Identifying the Needs and Future Directions of Seismic Hazard for Probabilistic Infrastructure Risk Analysis

Graeme Weatherill  
_*Seismic Hazard Researcher, Global Earthquake Model (GEM), Pavia, Italy*_

Marco Pagani  
_*Seismic Hazard Coordinator, Global Earthquake Model (GEM), Pavia, Italy*_

**ABSTRACT:** The vulnerability of urban infrastructure to both ground shaking and geotechnical failure during large earthquakes has been demonstrated by recent earthquakes such as the 2010 - 2011 Canterbury earthquake sequence (New Zealand, 2010 - 2011) or 2010 Haiti event. Probabilistic seismic risk analysis to infrastructure systems requires the characterisation of both the transient shaking and permanent ground deformation elements of the hazard, and must do so incorporating both the aleatory and epistemic uncertainties and the spatial correlations and dependencies that are inherent in both of these aspects. Recent developments in characterisation of spatial correlation and cross-correlation in the ground motion uncertainties form the foundations of a comprehensive Monte Carlo-based methodology for analysis of seismic risk to spatially extended systems. New research directions are needed, however, in order to ensure that secondary hazard aspects are incorporated in the same way. These include the treatment of site amplification of the ground shaking, the modelling of permanent ground deformation from slope displacement and liquefaction, and permanent displacement due to coseismic slip on and around the fault rupture. Key considerations for integrated probabilistic framework for physically-realistic characterisation of the ground shaking and permanent ground displacement are illustrated using the example of simulation spatially correlated fault slip on an active fault rupture in a manner that can be integrated within a Monte Carlo-based probabilistic seismic hazard methodology.

Probabilistic analysis of seismic risk is the most common methodology used by organisations responsible for maintaining infrastructures to make informed decisions based on the cost to benefit ratios of particular mitigation strategies. But analysis of infrastructural risk presents new challenges to both the hazard and risk modellers to provide models of ground shaking and permanent ground displacement that can be applied to spatially extended and interconnected systems. A single infrastructural system is dependent on many elements over an extended geographical region, and the performance of the system or systems may depend on the location of greatest damage. Further compounding the complexity is the fact that a single infrastructural system is composed of fragile elements that may respond dissimilarly according to different characteristics of the hazard. One example might be a gas network in which mechanical elements may be most adversely affected by high frequency acceleration, storage systems and pumping stations by low frequency ground motion, whilst underground pipes may be most at risk from permanent ground displacement due to geotechnical failures.

This paper outlines some of the main challenges facing the seismic hazard modeller in order to provide hazard input into probabilistic seismic risk analysis for interconnected and spatially extended infrastructures. Focus is placed on four critical elements: ground shaking, site amplification, geotechnical failure due to land-sliding and liquefaction, and finally co-seismic displacement due to rupture on the fault surface. A summary of current approaches for characterising each of these elements
is presented, along with descriptions of the challenges faced in ensuring that uncertainties are correctly incorporated into the process and that spatial correlations within these uncertainties are accurately captured within the seismic risk analysis.

1. SPATIAL ANALYSIS OF GROUND SHAKING

The characterisation of ground shaking hazard in a probabilistic manner is well established, both for a single site application using conventional probabilistic seismic hazard analysis (PSHA), and across a spatial extent using the Monte Carlo approach (e.g. Park et al., 2007; Crowley et al., 2008). The use of the Monte Carlo-based approach facilitates the incorporation of spatial correlations of the ground motion prediction equation (GMPE) residual term ($\varepsilon$) into the probabilistic seismic hazard. This permits the generation of ground shaking intensities for not just one but many ground motion intensity measures across multiple sites, whilst preserving the spatial correlation properties observed for each ground motion intensity measure across many sites ($\rho_{IM_1,IM_1}(h_{i,j})$), the cross-correlation between intensity measure values at the same site ($\rho_{IM_1,IM_2}(h_{i,j} = 0)$) and the spatial cross-correlation between different intensity measure values recorded at separate sites ($\rho_{IM_1,IM_2}(h_{i,j})$). Models of spatial correlation and cross-correlation, such as that of Goda and Hong (2008) or Loth and Baker (2013), can be readily applied within a Monte Carlo PSHA approach. For heterogeneous portfolios of building the impact of incorporating spatial correlation and spatial cross-correlation into the analysis has been illustrated by Weatherill et al. (2015) (Figure 1), who demonstrate for a heterogeneous portfolio of buildings the inclusion of spatial cross-correlation increases the likelihood of seeing greater losses for lower probabilities of exceedance. Conversely, lower losses for higher annual probabilities are observed when compared to the case for which no correlation is considered (solid black line), and even for the case in which spatial correlation is modelled but cross-correlation is neglected (dashed dark blue line).

For infrastructural systems, the generation of multiple fields of ground motion preserving the observed correlation and cross-correlation properties of ground motion residuals is not merely a means of increasing or decreasing the probabilistic estimates of loss, but a necessity for representing the ground motion inputs at multiple points of an interconnected network in a manner that can be considered representative of the possible realisation of ground motion. Simpler approaches using either the median ground motion (i.e. without variability) predicted by a GMPE for a given scenario event or a probabilistic seismic hazard map, which is effectively aggregating contributions of ground motion from multiple different events, cannot fulfil these requirements, and in doing so will provide an incorrect picture of seismic risk to a network.

Figure 1: Impact of incorporating spatial cross-correlation into a loss analysis of a heterogeneous portfolio of buildings under different correlation strategies (Weatherill et al., 2015)

2. PSHA REQUIREMENTS AT THE METROPOLITAN SCALE

Metropolitan areas occupy an anomalous middle ground in terms of the requirements and methodologies applied to PSHA. Local modulations to the expected strong ground shaking, most notably those relating to soil conditions, basin structure and near-fault directivity should be incorporated into the PSHA process. Many of these aspects are commonly analysed within seismic microzonation studies. In the ideal case the seismic microzonation information may be sufficient to characterise models
of site amplification that are calibrated to the local soil conditions.

2.1. Site Amplification

In a detailed seismic microzonation study, period-dependent functions for amplifying acceleration on a reference bedrock, \( S'_{A_j}(T_i) \), to that observed at the surface \( S^S_{A_j}(T_i) \), may be defined uniquely for each site in the area of interest, where \( F_j(T_i) \), defines the amplification at period \( T_i \) for site \( j \) such that:

\[
F_j(T_i) = \frac{S^S_{A_j}(T_i)}{S'_{A_j}(T_i)}
\]  

(1)

These functions can be obtained empirically or analytically using equivalent linear or nonlinear methods for propagating recorded or synthesised waveforms through a soil column with geotechnical properties possibly affected by epistemic uncertainties. Following the construction of Bazzurro and Cornell (2004b), it is assumed that both the spectral acceleration on bedrock is uncertain, with a mean, \( \ln(S'_{A_j}(T_i)) \), and standard deviation, \( \sigma_{\ln S'_{A_j}(T_i)} \), and that the amplification factor too is distributed such that \( \ln(F_j(T_i)) = \ln(F_j(T_i)) + \varepsilon_{\ln F_j(T_i)} \sigma_{F_j(T_i)} \). The spectral acceleration on the surface is given by:

\[
\ln(S^S_{A_j}(T_i)) = \ln(S'_{A_j}(T_i)) + \ln(F_j(T_i)) + \varepsilon_{\ln S^S_{A_j}(T_i)} \sigma_{\ln S^S_{A_j}(T_i)} + \varepsilon_{\ln F_j(T_i)} \sigma_{\ln F_j(T_i)}
\]

(2)

where \( \varepsilon_{\ln S^S_{A_j}(T_i)} \) and \( \varepsilon_{\ln F_j(T_i)} \) are the normalised residual terms of the rock ground motion and the amplification factor respectively. This formulation can be readily incorporated into the PSHA integral, and is well-suited to application within a Monte Carlo framework. The Bazzurro and Cornell (2004b) methodology is widely used in practice for site-specific PSHA studies, in which the \( F_j(T_i) \) is unique to the site in question. Total variability \( \sigma_{\ln F_j(T_i)} \) is therefore a composite of record-to-record variability and uncertainty in the properties of the soil profile. Bazzurro and Cornell (2004a) demonstrate that inclusion of the uncertainty in the site profile can increase the total uncertainty by a factor of up to 20\%, when compared to inclusion of record-to-record variability alone.

In the site specific application the decomposition of \( \varepsilon_{\ln F_j(T_i)} \) into its mixed effect components (record-to-record variability and uncertainty in the soil column) may not be necessary. For application over a spatial scale, however, this distinction cannot be neglected, nor can the cross-correlation in \( \varepsilon_{\ln F_j(T_i)} \) between spectral periods nor the spatial correlation between sites. There exists the likelihood that correlation may be found in the amplification function residuals \( \varepsilon_{\ln F_j(T_i)} \) by virtue of the similarities of the geotechnical properties of the soil profile. Conversely, however, discontinuities between the geotechnical units or strong lateral variation in the soil properties may erode the correlation or introduce local anisotropy into the correlation model.

2.2. GMPE Modifications and Non-ergodic Aleatory Variability

The calibration of existing GMPEs to local site conditions is now standard practice in the analysis of seismic hazard for critical and nuclear facilities (Rodriguez-Marek et al., 2014). Two common adaptations are the re-scaling of the GMPE to take into account local variation in kappa \((\kappa)\), and the use of local records of strong and weak motion to extract the average within-event residual for the site, thus leaving the site specific within-event variability (or single station sigma, \( \sigma_{SS} \)). Whilst largely applied to site-specific PSHA, there is little reason why these modifications should not be applied to metropolitan scale analysis. If adopting site-specific amplification functions using the Bazzurro and Cornell (2004b) approach, the adoption of the single station sigma is a necessary step to prevent double counting variability that will be reintroduced back into the calculation within the uncertainty in the site amplification factor. In some cases the number of observed records from within the region of interest may not be sufficient to determine the true single station sigma, but as noted by Rodriguez-Marek et al. (2014) the actual value of \( \sigma_{SS} \) has been shown to be relatively consistent
across different tectonic regions, and potentially a regional value could be adopted.

3. GEOTECHNICAL HAZARDS

For the most widespread application to both building and infrastructure risk analysis, the HAZUS methodology remains arguably the most persistent and practical to implement. This is in part due to the relatively qualitative categorisation of landsliding and liquefaction susceptibilities and the practical means by which values of permanent ground deformation can be retrieved. These properties also make the geotechnical hazard modules within HAZUS portable to other regions. Indeed, within the European FP7 SYNER-G project, the HAZUS susceptibility definitions, and the corresponding probability models, where integrated into the Monte Carlo assessment methodology adopted within the software (Franchin and Cavalieri, 2014).

Nonetheless, the current HAZUS models are relatively simplified, and within this approach the uncertainties and correlations within both the spatial domain and the parameter domain are largely neglected within this framework.

More comprehensive frameworks for probabilistic analysis of liquefaction and/or slope displacement can be found in the literature (e.g. Goda et al. (2011) in the case of liquefaction, and Rathje and Saygili (2008) in the case of slope displacement). These frameworks can be considered conceptually simple extensions of the standard PSHA integral:

\[
P(d^* > D^*) = \lambda_0 \int_z \int_m \int_r P(d^* > D^* | z) f_{GM}(z|m, r) f_M(m) f_R(r) \, dr \, dm \, dz
\]

where \( P(d^* > D^*) \) is the probability of exceeding a given level of a geotechnical hazard metric (e.g. permanent ground displacement, or liquefaction probability index) within a time period of interest, \( P(d^* > D^* | z) \) the probability of exceeding the level of the geotechnical hazard metric given a ground shaking intensity \( z \), \( f_{GM}(z|m, r) \) the probability density function of the ground motion (the lognormal distribution considered within the GMPE), and \( f_M(m) \) and \( f_R(r) \) the probability densities of the magnitude and distance distributions respectively. As with conventional PSHA, these frameworks are readily adapted, and in many cases better suited, for application within a Monte Carlo framework. It is also important to recognise that in the case of geotechnical hazards there are levels of ground shaking beneath which the phenomena will not be observed. Therefore the probability is broken into two components, the probability that displacement will exceed a specified level given that geotechnical failure occurs, and the probability of geotechnical failure given the earthquake rupture and ground shaking:

\[
P(d^* > D^* | z) = P(d^* > D^* | \text{failure}) \cdot P(\text{failure} | m, r)
\]

The primary focus therefore is the means by which \( P(d^* > D^* | z) \) is constrained, and the potential uncertainties and conditional dependencies therein.
3.1. Slope Displacement

The fully probabilistic slope displacement hazard methodology is well described in Rathje and Saygili (2008), in which the probability of exceeding a specific level of displacement given a ground shaking intensity is determined directly from a slope displacement predictive equation. The predictive equation itself is derived from a sliding block model subject to many different ground accelerations. This methodology is both conceptually and computationally efficient for direct implementation.

For application to infrastructure risk, the Rathje and Saygili (2008) approach can be readily applied over a spatially extended region. Even the vector-based approaches can be readily supported if taking into account the spatial correlation and cross-correlation of multiple measures of ground motion in the manner described in section 3 and in Du and Wang (2014). The dependence only on the yield acceleration and the ground motion parameters of interest also makes such a model practical to implement within a variety of environments.

Where the probabilistic slope displacement hazard analyses are limited, however, is in the inherent assumption of the sliding block model, which is a simplified idealisation of the landsliding process. The yield acceleration describes the dynamic stability of the slope, and therefore assumes that two slopes with the same yield acceleration will yield the same Newmark Displacement, regardless of differences in geometry or material properties. For other types of landsliding, however, such as debris flows or rock falls, no such methods exist. Neither, can the sliding block displacement method adequately capture differential displacements within the sliding mass that would result in patterns of concentrated displacements at the edge of the mass. In these circumstances probability of exceeding a given level of displacement, would contain spatial correlations that are as yet unaccounted for.

3.2. Liquefaction

As with the case of slope displacement a probabilistic framework for liquefaction hazard analysis has already been established (e.g. Baker and Faber, 2008; Goda et al., 2011). As is also the case, however, the manner by which \( P[D^* > d^* | z] \) is constrained is an area that is not so well established. Again, a similar problem emerges in that liquefaction itself encompasses a range of phenomena (e.g. lateral spread, volumetric settlement, sand blows etc.), the definition of specific measures from which predictive models of displacement can be conditioned are not yet consistent. Once again, for providing the information necessarily for loss analyses, the HAZUS approach is simple to implement and has a solid basis upon the fundamental understanding of the liquefaction process. Nonetheless, the simple characterisation of susceptibility that makes the process uncomplicated to implement, limits the consideration of uncertainties that are known to be prevalent in such analyses. A different approach is taken by Baker and Faber (2008), who use geostatistical simulation of correlated fields of uncertain soil properties, conditioned upon those same properties measured at known sample sites. These simulations are then used to determine the probability of exceeding a given proportion of an area that may experience liquefaction. This method can account for the considerable uncertainty in soil properties over an extended region, and may even be extended to account for empirical correlations between soil properties using a linear model of coregionalisation. This effectively mirrors the approach taken for generating spatially cross-correlated fields of ground shaking discussed previously. Whilst the Baker and Faber (2008) method may offer a theoretical basis for defining liquefaction hazard with uncertainty and spatial correlation, there are likely to be practical constraints as to how well the full suite of necessary geotechnical properties can be defined, and what can be practically implemented with available site data. Furthermore, the Baker and Faber (2008) approach defines only the probability of observing the liquefaction. Considerably more research is needed to define models of the expected displacement that could be incorporated into a probabilistic approach.

4. CO-SEISMIC FAULT DISPLACEMENT HAZARD

The constraint of hazard due to co-seismic fault displacement has become an area of grow-
ing interest, with the conceptualisation in a PSHA framework originating from the SSHAC Level 4 Yucca Mountain Nuclear Waste Repository site (Youngs et al., 2003). The probabilistic fault displacement hazard analysis (PFDHA) methodology initially proposed by Youngs et al. (2003) adopts a modified hazard integral compared to that of equation 3:

$$P(d^* > D^*) = \sum_{N} \lambda_n (m^0) \int_m f_M(m) \cdot \int_r f_R(r|m) \cdot P(slip|m,r) \cdot P(d^* > D^* | m,r,slip) drdm \quad (5)$$

where $P(slip|m,r)$ defines the probability of observing surface slip at a site given an earthquake magnitude and location, and $P(d^* > D^* | m,r,slip)$ describes the probability of displacement $d^*$ exceeding the specified value $D^*$ given the magnitude and distance from the fault. Furthermore, the problem is made more complex by the need to consider rupture on the principal fault plane, as well as ground displacement on smaller distributed ruptures located away from the principal displacement, even in cases where the principal fault does not rupture the surface. Several empirical models describing for both principal and distributed rupture are available in the literature, although in some cases such models are developed using a relatively limited dataset.

The PFDHA methodology itself incorporates aleatory variability in terms of the rupture properties into the hazard curve directly, whilst for some regions, namely active continental transform environments, multiple models are proposed in the literature that would permit a degree of epistemic uncertainty to be incorporated into the analysis (Petersen et al., 2011). These make the application of PFDHA to a particular site a robust approach to capture uncertainty in the fault slip process. For application to infrastructure, however, the picture is far more complex and the objectives of the analysis need to extend beyond those defined in the original PFDHA formulation of Youngs et al. (2003). A critical objective of infrastructural seismic risk analysis is that the ground shaking input must be compatible with the generating scenario of the fault displacement, and vice-versa. Within a Monte Carlo based approach, in order to generate a feasible realisation of the two, the source rupture used to generate the transient shaking and that used to determine the co-seismic displacement should be the same. Furthermore, the location and degree of displacement for distributed rupture around the surface, should be consistent with the distribution and magnitude of displacement modelled on the principal fault. Finally, consideration must be given to the possibility that connected linear elements may traverse the same fault rupture at many different locations, and as such the probability of exceeding a given displacement at one location on the fault cannot be considered as conditionally independent of the displacement elsewhere on the fault.

The problem of consistency between the generating rupture for the ground shaking and the generating rupture for the co-seismic displacement can be largely addressed by the use of “floating” ruptures across the fault surface, in the manner that is now common practice in PSHA. For a given $f_M(m)$ and $f_R(r)$, not only is $P(slip|m,r)$ already modelled but there exists for each rupture scenario a surface upon which the slip distribution can be rendered. With the probability of occurrence of the rupture and the probability of surface slip known, empirical models for $P(d^* > D^* | m,r,slip)$, such as those found in Youngs et al. (2003) and Petersen et al. (2011) can be readily applied to complete the evaluation of using either the conventional PSHA approach or its Monte Carlo alternative. This will incorporate the aleatory uncertainty in the slip given the occurrence of slip at the surface. At this point, however, spatial correlations are neglected. Whilst models of spatial correlation using the residual term of the displacement predictive model could be derived from geostatistical methods in the same manner as those for ground shaking correlation. Even if such models were available, for the greatest consistency with the physical properties of the fault system it would be desirable to condition the simulation of the residuals of distributed displacement upon the distribution of slip upon the principal fault.

Instead we opt for an alternative approach in which the spatial correlation of slip on the principal rupture is modelled using the approach de-
scribed in Graves and Pitarka (2010). Here a mean slip value for the fault is sampled from the slip scaling relation. An initial slip distribution is assumed, which may be uniform, tapered or may even be determined from empirical models such as those of Petersen et al. (2011). The slip distribution is then transformed into the wavenumber domain where is summed with a stochastically generated field of spatially correlated random wavenumber, with correlation length modelled using the von Karman correlation function, whose parameters are derived for fault slip distributions by Mai and Beroza (2002). The result is then returned form the wavenumber domain into the spatial domain and scaled such that the total moment is consistent with the moment of the earthquake. This process produces a spatially correlated slip model across the whole fault surface (as illustrated in Figure 3) and the surrounding environment.

Figure 3: Correlated field of co-seismic displacement for a rupture on the Tagus Valley fault. Principal rupture colour from 0.0 m (green) to 3.0 m (red), and distributed displacement from 0.0 (white) to 0.2 m (pink)

To generate the spatial field of distributed slip given the principal slip on the fault, the fault mesh is broken down into a large number of sub-faults, each with a corresponding slip value. For each sub-fault the surface displacement at the target locations is calculating using the model of Okada (1985) defined for elastic half-space. The final surface displacement field is then the sum all of the displacement fields from the sub-faults.

This approach to the generation of spatially distributed ground motion fields has a direct consistency with the rupture physics, in a manner that modelling by separate empirical models of correlation would not be able to achieve. Given the paucity of models for predicting displacements, particularly for distributed slip, a limited and unevenly distributed data set used for deriving empirical models, and a total absence of spatial correlation models the simulation approach described herein may be a practical means by which realistic correlations can be considered. Unfortunately, the implementation of the distributed slip is computationally costly potentially limiting the number of fields the modeller may wish to generate for a given rupture. Nonetheless, such simulations may also be used to supplement existing dataset of distributed slip to provide constraint of simpler empirical models and correlations that may be more efficient to implement.

5. CONCLUSIONS

This paper has presented an overview of some of the main elements of seismic hazard analysis that are of relevance to infrastructure risk analysis, placing this in context with respect to site-specific analysis. The need to consider both aleatory and epistemic uncertainties in the hazard input is of paramount importance, but in doing so one should not neglect the role that spatial correlations play in this situation. For transient ground shaking the spatial correlation and spatial cross-correlation can be readily included into Monte Carlo based probabilistic seismic loss analyses, but for geotechnical hazards the process is not so well established. The incorporation of more detailed seismic and geotechnical microzonation data is fundamental to high quality analysis of seismic risk to infrastructures. Yet whilst this provides the opportunity for more sophistication in the analyses, it is important not to neglect the correlations that are inherent within the uncertainty models of the new parameters. To facilitate this approach, seismic infrastructure risk analysis should endeavour to adopt practices more commonly used in site-specific studies, whilst new re-
search directions are emerging that will require theoretical and empirical models upon which to base the simulations of the ground displacement hazard.

6. REFERENCES