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PROBABILISTIC FAULT DISPLACEMENT HAZARD ASSESSMENT (PFDHA) FOR NUCLEAR INSTALLATIONS ACCORDING TO IAEA SAFETY STANDARDS

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Key Point #2:	Base case and sensitivity cases results show high variability in terms of hazard curves
Key Point #3:	The benchmarking project will deliver a document which will assist the Member States in performing PFDHA

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ABSTRACT

In the last ten years, the International Atomic Energy Agency (IAEA) revised its safety standards for site evaluations of nuclear installations in response to emerging fault displacement hazard evaluation practices developed in Member States. New amendments in the revised safety guidance (DS507) explicitly recommend fault displacement hazard assessment, including separate approaches for candidate new sites versus existing sites. If there is insufficient basis to conclusively determine that a fault is not capable of surface displacement at an existing site, then a probabilistic fault displacement hazard analysis (PFDHA) is recommended to better characterize the hazard. This new recommendation has generated the need for the IAEA to provide its Member States with guidance on performing PFDHA, including its formulation and implementation. This paper provides an overview of current PFDHA state-of-practice for nuclear installations that is consistent with the new IAEA safety standards. We also summarize progress in an on-going international PFDHA benchmark project that will ultimately provide technical guidance to Member States for conducting site-specific fault displacement hazard assessments.

Keywords: capable faults, probabilistic fault displacement hazard analysis, nuclear installations

INTRODUCTION

The International Atomic Energy Agency (IAEA) establishes "International Safety Standards" through a consensus process among Member States (i.e., all States that have joined the International Atomic Energy Agency) to ensure nuclear safety and security worldwide. The

IAEA’s Safety Standards Series consists of three elements: (i) Safety Fundamentals, (ii) Safety Requirements, and (iii) Safety Guides (Fig. 1). The Safety Fundamentals, which constitute the basis of the Standards, provide ten principles associated with the fundamental safety objective of protecting people and the environment from harmful effects of ionizing radiation (IAEA, 2006). To embody these principles, Safety Requirements are defined whereas the subordinate Safety Guides provide technical recommendations and guidelines to meet the Safety Requirements. Safety Guides are published with consensus from all IAEA Member States and provide high-level recommendations on how to meet the Safety Requirements. Safety Reports and Technical Documents (TECDOC series) provide specific technical guidance on the state-of-practice that can be applied to meet the recommendations in the Safety Guides (Fig. 1).

Fault displacement hazards for nuclear installations are addressed in the IAEA Safety Fundamentals (IAEA, 2006), Safety Requirements (IAEA, 2019), and Safety Guides (IAEA, 2010 and IAEA, 2021a). Safety Principle 8 (“Prevention of Accidents”) in the current Safety Fundamentals (IAEA, 2006) pertains to fault displacement hazards, stating that all practical efforts must be made to prevent and mitigate nuclear accidents, and the suitability and selection of a site must be evaluated considering the effects of external events, site characteristics, and environment (IAEA, 2006). Safety Requirement No. SSR-1 (IAEA, 2019) outlines 29 requirements a site shall satisfy to support Safety Principle 8. Requirement 15 ("Evaluation of fault capability") in SSR-1 (IAEA, 2019) concerns fault displacement hazards, mandating faults within a certain distance of the site that are important to safety shall be identified, and fault displacement hazards shall be evaluated if a fault is identified as capable (i.e., it has a significant potential for displacement at or near the ground surface). Safety Guide No. SSG-9 (IAEA, 2010) provides high-level recommendations that a site should meet to comply with Safety Principle 8 and the requirements in SSR-1. This 2010 Safety Guide (SSG-9) will be superseded by DS507 (IAEA, 2021a). Currently, there is one TECDOC that directly addresses fault displacement hazard analysis by giving an introduction and overview of PFDHA and examples of its application in some Member States (IAEA, 2021b).

Probabilistic analysis is recommended for fault displacement hazard evaluations in Safety Guide SSG-9 at existing nuclear sites if a capable fault is identified within the site vicinity (5 km radius) (IAEA, 2010). While the existence of a capable fault within 5 km of a candidate site is considered an exclusionary criterion for new nuclear installations under SSG-9, new data can emerge after a nuclear installation is operational. Recognizing the importance of systematically evaluating new data, SSG-9 recommends that fault displacement hazards should be evaluated using a probabilistic approach (i.e., PFDHA) if a newly identified fault has the potential to affect the safety of an existing nuclear installation, and that the evaluation should determine whether the expected displacement value would exceed a permissible displacement value (IAEA, 2010).

The IAEA's recommendation to use probabilistic approaches to evaluate fault displacement hazards is based on experience and regulations developed in United States, Japan, and other Member States. For example, the American National Standards Institute (ANSI) provides criteria and guidelines for assessing tectonic ground deformation and surface fault rupture for nuclear facilities (Standard ANSI-ANS-2.30, 2015). Similar to the IAEA's SSG-9 Safety Guide (IAEA, 2010), the ANSI-ANS-2.30 guidelines state that any known Quaternary fault (within 5 km) shall be evaluated for potential displacement hazards at the site. Per ANSI-ANS-2.30, the PFDHA evaluation may be performed in accordance with the Senior Seismic Hazard Analysis Committee's (SSHAC) principles developed for ground shaking probabilistic seismic hazard assessments (United States Nuclear Regulatory Commission, 2018). The Atomic Energy Society of Japan (AESJ) is also updating a standard procedure for probabilistic fault displacement risk assessment (The Standards Committee of AESJ, 2021).

The currently available documents and guidelines that recommend the use of PFDHA for nuclear installations do so at a high level, without details on the methodology or its implementation (IAEA 2010, 2021a, 2021b, and ANSI-ANS-2.30, 2015). The publication of only one, introductory TECDOC on the topic reflects the facts that PFDHA is relatively new and its practice uncommon. Example applications of PFDHA for nuclear installations are limited, and the related information is largely inaccessible to the Member States. Accordingly, the IAEA Member States expressed a desire to receive more practical guidance on PFDHA during the 14th Plenary Meeting, 'Technical Meeting on Protection of Nuclear Installations Against External Hazards', held in November 2020 in Vienna. Member States requested specific examples of PFDHA implementation through a new benchmarking exercise that could be documented in a TECDOC. The intent of the new benchmarking exercise is to provide a comparison of current methodologies and uncertainties. It will provide state-of-the-practice documentation to support Member States in their implementation of PFDHA at their nuclear installation sites, and allow Member States to conduct PFDHA at existing and/or new nuclear installations following the recommendation of SSG-9 (IAEA, 2010) and DS507 (IAEA, 2021a) and fulfilling the requirements of SSR-1 (IAEA, 2019).

In this paper, we provide an overview of the state-of-practice of PFDHA for nuclear installations and introduce the IAEA PFDHA Benchmarking Project. The project is an on-going international effort led by the IAEA, and preliminary results consisting of a base case for hazard calculation and model verification are documented herein. We also discuss sensitivity cases to explore how PFDHA models perform under different site-fault configurations, and remaining tasks in the benchmarking project are described.

PROBABILISTIC FAULT DISPLACEMENT HAZARD ASSESSMENT FOR NUCLEAR INSTALLATIONS

In Safety Requirement No. SSR-1 (IAEA, 2019), a fault is considered capable if, considering all available geological, geophysical, geomorphological, geodetic, and seismological data, one of the following conditions is satisfied: i) it shows evidence of past surface deformations and/or dislocations of a recurring nature, from which it can be inferred that future surface deformations could occur; ii) there is a structural relationship with a known capable fault, and movement of one could cause movement of the other, yielding ruptures at or near the surface; and iii) it is possible to infer, from the tectonic setting of the site and the maximum potential earthquake of the seismogenic structure, that movement at or near the surface could occur. In areas of high seismic activity where the earthquake recurrence intervals are relatively short, capable faults may be assessed by evaluating evidence for activity over time periods on the order of tens of thousands of years. In contrast, a much longer time period may be required in less tectonically active areas to better evaluate fault activity and assess the capability of a fault to produce surface-rupturing earthquakes.

IAEA Safety Guides SSG-9 (IAEA, 2010) and DS507 (IAEA, 2021a) differentiate primary (i.e., principle) and secondary (i.e., distributed) faults for fault displacement hazard assessment and provide siting recommendations based on the distinction. Primary fault ruptures occur along a fault rupture plane (or planes) from which seismic energy is released, whereas secondary fault ruptures occur near the primary rupture on associated faults such as splays or branches of the capable fault, or antithetic structures (Coppersmith and Youngs, 2000; Youngs et al., 2003; IAEA, 2021b). Safety Guide SSG-9 recommends that new nuclear installation sites be located at least 5 km from any capable fault that could potentially affect the safety of the installation, unless the effects can be compensated by proven engineering design or other protective measures (i.e., exclusionary criterion). If any capable fault is identified within 5 km of an existing nuclear installation, SSG-9 recommends conducting PFDHA. Safety Guide DS507 updates these criteria for both new and existing sites, considering if the capable fault is classified as primary or secondary.

Fig. 2 illustrates candidate (new) site selection criteria per DS507 (IAEA, 2021a). Two cases are shown: (a) secondary faults are identified within the site area, and the capable primary fault is within the site vicinity; and (b) secondary faults are within the site vicinity, but the capable primary fault is outside the site vicinity. According to DS507, case (a) should be a basis for excluding the candidate site if the effects of secondary fault ruptures cannot be compensated by any proven engineering design or other protective measures, whereas in case (b), selection of the candidate site remains at the discretion of the Member States' regulatory bodies. Per DS507, if a fault cannot be classified as primary or secondary, then the fault should be characterized as primary to be conservative. Both cases (a) and (b) were considered exclusionary criteria for new sites in Safety Guide SSG-9 (IAEA, 2010), which does not distinguish between primary and secondary fault rupture. The new distinction between primary and secondary fault ruptures in DS507 encourages Member States to perform detailed geological surveys for better characterization of faults in the vicinity of a nuclear installation.

New nuclear installations can avoid known capable faults. While detailed site investigations are required before the construction of a nuclear installation, new information can later be acquired that identify a capable fault. When capable faults are discovered near existing sites, the hazard needs to be assessed to identify potential safety issues. In this case, a PFDHA should be performed, per SSG-9 and DS507, to estimate the annual frequencies of exceedance for primary and secondary displacement values of interests at or near the surface. Assessments can be performed following the approaches described in the next section and should address epistemic uncertainty adequately, as recommended by the IAEA Safety Standard.

The IAEA exclusionary and discretionary criteria are summarized in Figure 2 for new sites and in Table 1 for new and existing nuclear installations. For new installations, Cases 1 and 2 are exclusionary criteria, but Case 3 is a discretionary criterion. For an existing nuclear installation, if the fault has a potential to affect the safety of the nuclear installation, PFDHA evaluations are recommended for Cases 1 and 2. There currently is no recommendation for Case 3.

Only three PFDHA nuclear installation case studies have been performed for IAEA Member States in the past 20 years with documentation of the uncertainties and limitations in the approaches used. These studies are: 1) the Yucca Mountain nuclear waste repository in Nevada, USA, 2) the Diablo Canyon nuclear power plant in California, USA, and 3) a planned additional power plant adjacent to the existing Krško nuclear power plant in Slovenia (IAEA, 2021b). A description of these three case studies and details about their approaches are given in the IAEA TECDOC 'An Introduction to Probabilistic Fault Displacement Hazard Analysis in Site Evaluation for Existing Nuclear Installations' (IAEA, 2021b).

OVERVIEW OF PFDHA METHODOLOGY

PFDHA aims to provide the likelihood of occurrence of various amounts of coseismic surface-fault displacement. The pioneering publication of Youngs et al. (2003) presented two approaches: an earthquake approach and a displacement approach. They provided parameterizations of the earthquake approach suitable for normal faulting environments. The earthquake approach was developed utilizing the well-developed probabilistic seismic hazard analysis (PSHA) framework for ground motion hazards. It relies on magnitude-recurrence relationship to derive the rate of exceedance for various amounts of displacement at a site on or near a fault. The displacement approach, in contrast, uses direct observations of past fault displacement at a site to constrain and quantify the relationship between exceedance frequency and displacement amount.

Subsequently, several groups proposed different approaches for different tectonic environments. Petersen et al. (2011) developed an earthquake approach and provided regression equations for both principal and distributed displacement on strike-slip faults, using their compilation of historical surface displacement data. Moss and Ross (2011) presented a similar earthquake approach and provided data and equations for principal displacement on reverse faults. Takao et al. (2013) provided data and regressions for strike-slip and reverse faults in Japan. More recently, Lavrentiadis and Abrahamson (2019) developed a wavenumber-domain methodology to capture the correlation of the surface-slip variability along a strike, avoid the surface-rupture length normalization, and narrow tails of the slip distribution, which is important for PFDHA at long return periods. Nurminen et al. (2020) developed a model for distributed displacement hazard for reverse faults and introduced a novel statistical approach to estimate the conditional probability of distributed ruptures as a function of distance from the principal fault.

In any PFDHA, the first step consists of seismic source identification and characterization to determine earthquake frequency and distance distributions, followed by calculating the annual frequency (λ) for fault displacement D exceeding D_0 (IAEA, 2021b):

$$\lambda\left(D > D_0\right) = \alpha_{DE} \cdot P\left(D > D_0\right) \quad (1)$$

where α_{DE} is the rate of displacement events at the site and $P(D > D_0)$ is the probability that displacement D exceeds the threshold level D_0. Eq. 1 is applicable to both primary and secondary displacements. Depending on whether there are data at or near the site of interest to quantify α_{DE} and the exceedance probability distribution $P(D > D_0)$, the displacement or earthquake approach can be followed.

Earthquake Approach

The earthquake approach formulation is similar to that for PSHA (Cornell, 1968), and uses an integration over a set of earthquake scenarios distributed on the fault. The simple event rate α_{DE} in Eq. 1 is replaced with the overall rate of events $\alpha(m_{min})$ with magnitudes larger than a given minimum magnitude (m_{min}) and a probability density function $f_{m,s}$ that describes the magnitude m earthquake, occurring along an active fault at distance s from the end of the fault, as follows (IAEA, 2021b):

$$\alpha_{DE} = \alpha\left(m_{\min}\right) \int f_{m,s}\left(m, s\right) dmds \quad (2)$$

Following this approach, the probabilistic term in Eq. 1 becomes an attenuation function for fault displacement at or near the ground surface and it contains two parts (Eq. 3):

$$P(D > D_0) = P[D \neq 0 \mid z, r, sr \neq 0] \times P[D > D_0 \mid l/L, m, D \neq 0] \quad (3)$$

The former part is the conditional probability that fault displacement exceeds D_0 at the site given slip occurs ($D \neq 0$). The latter represents the probability of having surface slip at distance r from the fault rupture, over an area z^2, with a magnitude m event that ruptures the surface. l/L is along-fault distance ratio, where L is the total rupture length and l is the distance from the nearest point on the fault rupture to the closest end of the rupture.

Not all earthquakes break the surface, depending on the magnitude of the earthquake, an additional magnitude-dependent term (Eq. 4) must be considered in Eq. 1 in order to define the probability that a fault produces surface rupture:

$$P[sr \neq 0 \mid m] \quad (4)$$

Moreover, a probability density function, $f_r(r)$, describing the perpendicular distance from the site to all potential ruptures is also incorporated. Combining Eqs. 2 through Eq. 4 and integrating over magnitudes and location distributions, Eq. 1 can be written as follows (IAEA, 2021b):

$$\begin{aligned} \lambda(D > D_0) = \alpha(m_{\min}) \int f_{m,s} P[sr \neq 0 \mid m] \times \\ \times \int P[D \neq 0 \mid z, r, sr \neq 0] \times P[D > D_0 \mid l/L, m, D \neq 0] f_r(r)\, dm\, ds\, dr \end{aligned} \quad (5)$$

This general form applies to principal faulting. Depending on seismotectonic setting and available data, this general form can contain additional details or variables introduced by model developers. For example, Takao et al. (2013) considered an additional conditional probability term to account for the observation that the ratio of surface and subsurface rupture lengths depends on magnitude. The general form of Eq. 5 can also be applied to distributed faulting by replacing the distance ratio *l/L* with the distance *r* between the principal fault and the site of interest. Several models are available to assess distributed faulting (Youngs et al., 2003; Petersen et al., 2011; Takao et al, 2013; Nurminen et al., 2020).

Displacement Approach

Developed as a part of the Yucca Mountain study (Stepp et al., 2001; Youngs et al. 2003), the displacement approach utilizes only the observations and characteristics of fault displacement at the point of interest to assess the hazard. Unlike the earthquake approach, there is no distinction between principal and distributed faulting, and the causative source is not explicitly considered. The rate of exceedance *v* for a given level of displacement *d* can be obtained by the general form:

$$v(d) = \lambda_{DE} \cdot P(D > d) \tag{6}$$

where λ_{DE} is the rate of displacement events and $P(D > d)$ is the conditional probability, given a slip on the fault, that the single-event displacement *D* will exceed the value *d*.

The rate of displacement λ_{DE} can be estimated from the slip rate *SR* and the average slip D_E in a faulting event ($\lambda_{DE} = SR/D_E$) or directly from the recurrence intervals R_{int} of paleoearthquake age ($\lambda_{DE} = 1/R_{int}$). The probability term in Eq. 6 can be estimated from a database of repeated slip events revealed at the same location or using generic distributions for normalized displacement along with an estimate of the average displacement.

IAEA PFDHA BENCHMARKING PROJECT

The objective of the IAEA PFDHA Benchmarking Project is to provide information on the state-of-practice and detailed technical elements related to PFDHA to assist Member States in implementing the recommendations of SSG-9 and DS507 for evaluation of fault displacement hazards at existing and/or new nuclear installations. Special attention is devoted to benchmarking available PFDHA models via scenario case studies, identifying necessary model refinements at individual sites, and discussion of evaluating uncertainty.

The benchmarking study consists of a simple verification exercise, calculating hazards for a straightforward set of test cases. The study consists of three steps: 1) verification of current published models and model comparison; 2) model implementation for two sites; and 3) documentation of the model verification, comparison, and test case implementation in an IAEA TECDOC. The project officially started in November 2020 and its expected duration is two years.

Step 1 includes a simple fictional scenario with a single seismic source parameterization and a logic tree capturing epistemic uncertainty in source parameterization. Although a range of scenarios is considered in a full PFDHA, we considered only specific scenarios because this is a benchmarking exercise. The goals of the first step are: i) to engage the PFDHA model developers and have them provide mean hazard curves, ii) to establish “baseline” hazard curves for later verification exercises, and iii) to analyse results to guide activities for the second step. The fictional scenarios and logic tree inputs for seismic sources were provided by the IAEA. In particular, the

IAEA provided site coordinates and site dimensions in Excel and Esri shapefile format, and source characterization logic trees. The lead modelers who participated in Step 1 are: R. Youngs (for Youngs et al., 2003), R. Chen (for Petersen et al., 2011), R. Moss (for Moss and Ross, 2011 and 2013), T. Annaka (for Takao et al., 2013, 2014, and 2016), and F. Visini (for Nurminen et al., 2020). They and other participants provided results as tables, plots, and short answers to questions about their approaches.

Whereas Step 1 only included only developers of currently published PFDHA models, Step 2 will expand to include other teams with experience in implementing PFDHA. Only five models are currently available, and they are for different tectonic environments (i.e., different styles of faulting; see Section "Overview of PFDHA methodology"), making comparison difficult but meaningful as shown in later sections of this paper. Inviting new PFDHA model development teams to participate in this project allows: i) more than a single model for a given kinematic conditions (e.g., Nurminen et al., 2021 for all dip-slip faults); ii) consideration of new regressions made for specific components of PFDHA (e.g., Ferrario and Livio, 2021, which revised and updated the conditional probability of slip for distributed ruptures published by Youngs et al., 2003); iii) incorporation of the epistemic uncertainty with logic trees and its exploration with tornado plots that will be provided by each team; and iv) verifications phase to ensure published PFDHA models are implemented correctly in computer codes.

An IAEA TECDOC will be developed in the final step (Step 3) to assist Member States with conducting PFDHA at existing and/or new nuclear installations. The TECDOC will contain: i) updated information about the main components of PFDHA, such as the conditional probability of slip given a magnitude and the conditional probability of exceedance for a given value of displacement on principal fault; ii) results of the benchmarking of all available models for two example sites in different environments and with different levels of seismic activity; and iii) guidelines on how to perform the earthquake and/or displacement approach considering all potential geological information available. The new TECDOC, which will be considered the final product of this project, aspires to deliver technical guidance on performing PFDHA that is not currently available in the existing documents and guidelines in the nuclear industry professional literature.

Base case and sensitivity cases

Step 1 includes a base case and four sensitivity cases to explore differences in seismic source parametrization and fault-to-site distance. The site dimension (*z*) is the same for the base and sensitivity cases: 100 x 100 m^2. The site is in the city of Kumamoto, Japan, near the Futagawa and the Hinagu fault systems (Fig. 3). The area was recently struck by a large right-lateral strike-slip earthquake (M_w 7.1, April 16, 2016; Shirahama et al., 2016) that ruptured the Futagawa fault and the northern tip of the Takano-Shirahata fault, as well as other conjugate fault planes like the Suizenji fault plane (Fig. 3). For our study herein, we considered only the Futagawa fault system and the Suizenji fault in seismic source parameterization. The Hinagu fault zone was not considered due to the large distance between the faults and the selected site.

Table 2 summarizes the base and sensitivity case spatial parameters, and Fig. 3b shows a map configuration of the cases. Deterministic seismic source characterization parameters for the fault systems are listed in Table 3, and all modelers used this characterization. A source logic tree with alternative branches for magnitude and mean occurrence rates is provided in Fig. 4. The magnitude uncertainty in the logic tree (Fig. 4) reflects a factor of 2 in seismic moment per event for each source, and the mean occurrence rate uncertainty is a factor of 3 around the middle branch. All modelers used the earthquake approach in their PFDHA calculations. The base case and the four sensitivity cases used here in Step 1 will also be used by other teams in Step 2. Furthermore, Step 2 will also include second site (location to be determined).

The base case hazard is from distributed faulting from a combination of three approximately located faults in Futagawa fault system (Futagawa, Uto, and Uto Hanto North faults), and the closest fault-to-site distance (*r*) is 5.2 km (Fig. 3 and Table 2). Four sensitivity cases were used to explore sensitivity of hazard to type of faulting (i.e., principal or distributed), magnitude, *l/L*, and *r*. The first sensitivity case also considers hazard from distributed faulting. In Sensitivity Case 1, the closest distance *r* is 0.6 km because the Suizenji fault (Fig. 3) is treated as a principal fault source, the map accuracy is inferred, and epistemic uncertainty in source parameters is not included (i.e., only the single-branch case for the Suizenji fault parameters in Table 3 were used). For the second and third sensitivity cases, the site was assumed to be on a principal fault, so the closest distance *r* is zero and the hazard is from principal faulting. The fourth sensitivity case is similar to the base case except fault distance *r* is 10 km (Fig. 3).

The source parameter characterization for the Futagawa fault system (Table 3) was provided by the IAEA and based on the source characterization by the Headquarters for Earthquakes Research Promotion (HERP, 2016). To evaluate moment magnitude (M_w) and the occurrence rates, the fault length is determined by the Geological Survey of Japan. The total length of each scenario is then obtained as the summed lengths of the included faults (i.e., Futagawa, Uto, and/or Uto-Hanto-North, Fig. 3). Then, earthquake magnitude (M_j) is computed by the Japanese Meteorological agency from the total fault length using the Japanese scaling rule (Matsuda, 1975), and M_j is converted to M_w according to Takemura (1990). M_w is then used to compute the seismic moment (Kanamori, 1977) and fault area by the characteristic source scaling (Irikura and Miyake, 2001). Other geometrical parameters, such as dip angle and seismogenic thickness, are inferred. To evaluate the occurrence rate of each scenario, the dislocation is evaluated (per event), as computed by the Japanese scaling rule between fault length and dislocation (Matsuda et al., 1980). Then, the average recurrence interval is calculated based on average slip rate and dislocation (per event), with the average slip rate determined from geomorphological survey results (HERP, 2016).

The same procedure was followed for the Suizenji fault. Because this fault was not identified by HERP (2016) before the 2016 Kumamoto earthquake, we use fault length and geomorphological survey results published by Goto et al. (2017) to compute the Suizenji fault M_w and mean occurrence rate (Table 3).

Step 1 results

Figure 5 shows the results for the base case and four sensitivity cases (Table 2) as displacement hazard curves. The hazard curves are expressed in terms of annual frequency of exceedance (AFOE, yr^{-1}) versus displacement (cm), and curves on Fig. 5 are for distributed displacement (Figs. 5a, 5b, 5c, and 5f) and for principal faulting (Figs. 5d to 5e). Epistemic uncertainty in the parameters listed in Table 3 was included only in Figure 5b. For the base case, the results represent the total hazard curve given by the sum of contributions from all Futagawa fault system scenarios considered (Fig. 3). For principal displacement, the models use conditional probabilities of slip given a magnitude and expected displacement given the location of the site along the fault. Distributed displacement is determined from a conditional probability of slip at distance r from the rupture, given a magnitude and expected displacement for the site location away from the fault.

The Youngs et al. (2003) model produces the highest distributed displacement hazard in the base case and sensitivity case 4, and the Nurminen et al. (2020) model produces the lowest hazard (Figs. 5a and 5f). All models show the same behaviour: hazard curves are flat curve in between 0.01 cm and 10 cm, and the slopes of the curves increase as AFOE decreases and displacement increases. The Nurminen et al. (2020) model produces the highest hazard in sensitivity case 1 (Fig. 5b). The Takao model hazard is slightly lower in sensitivity case 1 (relative to the base case), and the Petersen and Youngs model hazards are slightly higher. Because the mean occurrence rate for the base case (i.e., the sum of mean rate of four scenarios of the Futagawa fault system, Table 3) is similar to that of sensitivity case 1 (Suizenji fault only, Table 3)**,** the differences in hazard curves are probably related to different conditional probabilities used by each model. Sensitivity case 1 hazard curves from the Petersen, Takao, and Youngs models are all shifted slightly to the left compared to the base case (by about one order of AFOE magnitude). This indicates that in the Petersen, Takao, and Youngs models, the change in the conditional probability of distributed faulting with distance, r, has less of an impact than the maximum magnitude. However, the fault-to-site distance r is the controlling parameter in the Nurminen et al. (2020) model: base case distance is 5.2 km, and the distance in the first sensitivity case is 0.6 km. This change yields an AFOE that is almost six orders of magnitude higher in the sensitivity case 1 than in the base case.

Figure 5b shows mean displacement hazard curves and 90% confidence intervals, for the base case, considering epistemic uncertainty in source characterization (Fig. 4). For all models, the 90% confidence interval is always within about one order of AFOE magnitude. While the epistemic uncertainty in source parameters (M_w and occurrence rate) is important for PFDHA, more significant differences are observed between different models (and therefore among different kinematic styles) (Fig. 5b).

Figures 5d and 5e show sensitivity cases 2 and 3, which are related to principal faulting. In both cases and for all models, the hazard is about two orders of AFOE magnitude higher compared to the base case (Fig. 5a), where the site is 5.2 km far from the principal fault. In the sensitivity case 2 (Fig. 5d) the hazard is higher than the third sensitivity case for all models and this is mainly due to the difference in the M_w between the two cases (Table 2 and 3). However, the impact of this difference is much evidence for the Takao and Moss than the Youngs and Petersen models. This means that the conditional probability of slip and the conditional probability of exceedance (Eq. 5) for Takao and Moss models are more M_w sensitive than the Youngs and Petersen models.

DISCUSSION

The results of Step 1 (Fig. 5) highlight the importance of source parametrization in terms of maximum magnitudes, occurrence rates, and style of faulting when a PFDHA is performed. The results also reveal significant differences in the hazards calculated for different displacement models, which are based on fault kinematics and tectonic environment. Strike slip, reverse, and normal events have different stress regimes which, for a given magnitude, appear to yield different displacements along the principal fault and probabilities of surface rupture. This is illustrated in Figure 6, where probabilities of distributed surface rupture from the different models used in Step 1 are shown. For example, the difference in rupture probabilities between the Youngs and Takao models for the base case (r = 5.2 km, Fig. 6) is roughly two orders of magnitude, resulting in the same spread the displacement hazard curves (Fig. 5a). For sensitivity case 1 (r = 0.6 km, Fig. 6), the difference between the Petersen and Youngs models is less than an order of magnitude, and a similar spread is also reflected in the displacement hazard curves (Fig. 5c).

Each PFDHA model used in Step 1 is based on conditional rupture probabilities developed for different tectonic regimes using independent databases. Hence, differences in Figure 6 are not surprising. Each model is also developed following different assumptions. For example, the Petersen and Nurminen models do not consider triggered ruptures and are not recommended for distances greater than two or three kilometres. In contrast, the Youngs model for distributed ruptures was developed from a more spatially extensive database, providing assessments of rupture probabilities for distances up to 20 km. While it is important to select the appropriate model for a given tectonic environment, it is also necessary to understand how to correctly apply these models. Are the Nurminen and Petersen models suitable for a nuclear installation located at five kilometres from a capable fault? What site-specific data and knowledge are needed to correctly apply a given model? Answers to these questions are what the Member States expect from the TECDOC, which will be published at the end of this project. It is anticipated that the TECDOC will allow the Member States to better understand PFDHA and alternative models that can be applied.

Scarceness of data is another important point to keep in mind when performing PFDHA. The available datasets used PFDHA model development are limited compared to ground motion datasets used in probabilistic seismic hazard analysis model development. Existing datasets often lack details about the complexity of surface faulting and commonly include only seismological information such as earthquake magnitude, focal mechanism and hypocentral depth. To date, PFDHA model developers have relied on their own data compilations specific to the local tectonic regime of the area been investigated (e.g., Nurminen et al., 2020) or published datasets containing information of primary or secondary ruptures. For example, Youngs et al. (2003) used Wells and Coppersmith (1993) for conditional probability of principal surface rupture and Pezzopane and Dawson (1996) to assess conditional probability for distributed rupture. Petersen et al. (2011) collected additional data for both principal and distributed ruptures. In the last few years, efforts have been made toward a worldwide and unified database of surface rupture for fault displacement hazard assessment. The SURE database (Baize et al., 2020) contains surface rupture information and fault displacement data for 45 earthquakes with magnitude ranging from 5.0 to 9.0 and a total of 15,000 observed coseismic surface displacement measurements and 56,000 mapped rupture segments. The database includes geo-referenced GIS files of surface ruptures and three tables summarizing pertinent displacement and rupture observations and earthquake information. The next step towards developing a robust surface rupture dataset is utilizing a combination of traditional field mapping with remote sensing techniques. Recent advances in remote-sensing analysis (e.g., Monterroso et al., 2020) allow sampling of both principal and distributed rupture and displacement uniformly and systematically, improving statistical results and data coverage and precision. Moreover, these tools allow one to collect information on coseismic deformation in remote or inaccessible areas and provide broad spatial coverage, improving data collection for large magnitude ruptures. Finally, new remote sensing techniques also afford better differentiation of primary and secondary ruptures in moderate-to-small magnitude earthquakes (e.g., Ritz et al., 2020).

There are a lot of other issues in PFDHA that worth mentioning. For example, a key challenge in developing PFDHA databases and models is classifying faults and related displacements as primary or secondary. It is extremely important, to reduce epistemic uncertainty related to primary fault location, have a well-known and mapped principle fault trace and it is also important have a good record of distributed ruptures to better constraint the conditional probability of having distributed ruptures far from the principal fault. Therefore, more precise definition and classification methods are needed, for example, categorizing the distributed ruptures (e.g., only sympathetic, or only triggered ruptures) and applying a different regression for a different kind of distributed rupture. Another issue is the soil condition. In general, nuclear installations are or will be located where geological conditions are acceptable (i.e., rock). Soil sites may also be selected if bearing capacity is sufficient (IAEA, 2005). Soil conditions may play a role in PFDHA. Moss et al. (2013) show that the stiffness of the upper thirty meters of geologic material has a strong impact on rupture propagation from depth to the ground surface in reverse environment. Bray et al. (1994) argues that the characteristics of the soil overlying the bedrock fault strongly influence the observed earthquake fault rupture propagation behaviour. All models used in this benchmarking exercise do not consider the condition of secondary rupture sites. It is expected that soil effects will be considered in future studies for other tectonic environments. Finally, existing models were developed primarily using empirical approaches. It is expected that the advancement of 3-D physics-based numerical simulations (e.g., Dalguer et al., 2020) will complement empirical models. In particular, dynamic rupture approaches can be useful in the case where regressions for distributed ruptures need to be extrapolated to large rupture distances (e.g. the models of Nurminen et al. 2020 and Petersen et al. 2011 for distances greater than 2 to 3 km).

CONCLUSIONS

The IAEA recommends PFDHA as a tool to evaluate the impact of capable faults in the vicinity of an existing or planned nuclear installation. Because there is lack of documented case histories on PFDHA in the scientific and engineering literature, particularly compared to PSHA for ground motion hazard assessment, the Member States requested that the IAEA document a recommended approach and evaluation of available alternative parameterizations in the literature to better understand hazard results. To meet this request, the IAEA initiated the PFDHA Benchmarking Project.

The PFDHA Benchmarking project consists of three steps: 1) example applications to identify the most important aspects in the PFDHA models, 2) detailed analyses for understanding of model differences, and 3) development of a TECDOC to provide specific guidelines for PFDHA application. The project commenced in November 2020. Step 1 has been completed and is described in this paper. The results of Step 1 allow us to draw important preliminary conclusions, which will help in directing additional analyses in Step 2 and the contents of the TECDOC. It is shown, through the evaluation of epistemic uncertainty in source characterization and comparison among different models and their rupture probabilities (Figs. 5 and 6), that choosing appropriate models and correct model applications are important for any existing or new nuclear installations. Comparisons among different models that reflect different fault types or regional tectonic characteristics, performed during Step 1, will be useful for the Member States to better understand how each model is built and how to correctly apply it. The IAEA will invite other PFDHA modelling teams to participate in Step 2 to analyse two example sites in different tectonic environment, which will allow verification of model implementation and the comparison of hazard results for a given tectonic regime. The IAEA TECDOC will be delivered at the end of Step 3, which will assist the Member States in performing PFDHA and contribute to international nuclear safety.

DATA AND RESOURCES

The source parameters used to compute the hazard curves in Figure 5 are listed in Table 3. The PFDHA approaches used are described within the papers cited in the References.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge there are no conflicts of interest recorded.

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TABLES

Table 1. Summary of IAEA safety requirements and recommendations for the three different cases according to SSG-9 and DS507 (IAEA, 2010; IAEA 2021a).

	Case 1	**Case 2**	**Case 3**
Location of capable fault	**Within Site Area**	**Within Site Vicinity**	**Outside of Site Vicinity**
New site	Exclusionary	Exclusionary if identified as primary	Discretionary as a candidate site
Existing site	PFDHA is recommended*	PFDHA is recommended*	Continued operation

* If the identified fault has a potential to affect the foundations of items important to safety of nuclear installations.

Table 2. Summary of parameters used for base and sensitivity cases. The site dimension is 100 x 100 m^2 for all cases. For the base case and sensitivity cases 2 and 4 the ratio *l/L* ranges from 0.1 to 0.37 because in these cases the total hazard is given by a combination of the three FFS segments (Fig. 3 and 4). *r* = fault-to-site distance; FFS = Futagawa fault system; SF = Suizenji fault.

	***r* (km)**	**Type of faulting**	**Site coordinates**	**Source**	***l/L***	**Map accuracy**
Base case	5.2	Distributed	130.7417 – 32.7899	FFS	0.1 – 0.37	Approximately located
Sensitivity Case 1	0.6	Distributed	130.7417 – 32.7899	SF	0.39	Inferred
Sensitivity Case 2	0	Principal	130.7656 – 32.7474	FFS	0.1 – 0.37	-
Sensitivity Case 3	0	Principal	130.7656 – 32.7474	SF	0.39	-
Sensitivity Case 4	10	Distributed	130.7196 – 32.8288	FFS	0.1 – 0.37	Approximately located

Table 3. Sources and parameters used for seismic source characterization.

Source	**Max Rupture Length (km)**	**Max Rupture Thickness (km)**	**Average Dip (°)**	**Magnitude**	**Mean Rate of Occurrence (x 10^{-5} yr^{-1})**
Uto (2)	22	14	60 NW	6.5	18.9
Futagawa (1) + Uto (2)	46	14	68.6 NW	6.9	1.28

Uto (2) + Uto-Hanto-North (3)	54	14	60 NW	7	3.53
Futagawa (1) + Uto (2) + Uto-Hanto-North (3)	78	14	64.6 NW	7.2	1.28
Suizenji	5.4	5	60 SW	5.8	23.30

LIST OF FIGURE CAPTIONS

Figure 1. IAEA document hierchy. Current Safety Fundamentals are in SF-1 (IAEA, 2006); new Safety Requirements are in SSR-1 (IAEA, 2019); and revised Safety Guide DS507 (IAEA, 2021a) addresses seismic hazards, updating Safety Guide SSG-9 (IAEA, 2010).

Figure 2. Site selection for a new site according to IAEA Safety Guide DS507 (IAEA, 2021a). a) The primary fault rupture is in the site vicinity (5 km radius), and secondary fault ruptures are within the site area (1 km^2). This is an exclusionary criterion, per Table 1, if the primary and secondary fault rupture effects cannot be compensated for by proven design or engineering measures. b) The primary fault rupture is outside the site vicinity, while the secondary fault ruptures are within the site vicinity but outside the site area; this is a discretionary criterion, per Table 1.

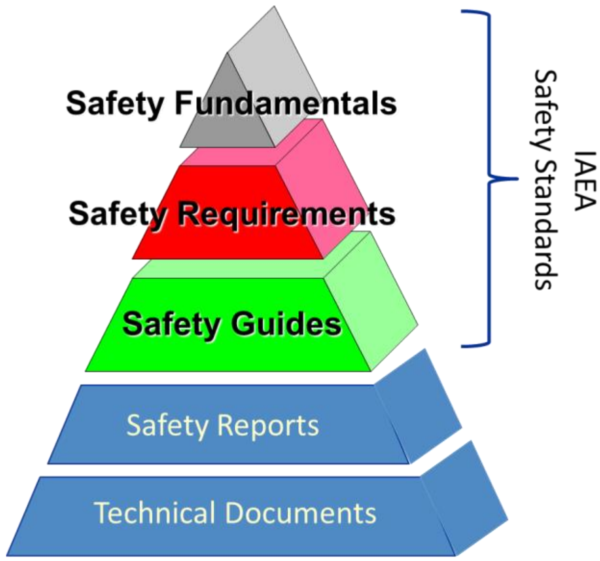
Figure 3. a) Map of the Futagawa fault system (Futagawa, Uto, and Uto-Hanto-North faults) and Hinagu fault system (Yatsushiro-Sea, Hinagu, and Takano-Shirahata faults) (modified after HERP, 2016). The green star is the location of the site area selected for Step 1. b) Simplification of Futagawa fault system and Suizenji fault and site locations for base case and four sensitivity cases.

Figure 4. Source characterization logic tree used in Step 1 for the Futagawa fault system. The weight of each branch is shown in square brackets. For each scenario, the magnitude uncertainty (± 0.2) reflects a factor of 2 uncertainty in seismic moment per event and the mean rate uncertainty

is a factor of 3 about the middle branch. The magnitude and mean rate of each scenario are listed in Table 3.

Figure 5. Distributed faulting displacement hazard curves in terms of annual frequency of exceedance (AFOE, yr^{-1}) versus displacement (cm), for base case single path (a) and all sensitivity cases (c to f). b) Mean displacement hazard curves (solid lines) and 90% confidence intervals (dashed lines) for base case (distributed faulting) calculated following the logic tree shown in Fig. 3. For the base case, the hazard curves were obtained by summing the contributions of four different scenarios considered for the Futagawa fault system (Table 3 and Fig. 4). Youngs (Youngs et al., 2003); Takao (Takao et al., 2013, 2014, 2016); Moss (Moss et al., 2011); Petersen (Petersen et al., 2011); Nurminen (Nurminen et al., 2020).

Figure 6. Conditional probabilities of slip for distributed faulting used by modelers in Step 1. Youngs and Nurminen probabilities are shown for different magnitudes (M) because their functional form is magnitude-dependent. Petersen and Takao probabilities are not magnitude-dependent, but they are site-size dependent. In this figure, Petersen and Takao regressions show probabilities for a site 100 x 100 m. Youngs (Youngs et al., 2003); Takao (Takao et al., 2014); Nurminen (Nurminen et al., 2020); Petersen (Petersen et al., 2011).



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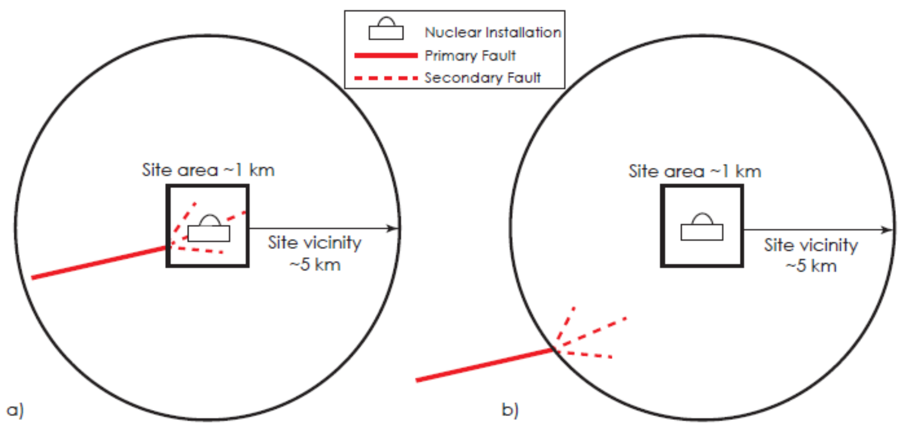

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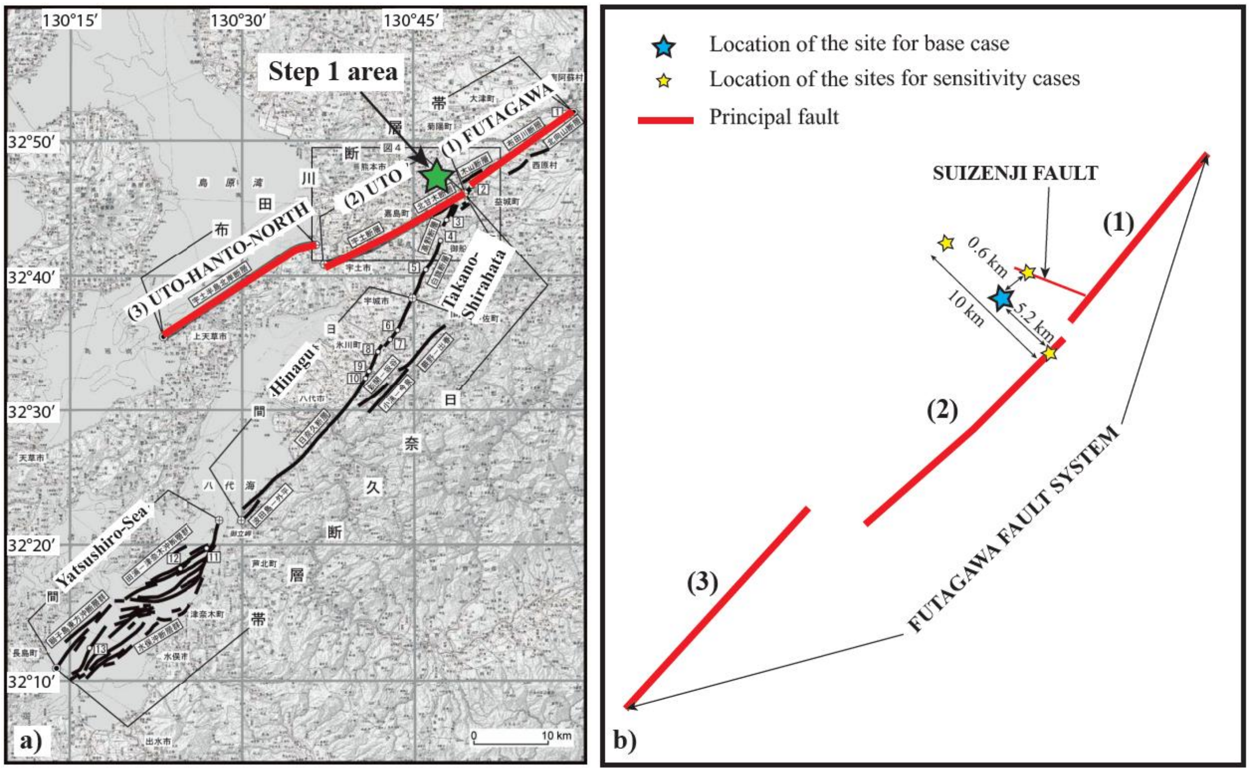


Figure 3. a) Map of the Futagawa fault system (Futagawa, Uto, and Uto-Hanto-North faults) and Hinagu fault system (Yatsushiro-Sea, Hinagu, and Takano-Shirahata faults) (modified after HERP, 2016). The green star is the location of the site area selected for Step 1. b) Simplification of Futagawa fault system and Suizenji fault and site locations for base case and four sensitivity cases.

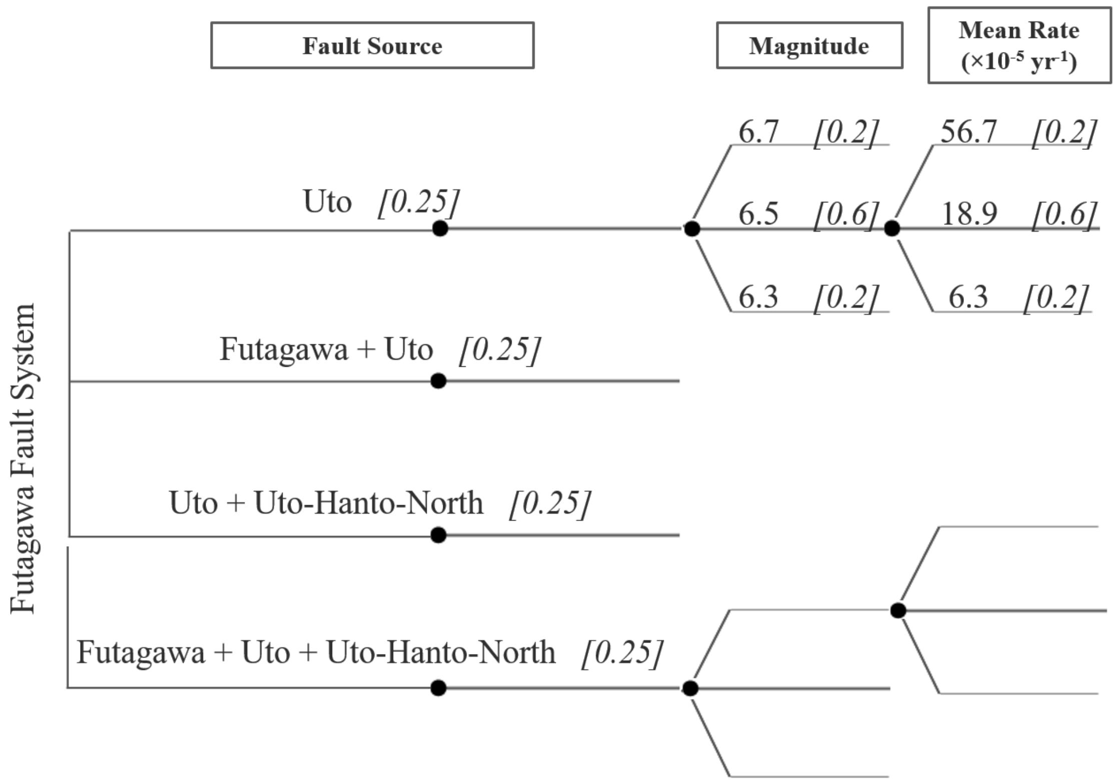
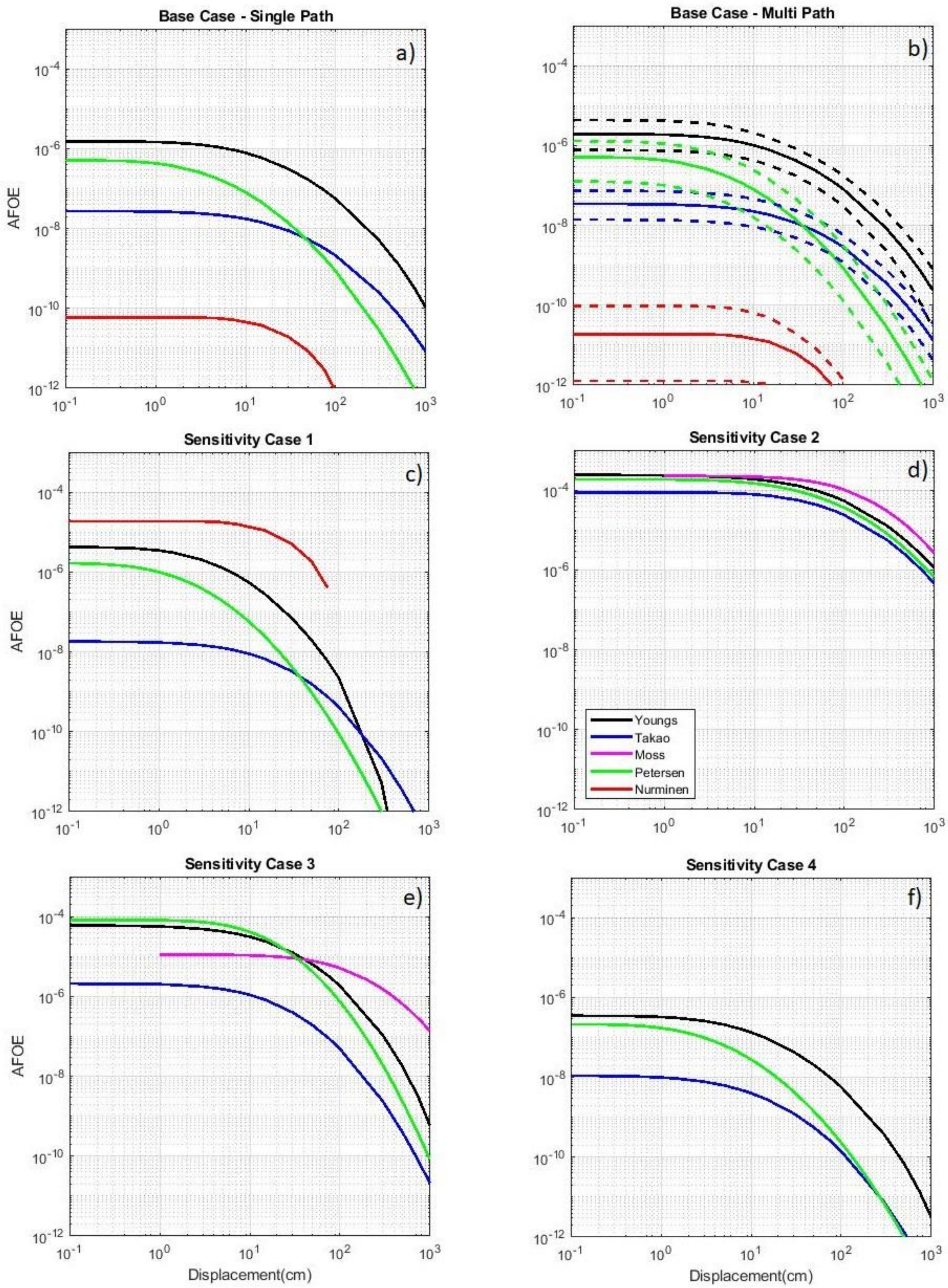


Figure 4. Source characterization logic tree used in Step 1 for the Futagawa fault system to capture the epistemic uncertainty. The weight of each branch is shown in square brackets. For each scenario, the magnitude uncertainty (6.5 ± 0.2) reflects a factor of 2 uncertainty in seismic moment per event and the mean rate uncertainty is a factor of 3 about the middle branch. The magnitude and mean rate of each scenario are listed in Table 3.


Base Case - Single Path
a)
Base Case - Multi Path
b)
Sensitivity Case 1
c)
Sensitivity Case 2
d)
Youngs
Takao
Moss
Petersen
Nurminen
Sensitivity Case 3
e)
Sensitivity Case 4
f)
AFOE
Displacement(cm)

793

Figure 5. Distributed faulting displacement hazard curves in terms of annual frequency of exceedance (AFOE, yr^{-1}) versus displacement (cm), for base case single path (a) and all sensitivity cases (c to f). b) Mean displacement hazard curves (solid lines) and 90% confidence intervals (dashed lines) for base case (distributed faulting) calculated following the logic tree shown in Fig. 3. For the base case, the hazard curves were obtained by summing the contributions of four different scenarios considered for the Futagawa fault system (Table 3 and Fig. 4). Youngs (Youngs et al., 2003); Takao (Takao et al., 2013, 2014, 2016); Moss (Moss et al., 2011); Petersen (Petersen et al., 2011); Nurminen (Nurminen et al., 2020).

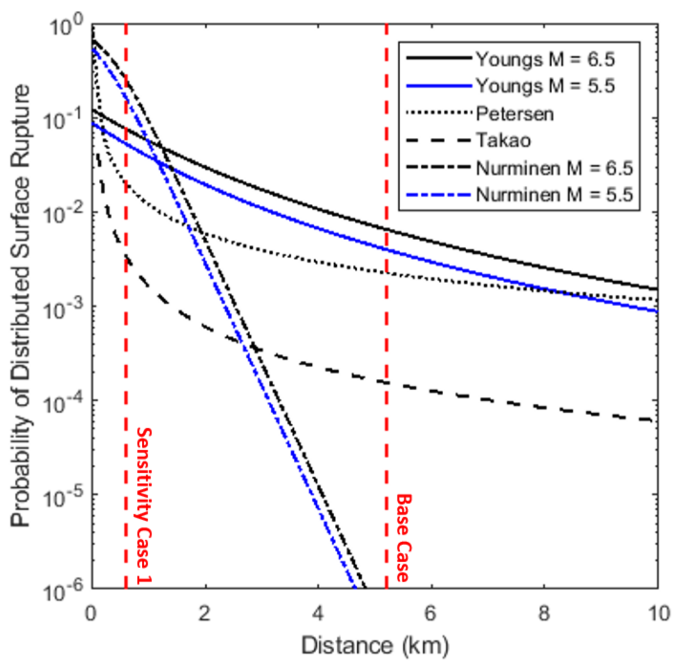


Figure 6. Conditional probabilities of slip for distributed faulting used by modelers in Step 1. Youngs and Nurminen probabilities are shown for different magnitudes (M) because their functional form is magnitude-dependent. Petersen and Takao probabilities are not magnitude-dependent, but they are site-size dependent. In this figure, Petersen and Takao regressions show

probabilities for a site 100 x 100 m. Youngs (Youngs et al., 2003); Takao (Takao et al., 2014); Nurminen (Nurminen et al., 2020); Petersen (Petersen et al., 2011).

Figure 1


Safety Fundamentals
Safety Requirements
Safety Guides
Safety Reports
Technical Documents
IAEA
Safety Standards

Figure 2

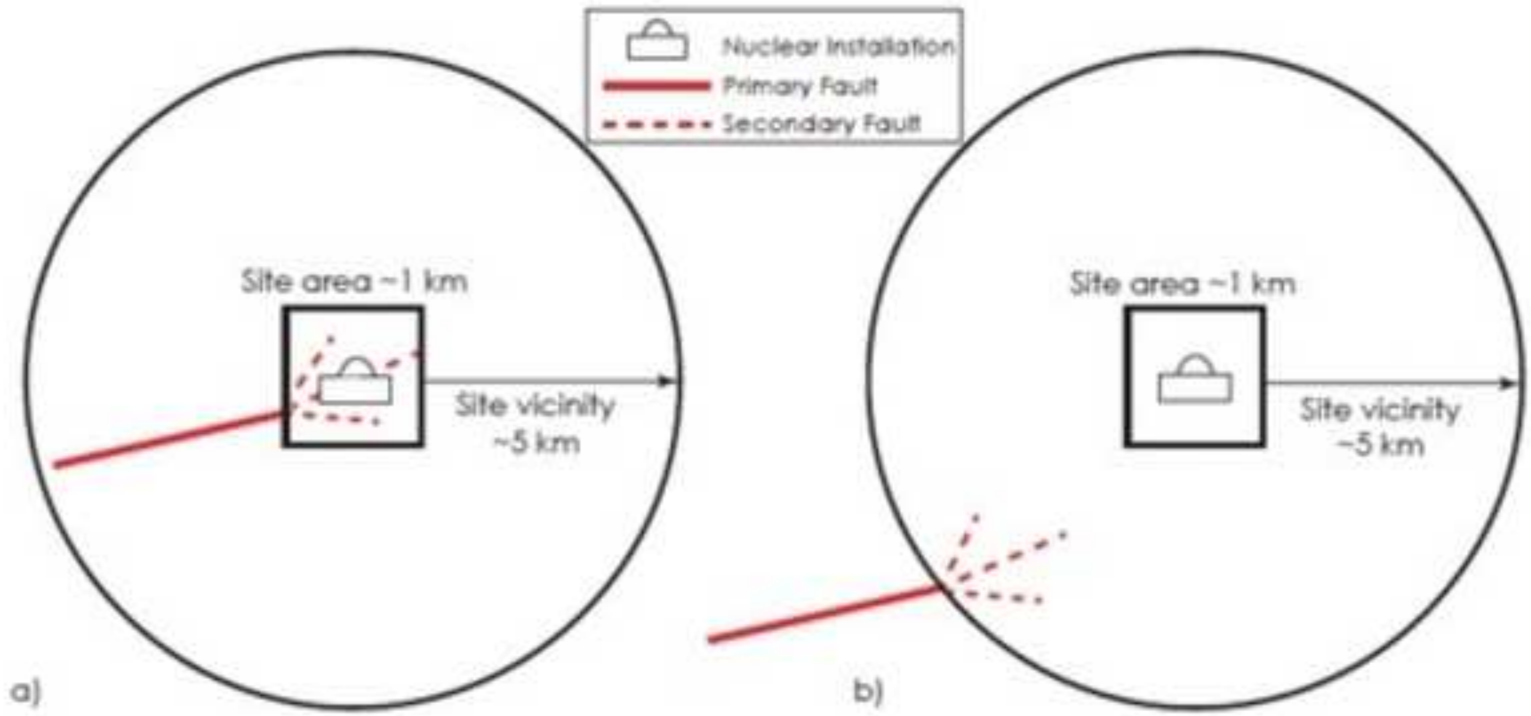

Nuclear Installation
Primary Fault
Secondary Fault
Site area ~1 km
Site vicinity
~5 km
a)
Site area ~1 km
Site vicinity
~5 km
b)

Figure 3 Click here to access/download;Figure;Figure3.jpg

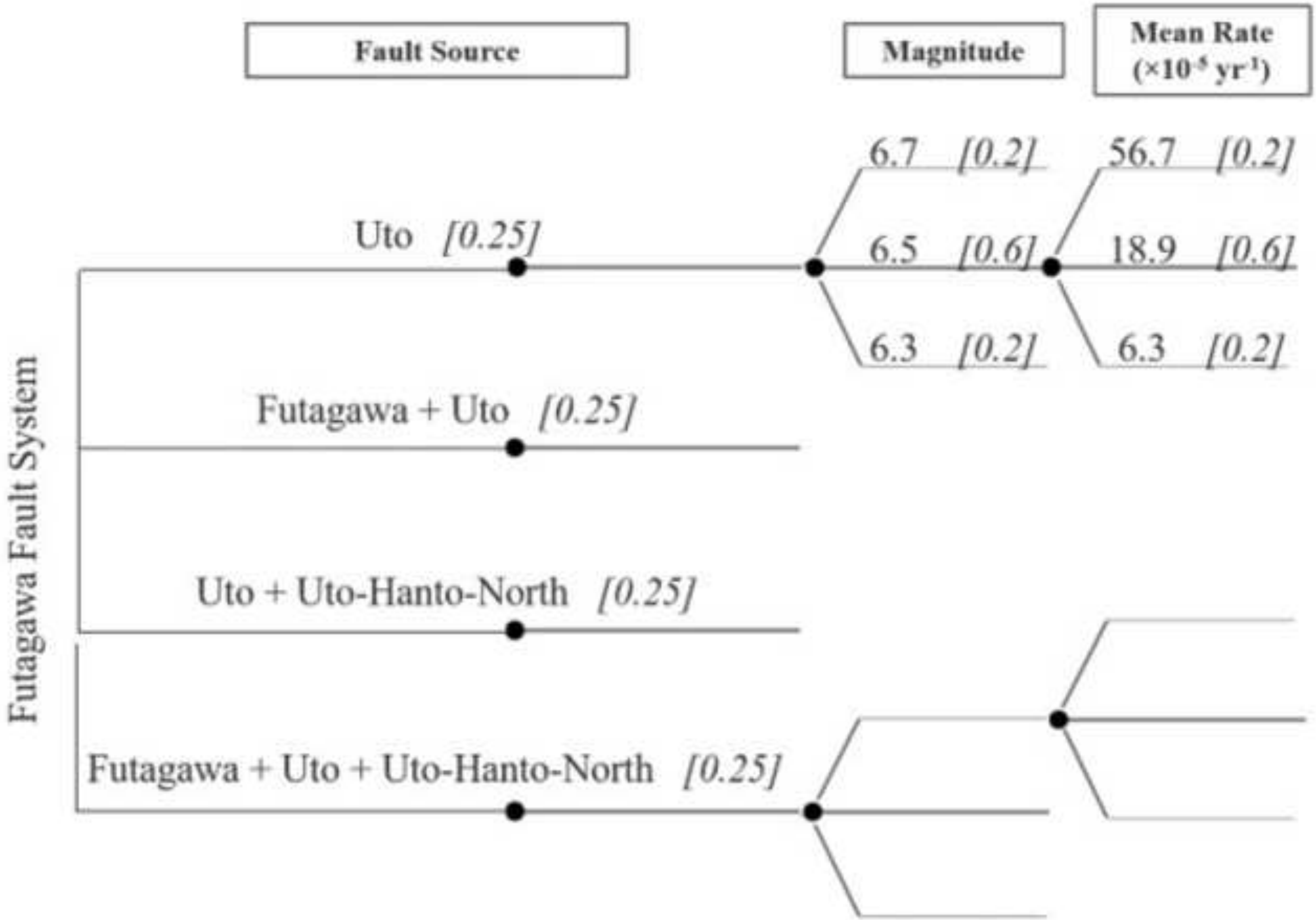


Figure 4

Click here to access/download;Figure;Figure4.pdf

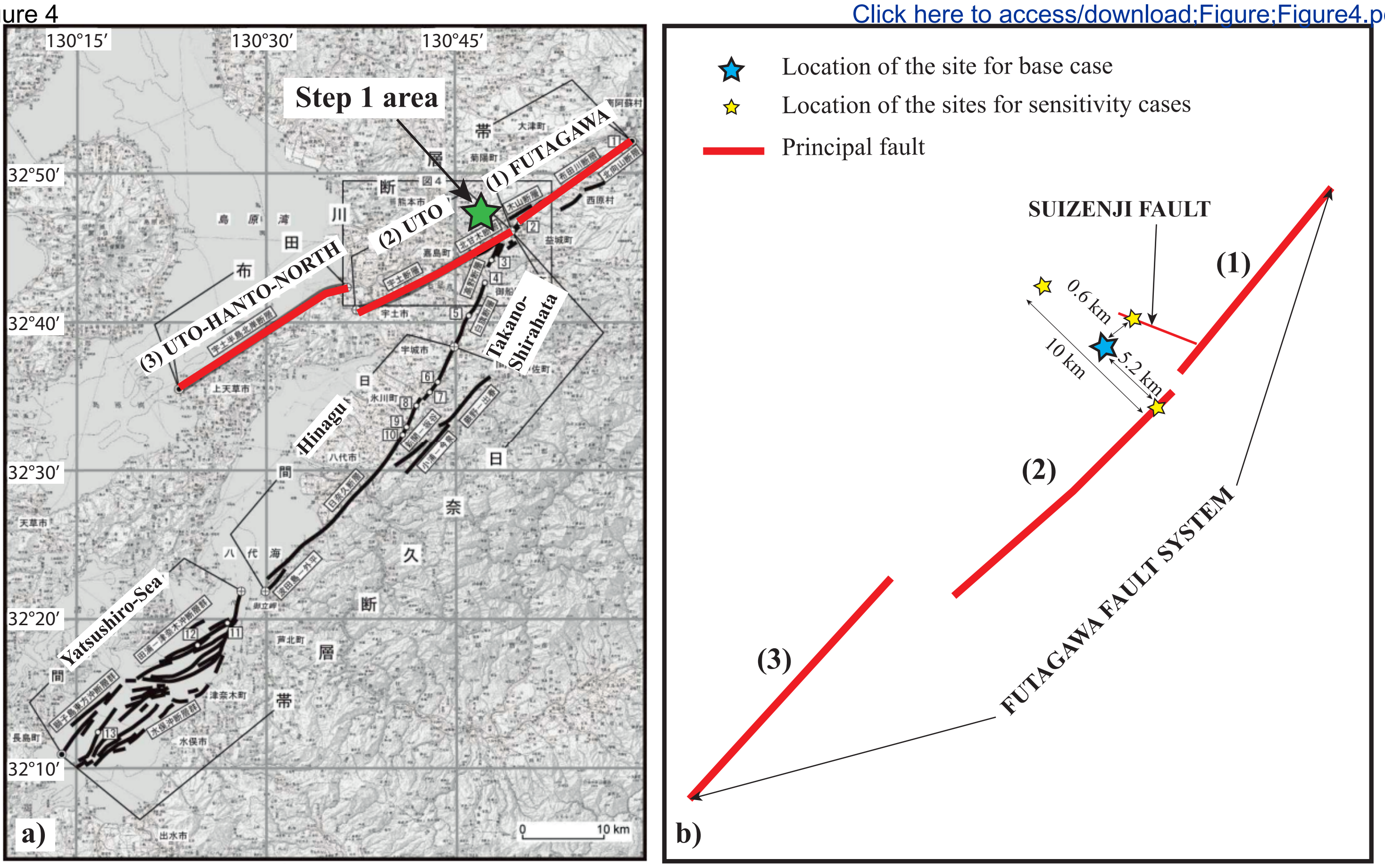


Figure 5

Click here to access/download;Figure;Figure5.jpg

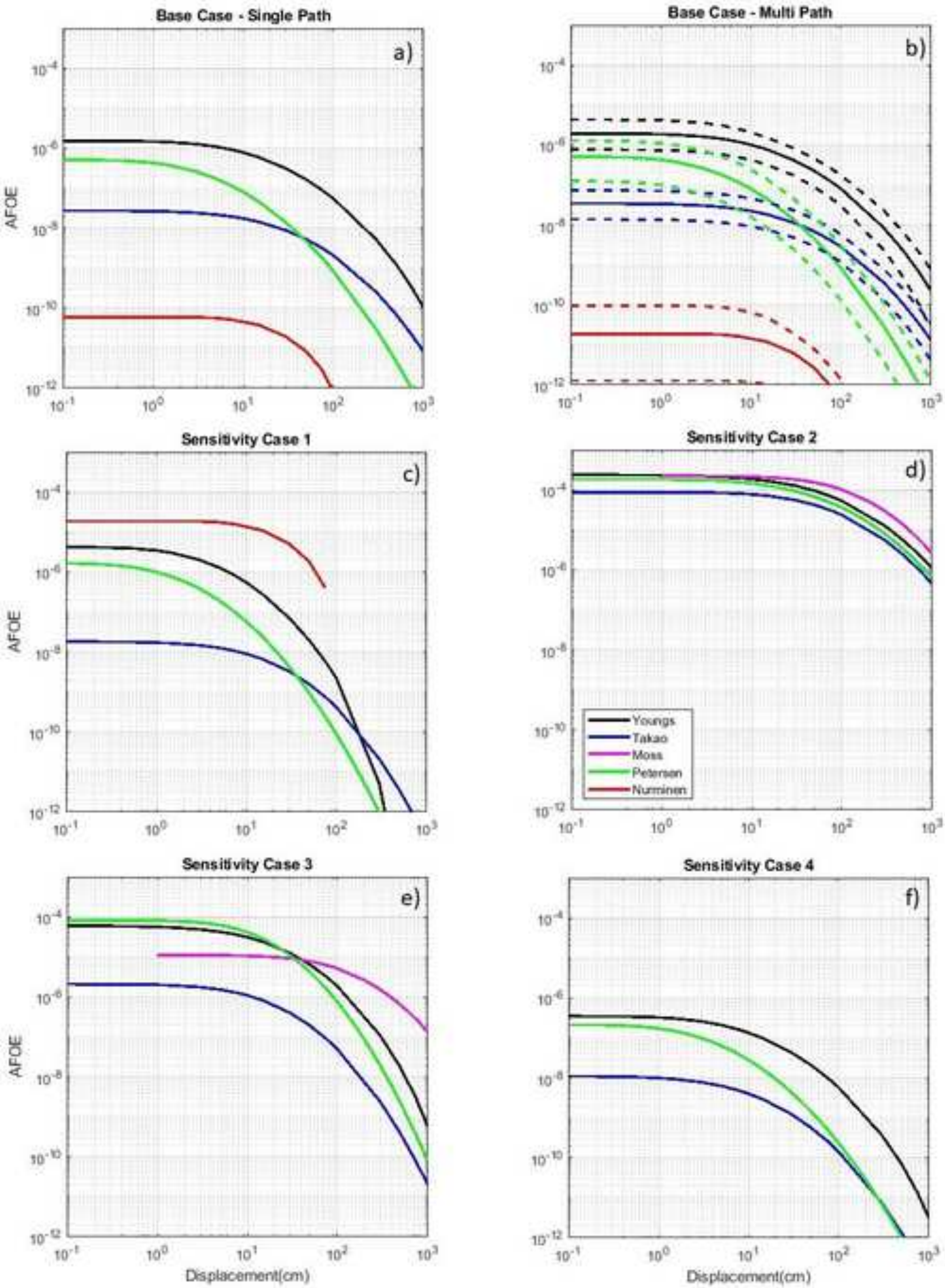
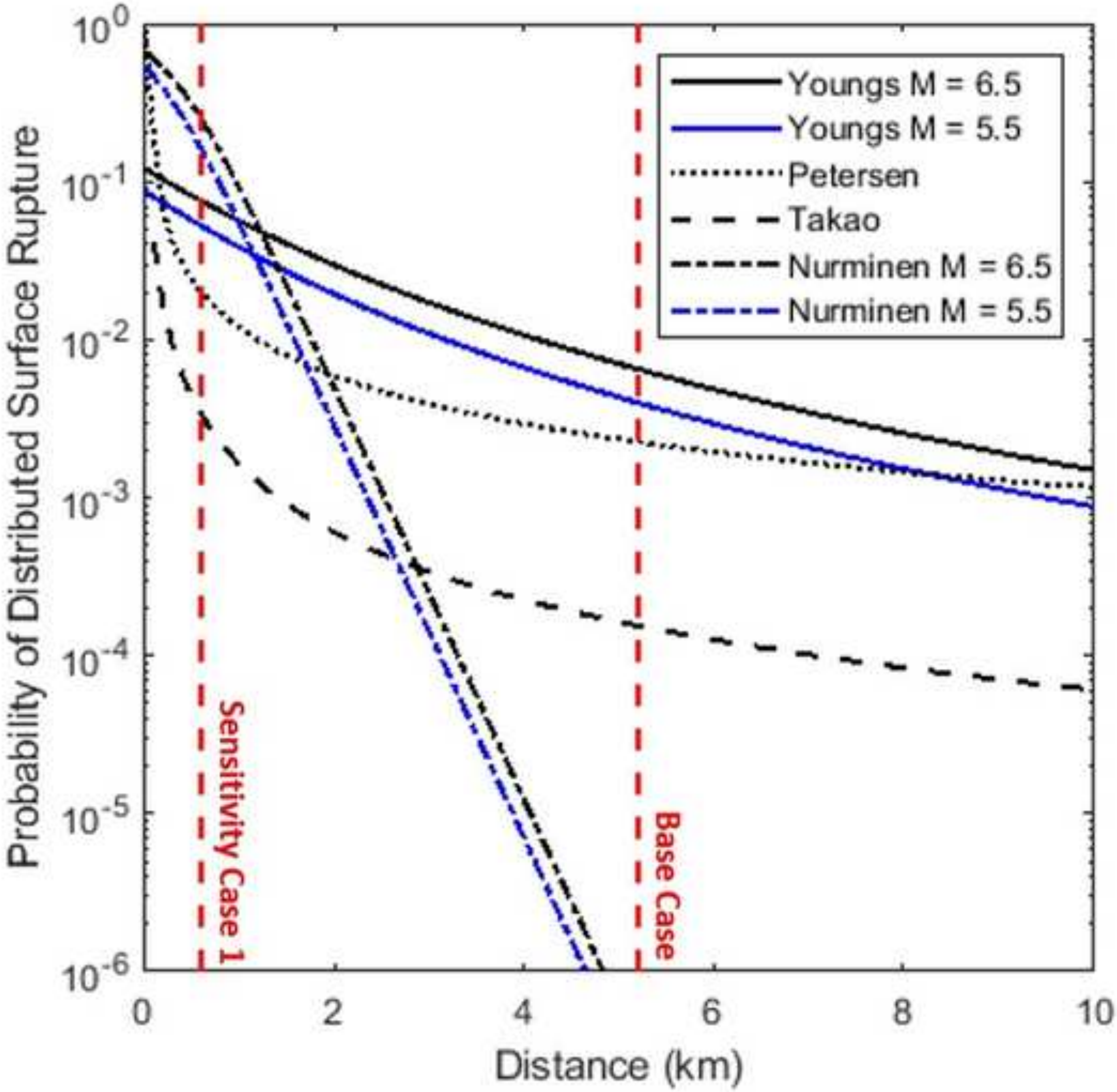


Figure 6



Probability of Distributed Surface Rupture
Distance (km)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
2
4
6
8
10
Youngs M = 6.5
Youngs M = 5.5
Petersen
Takao
Nurminen M = 6.5
Nurminen M = 5.5
Sensitivity Case 1
Base Case