Integration of Fault Rupture Models in Seismic Hazard Analysis. A Perspective from the Consultancy Side

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Abstract

Seismic hazard analysis (SHA) is an essential element in the site characterisation of a nuclear installation. A SHA comprises two major tasks: Seismic Source Characterisation (SSC) and Ground Motion Characterisation (GMC). Their respective outputs constitute the input for the hazard analysis, which includes obtaining ground motions at a reference rock, calculating the site response, and deriving compatible time histories.

The paper identifies, from the perspective of an engineering consultant, the aspects of a SHA that could benefit from the use of fault rupture models, analysing the advantages, identifying their costs, and bringing up the points that need to be analysed to establish their relevance.

Traditionally the GMC output has been a set of Ground Motion Prediction Equations (GMPEs). There are already GMPEs whose database has been completed with ground motions derived from simulations, which is a first (indirect) presence of fault rupture modelling in SHAs. The key question is whether generic GMPEs could be replaced by ad hoc fault rupture models in SHAs for the nuclear industry. Some ideas and even practical applications can already be found in the technical literature and in technical documents issued by official organisations like the IAEA.

The site response analysis and the generation of time histories, both usually uncoupled from the rest of the analyses, would probably be more easily integrated in the overall process when employing fault rupture models.

All these benefits would entail costs. Firstly, there is an obvious increase in the computational cost; second, the SHA team needs to be more multidisciplinary, enlisting specialists in fault rupture modelling, although this may be more an investment than a cost.

A SHA must take uncertainties into account. When deciding about the relevance of fault rupture models, the previously detected pros and cons have to be weighted together with the level of uncertainty of the input parameters and the impact on the reliability of the results.

Key Words: fault rupture, seismic hazard, GMPE, uncertainties.

1. Introduction

For any new nuclear installation, the seismic hazard analysis (SHA) is an essential element in the site evaluation ([1], [2]). Additionally, existing nuclear installations have to update their seismic design basis whenever dictated by the corresponding regulatory authority.

The nuclear industry has pioneered the adoption of the most advanced methodologies and techniques proposed by the scientific community; in fact, in the specific case of earthquake engineering, the nuclear industry has oriented in many cases the lines of research of the scientific community.

The way new methodologies are incorporated and accepted in the nuclear industry is probably much slower, sophisticated and thorough than in other industries. Regarding the definition of the seismic hazard, the presence of significant uncertainties calls for a systematic methodology that permits incorporating properly a wide variety of expert judgements. This is one of the main concerns of the so called “SSHAC guidelines”, initially published in 1997 [3], and completed with a companion document three years ago [4] that gathers up the lessons learnt during the fifteen years that separate both publications.

As outlined in the SSHAC guidelines ([3], [4]) and in the IAEA safety guide SSG-9 [5], after compiling the database with the needed geological, geotechnical, paleoseismic, and seismic information, two major tasks follow: Seismic Source Characterisation (SSC) and Ground Motion Characterisation (GMC). Their respective outputs constitute the input for the hazard calculation.

The physical process behind the seismic hazard consists of waves travelling from an earthquake source, first through the crust and the mantle, with a final stretch through the local soil. There is no physical motivation to split the process but, due to the different methodological approaches, the analysis usually includes a first step that models the process of the waves travelling from the source to a reference rock, and a second phase that deals with the local site effect caused by the shallow materials at the site. Finally, depending on the engineering needs, the output may need to include time histories.

At present, the most employed methodology for representing the earthquake wave propagation in SHA is the use of Ground Motion Prediction Equations (GMPEs), which are an analytical representation of the effects of the travelling waves, from the source to the reference rock, obtained by adjusting analytical equations to observations. In some cases, generic GMPEs can also account for the local site effect, although this practice is not accepted in the nuclear industry, which requires a specific calculation to account for the detailed effects of the underlying soil layers.

Finally, a SHA is the result of a multidisciplinary chain of studies, where geologists, seismologists and engineers need to interact and establish a fluent communication. Each step has an output that constitutes the input for the following step; each intermediate output, apart from being solidly supported, must be in the format needed in the next step. It is difficult to establish general rules for this flow of information because of the variety of geological environments and types of structure being designed against the seismic action.

2. Fault rupture models for improving GMPEs

The first GMPEs, at the time called attenuation relationships, were formulated in terms of intensity: they estimated the felt intensity as a function of epicentral intensity and distance to the epicentre, hence they just had two independent parameters and a single equation.

As significant amounts of strong motion data started to become available, new models were developed using other measures of the ground motion. A representative model in the 80’s is that by Campbell [6] which provides the peak ground acceleration (PGA) as a function of distance and magnitude, with a supporting database of a few tens of earthquakes, covering magnitudes from 5.0 to 7.7, and distances up to 50 km. During the 90’s the number of independent parameters started to increase, firstly by the introduction of the dependence on the local soil properties and, progressively, by accounting for other considerations, such as the type of faulting, hanging-wall effects or the geographical region. In parallel, GMPEs started to provide the ground motion for different spectral frequencies, which allowed obtaining uniform hazard spectra (UHS).

At present, with more information available and more powerful calculation resources, the GMPEs formulated are significantly more sophisticated than 30 years ago. The recent NGA West 2 program [7] is a clear example: the GMPEs have up to five or six independent parameters; the database derives from thousands of earthquakes; the spectral frequencies covered range from as low as 0.1 Hz up to 100 Hz; the magnitude validity range goes from 3.0 to 7.9; and distances extend to 1000 km. The database contains records from all over the world, all from shallow earthquakes in active tectonic regions. Incidentally, the author mentioned earlier as an example of a simple attenuation model in the 80s is also the author of one of the models in the latest NGA program.

In the program mentioned [7], simulations have been employed for constraining some aspects of the model like the scaling of the hanging wall (HW) or the nonlinear site response [8]; they have been also taken into account for comparing them with results of the database and deciding about how to incorporate them in the regression process.

Despite the considerable sophistication of GMPEs, when employing them for a SHA there are still some combinations of parameters that are not represented by the GMPE. However, in the absence of a better alternative, the GMPE is still used.

A typical example is the magnitude range. GMPEs have been calculated out of a database that covers a certain range of magnitudes. There have been studies that warn about the problems of extrapolating their use out of the range covered by the database [9]. Given the low probabilities targeted in the nuclear industry, in high seismicity places it is most likely that, for the probability level of interest, there is a significant contribution of magnitudes for which there are no recorded data, hence out of the validity range of the GMPEs. The database could in principle be supplemented with simulated records to cover the missing magnitudes, with the advantage that this would be transparent to the GMPE end user. To the author's knowledge this has not yet been implemented in the routine of generating GMPEs but, as indicated above, comparisons of simulations with actual data have been used for deciding about the weight that data from large earthquakes should have in the regression analysis [8]. Maybe the next step will be the integration of the simulations themselves in the regression.

The question of the distance is more complicated, but still could benefit from the inclusion of simulations in the GMPEs database. As is well known, records from important magnitude events at short distances from the epicentre are very scarce. There is an added difficulty in this respect which is the inclusion of near source, HW and directivity effects. Simulations would help improving the performance of GMPEs in this respect, however for some of the effects it is probably more appropriate to employ the simulations directly, as discussed in the next section.

For medium-low seismicity sites the available GMPEs can give an adequate coverage of all the ranges needed, provided there is an acceptable consistency of geotectonic settings. However, if a region-adapted GMPE is required, the same problems mentioned above arise due to the lack of records for the higher magnitude ranges. In places without records the available GMPEs cannot be verified for any range of magnitudes, as occurs, for example, in Northern Europe; a similar situation arises if there is a particular geological configuration for which generic GMPEs are not applicable. In both cases simulations could offer the possibility of generating ad-hoc GMPEs from scratch. The question though arises as to whether it is worth generating and employing such GMPEs, or one could employ directly the simulations in the SHA, as discussed in the next section. The advantage, at least in the short term, of having a GMPE is that it allows applying the existing methodologies: using a GMPE based on simulations does not entail methodological changes with respect to using one based on actual observations.

So we can say that fault rupture simulations are already present in the conventional SHAs through the modern GMPEs that use databases completed with simulated records. It seems likely that such databases will be expanded in the future. Ideally, places without records could have a GMPE created solely from simulations. Whatever the database origin, the SHA is not affected and the simulations remain an independent task of the SHA.

3. Fault rupture models as an alternative to GMPEs

For exploring the possibilities of replacing GMPEs by fault rupture simulations in a SHA, it is useful to review first the general outline of such an analysis, which can be divided into four steps:

1. Compilation of the geotectonic, paleoseismic, seismological, and geotechnical database.
2. Seismic Source Characterisation (SSC). Idealisation of the seismic activity rate, be it with identified faults, with diffuse seismicity, or a combination of both, using the terminology of SSG-9 [5].
3. Ground motion characterisation (GMC). Idealisation of the ground motion at the site as a function of the required source and path parameters. Traditionally this step consists in selecting the more appropriate GMPE(s).
4. Hazard calculation. Integration of the outcomes of the two previous step in the calculation of the seismic hazard at the site, with either a probabilistic or a deterministic approach.

The integral that summarises the numerical process in the probabilistic approach is:

$$P[Y > y] = \int\int P[Y > y \mid m, r]\, f_M(m) f_R(r) dm dr$$

where Y is a ground motion parameter; y is the value of the ground motion being exceeded; m is a measure of the earthquake size, usually the magnitude; r is a measure of distance; and $f(\cdot)$ is a probability density function.

The two probability density functions in the above expression are defined in the SSC (step #2).

The term $P[Y > y \mid m, r]$ is defined in the GMC, usually with the choice and/or construction of adequate GMPEs, hence employing fault rupture simulations instead of GMPEs would entail a major change in step # 3.

Additionally there will be some aspects of the database (step #1) that need to be enlarged in view of the subsequent fault rupture simulations. Similarly, the integration of the GMC output in the hazard analysis would also have to be adapted. Hence, the change with respect to the traditional procedure would not be minor.

In a plenary session of the 2012 World Conference Atkinson [11] anticipated the progressive replacement of GMPEs by simulations. She proposed a methodology that relied on a SHA based on long period catalogues generated by a Montecarlo approach, with the GMPEs replaced by consultation of a large and complete ground motion database composed by both observations and simulations.

At about the same time, the former Japan Nuclear Energy Safety Organization (JNES) proposed a SHA which also employs a Montecarlo approach to generate the earthquake catalogue and the ground motion at the site is obtained directly with “live” simulations (instead of searching in a database). The generated earthquake catalogue included randomly generated fault parameters, which constituted the basis for the simulations. The document [12] is in Japanese but a summary will be included in an upcoming IAEA safety report [13].

The use of simulations would also be possible with the traditional procedure consisting on a numerical integration of the seismic activity rates defined either with explicit faults or diffuse seismicity. Invoking the GMPE would be replaced with a "live" simulation: a set of variables, including uncertainties, would be passed to the simulation, at the end of which the resulting ground motion would appear as output. This output needs to include its uncertainty (the equivalent to the sigma in the GMPE), which would be somehow estimated during the simulation, probably with a Montecarlo approach. That proposed by JNES [12] for generating the catalogue is now transferred to the side of the simulations, so the final number of simulations would be similar (and very large) in both cases.

An example of software that performs simulations is the SCEC Broadband Simulation Platform which generates broadband (0-100 Hz) ground motions for both historical and user-defined earthquakes.

4. Integration with site effect and time histories

One of the weakest points of GMPEs is capturing the local site effect. This phenomenon depends on the soil layers underlying the site and, barring a certain uniformity, it is not possible to represent it with a reduced number of parameters. A large effort has been made in this respect in the latest NGA program [7], including some iterative processes in the definition of the GMPE to account for the nonlinearity [8]. Despite all this, the nuclear industry requires detailed models of the underlying soil layers, their mechanical properties, and all uncertainty parameters.

At present, several uniform hazard spectra are normally obtained at a reference rock for different probability levels; the local site effect is introduced in a subsequent calculation, usually through the generation of time histories (although it would not be strictly needed) and finally response spectra are again obtained. Along this process it is not always possible to keep track of the probabilities for all spectral ordinates or the time histories obtained.

The use of ad-hoc simulations allows accounting for the local site effect in a rather natural way, leading to a direct determination of the final uniform hazard results at the ground surface. Additionally time histories and their corresponding response spectra are naturally obtained as outputs of the calculation process.

5. Costs

When employing a GMPE, the type of information transferred from the GMPE developer to the GMPE end user is an analytical expression with an explanation of the meaning of the different parameters. The values to be assigned to those parameters can usually be found in the compiled database and are familiar to the consultant performing the SHA. It can therefore be said that the GMPE end user, the seismic hazard analyst, is self-sufficient for integrating the model within the hazard calculation.

If simulations are employed instead of GMPEs, the practical integration of both calculations, probabilistic SHA and simulations, calls for a close collaboration between the expert performing the SHA and the one in charge of the simulations; this is in contrast with the autonomy that the SHA analyst has when employing GMPEs. Hence the hazard analysis team becomes more multidisciplinary and new experts are needed, although this may be more an investment than a cost since the simulations will benefit from more than simply substituting the GMPEs.

As anticipated in section 3, the number of simulations required in a probabilistic SHA is very large and the calculation times are several orders of magnitude larger than those that are customary when employing GMPEs. However this may not be a lasting unsurmountable barrier given the pace of evolution of computer capabilities.

6. Uncertainties

Uncertainties play a crucial role in a SHA. GMPEs provide a measure of the uncertainty and, at present, it is normal practice to take that uncertainty into consideration in the hazard analysis. The overall formulation of GMPEs has become significantly more sophisticated, including the definition of the standard deviation, but the uncertainties have not decreased greatly, at least not to the point of strongly affecting the hazard results. This was openly recognised by Ambraseys et al in 2005 [10].

The main methodology proposed for reducing the GMPE uncertainties is the so called “single-station sigma”, as in the work by Rodriguez-Marek et al [14] where the random variability is reduced by elimination of the site-to-site variability term in the GMPE. This method requires making measurements at the site for a certain period of time. An option that could be explored is whether it is possible to perform the “single-station sigma” methodology using simulated records at the site.

Simulations are of interest only if they improve the final result and one of the most sought improvements is to reduce its uncertainty. Note that unless some conditions are fulfilled there may be little point in conducting a calculation, such as a fault rupture simulation, that is very sophisticated in comparison with a direct GMPE application: if the calculation is fed with a highly uncertain input, the same will be applicable to the results.

7. Conclusions

A brief review has been conducted, from the perspective of an engineering consultant active in this field, of the present methodologies for performing seismic hazard analyses for nuclear sites. In particular, especial attention has been paid to the use of fault rupture models for improving what is currently achievable with ground motion prediction equations (GMPEs).

As a result of this review a number of findings can be presented.

- Fault rupture simulations are already present in the conventional SHAs through modern GMPEs, which use databases completed with simulated records.
- There have already been proposals to use simulations instead of GMPEs, in the context of methodologies that employ the Montecarlo approach for generating catalogues. This replacement could also be implemented in the traditional numerical integration of the activity rate, although the Montecarlo approach would still be needed for calculating the standard deviation of the simulated ground motion.
- Employing ad-hoc simulations permits a more natural way of accounting for the local site effect, of particular interest for the generation of time histories.
- Fault rupture simulations take several orders of magnitude more time than the simple application of GMPEs.

- The use of simulations in SHA requires incorporating additional specialists into the hazard analysis teams, thus making them even more multidisplinary.
- The incorporation of simulations to the SHA is of interest only if leads to improved results, such as a reduction in their uncertainty. Indeed there may be little point in conducting fault rupture simulations unless the uncertainties in their input can be limited, as those uncertainties will inevitably be reflected in the results of the simulations.

Appendix 1: References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, "Site Evaluation for Nuclear Installations", IAEA SAFETY STANDARDS SERIES No. NS-R-3, IAEA, Vienna, 2003.

[2] NUCLEAR REGULATORY COMISSION, "NRC Regulations. Title 10, Code of Federal Regulations, Part 100 Reactor Site Criteria", 2015.

[3] NUCLEAR REGULATORY COMISSION, "NUREG/CR-6372 Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and the Use of Experts", 1997.

[4] NUCLEAR REGULATORY COMISSION, "NUREG-2117 Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies", Rev. 1, 2012.

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, "SSG-9 Seismic Hazards in Safety Evaluations for Nuclear Installations", SPECIFIC SAFETY GUIDE SSG-9, Vienna, 2010.

[6] CAMPBELL, K.W. "Near Source Attenuation of Peak Horizontal Acceleration", Bulletin of the Seismological Society of America, Vol. 71, No. 6, pp. 2039-2070, 1981.

[7] BOZORGNIA, Y. et al, "NGA West 2 Research Project", Earthquake Spectra, Vol. 30, No. 3, pp. 973–987, August 2014.

[8] ABRAHAMSON, N.A. et al., "Summary of the ASK14 Ground Motion Relation for Active Crustal Regions", Earthquake Spectra, Vol. 30, No. 3, pp. 1025–1055, August 2014.

[9] BOMMER, J.J. et al "The Influence of Magnitude Range on Empirical Ground-Motion Prediction", Bulletin of the Seismological Society of America, Vol. 97, No. 6, pp. 2152-2170, 2007.

[10] AMBRASEYS, N.N. et al., "Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Horizontal Peak Ground Acceleration and Spectral Acceleration", Bulletin of Earthquake Engineering, Vol. 3, No. 1, pp. 1-53, 2005.

[11] ATKINSON, G. "Integrating Advances in Ground-Motion and Seismic-Hazard Analysis", 15th World Conference on Earthquake Engineering, Lisbon, 24-28 September 2012.

[12] Japan Nuclear Energy Safety Organization (JNES) "On the Development and Improvement for Evaluation of Exceedance Probability of Design Basis Ground Motion", Annual Safety Research Report, JFY 2011, JNES-RE-2012-0001, www.nsr.go.jp/archive/jnes/content/000123375.pdf , 2012.

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, "Diffuse Seismicity in Seismic Hazard Assessment for Site Evaluation of Nuclear Installations", IAEA SAFETY REPORT, in publication process, latest version 2014.

[14] RODRIGUEZ-MAREK, A. et al., "A Model for Single-Station Standard Deviation Using Data from Various Tectonic Regions", Bulletin of the Seismological Society of America, Vol. 103, No. 6, pp. 3149–3163, December 2013.