A method for inclusion of uncertainties in seismic PSA

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Abstract: PSA softwares such a RiskSpectrum allow data uncertainties to be included by assigning probability density functions (pdfs) to basic events representing System Structure or Component (SSC) failures. This approach presents some difficulties in seismic risk assessment, as the fragility curves that model the conditional probability of failure of an SSC in a seismic event are expressed as functions of the seismic load, thus cannot be directly input into the PSA model. Also the uncertainty of the seismic load on an SSC in an earthquake of given return frequency is not generally included in the fragility curve. In this paper a one-step method is described for deriving the cdf for core melt probability using probability distributions that accounts for both the SSC fragility curve and the uncertainty in the magnitude of the seismic initiating event. The method is illustrated by an test case that employs a single-step Monte Carlo method to derive the cdf of core melt frequency using a simplified seismic event tree for a PWR type reactor. The method is compared to results obtained using a nested Monte Carlo method.

Keywords: PRA, External Hazards, Uncertainties

1. INTRODUCTION

Earthquakes are movements of the Earth's crust due to sudden release of accumulated energy [1]. The impact of seismic events on human settlements and activities can be devastating thus conservative design practices have been adopted in order to make structures and buildings more likely to withstand earthquakes. However these 'good practices', if correctly implemented, only guarantee a safety margin against earthquakes of a pre-fixed 'design' value. Probabilistic assessment methods provide a more flexible tool in assessing the probability of buildings/structures to withstand an earthquake of any given size.

In particular for nuclear power plants (NPPs), operating licences require that the plant to be designed against a specified level of earthquake intensity, termed Safe Shutdown Earthquake (SSE). However deterministic design criteria are not sufficient to guarantee the safety of the plant, this is because (a) seismic events may influence many systems, structures and components within the power station and (b) prediction of the intensity of seismic events is subject to large uncertainties.

A full probabilistic safety assessment can be a useful tool to capture the contribution to core melt probability due to seismic events. Seismic probabilistic safety assessment models are developed starting from the already-existing PSA models for internal events. The base case PSA is modified to include the estimated frequency of the seismic initiating events and the probability of failure of system and components under the postulated seismic event.

The usual objective of an S-PSA for a nuclear plant is to calculate the core melt frequency due to all possible seismic events at a site, together with its uncertainty. This calculation is performed by first finding the conditional core melt probability due to seismic events corresponding to a number of specified frequencies, typically in the range 10^{-3}/yr to 10^{-6}/yr. These conditional core melt probabilities are then combined with the hazard frequencies to give an overall core melt frequency due to all seismic

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events.

This work presents a method to include the seismic hazard uncertainty into the seismic PSA model. This method is applied to a simplified PSA model and the results are compared with those obtained with a complete method requiring two sets of Monte Carlo calculations. The structure of this paper is as follow: section 2 reviews the literature on the treatment of uncertainties in seismic PSA, section **??** illustrates a complete Monte Carlo method for uncertainty inclusion in seismic PSA, section 4 introduces an innovative simplified method for uncertainty inclusion and finally the result section contains a comparison of the results obtained with the complete and simplified method when applied to a test model.

2. SEISMIC PSA UNCERTAINTY QUANTIFICATION METHODS IN LITERATURE

Zion NPP [2] was the first power plant for which a full seismic PSA was developed in the 80s. Since then while seismic PSA is not required by many national regulatory bodies, guidance on how to develop a seismic PSA has been published by IAEA [3], EPRI [4], and a number of power plants have undergone a full seismic probability safety assessment, both in the United States [5] and in Europe [6]. However the authors have not found a consistent treatment of uncertainties in seismic PSA. In the next 3 subsections a brief overview of uncertainty methods for seismic PSA is presented.

2.1. Kaplan's Discrete Probability Distributions

Kaplan and colleagues were the first to develop a method (discrete probability distribution - DPD method) to consider the uncertainties in seismic PSA [7], [8]. In the DPD method, the probability density function (pdf) of a random variable x, $f_x(x)$, is represented by a set of discrete probability values $f_1, f_2, ..., f_n$ defined at n values of x: $x_1, x_2, ..., x_n$, such that $\sum_{i=1}^{n} f_i = 1$. The discrete probability f_i corresponds to the probability of x lying in an interval surrounding x_i i.e. to the area under the $f_x(x)$ curve within the interval. Thus the set of doublets $\langle f_i, x_i \rangle$ describes a discrete probability distribution that represents the pdf $f_x(x)$. Kaplan observed that the DPD for a random variable that was a sum or product of independent random variables could be found straightforwardly from the DPDs of these independent variables.

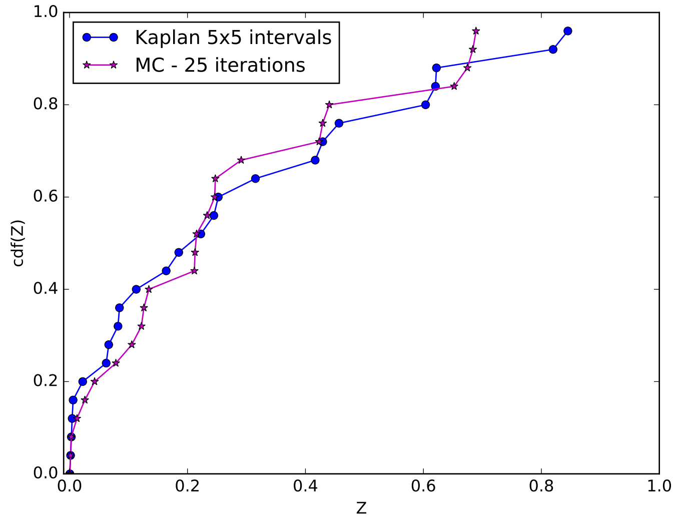
The DPD method was tested to find distribution Z whose random variable z is the the product of the random variables of probability functions X and Y and the method was found equivalent to a Monte Carlo method. The resulting product function Z obtained through both a Monte Carlo with 25 iterations and DPD method using a number of intervals $n = 5$ for the DPD of both X and Y is shown in figure 1.

The main drawback of the DPD method for a PSA analysis seems to be the potentially large number of Z calculations needed to find the Z distribution. Even for the very simple example of 2 components and 5 frequency intervals described above, 25 Z values had to be calculated and re-ordered to find the Z distribution. In a PSA, the Z function would correspond to a sum of many cutsets each of which could consist of combinations of several failure probabilities. For a simple model consisting of 10 cutsets each containing only one failure probability, the number of Z evaluations needed to find the DPD of Z would be $5^{10} = 9.8 \cdot 10^6$, if 5 intervals were used. Due to the large number of evaluations and the complexity in reordering the list of values, the approach does not appear practical for use with conventional PSA model which often involve many tens of cutsets each of which may consist of multiple failure events.

2.2. Westinghouse SHIP method

Maioli et al [9] describe the Seismic Hazard Integration Package (SHIP) software tool developed by Westinghouse that is designed to quantify the seismic core melt frequency in NPPs. According to Ref

Figure 1: Plot of the cdf distribution of Z = XY obtained with Kaplanś method and with a Monte Carlo method



[9], SHIP takes as input data the cutset list developed from a full seismic PSA analysis performed with a code such as RiskSpectrum of CAFTA. Fragility curves and their uncertainties are entered for each of the seismic basic events in the cutset list, for a range of different seismic accelerations, and the uncertainty distribution on the conditional probability of core melt (plant level fragility) is determined by the SHIP solution algorithm. In a final step the plant level fragilities for different acceleration levels are combined with the uncertain hazard curves probabilistically to find the overall core melt frequency and its uncertainty distribution.

The solution algorithm used by SHIP software to determine the core melt probability (plant level fragility) at different seismic acceleration levels is not explained in detail in published references, although Ref [9] states that the final probabilistic integration of the fragility curves with the hazard curves is carried out using Latin Hypercube simulation, which is a form of Monte Carlo sampling.

2.3. Hazard Lite

Hazard Lite is a proprietary software package that is designed to be used alongside RiskSpectrum to perform seismic PSA calculations.

The Hazard Lite manual [10] gives a high-level description of the approach used to estimate the core melt frequency due to seismic events. Hazard Lite is used in conjunction with RiskSpectrum to perform the data preparation, but the fault tree/event tree solution is still performed within RiskSpectrum. In Hazard Lite, the hazard curves and fragility curves are divided into acceleration intervals in which mean values of hazard and component fragilities are specified. A PSA model is used to obtaining a core melt frequency for each pga interval. In Hazard Lite calculation, the hazard curves are typically divided in about 8-10 discrete intervals by the analyst. The fragilities for different components are combined in cutsets, but it is not clear from the manual whether the combination of fragilities is performed by Hazard Lite or by RiskSpectrum.

According to the manual, Hazard Lite can be used in ”uncertainty mode”. This allows a family of fragility curves to be found associated with different probability weightings. Similarly, a family of hazard curves at different probability weightings are derived and used as input data. A probabilistic analysis using the Monte Carlo sampling method is then used to find the probability distribution of the core melt frequency.

3. COMPLETE METHOD FOR UNCERTAINTIES INCLUSION IN SEISMIC PSA

As mentioned in the introduction the objective of seismic PSA is to find the core melt frequency, which will be denoted by H_{CM}. To obtain core melt frequency information about the frequency of seismic events and the core melt probability of such events are needed. In fact core melt frequency is related to probability of core melt by:

$$H_{CM} = \int_0^{H_{max}} P_{CM,H} dH \tag{1}$$

where H_{max} is the maximum earthquake exceedance frequency deemed capable of causing significant plant damage (often taken as 10^{-3}/yr in practical studies), $P_{CM,H}$ is probability of core melt at exceedance frequency H and dH is the variation of exceedance frequency for the seismic initiating event. Exceedance frequency is the value traditionally used in seismic PSA and it is the frequency of event with acceleration higher than a threshold value. Also the ground acceleration is normally the peak ground acceleration (pga) [11].

To find the total core melt frequency the first step is to find the core melt probability at different seismic event frequencies. Given a seismic event of excedance frequency H, its intensity is uncertain thus a seismic event can be associated with a range of possible ground acceleration values at different probability levels, represented by a probability density function $f_aH(a)$. The core melt probability due to event H is then given by:

$$P_{CM,H} = \int_0^{\infty} f_{aH}(a) Z(a) da \tag{2}$$

where $Z(a)$ is the conditional core melt probability for a seismic event of ground acceleration a. A PSA fault/event tree solver is used to find $Z(a)$ and its uncertainty distribution $F_{Z(a)}$ for different values of a.

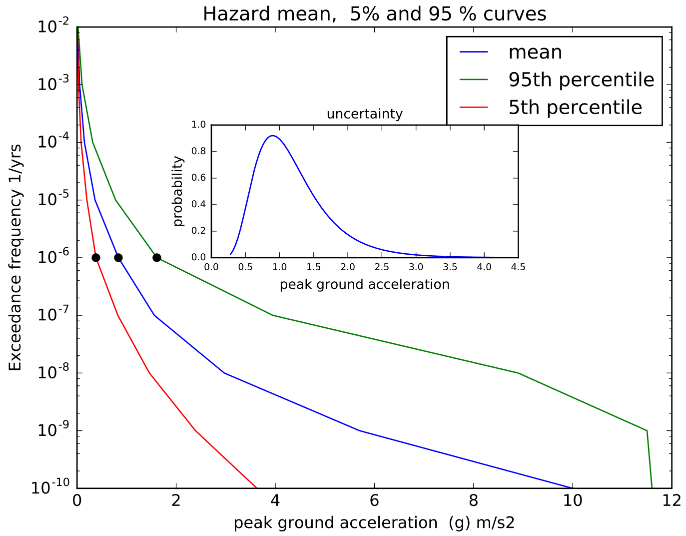
The values of $f_{aH}(a_j)$ in (2) can be found using the uncertainty distribution in the seismic magnitude for the specified value of H. This uncertainty distribution is found by assigning a lognormal uncertainty distribution to the acceleration associated with a given exceedance frequency. This approach is illustrated in Fig 2 which shows the pga uncertainty distribution calculated for a seismic event of a 10^-6/yr return frequency, for the case of a UK site.

The $F_{aH}(a)$ lognormal distribution has the following equation

$$F_{aH}(a) = \Phi\left(\frac{log(a/A_S)}{\beta_S}\right) \tag{3}$$

where A_S is the median value of pga and β_S^2 is the logarithmic variance of the pga for a seismic event with an exceedance frequency H.

Figure 2: An example of uncertainty distribution on the peak ground acceleration for a value of the exceedance frequency of 10^{-6}/year



Equation (2) is then used to summate the results to find the total core melt probability $P_{CM,F}$(and its uncertainty) due to event H, using the $Z(a)$ results and the known function $f_{aF}(a)$.

Once $P_{CM,H}$ is established for a range of different exceedance frequencies, a final summation can be performed to find the core melt frequency due to seismic events over the entire hazard curve for the site.

A PSA software such as RiskSpectrum [12] is generally used to create a model an NPP in order to find Z, the conditional core melt probability for a seismic event of pga a. The input to the PSA model is a set of "basic event" data P_{fi} representing structures systems components (SSCs) failure probabilities. The PSA model expresses the core melt event as a logical equation involving the sum of cutsets where a cutset is defined as irreducible combination of elementary failures that together result in the core melt occurring. When the probabilities P_{fi} are small, the function Ψ can be expressed in a multi-linear form:

$$Z(a) = \Psi(P_{f1}(a), P_{f2}(a), \ldots, P_{fn}(a)) = \sum_{j=1}^{m} \prod_{i=1}^{n(j)} P_{fi(j)}(a) \tag{4}$$

where each term in the summation gives the probability of the combination of failures represented by the cutset; the integer m is the total number of cutsets in the problem, and $n(j)$ is the number of events in the j$^{\text{th}}$ cutset. (Note that in a seismic PSA the values of P_{fi} may not be small, as the seismic failure probability of some components may be close to unity, so a modified form of (4) is used).

There are two ways in which uncertainty in Z arises in the PSA model namely: (i) the uncertainty in the form of the function, i.e. structural uncertainty of the PSA model, and (ii) the uncertainty in the magnitude of the component fragilities P_{fi}, i.e. data uncertainty. The PSA uncertainty considered in this thesis is restricted to the latter type of uncertainty, model structure uncertainty being ignored.

For SSC failures caused by the seismic event, the uncertainty over the failure probability P_{fi} was derived:

$$F_{P_{fi}}(P_{fi}) = 1 - \Phi(\frac{1}{\beta_{Ui}}\log(\frac{a}{A_{mi}}) - \frac{\beta_{Ri}}{\beta_{Ui}}\Phi^{-1}(P_{fi})) \tag{5}$$

where a is the pga and A_{mi}, β_{Ri} and β_{Ui} are fragility parameters for component i. For the randomly occurring failures, $F_{P_{fi}}$ can be found by one of the standard approaches described in the literature [13]. To note that the value of $F_{P_{fi}}$ depends on the value of a chosen, this dependence will be used in the next section.

Using the formulae for the $F_{P_{fi}}$, the cdf of Z, denoted by $F_{Z(a)}$, can be found by assigning a value of a and using the PSA model by a standard Monte Carlo method. This is straightforward in PSA models such as RiskSpectrum that can be executed in Monte Carlo mode provided the fragility functions for each basic event, $F_{P_{fi}}$, are entered as data.

3.1. Determination of $P_{CM,H}$ and its uncertainty

To use (2) to find the core melt frequency for a sismic event with a given exceedance frequency, the integration must first be simplifiedd as a summation over n discrete intervals Δa_j:

$$P_{CM,H} = \sum_{i=1}^{n}[F_{aH}(a_{j+1}) - F_{aH}(a_j)]Z(\bar{a}_j) \tag{6}$$

In (6) a_{j+1} and a_j are the pga values at the upper and lower limits of interval Δa_j and F_{aH} is the cumulative distribution function corresponding to the pdf f_{aH}. The term in square brackets corresponds to the probability of the pga lying in the interval Δa_j and $Z(\bar{a}_j))$ represents the mean conditional core melt probability for pga values in the interval Δa_j.

Equation (6) expresses $P_{CM,H}$ as a weighted sum of n random variables $Z(\bar{a}_j)$ whose cdfs $F_{Z(\bar{a}_j}$ can be determined from Monte Carlo runs of the PSA model. Using the weighted sum, the uncertainty distribution (cdf) of $P_{CM,H}$, denoted by $F_{P_{CM,H}}$, can be found by performing a further Monte Carlo analysis by sampling from the known cdfs $F_{Z(\bar{a}_j)}$.

4. INNOVATIVE ONE STEP METHOD TO INCLUDE UNCERTAINTIES

As discussed in section 3 above, a calculation of the uncertainty distribution in the core melt probability for a seismic event of a specified return frequency that takes into account uncertainties in both component fragilities and pga associated with the event, is very involved, requiring two Monte Carlo calculations with the PSA solver, each of which requires different input data for the basic events representing the seismic failures.

In view of the difficulties with the complete calculation, and the drawbacks associated with alternative approaches described in Section 2, a simplified method has been developed as part of this project in which an approximation to the core melt probability uncertainty distribution $F_{P_{CM,H}}$ can be achieved in a single run of a PSA solver such as Risk Spectrum without using additional software. The simplification proposed is to incorporate the seismic hazard uncertainty into the uncertainty distributions in component fragilities that are input to the PSA solver as basic event data. The seismic initiating event is then treated as an event of a given exceedance frequency, rather than an event of a specific pga magnitude. This simplification allows the multiple nested Monte Carlo calculations previously needed to be replaced by a single Monte Carlo run. However, the simplified method must only be regarded as an approximation, as it introduces dependencies between basic events in the PSA model are not fully accounted for in the PSA model solution.

The simplified Monte Carlo method is discussed below.

4.1. Formulation of basic event uncertainty distribution

Equation (5) does not take into account the fact that due to the imperfect knowledge of seismic events of a specified return frequency, the pga a may itself subject to significant uncertainty. It is possible to modify (5) to take into account the uncertainty in the seismic pga associated with an event of specified frequency. To do this let's note that EPRI [4] models the probability of failure (fragility) P_f of a component in a seismic event with a pga of a, ignoring the epistemic uncertainty, is:

$$P_f = \Phi\left(\frac{\log(a/A_m)}{\beta_R}\right) \tag{7}$$

where as previously Φ is the cumulative distribution function of the standard normal distribution, A_m is the median seismic capacity of the component and β_R is the logarithmic uncertainty in the seismic capacity due to randomness and a is the pga. To allow for the fragility uncertainty (epistemic uncertainty) the median capacity A_m is itself assumed to be uncertain, with a probability density function given by a lognormal distribution with an overall median A_{mm} and logarithmic uncertainty β_U. Hence the cdf of A_m is given by:

$$F_{A_m} = \Phi\left(\frac{\log(A_m/A_{mm})}{\beta_U}\right) \tag{8}$$

Then it is noted that the uncertainty in the pga associated with a seismic event of a given return frequency is also assumed to follow a lognormal distribution. Therefore the cdf of a can be written as it was done in (3).

Now (7) can be written as:

$$P_f = \Phi(\frac{\log W}{\beta_R}) \tag{9}$$

where W is a random variable defined by:

$$W = a/A_m \tag{10}$$

Thus W is the ratio between random variables a and A_m each of which has a lognormal uncertainty distributions. Now the pdf of a random variable that is the ratio between two random variables with lognormal distributions is itself a lognormal distribution, with a median equal to the ratio of the medians of the two variables and a logarithmic variance which is the sum of the logarithmic variances of the two variables. Therefore using (8) and (3) it follows that the cdf of W is given by:

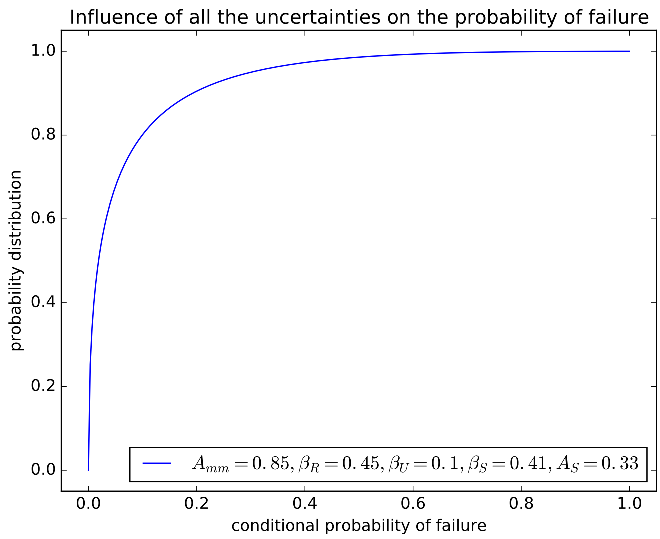
$$F_W = \Phi\left(\frac{\log[\frac{W}{A_{ms}/A_{mm}}]}{(\beta_S^2 + \beta_U^2)^{1/2}}\right) \tag{11}$$

Using this result, the cdf of P_f can be found from (9) using the formula for the cdf of a monotonically increasing function of a random variable with a known cdf. The result is as follows:

$$F_{P_f} = \Phi\left(\frac{\beta_R \Phi^{-1}(P_f) - \log(A_s/A_{mm})}{(\beta_S^2 + \beta_U^2)^{1/2}}\right) \tag{12}$$

The F_{P_f} distribution for a component with $A_{mm} = 0.85$, $\beta_R = 0.45$ and $\beta_U = 0.1$ at exceedance frequency $10^{-5}/yr$ is illustrated in Figure 3.

Figure 3: Probability of failure distribution F_{P_f} obtained with simplified method at exceedance frequency $10^{-5}/yr$



The value of the failure probability P_f corresponding to percentile F_{P_f} can be found by inverting (12).

$$P_f = \Phi\left(\frac{1}{\beta_R}\log\left(\frac{A_s}{A_{mm}}\right) + \frac{\sqrt{\beta_S^2 + \beta_U^2}}{\beta_R}\Phi^{-1}(F_{P_f})\right) \tag{13}$$

4.2. Monte Carlo calculation of the cdf of the core melt frequency

Using Eq (12) to define the uncertainty distributions of the seismic basic events, a single run of a PSA code such as RiskSpectrum in Monte Carlo mode will provide an estimate of the uncertainty distribution of the core melt probability $P_{CM,H}$ associated with a seismic event of exceedance frequency H.

Thus, a single Monte Carlo is able provide an estimate of the probability distribution of the core melt frequency that takes into account the uncertainties in both the component fragilities and the seismic magnitude. This is clearly a much simpler calculation than the full Monte Carlo treatment described in Section 3, which requires multiple Monte Carlo runs of the PSA model for different pga assumptions, each of which requires different basic event input data, followed by a further Monte Carlo calculation to combine the results.

The main drawback of the simplified method are the errors arising due to the introduction of dependencies between seismic basic events in the PSA model. The errors introduce have been quantified and more details will be available on the paper in preparation for 'Risk Analysis' journal.

5. RESULTS

For the implementation of the method described in section 4, due to issues of commercial confidentiality, a recent seismic PSA model for a nuclear power plant was not available for use in the current work. Therefore, an early seismic PSA model found in literature was used to perform the illustrative PSA uncertainty analysis. The particular model used was a seismic event tree model given by Kaplan [7] developed for the Zion PWR power plant in the early 80s: according to Ref [4] the Zion PSA was the first seismic PSA to be performed for a commercial nuclear power plant. In Kaplan's model the seismic core melt event is expressed as a logical equation involving ten basic events that represent seismically induced failures of plant components. These ten basic events are listed in Table 1 together with the fragility data applicable to each of the components.

Table 1: basic events and component fragility data for the Zion NPP Seismic PSA [7]

Basic event label	Basic event description	A_{mm}	β_R	β_U
E_4	Service water pumps failure	0.63	0.15	0.36
E_8	Failure of concrete shear wall of auxiliary building	0.73	0.30	0.28
E_9	Refueling water storage tank failure	0.73	0.30	0.28
E_{10}	Interconnecting piping/soil failure beneath reactor building	0.73	0.2	0.33
E_{12}	Condensate storage tank failure	0.83	0.28	0.29
E_{14}	Collapse of crib house of pump enclosure roof	0.86	0.24	0.17
E_{17}	125V DC batteries and racks failure	1.01	0.28	0.63
E_{21}	Failure of service eater system buried pipe (48")	1.40	0.20	0.57
E_{22}	C piping (20")	1.40	0.20	0.57
E_{26}	Collapse of pressuriser enclosure roof	1.80	0.39	0.34

In Kaplan's paper the value of β_R for failure E_{10} (failure of interconnecting piping/soil failure beneath reactor building) was not given so the author has assigned to β_R the value of 0.2, which is considered reasonable given the β_R value of the other systems.

According to the Ref [1] model the core damage event E_{CM} is related to the failure events in Table 1 by the following Boolean expression:

The failure of the components listed in Table 1 leads to core melt if combined in the following Boolean expression:

$$E_{CM} = E_4 + E_8 + E_{10} + [E_{12} \cdot E_9 + E_{22} \cdot E_9 + E_{26} \cdot E_9] + E_{14} + E_{17} + E_{21} \tag{14}$$

where $(+)$ signifies logical operator *OR* and $(\cdot)$ signifies logical operator *AND*.

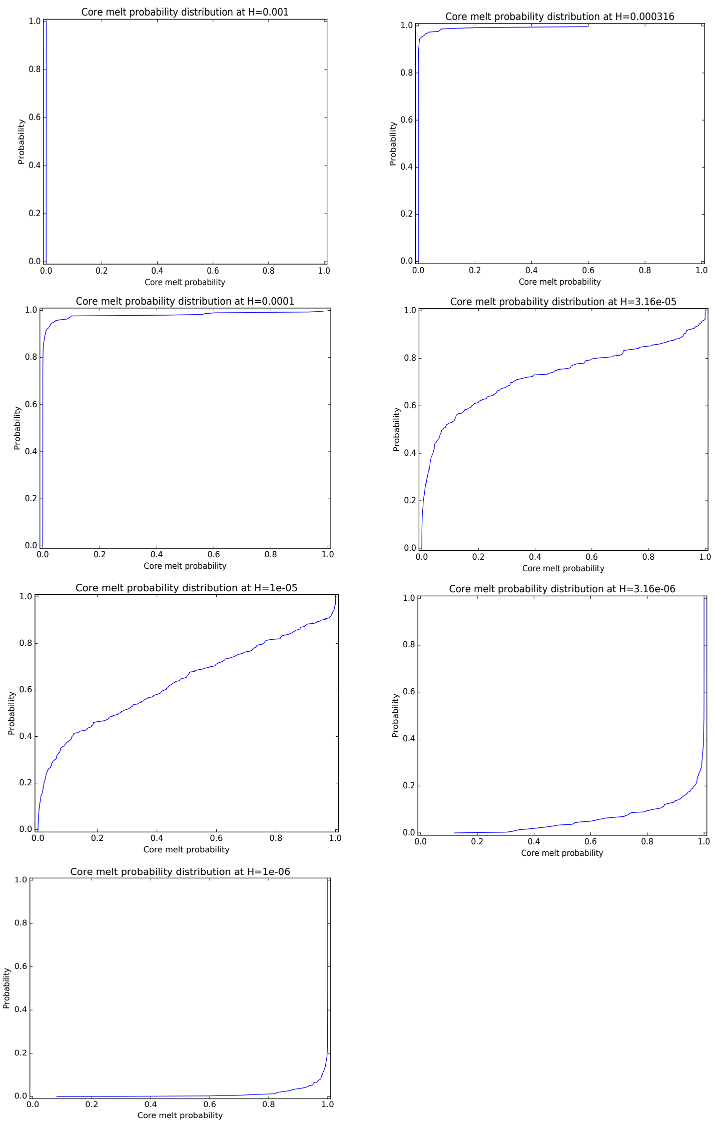
6. IMPLEMENTATION OF SIMPLIFIED METHOD TO OBTAIN CORE MELT PROBABILITY

The simplified MC method was implemented as a single algorithm in Python for the PSA model.

From the data set represented in table 1 and the data from the uncertainty of the hazard curves, for each exceedance frequency value, it is possible to derive the distribution of the probability of failure for each component F_{P_f} (from equation (12)).

To obtain the core failure cdf a Monte Carlo calculation was set up. The seven $F_{P_{CM,H}}$ curves obtained by applying the simplified method are illustrated in Fig 4.

Figure 4: Illustration of the 7 $F_{P_{CM,H}}$ obtained with the simplified method



The mean value $\mu_{CM,H}$ of $P_{CM,H}$ was obtained from the numerical results of the Monte Carlo through statistical analysis. The mean values for for exceedance frequencies in the range 10^{-3}/yr - 10^{-6}/yr are presented in Table 2:

6.1. Comparison of mean core melt probability values

The data represented in Table 2 is plotted in a frequency-probability space to easily compare the numerical results. The plot is presented in Figure 5. Note that the frequency is on a logarithmic scale

Table 2: Mean core melt probability values (simplified method) for H in the range 10^{-3}/yr - 10^{-6}/yr

H	10^{-3}/yr	$3.16 \cdot 10^{-4}$	10^{-4}/yr	$3.16 \cdot 10^{-5}$	10^{-5}/yr	$3.16 \cdot 10^{-6}$	10^{-6}/yr
$\mu_{CM,H}$	0	$1.7 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$	0.26	0.34	0.73	0.76
$\mu_{CM,H,approx}$	$1.35 \cdot 10^{-5}$	0.007	0.012	0.27	0.38	0.95	0.98

Figure 5: Comparison of mean core melt probabilities obtained with no uncertainty, complete method and simplified method

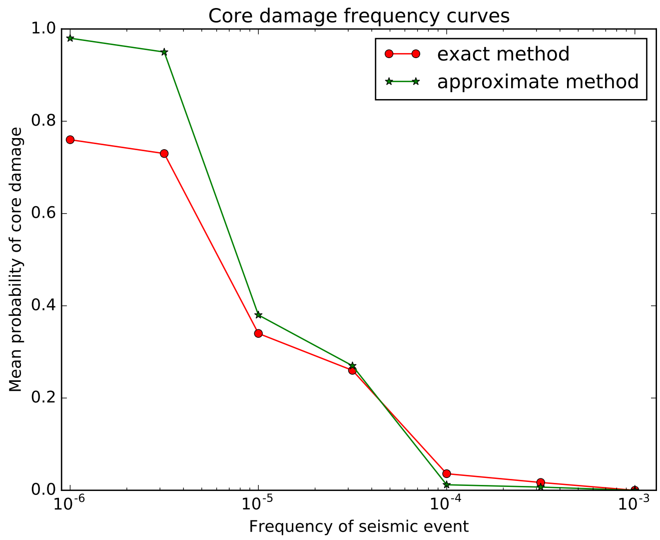


Fig 5 shows how the simplified method gives results that closely resemble those of the complete method. However to correctly understand the risk contributions due to seismic events however it is not enough to visualise the results but it necessary to estimate the seismic core melt frequency H_{CM}.

As in the present section the objective was to implement the numerical integration of Equation (**??**). Because the curve is not easily fitted with a polynomial curve the trapezium rule has been used to find the H_{CM}. The formula for the trapezium rule is:

$$H_{CM} = 0.5 \sum_{i=1}^{7} (H_{i+1} - H_i)(P_{CM,Hi+1} + P_{CM,Hi}) \tag{15}$$

The results of the application of equation (15) are presented in Table 3.

Table 3: Estimates of seismic core melt frequency

H_{CM} simplified method	$2.87 \cdot 10^{-5}$
H_{CM} complete method	$3.42 \cdot 10^{-5}$

7. CONCLUSION

In this work the comparison an complete method, described in section 3 and an simplified method, described in detail in section 6 were presented. The simplified method is an innovative method developed with the aim to provide a method that includes the seismic acceleration uncertainty and the fragility uncertainty in the PSA but that requires only a single Monte Carlo process to obtain the core melt probability. In this paper the simplified method was tested against the complete method using a simplified PSA fault tree. The estimate mean core melt frequency for the two methods differs only by less than half an order of magnitude.

The hope is that extensive testing to more realistic PSA models will confirm the accuracy of the model and it will allow this method to be implemented more widely.

Acknowledgements

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