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Earthquake-induced crustal deformation and consequences for fault displacement hazard analysis of nuclear power plants

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HIGHLIGHTS

- A three-step procedure to incorporate coseismic deformation into PFDHA.
- Increased scrutiny for faults in the area permanently deformed by future strong earthquakes.
- These faults share with the primary structure the same time window for fault capability.
- VGM variation may occur due to tectonism that has caused co-seismic deformation.

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ABSTRACT

Readily available interferometric data (InSAR) of the coseismic deformation field caused by recent seismic events clearly show that major earthquakes produce crustal deformation over wide areas, possibly resulting in significant stress loading/unloading of the crust. Such stress must be considered in the evaluation of seismic hazards of nuclear power plants (NPP) and, in particular, for the potential of surface slip (i.e., probabilistic fault displacement hazard analysis - PFDHA) on both primary and distributed faults.

In this study, based on the assumption that slip on pre-existing structures can represent the elastic response of compliant fault zones to the permanent co-seismic stress changes induced by other major seismogenic structures, we propose a three-step procedure to address fault displacement issues and consider possible influence of surface faulting/deformation on vibratory ground motion (VGM). This approach includes: (a) data on the presence and characteristics of capable faults, (b) data on recognized and/or modeled co-seismic deformation fields and, where possible, (c) static stress transfer between source and receiving faults of unknown capability.

The initial step involves the recognition of the major seismogenic structures nearest to the site and their characterization in terms of maximum expected earthquake and the time frame to be considered for determining their "capability" (as defined in the International Atomic Energy Agency - IAEA Specific Safety Guide SSG-9). Then a GIS-based buffer approach is applied to identify all the faults near the NPP, possibly influenced by the crustal deformation induced by the major seismogenic structures. Faults inside these areas have to be tested for "capability" according to the same time window defined for the primary seismogenic structures.

If fault capability is confirmed or, eventually, cannot be assessed, the next step is to implement an approach based on the potential to affect the safety of the NPP site in terms of fault geometry, and potential displacement.

Finally, in the case where the fault can affect the safety of the site, the third step is the PFDHA or, in other words, the calculation of the annual probability of exceedance of the potential co-seismic fault displacement; this displacement is to be compared with the fault displacement threshold that will impact the safety of the NPP site.

We also consider the effect of site vicinity tectonism on site vibratory ground motion and discuss an example in the light of the use of the GMPE.

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1. Introduction

Earthquake-induced permanent ground deformation can significantly impact the safety of Nuclear Power Plants (NPPs) in a two-fold way. The first issue is the potential for ground rupture or fault displacement at the site: the fault capability (i.e., the potential for surface or near-surface faulting, ground deformation, or folding, sensu IAEA, 2010). This factor is among the important exclusionary criteria for the siting of nuclear installations (e.g., CFR, 1962; IAEA, 2010; ANSI/ANS-2.30, 2015) and great care is taken to avoid siting NPPs that could be affected by such ground behavior. The second issue relates to the impact of vibratory ground motion (VGM) associated with tectonic structures in the site vicinity (and possibly within the site area), and how this may contribute to what is generally called "site effects."

Both issues definitely rely on predicting the location and amount of surface faulting given a future strong earthquake in the proximity of the plant (Fault Displacement Hazard analysis, FDHA hereafter). Even if significant advances have been made for locating and mapping the primary fault, this task still remains problematic in the case of secondary ruptures and for distributed faults, (i.e., secondary or distributed faulting – DF) defined as ruptures that occur on faults in the proximity of a principal seismogenic structure, in response to the displacement on the primary fault (ANSI/ANS-2.30, 2015). Present probabilistic approaches (e.g., Youngs et al., 2003; Petersen et al., 2011; Quittmeyer et al., submitted for publication) may underestimate the frequency of occurrence of secondary faults, especially far from the primary structure, as demonstrated by recent case studies (e.g., Napa Valley earthquake, Baize and Scotti, 2015; L'Aquila earthquake, Livio et al., 2016).

InSAR data from recent earthquakes clearly show that major earthquakes cause significant crustal strain over wide areas, resulting in permanent stress transfer to surrounding rock volume and pre-existing faults (i.e. Coulomb or Static Stress Transfer, King et al., 1994; Stein, 1999). These structures, in turn, can experience co-seismic or post-seismic reactivation, resulting in a localized rupture of the surface that may be of significant concern for the siting of an NPP. Relatively small Coulomb stress changes can potentially induce slip on a secondary fault (Stein, 1999) and the elastic response of compliant faults to the permanent co-seismic stress change may exceed the effect of dynamic triggering or regional stress field, resulting also in an induced motion on DF opposite to the long-term geologic slip (Fialko et al., 2002).

In this paper, we first explore the shortcomings from current PFDHA procedure, at the light of recent earthquakes (Section 2). Then, we consider the 2009, L'Aquila earthquake (Mw 6.3) case study (Section 3) to explore possible regressions on the occurrence of DF, other than a mere distance-based method (i.e., calculating loading due to static stress transfer and performing a curvature analysis). Finally, a performance based risk informed approach is proposed for FDHA (Section 4). The methodology is based on axiomatic informed engineering judgement and partially relies on the assumption that a strong spatial correlation between DF and co-seismically-induced strain, as recently shown by several InSAR-derived datasets, exists.

In addition, we consider the potential effects of site vicinity tectonism on site vibratory ground motion and discuss an example through the use of a GMPE. Present-day ground motion prediction equations (GMPE's) have a level of uncertainty that has to be addressed, both aleatory and epistemic, particularly near a rupture. If tectonic features exist in the site vicinity, the profession must account for this uncertainty.

2. Shortcomings with the database for probabilistic fault displacement hazard analysis and new insights from InSAR data

It is well known that only earthquakes above a certain magnitude typically produce surface rupture, while all macro-earthquakes produce crustal deformation (e.g. events whose $M > 3.0$). For example, the $M = 3.5$ earthquake that occurred in June 1994 near L'Aquila, Italy, resulted in a deformation of 1 μm, measured in the underground Gran Sasso physics laboratories (Serva, 1995). This crustal deformation, together with the VGM generated by the earthquake, produces significant effects on the ground. These effects are catalogued in the Earthquake Environmental Effects (EEE) Global Catalogue of Earthquake Environmental Effects (www.eeecatalog.sinanet.apat.it), which supports the definition of the Environmental Seismic Intensity Scale (i.e., ESI 2007 scale; Serva et al., 2016).

Regarding primary faulting, Fig. 2.1 represents the state of the science for correlation between Mw and probability of primary surface faulting (Youngs et al., 2003; Moss and Ross, 2011). Variable lower-threshold Mw values for surface faulting can be assessed, depending on different regression datasets and fault kinematics. It is clear that the probability of primary surface faulting can be significant for Mw values between 5.5 and 6.0.

Assessment of displacement for DF is somewhat more complicated. In Figs. 2.2 and 2.3, the currently available data regarding slip on DF and the conditional probability of slip are respectively given as a function of distance from the primary fault (e.g., Youngs et al., 2003; Petersen et al., 2011; Takao et al., 2013). The dataset of Petersen et al. (2011) is derived from observations on steeply dipping, strike-slip faults of Mw 6.5–7.6, whereas the distribution considered by Youngs et al. (2003) is developed from a dataset mainly composed of normal faults. Takao et al. (2013) analyzed data from reverse and strike-slip faults in Japan.

Petersen et al. (2011) conclude that the hazard for off-fault ruptures is much lower than the hazard near the fault. Nevertheless, the data indicate that displacements up to 35 cm (cm) can be triggered on adjacent faults at distances of 10 km (km) or more from the primary fault and with a meter-scale offset on the primary fault.

The aforementioned probabilistic models, even if well-based, are biased by epistemic uncertainties, resulting from unknown factors varying from one earthquake to another (Youngs et al., 2003). In particular, the predictive power of these models is challenged for areas far from the primary structure, where a higher occurrence of DF has been highlighted during recent earthquakes (e.g., the 2014 South Napa Valley earthquake, Mw 6.0, Baize and Scotti, 2015 and the 2009 L'Aquila earthquake, Mw 6.3, Livio et al., 2016). We suggest that some of the uncertainty has to be ascribed to deterministic factors commonly referred to as the geologic and stratigraphic setting of the faulted area (i.e., depth of the propagating fault, thickness of the brittle layer, fault geometry, basin architecture, etc.) and assume that a possible approach in predicting the occurrence of DF can be based on the overall co-seismic deformation field associated to a certain slipping fault. Such a co-seismic deformation field, well imaged by remote sensing (i.e. InSAR data), is spatially correlated with DF also in areas far from the primary rupture (Livio et al., 2016), partially explaining an occurrence of DF more frequent than predicted from distance-based regressions. Earthquake-induced permanent strain can in fact result in the reactivation of pre-existing structures as compliant faults accommodating elastic deformation or in the promotion of new localized ground breaks.

Moving from this assumption, we firstly compare probabilistic models of occurrence of DF with the co-seismic deformation field