# CONCEPTUAL FRAMEWORK FOR PHYSICS-BASED SIMULATIONS IN PRACTICAL PROJECTS AND INTERFACE TO ENGINEERING DEMANDS

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**Abstract**. This paper is intended to provide an overview of the most important aspects on how to integrate physics-based simulation models in the seismic hazard assessment framework and share thoughts with the community on how to make best use of the available models in practical application. Up to now, also a lot of research has been performed and advancements have been achieved to make use of physics-based models through numerical simulations for the assessment and prediction of ground motions. Nevertheless, still empirical ground motion prediction equations (GMPE) are the predominant way of modelling ground motions for a site-specific PSHA or also a national seismic hazard map. There are a lot of aspects where physics-based simulations are better than GMPEs to predict ground motions, but on the other hand there are still some issues to be resolved. In the meanwhile, it is worth to consider the option of developing hybrid GMPEs. Such are based on one hand on available observations and on the other hand, where no data exists, those are substitute by simulated scenarios. As computational resources are today not a limiting factor anymore, large scale finite-fault simulations are not a problem anymore and state-of-practice. Ideally the simulations are or will be able to include all effects to predict the motions from the source to the structure and already taking into account the soil-structure interaction and local site-amplification effect. At this interface between bedrock and soil sediments there are a lot of aspects which need to be carefully considered and modeled. Those are discussed and specific aspects are highlighted to remind that this is a multidisciplinary approach the needs of the end users need to be respected since the very beginning.

**Key Words**: PSHA, PSA, Finite-Fault Simulations, Hybrid GMPE, Uncertainties.

### Introduction

Today, a lot of tools and methods are available to perform probabilistic seismic hazard assessments (PSHA) and probabilistic safety assessments (PSA) and are also used in practical projects for critical infrastructures. Furthermore, in the last decade a couple of pioneering and state-of-the-art projects have been carried out which provided a wealth of information (e.g. nuclear projects: PEGASOS Refinement, Thyspunt, Hanford, Hinkley Point and Sinop feasibility study). Also, research projects have been launched with the goal to address the open items and address the potential improvements when dealing with seismic issues from the source to the site/structure (e.g. SIGMA [1], SINAPS@ [2][3]). Up to now, also a lot of research has been performed to make use of physics-based models through numerical simulations for the assessment and prediction of ground motions. Nevertheless, still empirical ground motion prediction equations (GMPE) are the predominant way of modelling ground motions for a site-specific PSHA or also a national seismic hazard map. Furthermore, it is common practice to treat the technical phenomena in projects separately even though the physical reality does not stop at interfaces set by professional disciplines: source characterization, ground motion characterization, site response characterisation, probabilistic vs. deterministic assessment. Physics-based models have moved from the academic sector to the industry and become accessible and affordable (with respect to computation time) to interested users, but still lack to fulfil all expectations from the earthquake engineering community and practical requirements.

This paper is intended to provide an overview of the most important aspects and share thoughts with the community on how to make best use of the available models. An improvement can be achieved when multidisciplinary teams are working together to get the best solution. This sounds trivial and common sense, but in reality, the interface issues and different interpretations of the delivered products still persist. Some of the described issues are hopefully stimulating the discussion on the needs on how to move forward and benefit from the available knowledge. The aim is to base the discussion on the current practice and not to cite regulations, codes and guidelines.

### Seismic Hazard and Safety/Risk Assessment

Seismic hazard assessment (SHA) with sophisticated logic trees are today state-of-the-art and representing one part of the overall model for safety or risk assessment, respectively. There is in the industry no distinction between safety and risk assessment. It is only an established terminology where in the US related projects the term “risk” is commonly used whereas in Europe and some other countries the term “safety” assessment is preferred. The schematic sketch in Fig. 1 illustrates the role of the SHA and how it is used within the whole chain of evaluations for a safety assessment.



*FIG. 1. Schematic sketch of the elements of a full probabilistic risk assessment.*

The required periodic safety assessment is the main motivation for critical infrastructures such as a nuclear power plant to run deterministic or probabilistic SHA in order to fulfil the regulatory requirements [4] and be able to make risk informed decision making when it comes to retrofit or investment decisions. In Japan, the regulatory framework [5][6] is heavily relying on finite-fault simulations (but not exclusively) and as computer resources are not a limiting factor anymore, large scale models are state-of-practice. As the seismic risk assessment is tied to the ground motions as main input the interface issues deserve some special attention and especially the topic of soil-structure interaction modelling.

At the beginning finite-fault simulations have been mainly employed to explore the physical maximum possible ground motions. The Yucca Mountain Project in the USA for the nuclear waste repository site was probably the first large industrial project to make extensive use of such physics-based models. Also, in the PEGASOS Project [7] finite-fault simulations were used to check and constrain the maximum ground motions. Whereas in the PEGASOS Refinement Project [8] the finite-fault simulation approach was used for comparison with the GMPE predictions as a basis to decide if the global imported models capture the region specific features but were not included in the logic tree.

The seismic hazard assessment is today mainly based on the use of alternative GMPEs to populate a logic tree, reflecting the various technical defensible interpretations for predicting the ground motions at a site in a probabilistic way. Each branch represents a part of the epistemic uncertainty and such branches should be in theory mutually exclusive but still exhaustive. When making use of physics-based simulation models the various scenarios, representing alternative parameter combinations are also represented as logic tree branches. Nevertheless, it is not straightforward to associate a probability of occurrence to each scenario. Probably due to the complexity of both approaches and lack of maturity of some physics-based models no industrial project has considered having a mixed logic tree where one part is populated by the classical GMPEs and the other by physics-based models. Theoretically, there is no argument against such an approach, apart from the necessary effort to do both and afterwards to have to combine both to be used by a hazard computation code.

### Discussion of Specific Issues

This chapter is intended to elaborate on specific issues and discuss them in the light of known interface issue or potential candidates for a relevant future improvement. Of course, it should be understood that this is certainly not an exhaustive list but should reflect the key items of relevance.

#### Non-ergodic models

Nowadays, there is an increasing consensus in the engineering seismology community that it is preferable to use non-ergodic models for the seismic hazard estimation [9][10]. This is of course only possible and justifiable if enough local data is available to support the argument of being different that the global effort. The ultimate goal is understood to be a fully non-ergodic PSHA. Nevertheless, today only partially non-ergodic models exist and yet, nobody has attempted to claim that all elements of the PSHA are non-ergodic.

* Single-station / single-path sigma:

The single-station sigma concept [11] has already been applied in the recent path in industrial projects and the separation of epistemic uncertainty and aleatory components helped to further improve the hazard results (see e.g. [8]). To apply and justify such an approach for a site/region specific study comes with the burden of data collection and/or evaluation in order to study and demonstrate that the local data is leading to a smaller aleatory variability than predicted by the global average. The data collection needs to be understood not only as recordings from seismic stations, but also the geotechnical measurements in the soil layers in the site of interest in order to have a precise knowledge of the site effects and how much they deviate from standard site conditions. This then allows to split the GMPE in the median prediction and a separate model for the aleatory component to be replaced by the single-station sigma. With more and more observations it is also possible to quantify the single-path sigma and extract this portion from the standard deviation of the GMPEs.

In order for physics-based simulations to be used in such a framework they need to be able to reflect the observed local variability, which is supposed to lead to a reduction compared to the standard model. As simulations can include the local site specifies there is a good argument to prefer those compared to using GMPEs with only VS30 as parameter, which will not be able to reflect local site effects and this is a know issue. Unfortunately, at the moment the standard deviation based on simulations is larger compared to the standard deviation defined by the empirical GMPEs.

* Partially non-ergodic GMPE, region / site specific GMPEs:

In SHA the GMPEs still contribute to a very large extent to the uncertainties (especially at very low probabilities). In the framework of the SIGMA research project new regional / site specific GMPEs, appropriate for the local European context [12], were developed and comparable efforts have been made also in other regions of the world [13]. This of course, contributes to a more realistic hazard estimation, but relies on resilient data. Furthermore, it was recognized that it somehow necessary to develop a new generation of GMPEs for very hard rock conditions, as often the case for site-specific approaches like necessary for critical infrastructures as a nuclear power plant (NPP).

In this context the physics-based simulations of ground motions can be part of the solution to the problem. In most regions of the world the data is scarce, especially in the range of magnitudes and distance of interest which contribute most to the hazard. Which means that in most cases for a site-specific study there is no recording in site vicinity of a larger ground motion. From a risk point of view this is of course good, as the site is not shaken on a regular basis by large earthquakes and thus the likelihood for larger damage is low, but from the modelling point of view there is no anchor point to check if the ergodic models also apply to the site of interest. For those cases the idea would be to develop hybrid GMPEs which on one hand are based on available observations and on the other hand, where no data exists, those are substitute by simulated scenarios. Thus, the development of the functional form of such a hybrid GMPE could benefit from the advantages of both worlds: empirical and simulated ground motions.

#### Uncertainties and Variabilities

The proper and realistic consideration of uncertainties is of tremendous importance in order to have a correct estimate for the risk assessment. Therefore, it is necessary to pay attention to have a close look at all pieces of uncertainty within the evaluation and calculation process and distinguish the epistemic uncertainty for the aleatory variability. Only an adequate treatment of the corresponding piece will allow to reduce the hazard and risk estimates in a longer term. At low annual probabilities of exceedance (<1E-5) the standard deviation is dominant for hazard results and this is exactly the range of interest for (nuclear) applications where robust estimates are necessary.

The variability (standard deviation) of simulations appears at the moment to be larger than for the empirical GMPEs, but overall are approximately consistent for most reproduced events. This is not a satisfactory situation from the end user perspective, as it is not clear what is closer to the reality (truth). Based on the experience with empirical data available today, the overall variability seems to be known, but it could be criticized that still there is not enough observation for a site to be confident enough that we have really seen the full range of possible ground motions. On the other hand, the larger scatter of the simulations could be justified by stating that the simulations can produce in a much more systematic way all potential realizations and thus is spanning the correct range. But it must also be admitted that today the correlation of all parameters used to feed a physics-based simulation is not completely known and mapped into the models and computer codes, respectively. Thus, it might be very likely that some of the realizations are simply the result of the combination of physically impossible parameter combinations. Thus, there are from a practitioner point of view still some open items to be closed before being confident enough to base SHA solely on numerical simulations. There is a larger ongoing effort at the Southern Californian Earthquake Center (SCEC) to try to address this issue [14][15].

An important aspect of relevance for the correct quantification of the site-response effect is the appropriate consideration of uncertainties in the soil velocity profile(s), as well as in layer thicknesses and in the soil material properties (shear modulus, damping, density, …). In the classical SHA approach where the rock hazard is first evaluated and the site-specific site response characterization is added on top it is not straightforward, but obvious that those uncertainties are covered when evaluating the response spectral site amplification functions by the geotechnical engineers. As there is also a link to the soil-structure interaction computation to be done by the geotechnical or civil engineers to evaluate the in-structure responses (e.g. floor response spectra) it is very important to communicate and transfer all information about the uncertainty treatment by each group and check if it satisfies the needs of the users at the end of the chain. If the decision is made to make use of finite-fault simulation models which can incorporate already in the model the site effects, then this implicitly resolved, but will lead to a significant increase of scenarios to run, to cover the same uncertainty range. An intermediate way is to use methods based on the substructure technique, which model the infinite domain of the bedrock separately from the near-foundation region with a defined interface (e.g. [16],[17],[18]). In this case the consistency of the scenarios and soil properties between the two needs to be considered carefully in order to not model unphysical combinations. Furthermore, as those computations are heavy on both sides a more efficient way of combining those scenarios should be looked for, but still satisfying the regulatory and end user needs with respect to robustness and technical defensibility.

#### Stochastic Simulations

Stochastic simulation models like SMSIM [19] and EXSIM [20] are another way to predict ground motions which must be mentioned in this context, as they stand between the empirical GMPEs and the pure physics-based models. In practice the stochastic simulations are easier to use and less resource intensive than full scale physics-based models with distant sources. Furthermore, in the direct comparison to reproduce past events they perform quite well and lead of course to similar results as the classic GMPEs. Nevertheless, there are also some issues to consider for engineering application and which become very relevant when there is an interface to the structural design or assessment. The normal output of those approaches is a single component (geom. mean), but the engineers need three component time histories or spectra to perform a structural analysis. As for a real event there is some interdependency between the three orthogonal components it is unsatisfying from an engineering point of view to receive maybe three components, but there is no correlation between those components which can be compared to the observed correlation. Furthermore, the separation into two horizontal components implies to take care of the peak-and-valley variability within each component and the component-to-component variability between the two horizontal components. There exist empirical functions with which this effect could be added back in, but this becomes questionable on how realistic this is compared to the effort to simply take real observations and scale them. Another underestimated issue is the consistency of the V/H ratio with empirical data. The stochastic simulations do not make a difference between the vertical or horizontal component, but from observation we know that there is one.

In the light of those issues, even if the stochastic simulations are much more affordable and there are far less parameters to define to get a result, it is clear that physics-based simulations are superior, as they implicitly respect all physics of the three components of motion.

#### Model Interfaces and Multidisciplinary Interfaces

Seismic hazard assessment is composed of several interfaces and requires a multidisciplinary expert team to be performed (see Fig. 2). Often the interfaces are the cause of issues which were not fully explored or simply neglected. Those issues apply to the empirical GMPE approach as well as to physics-based simulation models, but then sometimes differently. On the other hand, the different involved professional disciplines have sometimes different needs and also differing interpretations of the provided data and information.



*FIG. 2. Full integrated source-to-site-into-structure simulation.*

Interface issues between the seismic source characterization, ground motion characterization and site-response characterization are the following:

* Rupture dimensions:

The Area(M) scaling relations are used as well in the conventional approach as by the finite-faulting simulations. The GMPEs are based on a subset of earthquakes with a given Area(M) distribution. The Area(M) scaling used should be consistent and it should be checked if the Area(M) model used in the finite-fault simulations is consistent for larger areas with the empirical based formulations.

* Distance conversions:

In a classical SHA with GMPEs it was in the past sometimes necessary to apply a conversion in the distance metric, as not all GMPEs are developed for all available distance metrics and ultimately the hazard code should take care of the conversion and be using the native distance measures of the ground motion models. Physics-based simulations do not explicitly have such an issue as the distance is part of solving the equation of motion and no distance conversion is necessary.

* Distance extrapolation:

Depending on the extent of the source characterization models, sources out to 500 km or even more might be necessary to consider, but often GMPEs are only defined up to 250 km. Thus, in the classical approach GMPEs need to be extrapolated out to necessary distance. This does not have a significant effect on the hazard but should be addressed for consistency. The finite-fault simulations do not have such a problem, as the distance or size of the model respectively, is only limited by the available computational resources.

* Minimum magnitude for hazard integration:

Depending on the target needs, hazard calculation will be based on a minimum magnitude of e.g. 4.5 or even lower. The available ground motion models may not extrapolate well to smaller magnitudes. Thus, it might be necessary to adjusted the selected GMPEs for smaller magnitudes using local ground motion data as a constraint. Furthermore, models for potential non-linear effects in the site response assessment need to be checked to also work for a lower magnitude level. Usually, there is not such an issue when using finite-fault simulations. Toward the other end of the magnitude range (e.g. M8) the GMPEs would need to be checked how well the extrapolate beyond their range of applicability, but the same applies to physics-based models, as there are too few observations available to reliably be able check if the formulated relation is reflecting the reality.

* Avoid double counting of site amplification variability:

A key issue for the attenuation and site response interface is the treatment of the variability. The variability of site amplification (between sites with the same VS30 and within a single site for different input motions) is included in the ground motion characterization if the traditional standard deviations for GMPEs are used. It is also included in the epistemic uncertainty of the site profile for the site response calculation and in the variability of amplification from different input time histories. Approaches to address this double counting were reviewed in the past. There is a strong support to remove the epistemic part in the ground motion characterization by switching to a single-station sigma approach and having the site response not add the variability from different input time histories for the linear range of input ground motions. In the case of finite-fault simulations which include already the possibility to have a detailed modelling of the site-specific soil conditions, this is not a problem, as there is no interface in terms of different models to generate the ground motions. If the simulation code is not capable of having the full modelling of the source to the structure propagation in one model then of course the case of double counting of uncertainties needs to be checked again carefully.

* 2D/3D-effects on the variability:

There are 2D and 3D-effects in reality, but often in the SHA those are neglected, unless they are obvious or significant in terms of amplitude. Some of the variability due to 2D and 3D-effects is captured in the GMPE aleatory terms. For the site response characterization, the 2D/3D effects need to be addressed in order to have the most realistic model to predict the ground motions at the surface and directly beneath the structure. It is not clear how much double counting exists due to this issue. Within the finite-fault simulation framework there is not such an issue, as most of the codes are fully 3D and the wave-propagation is implicitly modeled in a consistent way.

* V/H Models for rock and soil:

In a SHA where the rock and soil hazard are treated sequentially, the rock V/H ratios are evaluated and weighted separately but combined at the end with the one resulting horizontal rock hazard and are, thus completely independent of any underlying shear-wave velocity profiles. In the rock site hazard calculation, the V/H ratios are applied to the combined fractiles of the hazard curves for the horizontal component for all scenarios.

For the site response characterization, two approaches may be used to provide V/H ratios and amplification factors, which scale the horizontal rock ground motion to vertical soil ground motion: (1) V/H ratios for soil and amplification factors for horizontal motion are developed by the site response group and are combined, and (2) V/H ratios for rock by the ground motion group and amplification factors for vertical motion site response group are combined. For the first approach, the specific soil V/H ratios are combined on a per-branch basis with the expert-specific horizontal motion amplification. For the second approach, the V/H rock ratios of all ground motion branches are combined with the site response vertical motion amplification factors. Both approaches cover horizontal-to-vertical motion scaling and amplification. The results of both approaches are combined into a single soil input file per site. This soil input file is used to compute the vertical soil motion hazard on the basis of the horizontal rock motion hazard, which is always the "full" (all fractiles, complete source and ground motion models) horizontal motion rock hazard. Approach 2 above is similar to the computation of the vertical motion rock hazard in that the full horizontal motion rock hazard is combined with all ground motion V/H models, i.e. there is no correlation between (but full combination of) the ground motion branch-specific rock hazard subsets and the ground motion-specific V/H rock ratios.

In the case of physics-based simulations it is still a challenge on how to satisfy all those needs and considerations when the simulation is only performed up to the bedrock and the soil is treated separately. At the moment most of the time the logic tree approach is used to combine different models and how to integrate a simulation branch (or a full set of sub-branches) and still be consistent with the overall framework is a challenge. As the 3D simulations of course do not have to treat the V/H issue additionally, as the wave propagation already implicitly includes this aspect a combination with the GMPE branches must be well thought trough in order to not double-count effects and introduce new uncertainties.

* Soil-structure interaction:

Up to now, the soil-structure interaction computation is done after the seismic hazard assessment, even if today it would be possible to include this already in the SHA process. But as this is usually done by another group of experts which are not the ones how define the seismic hazard there is still a strong separation of competences. Based on the personal experience of the author this is very unfortunate, as this unnecessary separation introduces a lot of interface issues and there are many misinterpretations of what is part of the hazard curve already. The consequence is a potential double counting of uncertainties or site response effects which in the end affects the fragility curve development and thus, the risk estimate at the end.

This is why it is strongly recommended to define at the beginning of any project very clearly the reference rock level or “control point” which determines the interface between rock and soil. Furthermore, it is also important to check the consistency of the rock velocity profiles at the specific sites with the rock profiles for the GMPE datasets. This applies also to the physics-based simulations.

Today, modeling with 1D motions is state of practice and research. 3D is also state-of-practice but only for some very specific cases. As models are getting more and more realistic, the consideration of 6D motions deserves some attention: body (P, SH, SV) and surface waves (Rayleigh, Love).

As the goal is to get realistic surface motions in the near field there is a big opportunity for physics-based models close the gap. Local geology can amplify and de-amplify motions. Of course, a very detailed knowledge of geology is necessary and the inelastic behavior needs to be known, but this is a matter of data collection/availability and should not hinder us from doing our best.

* Non-linear effects in SHA models:

The detailed and specific approach to evaluate the site response will use models which incorporate non-linear effects. In the classical SHA approach the GMPEs used to predict the ground motions also include inherently non-linear effects. These non-linear effects should be consistent with the expected site conditions. If the reference rock condition will be greater than approx. 700 m/s, the non-linearity in the ground motion model will be very small. The differences in the non-linear models between attenuation part and site response modelling will therefore not cause a significant effect.

* Non-linearities in soil and structures:

As mentioned above, there is room for improvement for a more realistic modelling of the soil-structure interaction and here possibility to consider non-linearities in the soil near the foundations and in the structures comes into play. It has already been shown that the soil non-linearities in the near field next and below to a structure with a heavy and large foundation (as e.g. a NPP) can significantly influence the in-structure response. In the past, a very large effort has been done to have a more realistic evaluation of the seismic hazard (through hazard curves or UHS). Nevertheless, on the side of the geotechnical and engineering community the tools and methods at hand since 30-40 years have been deemed to be good enough and thus, not a lot of effort has been dedicated to also improve the state-of-the-art and practice in this field. Consideration of spatial incoherence is another topic in this context, but it would go beyond the scope of this paper to address all issues here.

* Time histories – consistency with UHS

As a hand over to the engineers 3 component time histories consistent with the hazard need to be provided. There are numerous small issues to be addressed but the most important ones are certainly the realistic mapping of the horizontal component-to-component variability (e.g. through empirical correlations), the peak-to-trough variability of each component and consistency with the hazard. The latter is already part of the hazard curve via the aleatory variability represented by the fractiles and the component-to-component variability is not, as the classical hazard curve is only a geometric mean of the horizontal component. Furthermore, regulators pay attention to have realistic V/H ratios (which can be compared to empirical correlations) between horizontal and vertical components.

A common requirement by the end users is that the duration, ratios of V/A (peak ground velocity over peak ground acceleration) and AD/V2 (peak ground acceleration· peak ground displacement over the square of peak ground velocity) should be consistent with characteristic values for the magnitude and distance of the appropriate controlling events defining the uniform hazard response spectra.

Yet, it is probably not clear for the engineers how physics-based models take care of these effects and how this compares to the observations. Thus, in order to increase the credibility and robustness of the simulations there is a need of information exchange.

* Frequency content:

Modern GMPEs provide predictions for response spectral frequencies between 0.1 and 100 Hz, where sometimes 100 Hz is set equal to PGA. Engineering applications need robust, realistic estimates up to 100 Hz, as high frequencies up to 50 Hz are significant for the assessment and design of some structures and components (e.g. pipes, cable trays, pumps). Up to the authors knowledge the physics-based models are using models which contain at frequencies between ~ 0.5 to 1 Hz all the physics of the dynamic rupture model and the hybrid broadband motions claim to be valid out to ~ 10 Hz. If simulations up to 50 Hz are technically defensible needs to be demonstrated, but it is a fact that at least up to those frequencies the ground motion needs to be computed and provided. This is certainly also an important criterion if the physics-based models can be included in a logic-tree approach to populate equal branches as their GMPE colleagues. As already mentioned earlier, a temporary compromise could be hybrid GMPEs which are developed based on filling the gaps of ground motions for the relevant earthquake scenarios by simulations.

#### Target application

Depending on the target application and regulatory framework, physics-based simulations are an alternative to seriously consider beside the empirical GMPE approach. GMPEs and physics-based models can be used either for DSHA, PSHA, design or verification purposes. E.g. the SINOP feasibility study for the nuclear siting project in Turkey has nicely shown that DSHA and PSHA can lead to consistent results and that simulations and empirical GMPEs are both applicable in practice within one project, using the same boundary conditions and assumptions.

There is another aspect where the physics-based models have or can have a significant advantage over GMPEs. When it comes to the determination and quantification of the fault slip to be considered for a fault displacement (rupture) hazard. It is worth to make a note about the terminology here, as often both terms are used: Fault slip = relative displacement of both sides of the fault, which is of interest for the engineering evaluation if something could break! Fault displacement has for seismologists a different meaning = is the displacement of the fault at the surface compared to the initial position. Simulation based approaches provide both quantities directly, while classical GMPEs only express the ground motion to be expected in an absolute sense but will not give any insight in the exact relative displacement at the fault rupture trace. For this empirical fault displacement predication equations must be used, which also exist, but are something different and require a separate evaluation.

* Site-specific instrumentation:

Site-specific instrumentation for comparison and calibration of expert models or adjustment of empirical as well as physics-based models is also corroborated by [21] recommendation on seismic assessment of existing nuclear installations to meet international safety standards. In addition to the long-term development of a site-specific ground-motion database build on such instrumentation, it is should be possible to evaluate detailed site-specific parameters such as rock-surface site amplification, V/H ratios, kappa (high-frequency damping), and site-specific aleatory variability (Single-Station Sigma). The interested reader is referred to e.g. [22],[23], [24],[25] and [26] for complementary information on those parameters. Nevertheless, there are some reservations from the practical interpretation point of view with respect to if recordings from low ground motions are meaningful in predicting the above-mentioned characteristics for larger ground motions which could be of relevance for such robust structures as NPPs. Only the collection of more data over a large amplitude range will help to address and resolve this issue.

### Conclusions

This contribution does not present any new scientific results or advancements, but rather is intended to provide an overview of the actual state-of-practice and discuss the conceptual framework for physics-based simulations in practical projects and elaborate on the on the issues and interface to engineering demands. Physics-based simulations are state-of-practice but many of the model parameters are not well constraint and are not available for most parts of the world – especially the low to medium seismicity regions, where no faults are identified. Today, finite-fault simulations results are already very useful for comparison purposes (range) but yet not applied as fully equivalent substitute within industry projects. Nevertheless, physics-based simulations are providing a promising outlook for integration in future SHA. The key advantages for integration of finite-fault simulations in SHA are the implicit 3D components of ground motion and the possibility to use the same model for surface fault displacement (rupture) / fault slip hazard assessments.

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