of failure are needed and many tests on a shaking table must be performed. In this context, a methodology will be developed to assess fragility curves based on statistical analyses of available data (data bank, feedback experience,…), specific testing and using a concept of Bayesian approach.

CONCLUSIONS AND PERSPECTIVES

Probabilistic methods based on combination of fragility curves with seismic hazard allow for quantifying the seismic risk relative to risk from other initiating events in Nuclear Power Plants. In particular, the "hybrid method" proposed by Kennedy and applied on the simplified model can be considered as suitable to assess mean core damage frequency from SMA results.

However, sensitivity studies need to be conducted in order to quantify with accuracy a "realistic" value of mean core damage frequency. Furthermore, as highlighted by the parametric studies, the modelling of components screened out at lower level by means of surrogate element can have a significant effect on core damage frequency. The use of surrogate element could then mask the real risk by significantly contributing to the CDF. Consequently, its use is strongly discouraged by the ANS standard, since insight into the dominant contributors is lost, as well as guidance for plant improvements. For more precise analysis, seismic hazard curves should be used to determine the Screening Level PGA (e.g. a median capacity or HCLPF) that results in non-significant contribution to CDF or LERF.

In this first step, CEA and EDF have assessed the performance of the "hybrid method" on the simple model. In the following, the working program will be concerned with the appropriation of more or less complex probabilistic methods intended to quantify seismic risk on French nuclear power plant.

With methodologies based on Monte Carlo scheme, it will be possible to propagate the random and epistemic uncertainties in order to evaluate their influence on CDF and to include the correlation effects between the failure modes.

In many cases active equipments are qualified by seismic testing that has not conducted the failure. For this purpose, a methodology will be developed to assess fragility curves based on statistical analyses of the incomplete information available from data banks, feedback experience, etc.

Finally, a better assessment of the uncertainties is necessary to quantify CDF more accurately from analyses of tabulated available data, testing results and studies conducted on nuclear power plant world wide by the past.

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