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A RISK INFORMED ENGINEERING APPROACH TO CONSIDER FAULTS NEAR AN NPP

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ABSTRACT

Available interferometric data from recent earthquakes clearly show that major earthquakes produce large crustal deformation in wide areas. As a consequence these large areas undergo stress variations that may have significant consequences that need to be considered in the analysis of seismic hazards for the site of an NPP.

The major issue is related to fault displacement hazard. This has special significance especially for the acceptability of NPP sites. Fault capability (i.e. potential for surface or near surface rupture) is one of the important exclusion factors for the siting of nuclear installations. While, in general, special care is taken not to site NPPs near major causative faults, it is not always easy to avoid siting in the proximity of secondary tectonic structures that may have the capacity for coseismic surface or near surface rupture. Although, the surface rupture related to these structures would be much smaller than those related to the causative fault, nuclear regulations as yet do not prescribe the amount of rupture that can be tolerated by NPP foundations.

In this paper, a performance based risk informed approach is proposed. The methodology is based on axiomatic informed engineering judgement. This approach has already been used for one NPP and proposed for another one, both of which are located in tectonically active regions.

INTRODUCTION

The potential for fault displacement hazard has been regarded as one of the substantial exclusionary criteria in the site suitability for a nuclear power plant. It has first made its way into nuclear regulations through the United States Code of Federal Regulations 10 CFR 100 Appendix A (1962). Several terms have been used since that time to characterize this hazard. The IAEA Safety Guide SSG-9 (2010) uses the term “capable fault” for the tectonic feature that is to be identified, whereas the term “fault displacement hazard” is used to characterize the effect of this feature on the NPP structures, systems and components (SSC).

In the IAEA Safety guide SSG-9, fault displacement hazard is considered as part of seismic hazard and both deterministic and probabilistic approaches are recommended to characterize this hazard. The following paragraph (Paragraph 8.8) is the key for the decision to be made regarding capable faults.

“Where reliable evidence shows that there may be a capable fault with the potential to affect the safety of a plant at a site, the feasibility of design, construction and operation of a plant at this site should be re-evaluated and if necessary, an alternative site should be considered.”

This paragraph is for new NPPs and a probabilistic evaluation of fault capability is further recommended for existing plants, i.e. those near which capable faults have been discovered afterwards.

The two important considerations for a fault which is near a NPP are, (i) its “capability”, and (ii) if it is capable, its “potential to affect the safety of the plant”. The issue of “capability” of a fault is clearly tied to the age of its last (and recurrent) movement and the seismo-tectonic context in which it is located.

This is explained further in the section below. Its potential to affect the safety of the plant (if the fault was found to be capable) is first evaluated on the basis of "site vicinity investigations" (Paragraph 3.17 of SSG-9). Site vicinity investigations generally cover a minimum radius of 5 km and the data is presented in detailed maps (~ scale 1:5000).

These investigations aim to understand the impact of the postulated fault displacement on the foundations of the safety related SSCs of the plant.

In the following, first the regulatory approaches are described, then the considerations for the appropriate time frame are discussed and finally an engineering approach is proposed.

REVIEW OF CURRENT SAFETY STANDARDS AND REGULATIONS

Aside from the IAEA Safety Standards, national regulations of two other countries (i.e. USA and Japan) make specific reference to this hazard and provide some guidance in the characterization of fault capability and how this is related to fault displacement hazard analysis.

In Japan, the word "active" is still used (instead of capable) and because the seismic hazard analysis is deterministic, the nearby faults (that are considered to be capable) are directly integrated into the seismic hazard analysis model with a potential to cause very high accelerations. Until 2006, the time frame considered for a fault to be "active" was 50000 years. Together with this criterion, a default local earthquake of Magnitude 6.5 was considered in the seismic hazard analysis. After the year 2006, the time frame was extended to Late Pleistocene (125000 years).

After the accident at the Fukushima Daiichi NPP in 2011, the nuclear regulatory authority in Japan was reorganized and an independent authority (NRA) was established. Regarding capable faults, NRA has started checking the fault displacement hazard at many Japanese NPPs. They have also revised the time frame criterion to consider capability of faults. NRA (2013) now requires 400000 years in cases where unconformities do not allow younger horizons to be age dated.

As already mentioned above, the hazards related to fault displacement were first addressed in US nuclear regulations. At the present, both the Regulatory Guide 1.165 (1997) and 1.208 (2007) define surface rupture potential with movement in 50000 years (once) and 500000 years (recurrent). These are similar to the original 10 CFR 100 Appendix A time frames (35000 and 500000 years respectively). However, both of these regulatory guides add a paragraph at the end of the definition which is provided below:

"Notwithstanding the foregoing paragraphs, the association of a structure with geological structures that are at least pre-Quaternary, such as many of those found in the Central and Eastern regions of the United States, in the absence of conflicting evidence will demonstrate that the structure is not a capable tectonic source within this definition."

This additional provision implies that a fault is considered to be capable if it has moved once within the past 50000 years (or more than once within the past 500000 years), but in order to declare it "not capable" it must be shown that there was no movement in the Quaternary (for the central and eastern United States).

From the IAEA Safety Guide SSG-9, the NRA Regulation and the USNRC Regulatory Guides, the concept that emerges is that, not only the capability of a fault is clearly associated with a geologically defined time frame, but also that this time frame depends on the seismotectonic framework in which the fault is located.

AN IMPLICIT PROBABILISTIC FRAMEWORK

First of all, it is worth recalling that the major difference between a probabilistic versus a deterministic approach in the context of seismic hazard analysis is the fact that in a probabilistic approach the recurrence rates of earthquakes are also considered. In fact, the IAEA Safety Guide SSG-9 emphasizes that, the two approaches should utilize the same database and also treat the aleatory and epistemic uncertainties in a similar manner in a PSHA and a DSHA. The recurrence rates that are considered in a PSHA require the definition of a time frame. This is generally done using the historical seismicity data with the application of completeness corrections and truncating the curve at some Mmax which is generally based on the tectonic capability of the causative structures.

For the definition of capable faults, there was always an underlying consideration of a probabilistic approach (even though never explicitly stated) because of the time element involved. Another implicitly applied probabilistic concept was the consequential failure (e.g. core damage) due to vibratory ground motion and fault displacement. The mean 10-4 per year target for vibratory ground motion hazard level was reduced to 10-5 to 10-6 per year (considering events in the Quaternary) implying that the occurrence of such an event (i.e. fault displacement) would directly result in core damage (i.e. a singleton event). This had two underlying reasons; (i) the difficulty in assessing the actual fault displacement that can occur, (ii) the difficulty in analysing the safety of SSCs when challenged by fault displacement. The works such as Youngs et al (2003) and Petersen et al (2011) introduced the concept that the most likely fault displacement hazard could be from co-seismic movement on nearby faults and the displacement on these can be quantified in terms of a probabilistic hazard (displacement versus annual probability of exceedance). These studies respond to the first type of difficulty cited above. The second issue is an engineering problem which is yet to be fully addressed and documented in literature.

TIME FRAME CONSISTENT WITH THE SEISMOTECTONIC CONTEXT

The main concept in the IAEA SSG-9 for the demonstration of fault capability is expressed with the following:

"On the basis of geological, geophysical, geodetic or seismological data, a fault should be considered capable if it shows evidence of past movement or movements (such as significant deformations and/or dislocations) of a recurring nature within such a period that it is reasonable to conclude that further movements at or near the surface may occur. In highly active areas, where both earthquake data and geological data consistently reveal short earthquake recurrence intervals, periods of the order of tens of thousands of years (e.g. Upper Pleistocene–Holocene, i.e. the present) may be appropriate for the assessment of capable faults. In less active areas, it is likely that much longer periods (e.g. Pliocene–Quaternary, i.e. the present) are appropriate."

As indicated in the previous section, the US and Japanese approaches more or less follow a similar logic. The concepts of "highly active areas" and "less active areas" need further discussion because of their importance in the assessment of fault capability. A first step approximation could be to associate these terms to inter-plate and intraplate areas. However, this assumption alone may be too simplistic since the definition of intraplate and inter-plate is not sufficiently refined and does not consider the crust/lithospheric characteristics as, for example, shown in Fig.1 and Fig.2.

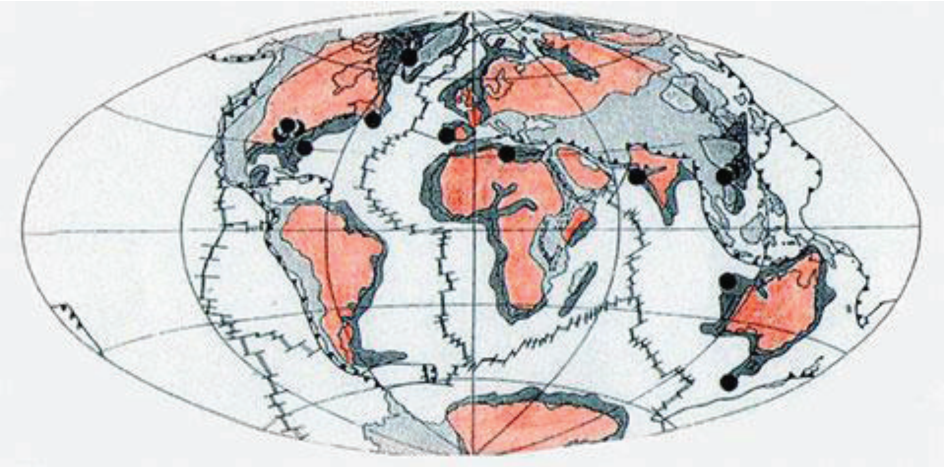

Fig. 1. This figure shows the strongest earthquakes that occurred in the last centuries in so-called “intraplate” areas. The “intraplate” zone (dark grey and red areas) has been divided in two sectors on the basis of crustal characteristics. The dark grey can be referred to as the Extended Continental Crust and defines domains that experienced post-Mesozoic tectonic deformation but are no longer active. Red indicates purely continental crust (more or less pure cratonic areas). From EPRI (1994), modified.

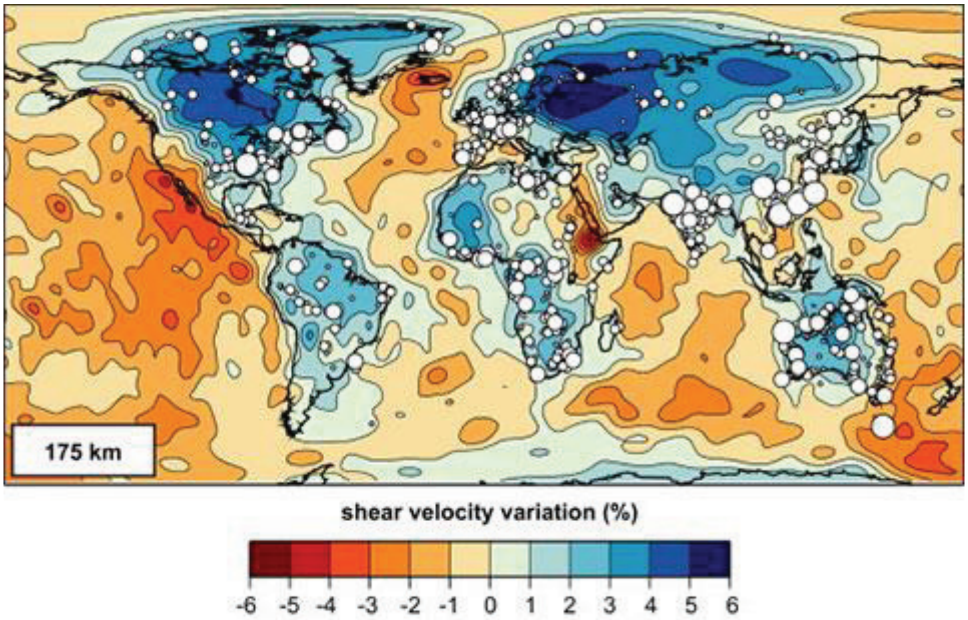

Fig.2. Crustal intraplate seismicity (solid circles related to Mw = 4.5 (the smallest ones), Mw = 5.6, Mw, 6.7 and Mw > 7.0) plotted on a global map of S-wave velocity variations in the mantle, δVS, at a depth of 175 km. Earthquakes outside stable continental regions (SCRs) have been excluded. Orange and red regions show negative δVS anomalies and correspond to regions where lithospheric thicknesses are less than 175 km. Blue regions show positive δVS anomalies and correspond to regions with a lithosphere thicker than 175 km. Blue regions, corresponding to δVS anomalies greater than 2%, are restricted to the continents, and dark blue regions with δVS anomalies >3% correspond to stable Precambrian cratons underlain by thick lithospheric roots. Few crustal earthquakes occur within the seismically-defined cratons; however, many earthquakes are located in the regions surrounding these cratons. Source: W. D. Mooney et al. (2012).

A second issue is related to the extent of significant subduction effects on the above lithospheric plate that depends mainly on the relative velocity of the converging plates and the behaviour of the subduction hinge (Doglioni et al., 2007) and on the extent of the penetration of the subduction slab below the upper plate as clearly shown by Fig. 3.

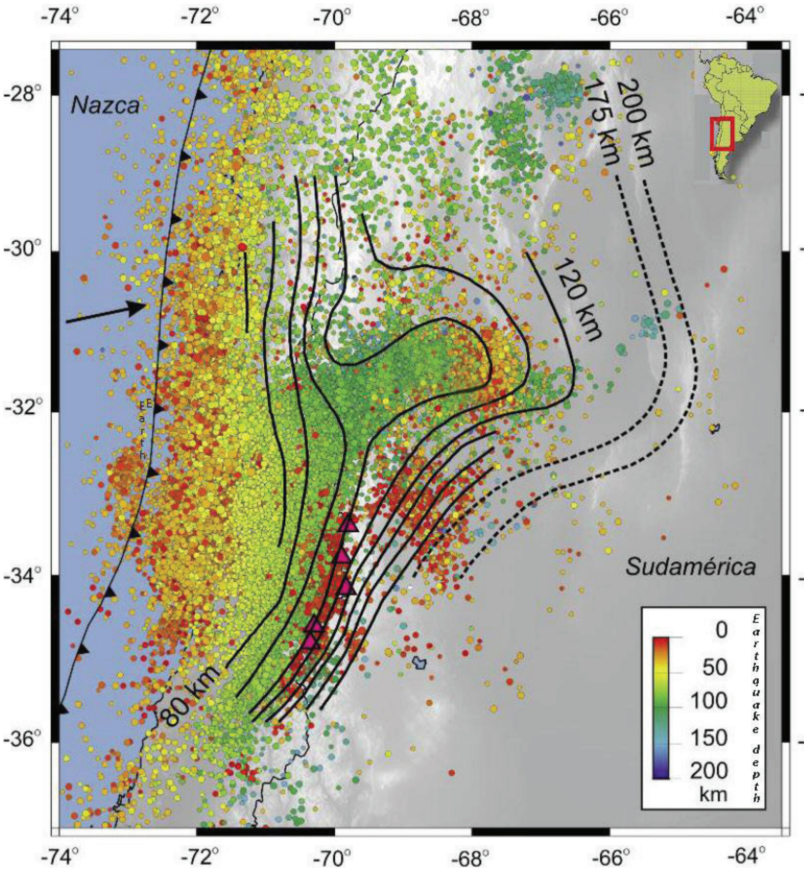

Figure 3: The black lines indicate the depth of the Nazca plate under the south America Plate. The significant difference of the penetration of the Nazca Plate below the South America plate is evident together with its implication on the seismotectonics of this region. Modified from Perarnau M. et al. (2010)

Regarding the time intervals given in the IAEA SSG-9, we can interpret these time intervals as the extreme points of a scale that start in the very highly active areas like plate boundaries (e.g. California and Japan) and huge and well known transform zones (e.g. Dead Sea fault zone, North Anatolia fault zone) and end with the other extreme, i.e. cratonic areas significantly far away from subduction zones like Russia-Siberia. This scale, therefore, needs to be graduated into smaller intermediate steps linked with the particular seismotectonic setting of the fault location.

Elements that need to be considered when assessing the appropriate time frame for a fault to be considered capable are mainly related to the plate motion and the rheological characteristic of the fault. However, other important elements in some particular areas of the world could also be phenomena such as isostatic glacial rebound (Lundqvist & Lagerbäck, 1976) and induced seismicity (The National Academic Press, 2013).

In recent project experience, time intervals going from several tens of thousands of years (North Anatolia fault zone) to 1 million year in the case of Bangka island in Indonesia, have been considered.
One of the key questions would be the distance from the assessed potential capable fault inside which the same time interval can be used. In order to answer this question the use of interferometric data is suggested, as those provided in (Fig.4).

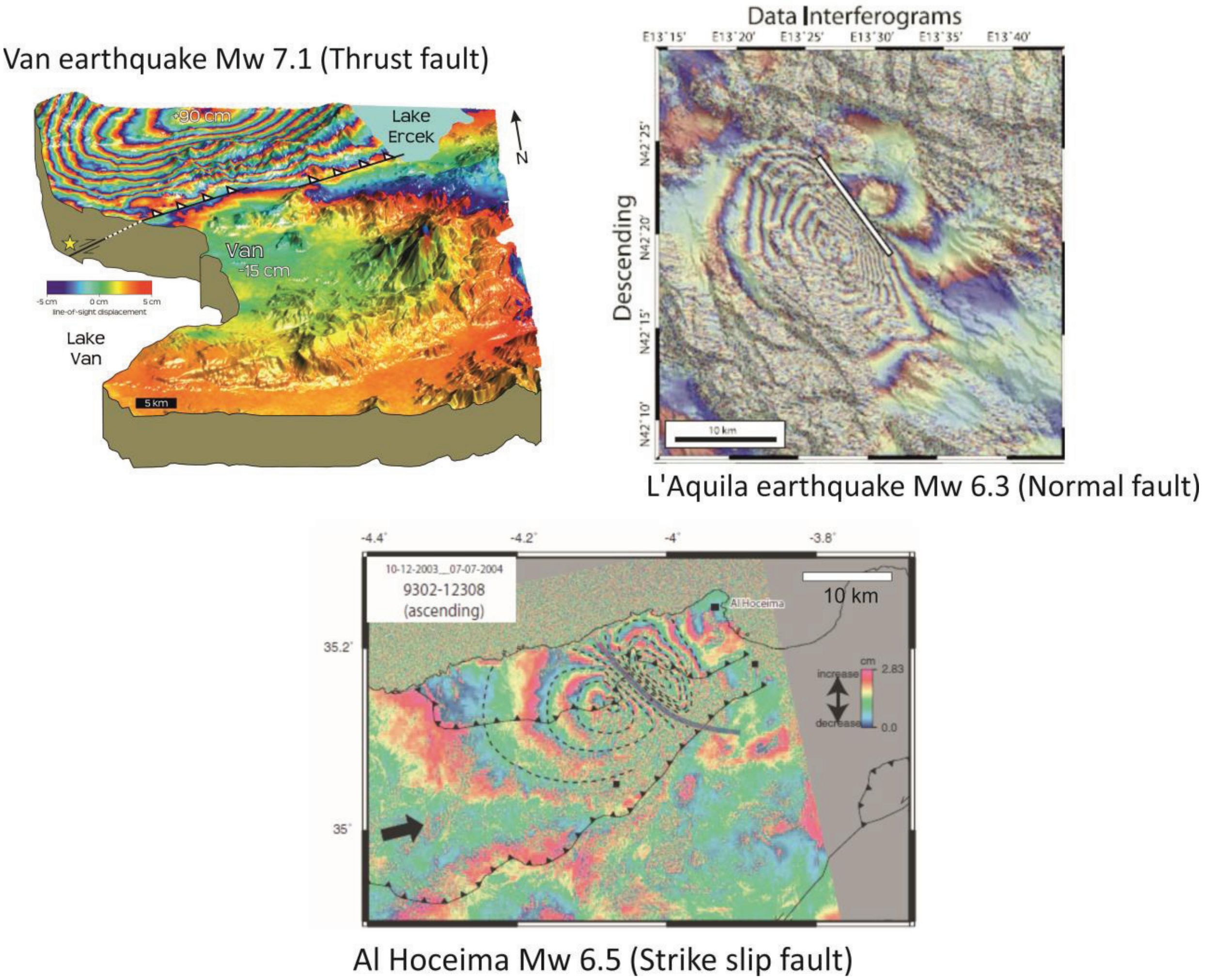

Figure 4. example of coseismic surface deformation across three considered faults of different kinematics. Maps are from Dogan & Karakas (2013), Walters et al. (2009) and Cakir et al. (2006) for the Van, L'Aquila and Al Hoceima earthquakes respectively.

With these type of data and in particular with those reported in Table 1, a relationship can be established between the Magnitude and the total area that can undergo significant deformation (Fig. 5). The details of the calculation of the deformed area are given in the legend of Table 1.

Table 1: Earthquake dataset used in Fig, 5. Legend: Date, date of the event; Event, name of the event; Mw, Magnitude; Depth, depth of the event; K, kinematics of the fault movement (N= normal , NL = normal left, SL = left-lateral, SR = right-lateral, SRN = right transtensive, TH = thrusting); HW length/width/area: length/width/area of the deformed hangingwall sector; area; FW length/width/area: length/width/area of the deformed footwall sector; Ref:reference used to measurements.

Date	Earthquake	Mw	depht	Kin.	HW lenght (km)	HW width (km)	HW area (kmq)	FW lenght (km)	FW width (km)	FW area (kmq)	Total area (kmq)	Ref.
06/04/09	L'Aquila	6,30	8,8	N	31,9	16,9	539	25,2	8,6	217	756	Walters et al. (2009)
17/05/93	Eureka Valley	6,10	13	N	32,9	12,7	418	26,9	14,3	384	802	Peltzer&Rosen (1993)
06/06/00	Orta–Cankırı	6,00	8	NL	26,8	16,9	453	0,0	0,0	0	452	Taymaz et al. (2007)
08/11/97	Mainji	7,60	22	SL	166,9	48,1	8035	170,0	56,8	9654	17688	Funning et al. (1997)
12/01/10	Haiti	7,00	13	SL	52,6	14,3	753	45,3	20,6	935	1688	Lepinay et al. (2010)
24/02/04	Al Hoceima	6,50	13	SL	16,5	8,3	137	19,8	9,6	190	327	Cakir et al. (2006)
26/12/03	Bam	6,60	10	SR	24,1	11,3	271	31,7	12,0	379	650	Fialko et al. (2005)
16/10/99	Hector Mine	7,10	0,1	SR	81,0	36,3	2941	131,6	26,2	3444	6385	Simons et al. (2002)
28/06/92	Landers	7,30	1,09	SR	69,5	26,4	1836	86,1	45,5	3911	5746	Massonnet et al. (1993)
24/08/14	Napa Valley	6,00	10	SR	25,4	10,2	258	20,1	10,2	204	462	http://aria.jpl.nasa.gov/node/39
22/02/11	Christchurch	6,42	5	SR	64,0	31,4	2009	55,8	21,9	1220	3229	Elliott et al. (2012)
17/08/99	Izmit	7,40	17	SR	224,4	107,2	24055	236,7	100,8	23864	47919	Delouis et al. (2002)
12/11/99	Duzce	7,20	14	SRN	61,6	27,6	1703	78,5	25,6	2011	3714	Burgmann et al. (2002)
20/05/12	Emilia 1	5,86	5	TH	32,8	12,5	410	0,0	0,0	0	409	Bignami et al. (2012)
29/05/12	Emilia 2	5,66	9,6	TH	32,9	11,3	370	0,0	0,0	0	369	Bignami et al. (2012)
23/10/11	Van	7,10	7,2	TH	33,4	18,1	603	36,9	24,6	909	1511	Dogan&Karakas (2013)
11/03/11	Tohoku	9,00	30	TH	764,0	396,0	302544	0,0	0,0	0	302544	Kobayashi et al. (2011)
08/10/05	Kashmir	7,60	10	TH	69,3	37,4	2589	62,1	20,4	1266	3855	Pathier et al. (2006)

It is proposed that major regional tectonic structures such as subduction zones and transform faults will dominate the time frame to be considered for capability of faults in the region of consideration. In order to estimate the applicable time frame to assess fault capability, the following approach may be suggested:
- Estimate a maximum potential magnitude for the earthquake that is appropriate for the major fault(s) in the region.
- Using Figure 5, estimate the size and shape of the significantly deformed area that would result from this earthquake.
- Superimpose this figure on the region of interest to identify the faults whose capability assessment time frame would be associated with the major regional tectonic structure.
- Consider uncertainties in the assessment.

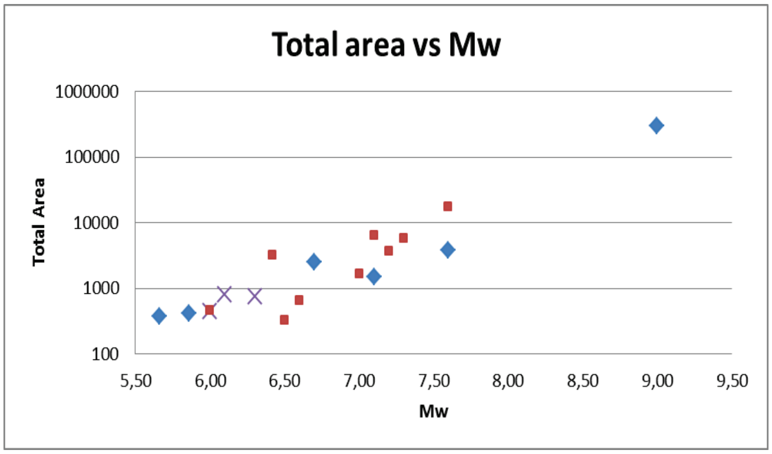

Figure 5. correlation between Mw and total area of deformation (Km^2). Symbols group different fault kinematics: ◊ = thrust; □ = strike slip; X = normal faulting.

PROPOSED ENGINEERING APPROACH

Taking into consideration the IAEA Safety Standard SSG-9, the following procedure is proposed to address fault displacement issues at nuclear power plant sites.

The procedure is comprised of two major steps. The first step involves the determination of fault capability using the definition of SSG-9 (Definitions of the USNRC and NRA are also compatible with this). The major issue in this definition as provided above is related to the appropriate time frame to be taken. This depends on the seismotectonic characteristics of the region in which the fault under investigation is located. While there is general guidance provided in the above mentioned standard and regulations on this subject, in practice, it is often difficult to take a decision on the appropriate time frame. In the section above, an approach was proposed to be considered for this process. This is considered by regulatory authorities as a deterministic approach which however does consider the recurrence of events in a given time interval.

The second major step is needed only if the result of the fisrt step concludes that there is one or more faults in the site vicinity which have the potential to affect the safety of the NPP. This step is clearly probabilistic as the decision related to impact on safety is needed to be in the context of plant safety metrics that are readily quantifiable.

The following procedure is proposed for each fault that was determined to have a potential impact on plant safety (as determined in the previous step):

- Using engineering methods and judgment estimate a conservative lower bound fault displacement under the plant for which there will be no safety impact on the NPP structures given the foundation basemat dimensions and soil conditions. There should be expert consensus regarding this value. Conservatively this value could range between 5 – 10 cms.
- Calculate the annual frequency of exceedance of displacements that can occur at the main causative fault using the methods available in literature. (e.g. Youngs et al and Petersen et al)
- Calculate the annual frequency of exceedance of displacements that can occur at the foundation of NPP structure(s) using published literature, empirical relationships and engineering models (such as FEM) compatible with the type of faulting and the site area geological conditions. (This step is necessary if the

fault under the NPP foundation is expected only to move coseismically with the causative fault which is the usual situation).

- Take a threshold value of say 1 % of the core damage frequency calculated from a recent Probabilistic Safety Analysis for the NPP. (this could be about 10-7 , i.e. 1 % of the CDF). Such a value can be considered to be a screening value.
- If the displacement corresponding to the small pre-selected value occurs with a frequency less than the screening value, then this hazard will not be significant for the plant because at worst it will contribute 1 % to core damage frequency even if it is postulated as a singleton to core damage (i.e. its occurrence will directly result in core damage).

It should be pointed out that the numbers provided above are indicative and need to be decided on a case by case basis and in compliance with national regulatory requirements.

CONCLUSIONS

A systematic approach is proposed to address fault displacement issues that may arise at new or existing NPP sites. The approach is divided into two major steps. The first is mostly deterrministic and involves the characterization of the nearby faults as “capable” or “not capable” using definitions from regulatory guidance and IAEA Safety Standards. In this regard, the article provides some additional clarification to the time frame needed for capability evaluation. The second major step is probabilistic and aims initially at evaluating finite (i.e. a preselected value) fault displacement in terms of its recurrence frequency. Then this is put into the framework of Probabilistic Safety Analysis of the NPP. This approach is consistent with the IAEA Safety Standards.

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