The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of
Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Uncertainties and variabilities in seismic ground response analyses

S. Foti & F. Passeri
Politecnico di Torino, Torino, Italy

A. Rodriguez-Marek
Virginia Tech, Blacksburg, VA, USA

ABSTRACT: Ground response analyses (GRAs) represent a key element for the non-ergodic (site-specific) evaluation of the seismic hazard. In this respect, epistemic uncertainties and aleatory variabilities need to be properly identified, quantified, and managed to obtain consistent estimates. Several collaborative efforts have been carried out in recent years to assess the influence of uncertainties and variabilities in the GRA parameters through benchmark studies. Specifically for site characterization, efforts are required to guarantee a sufficient quality of in situ and laboratory tests. However, benchmark tests have shown the existence of a certain level of “uncompressible uncertainty”. Stochastic models implemented in GRAs are therefore required to evaluate the impact of uncertainties and variabilities on the computed seismic hazard. Such models are to be based on large databases of experimental data to produce consistent estimates. Examples will be provided with a specific focus on geophysical tests for the evaluation of shear wave velocity models, which are likely the most influent parameters in GRAs.

1 INTRODUCTION

1.1 *Motivation*

The prediction of the effects of a seismic event is a multidisciplinary process that involves seismologists, engineers, risk management experts, and public policy experts. The assessment of the seismic risk can be split into three separate components as suggested in the Performance-Based Earthquake Engineering (PEER, Pacific Earthquake Engineering Research center) methodology. These components are usually termed *hazard, vulnerability*, and *exposure*. Each of these components is affected by uncertainties that propagate to the final result. Moreover, the evaluation of the site-specific seismic risk should account both for the contributions of the uncertainties in the engineering approach and the inherent randomness of the seismic phenomenon. For these reasons, a rigorous procedure has to be established and followed (Stewart et al. 2014). This methodology is based on three sequential steps: identification, quantification, and management (IQM) of uncertainties (Passeri 2019).

The seismic *hazard* is characterized in terms of design ground motions expected at a site due to future earthquakes. The evaluation of the seismic hazard is most often performed following the Probabilistic Seismic Hazard Analysis (PSHA) method (Cornell 1968). The factors that control the ground motion are generally grouped into the *source, path*, and *site* terms. The PSHA studies conducted for large areas are usually limited to the study of the source and path contributions with site effects considered only through crude proxies. For a more detailed evaluation of site effects, a common approach is to perform a PSHA study for a *reference* rock condition and then modify the selected ground motions by performing specific site response analyses. In recent years, site-specific PSHA studies have been conducted within the framework of the “non-ergodic” approach (Anderson & Brune 1999). In a non-ergodic PSHA, the uncertainty related to site-to-site variability is removed from the uncertainty in predicting ground motions, and it is replaced by estimates of the epistemic uncertainty in site response at a site. Therefore, a non-ergodic analysis uses site-specific estimates of the median and the uncertainty of future ground motions. In contrast, an ergodic analysis takes spatial averages of the mean site response (i.e., through the use of $V_{S,30}$-based site terms) and ground motion uncertainty and applies them to the predictions of ground motion at a specific site. For this reason, the term "non-ergodic" can be seen as a synonym of "site-specific" (Stewart et al. 2017).

The specific site term is usually evaluated through the analysis of recorded ground motions (i.e., *data-based*) and/or 1D numerical simulations (termed *simulation-based* Ground Response Analyses, GRAs). Both the mean and standard deviation of the site amplification function must be estimated. Note that also 2- or 3D models could be used for the estimation of the site-specific response. Indeed, the most critical point in this framework regards the study of the applicability of a one-dimensional simulation. The analysis of the advantages and disadvantages of each method (i.e., 1D vs. 2- or 3D) should always be carried out, accounting for all the characteristics of the specific problem from a global perspective. Nevertheless, GRAs are still primarily used in this framework for their good compromise in terms of computational demand and number of requested model parameters.

Finally, the nonlinear response of the site deserves further attention. The nonlinear response of natural materials was examined since the '60s along with the experimental observations of earthquake consequences. It is nowadays recognized that natural materials exhibit nonlinearity and hysteresis even at small strains. Therefore, both the abovementioned approaches for site response analyses (i.e., data-based or simulation-based) should account for the effects of nonlinearity of the soil response on the frequency contents and amplification of ground motions.

1.2 *The IQM methodology*

Accounting for *uncertainties* in the evaluation of the non-ergodic seismic hazard requires a comprehensive framework for their *identification, quantification, and management* (IQM). First, the general uncertainties have to be *identified* and classified in two main groups: Epistemic Uncertainty (EU) and Aleatory Variability (AV). Epistemic is the transliteration of the Greek term meaning "scientific knowledge", which Plato opposed to *dòxa*, the opinion. In contemporary philosophy, it is a set of positive knowledge and scientific theories. On the other hand, aleatory derives from the Latin word *alea*, "dice", and it represents a total uncontrollable and random process, as in gambling.

Beyond the semantics, nowadays the epistemic and aleatory concepts have been used in different scientific areas. One of the first comprehensive discussions of the topic is presented in Budnitz et al. (1997): the epistemic portions are *"due to the lack of knowledge, the uncertainties arising because our scientific understanding is imperfect for the present, but are of a character that in principle are reducible through further research and gathering of more and better earthquake data"*. The aleatory portion regards *"uncertainties that for all practical purposes cannot be known in detail or cannot be reduced"*. Budnitz et al. (1997) also admitted that the division between the two different types of uncertainty is somewhat arbitrary. This is because, conceptually, some of the processes and parameters whose uncertainties are classified here as aleatory may be partially reducible through more elaborate models and/or further studies. Toro et al. (1997) distinguished the reducible and non-reducible characteristics of the two contributions and coined the term "randomness" for aleatory variability, suggesting the adoption of randomization methods for reproducing this type of variability.

A further contribution to the clarification of the EU and AV concepts is given by Bommer (2003). In his opinion paper titled *"Uncertainty about the uncertainty in seismic hazard analysis"*, the author included the terms epistemic and aleatory in the "probabilistic arsenal". Later, a rigorous distinction between epistemic uncertainty and aleatory variability is given by Abrahamson & Bommer (2005) and Bommer & Abrahamson (2006). Der Kiureghian & Ditlevsen (2009) discussed the sources and characteristics of uncertainties in engineering modeling for risk and reliability analyses. Their primary distinction criterion is based on the possibility of reducing these sources.

After the identification step that distinguishes (whenever possible) the EUs and AVs, the following step regards the *quantification* of uncertainties. A critical aspect for EUs and AVs is their balancing (i.e., the amount of each component in the global problem). It must be clear that a specific amount of the two contributions is involved in each engineering application. The amount of EUs and AVs should be carefully evaluated, moving from the global scale of the problem to a smaller scale. Each source of uncertainty should be rigorously classified before any further application is performed. In particular, for seismic hazard assessment studies the spatial scale of the problem represents an essential aspect in the quantification of uncertainties and variabilities.

Once the identification and quantification steps are completed, the *management* step should be considered (Budnitz et al. 1997). In particular, Abrahamson & Bommer (2005) assumed that the epistemic uncertainties should lead to alternative hazard curves, whereas the aleatory variabilities have to modify the shape of the single curve. Epistemic uncertainties should be handled establishing a rigorous logic tree approach with weights assumed after an engineering judgment. On the other hand, the aleatory variabilities have to enter the hazard integral as the PSHA is defined as the result of integration (i.e., aggregation) over AVs (e.g., future earthquake locations, future earthquake magnitudes). On a local scale for GRAs, aleatory variabilities are mainly related to lateral variations of ground properties.

2 EPISTEMIC UNCERTAINTIES AND ALEATORY VARIABILITIES IN GRAs

2.1 *General problem*

Site response is the process in which modifications of the seismic waves are produced by variations of the material properties and/or surface topography close to the Earth's surface (Aki 1993, Kramer 1996). A site response analysis considers the differences in the expected motion for amplitude, frequency content, and duration, between a reference condition and a defined site condition. Site response studies are usually performed by means of recorded data and/or GRAs. Both approaches allow for a specific (non-ergodic) evaluation of the mean hazard at the site and the estimation of EUs and AVs (Stewart et al. 2014). Indeed, the product of both approaches is a mean amplification function along with the associated standard deviation.

The data-based methods estimate the site response by collecting a large number of high-quality records (if available), whereas for GRAs a significant number of simulations should be performed in a probabilistic (i.e., stochastic) framework, often leading to high computational demands. However, it is mostly recognized that ground response analyses are a powerful tool to investigate the role of EUs and AVs in the site-specific hazard assessments (Field & Jacob 1993). A set of GRAs allows studying the effects of uncertainties and variabilities in the soil property measurements and the adopted numerical approach. Ground response analyses are based on the assumption that all boundaries are horizontal, extend infinitely, whereas the response is dominated by vertically- propagating shear waves. These formulations involve the propagation of SH waves from the base rock to the ground surface through soil layers that can be modeled as lumped or distributed masses. However, it is clear that the influence of the non-vertical incidence of the waves, surface waves, basin effects, and topographic effects cannot be studied with GRAs. These additional sources of uncertainty could be handled using 2- or 3D models in conjunction with an appropriate site characterization. The use of 2- or 3D models includes a significant number of parameters, which critically complicate the discussion and the propagation of uncertainties on the results, particularly for nonlinear simulations. For these models, the distinction of each singular contribution to the final uncertainty or variability appears still very challenging (Taborda et al. 2010, Amorosi et al. 2016, Hollender et al. 2018). For these reasons, ground response analyses are still primarily used for the non-ergodic assessment of the site response and, particularly, within the IQM of uncertainties and variabilities.

Stewart & Baturay (2001) showed that non-ergodic GRAs always resulted in better predictions of the mean amplification than ground motion prediction equations. Moreover, Baturay & Stewart (2003) showed a better result regarding both bias and variability and agreement with the spectral shape, compared to the ergodic methods. However, it should be acknowledged that mixed and controversial results have been obtained using GRAs in the literature predicting the mean site response (see Passeri 2019 for more details). These evidences indicate that the user should possess specific expertise and particular knowledge of the global procedures and phenomena. This is particularly true in case of strong nonlinear responses of the site (Hashash et al. 2010, Kim et al. 2016, Régnier et al. 2018) or for complex geological environments (Thompson et al. 2012). Indeed, an initial assessment of the applicability of GRAs should always be performed, for example, by a taxonomic procedure (Baise et al. 2011). Nevertheless, the GRA always represents a step forward for the evaluation of the mean response of the site, compared to ergodic methods. Ground response analyses also represent the only chance, when no records are available at the specific site (Rodriguez-Marek et al. 2014, Bommer et al. 2015).

In addition to the mean amplification, an important step regards the identification/quantification of different contributions of EUs and AVs in ground response analyses. There are examples for which the resulting uncertainties and variabilities can be biased (Goulet et al. 2007). Generally, uncertainties and variabilities are overestimated for low periods and underestimated for long periods of the response spectrum (Rodriguez-Marek et al. 2014, Afshari & Stewart 2015), compared to the results obtained with the data-based approaches. However, other examples showed consistency with the variability obtained with recorded data (Papaspiliou et al. 2012, Kaklamanos et al. 2013). These inaccuracies obtained by the ground response analyses can be due to an inadequate quantification step in the IQM process. Indeed, the amount of epistemic uncertainties is dramatically dependent on the specific engineering application. For each problem, an ad-hoc evaluation of the relevant EUs should be performed. Specific expertise and a deep understanding of the physics of the problem is fundamental in the quantification of the EUs. Similarly, the amount of aleatory variabilities in the ground response analyses should be explicitly quantified depending on the size of the studied area and its geological complexity. This is inherent in the definition of spatial variability (i.e., AV). For example, if the analyst considers a single building/facility, in a restricted and spatially homogeneous area, the most critical contribution to uncertainty in GRAs comes from the epistemic uncertainties. Of course, enlarging the studied area in geologically complex environments (e.g., for road projects or microzonation of heterogeneous regions), the contribution of the aleatory variability increases and can be much more influent than epistemic uncertainties (Passeri 2019).

2.2 *Sources of uncertainties and variabilities*

Six main factors can be identified as sources of uncertainties on the results of GRAs (Figure 1), in agreement with Idriss (2004) and Rathje et al. (2010):

- Shear wave velocity (V_S) profile;
- Nonlinear approach;
- Modulus reduction and damping (MRD) curves;
- Input motions;
- Shear strength;
- Small strain damping (D_{min}).

Idriss (2004) and Rathje et al. (2010) did not explicitly identify the shear strength and the small strain damping ratio as crucial parameters. In this work, also these further sources of uncertainties and variabilities are briefly presented, even if they are likely of second-order importance (at least for shallow profiles, as discussed in Cabas & Rodriguez-Marek (2018)) compared to the four main ingredients. In fact, for these two sources, there is not a large number of studies in the literature where only their influence on the results is only mentioned.

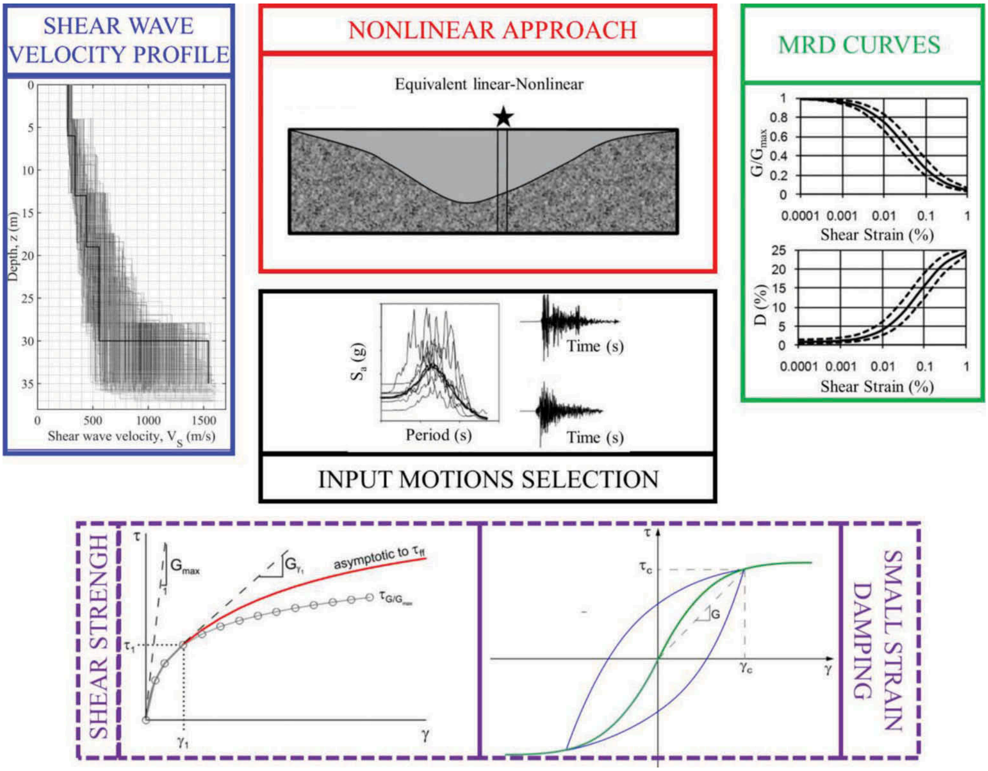

Figure 1. Main factors that cause uncertainties in the results of a ground response analysis.

However, D_{min} and the shear strength can strongly influence the small strain and the large strain response, respectively.

2.2.1 *V_S profile*

The shear-wave velocity profile is the input parameter that governs wave propagation in the elastic medium. It controls resonance frequencies and amplifications, especially for shallow depths. The V_S profile controls the mechanical amplification/deamplification of the motion at the interfaces. The adopted V_S profile for a ground response analysis must be based on in situ geophysical measurements (Stewart et al. 2014). Each type of test shows a different amount and proportion of EUs and AVs (Foti & Passeri 2018, Passeri et al. 2019), also depending on the site complexity (e.g., deposition environment) (Rathje et al. 2010, Baise et al. 2011, Thompson et al. 2012).

Table 1 specifies the sources of EUs and AVs identifiable for the most common *invasive* (down-hole, cross-hole, PS suspension logging) and *non-invasive* (seismic refraction, surface wave analysis, and horizontal-to-vertical spectral ratio, HVSR) seismic tests. This table provides a reference for to the analyst who adopts seismic tests for near-surface site characterization.

The most critical observation regards the quantification of EUs and AVs in relation to the specific test and the characteristics of the investigated site. The identification and quantification of the EUs is dependent on the type of test, and every single source is specified in Table 1. It is necessary to consider also the different test resolution with depth. For example, the achievable resolution of surface wave tests decreases as the depth increases while invasive tests guarantee a good (for the down-hole test) or excellent (for the cross-hole and PS suspension logging tests) detail even at considerable depths. On the other hand, for AVs, each geophysical test investigates a different volume of the deposit, which should be compared to the extension

Table 1a. Major sources of epistemic uncertainties and aleatory variabilities for the most adopted invasive geophysical tests (after Passeri 2019).

Test	Epistemic uncertainties	Aleatory variabilities
Down-hole seismic testing	• Gross errors in the source, receivers, and acquisition system (inappropriate instruments) • Inadequate preparation of the borehole (i.e., casing, grouting) • First arrivals picking (mainly for pseudo- and true-interval interpretations) • Potential near-surface refractions • Triggering (particularly for pseudo-interval method interpretations) • Decreasing resolution with depth and low-energy sources • Insufficient coupling of the shear beam with the soil • Straight ray path assumption (true- and pseudo-interval and slope-based interpretations) • Inverse problem non-uniqueness (raytracing velocity interpretation) • Preliminary choice of layer discretization (slope-based interpretation method) • Tube waves generation (especially in water-filled boreholes)	None (restricted and localized measurements)
Cross-hole seismic testing	• Gross errors in the source, receivers, and acquisition system (inappropriate instruments) • Inadequate preparation of the boreholes (i.e., casing, grouting) • First arrivals picking (trigger, P-, and S-wave) • Potential refractions and generation of head waves • Interpretative 1D model inadequateness (vertical homogeneity of the deposit) • Triggering/timing (in the case of 2-holes setup) • Decreasing resolution with the distance between the boreholes and low-energy sources • Insufficient coupling of the source lowered into the borehole with the surrounding soil • Borehole/cone vertical deviation	None (restricted and localized measurements)
Susp. logging	• Picking strategies for first arrivals • Possible detection of tube waves for first arrivals (particularly pronounced with heavy casing and thick grout) • Poor signal quality • Very restricted investigated volume • Insufficient coupling of the source lowered into the borehole with the surrounding soil	None (restricted and localized measurements)

of the area under analysis (Figure 2). The most localized measurements are obtained by using the PS suspension logging. Then, down-hole and cross-hole tests that investigate a volume depending on the test configuration and source-receiver distance. Finally, non-invasive tests investigate a large volume and produce an average response for the particular deposit (i.e., more appropriate in cases when only $V_{S,30}$ is required). For these reasons, the quantification of the AVs requires a systematic analysis of the site and test contributions to variability.

Table 1b. Major sources of epistemic uncertainties and aleatory variabilities for the most adopted non-invasive geophysical tests (after Passeri 2019).

Test	Epistemic uncertainties	Aleatory variabilities
Seismic refraction	• Gross errors in the source, receivers, and acquisition system (inappropriate instruments, particularly in the case of S-wave refraction test) • Triggering/timing • Influence of pavements, asphalt or concrete (or shallow thin stiff layers as desiccated crusts) • Picking strategies for first arrivals • Insufficient coupling of the source (e.g., shear beam) with the soil • Presence of stiff layers on top of softer ones • Stratigraphy with thin interbedded materials (hidden layer and refraction equivalence) • Inverse problem non-uniqueness (tomography and multiple shots interpretation)	Dependent on the spatial length of the array and the interpretation strategy. Tomography and Generalized Raypath Method allow for the reconstruction of 2D models
Surface wave testing	• Gross errors in the source, receivers, and acquisition system (inappropriate instruments) • Insufficient coupling of the geophones with the ground or the pavement • Inadequate geometric initial design of the array or recording parameters, and/or insufficient number/locations of shots (for active) • Inadequate energy or narrow frequencies band produced by the source (for active) • Inadequate geometric initial design of the array or of recording parameters (for passive) • Insufficient ambient vibrations level (for passive) • Lack of a critical interpretation of the experimental dispersion curve (maximum and minimum resolvable depths and the initial range of possible solutions, possible velocity inversions, relationship with the $V_{S,z}$) • Higher modes misinterpretation • Incoherent noise (e.g., electric or electronic noise) • Near-field effects, body waves, air blast, incoherent noise (e.g., anthropic activities) and non-planar Rayleigh wavefront (for active) • Nondirectional energies (f-k methods), irregular arrays and modes mixing (SPAC methods) (for passive) • Ill-posedness of the problem solution non-uniqueness	Dependent on the spatial length of the array (for active). Sites with strong lateral/spatial variations should be avoided. Passive tests measure ambient vibrations that provide a global average of the site response. The use of multiple arrays can help in the identification of lateral variations by comparing the results. Spatial windowing for long arrays can be used to obtain approximate 2D models

(*Continued*)

Table 1b. (*Continued*)

Test	Epistemic uncertainties	Aleatory variabilities
	• Nonlinearity and mixed-determination of the problem • Investigation of a limited space of solutions • Unacceptable differences between experimental and theoretical dispersion curve evaluated by the misfit function • Inadequacy of the inversion model made by stacked horizontal layers (i.e., the presence of lateral variations) • Wrong use of a-priori information (e.g., borehole logs and saturation depth)	
HVSR	• Gross errors in the receiver (especially the natural frequency of the sensor) and acquisition system (inappropriate instruments) • Insufficient coupling of the geophone with the ground • Short acquisition windows • Noisy environments (i.e., incoherent noise) • No evidence of a clear peak (inversely dispersive or outcrop sites, very low-frequency resonance for soft sites, insufficient ambient vibrations level) • Use of the test as a standalone method for performing dynamic site characterization (i.e., estimation of the V_S profile)	These tests measure ambient vibrations that provide a global average of the site response regardless of lateral variations. Multiple tests can help in the identification of lateral variations

Numerous inter-method (i.e., invasive vs. non-invasive) and intra-method (i.e., within the same class of tests) comparisons are reported in the literature. These benchmarks conducted for site characterization purposes are usually based on independent analysis of the experimental data and called “blind tests”. They showed that the agreement between the results is good if the tests are scrupulously conducted and interpreted. However, a certain level of “uncompressible uncertainty”is always detected and can be due to the AV in the measurements. Uncertainties can be reduced with the adoption of testing standards and/or guidelines (e.g., Foti et al. (2018))

The first pioneer example is proposed by Boore & Brown (1998). They attested a substantial underestimation of V_S for the shallower layers, and a substantial overestimation for the deeper layers with the surface wave methods compared to down-hole tests. At that time, the latter were indisputably considered as the true target. They stated that a possible explanation for the difference could be the different investigated volume (classifiable as AV).

Brown et al. (2002) expressed more confidence in the surface wave testing methods showing ten examples of inter-method comparisons. In one case, the site presented no lateral variations, and the surface wave test array was very close to the invasive tests. Likewise, the comparisons of the surface wave test profile against down-hole and suspension logging results were very satisfying. For a second example, there were more substantial differences in the inter-method comparison, especially close to the surface. Brown et al. (2002) generally found lower values of the velocity close to the surface by the surface wave test (i.e., around 15%). Furthermore, it should be noted that the down-hole tests were interpreted with the known stratigraphy, while for the surface wave test this information was not available. Also, the authors confirmed that the usual difference might be related to aleatory variabilities seen as lateral variations of different investigated volumes (Boore & Brown 1998).

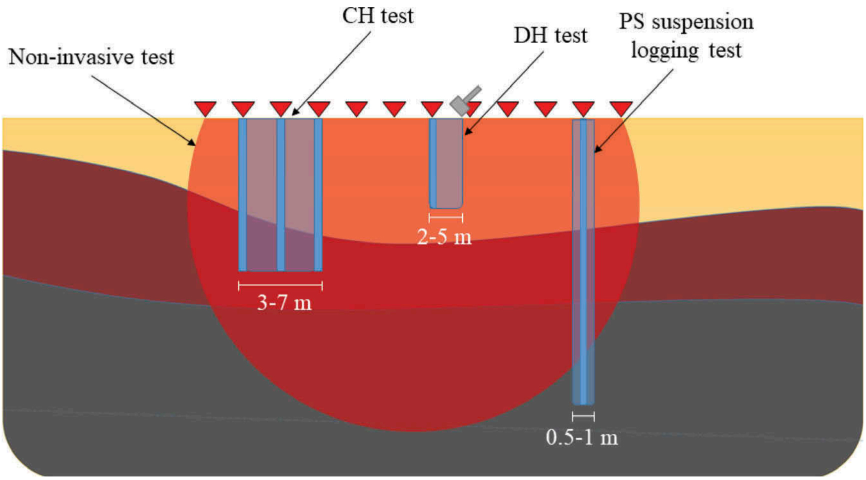

Figure 2. Illustration of the complex contribution of aleatory variabilities within each geophysical method performed (after Passeri 2019).

A benchmark for site characterization was recently carried out in the InterPACIFIC project (Garofalo et al. 2016a, Garofalo et al. 2016b), in which three sites were characterized using repeated realizations of invasive and surface wave tests. The sites were selected to be representative of different stratigraphic situations: a rock outcrop characterizes the site of Cadarache; the Grenoble site consists of coarse deposits, which are alluvial relatively stiff with a deep seismic substrate; finally, the Mirandola site has relatively deformable deposits above a stiff substrate placed at around 100 m depth. For each site, down-hole, cross-hole, seismic dilatometer, and suspension logging tests were repeated by different analysts.

Furthermore, a surface seismic dataset was distributed to different groups of analysts who interpreted it using different approaches. The results obtained in the study show comparable levels of uncertainty between invasive and surface wave tests. However, the lower resolution guaranteed by the surface wave tests is reflected in greater uncertainties in the identification of stratigraphic layers and consequently in the estimation of interval velocity, especially at significant depths.

2.2.2 *Modulus reduction and damping (MRD) curves*

The modulus reduction and damping curves are the input parameters in equivalent-linear GRAs that characterize the nonlinear response of each material. Modulus reduction and damping curves describe the shape of the backbone curve (MR) and the relationship between hysteretic damping (D) and shear strain. MRD curves can also be used to constrain parameters of nonlinear stress-strain models. Various laboratory tests can be used to evaluate modulus reduction and damping curves (e.g., resonant column, cyclic triaxial test, cyclic torsional or simple shear test), however, they are often selected from a large number of empirical models proposed in the literature (Passeri 2019). Each empirical model considers different variables (e.g., IP, mean confining effective stress, OCR, K_o, frequency). Cross-validation between laboratory and empirical curves is always encouraged, before starting large-strain numerical simulations (Régnier et al. 2018).

Along with the mean values, for each shear strain level, some empirical formulations also give the EUs as standard deviations. This uncertainty represents experimental errors and can be used for a stochastic study of the parameters sensitivity (Darendeli 2001, Zhang et al. 2005). A further EU is related to the adoption of the empirical correlation itself (Papaspiliou et al. 2012, Faccioli et al. 2015, Kaklamanos et al. 2015) and great care should be taken respecting the model assumptions (e.g., strain range applicability) (Baturay & Stewart 2003, Stewart et al. 2014). In case of laboratory results, usual experimental limitations (state of stress, boundary conditions, and sample disturbance) should be evaluated as EUs, particularly in case of high confining pressures (i.e., deep deposits) (Park & Hashash 2005). The aleatory variabilities in the MRD curves can be seen as the natural randomness of these properties at the site scale, always quantifying a realistic amount of variability, due to the geological complexity and the size of the study (Park & Hashash 2005).

2.2.3 *Input motion selection*

The input motions for GRAs should correspond to a seismic demand consistent with the hazard at the reference condition as defined by PSHA studies. There are two types of inputs for a GRA: recorded time histories and stochastic/physics-based motions (Boore 2003). Generally, recorded time histories that reproduce multiple hazard levels are used for GRAs to better constrain the evaluation of the site amplification function. The goodness of fit can be evaluated following the approach by Kottke & Rathje (2008) which accounts for the fit with both the mean and standard deviation of the target spectrum. Moreover, the input motion suite has to produce stable results (Baturay & Stewart 2003, Bazzurro & Cornell 2004, Rathje et al. 2010).

An alternative to real records is the use of stochastic/physics-based motions. The use of these motions can be very appealing when there is a small number of real records to choose from, and when a large number of analyses are required. However, care has to be taken for the correct simulation of the wave propagation from the source to the near-surface.

The EU in the selection process is due to the choice of the hazard level, the type of reference spectrum (e.g., uniform hazard spectrum or conditional mean spectrum), and the matching approach adopted (scaled or modified). Then the type and number of inputs (Rathje et al. 2010), the searching method, and the consistency with the reference condition (Passeri et al. 2018), also accounting for near-field and far-field effects (Stewart et al. 2014).

In this case, the AV should be due to the source and path spatial variabilities that control the hazard at the reference condition. These aleatory variabilities are included in the PSHA results in terms of spectral standard deviations that have to be respected.

2.2.4 *Nonlinear approach*

Several approaches may be used to simulate the nonlinear response of a site. A GRA is typically implemented in numerical codes adopting one of the following methods to account for the nonlinear response of the medium: frequency-domain EQuivalent Linear (EQL) and time-domain NonLinear (NL). However, also visco-ELastic (EL) analyses are useful for the initial validation of the model. Note that the choice of the nonlinear approach regards only the epistemic uncertainties, as it is specifically due to pure model uncertainty.

Depending on the expected strain level and/or the possible development of excess pore pressure (i.e., total or effective stress analyses), the choice should be made between EQL and NL approaches (Kramer & Paulsen 2004, Stewart et al. 2014, Kim et al. 2016). In particular, the EQL method is a simplified and usually more stable procedure, however, NL analyses are catching on in the usual practice showing more consistent results, even if they are more computationally demanding. Many shear strain applicability boundaries are suggested in the literature for the use of a given approach. However, a single value cannot be proposed, as the effectiveness of each method is depending on the specific characteristics of the model.

Equivalent linear analyses should be avoided in case of strong nonlinear response and large induced shear strains (i.e., soft, sandy soils subjected to strong high-frequency motions) (Baturay & Stewart 2003, Asimaki et al. 2008, Asimaki & Li 2012, Kim et al. 2013, Kaklamanos et al. 2015, Kim et al. 2016) and in case of no convergence of the iterative process. A further source of epistemic uncertainties in the EQL analysis is related to the time-independent assumption of the converged stiffness and damping parameters (Kaklamanos et al. 2013). In particular, a Shear Strain Ratio (SSR) is adopted in the EQL analyses to scale the shear strain time history by a factor less than one (usually 0.65). This scaling should account for the time-invariant choice of the operative mechanical parameters. However, there are no specific studies that prescribe a consistent value, depending on other simulation parameters (Kim et al. 2016).

The results of NL approaches should be initially verified against more straightforward methods (EL or EQL) and experimental evidence (e.g., from down-hole arrays) as the user expertise plays a dramatic role in this framework (Kwok et al. 2007, Stewart & Kwok 2008, Hashash et al. 2010, Kaklamanos et al. 2015, Kim et al. 2016). Many specific sources of EUs can be identified in the NL methods. The PRENOLIN (PREdiction of NOn-LINear soil behavior) project investigated the primary sources of EU in ground response analyses due to differences in NL codes and various constitutive models (Régnier et al. 2016, Régnier et al. 2018). The project was organized in two steps: the verification phase (i.e., the comparison between numerical codes on simple idealistic cases) and the validation phase (i.e., predictions of numerical estimations with actual strong-motion recordings obtained at well-known sites). Twenty-three different computational codes were used in this international benchmark for the assessment of the state-of-the-art of NL ground response analyses. The results of these studies demonstrated that the most critical aspects for an NL ground response analysis are numerical integration schemes, damping formulations, constitutive models and parameters calibration (curve fitting), especially in the case of pore water pressure generation models. The boundary conditions (mainly for the input motion boundary) and layers thickness should also be checked to guarantee a consistent wave propagation within the model. Other references on this topic can be found in Passeri (2019).

2.2.5 *Shear strength*

The shear strength is to be taken into account when very large strains are expected. Indeed, MRD curves are typically obtained with tests that do not cover the failure conditions. An incorrect prediction of the failure conditions may lead to unrealistic results. Several procedures to ensure a correct transition of the MRD curves to failure conditions are proposed in the literature (Yee et al. 2013, Zalachoris & Rathje 2015, Shi & Asimaki 2017, Régnier et al. 2018).

The associated EU has to be evaluated depending on the type of laboratory test adopted for the evaluation of the shear strength. A further source of EUs is the model adopted for "merging" the small-strain and large-strain (i.e., at failure) behavior (Li and Assimaki 2010). An example adopting the Yee et al. (2013) is presented in Zalachoris and Rathje (2015). However, a new perspective for consistent modeling from stiffness to strength is given in Shi and Assimaki (2017). The authors showed that their model could reproduce both the small-strain behavior from a resonant column test and a moderate-to-large strain behavior from the direct shear test. In addition, the empirical correlations they propose between the shear wave velocity and the model parameters are appealing for the initial calibration process and can capture the material strength. As for the MRD curves, the contribution of aleatory variabilities depends on the geological variability (complexity) of the project area under analysis.

2.2.6 *Small strain damping* $D_{\min}$

Laboratory measurements of damping at low strains ($D_{\min}$) are generally at odds with experimental evidence from down-hole seismic arrays. In fact, at the site scale, larger values of energy loss are observed at very low strain levels (Régnier et al. 2018), likely due to complex wave propagation interaction (Stewart et al. 2014). One of the controlling phenomena is the wave scattering, which produces a variable energy loss, depending on the site conditions. This phenomenon is more evident in the case of strong impedance contrasts (Zalachoris and Rathje 2015). The central problem of this parameter regards the amount of damping at various depths (even five times the one from laboratory tests). This $D_{\min}$ profile can be evaluated, for example, using weak motions recordings and back-calculation procedures (Park & Hashash 2005). Then a complex mix of EU and AV strongly influences this parameter, as it represents the portion of geometrical damping that controls the global spatial wave propagation.

Table 2. Summary of the most significant sources of epistemic uncertainties and aleatory variabilities in ground response analyses (after Passeri 2019).

Source	Epistemic uncertainties	Aleatory variabilities
V_S profile	Epistemic uncertainties are associated with measurement errors; AVs are associated with spatial variability. Different tests used to measure V_S in the field have different amounts of EUs, and capture spatial variability (AV) in different ways, depending on the site complexity (see Table 1)	
MRD curves	Regression residuals and specific characteristics of the adopted model (in the case of empirical curves). Experimental measurements limitations (in the case of laboratory tests). Cross-validation between laboratory and empirical curves is always encouraged.	Variation of these properties at the site scale depending on the geological complexity and the size of the study
Input motion selection	• Choice of the hazard level • Type of reference spectrum and goodness of fit evaluation • Matching approach • Number and type of inputs • Searching method • Consistency with the reference condition • Near-field and far-field effects	Variability included in the reference hazard result that is obtained by the PSHA
Nonlinear approach	EQL • Time-independent parameters • High nonlinear responses (i.e., soft, sandy soils subjected to strong high-frequency motions) • Convergence • Shear Strain Ratio (SSR) assumption • Total stress analysis (possible development of excess pore pressures) NL • Integration schemes (e.g., implicit or explicit) • Damping formulations • Constitutive models and parameters calibration (curve fitting), especially in the case of pore water pressure generation models • Boundary conditions (especially at the halfspace) and layers thickness • Requirement of a specific expertise	No aleatory variability (1D analysis)
Shear strength	Dependent on the laboratory test used for the shear strength evaluation and in situ stress conditions. Choice of the merging law (i.e., between small strains and large strains) or of the constitutive model.	Variation of these properties at the site scale depending on the geological complexity and the size of the study
Small strain damping	Lack of a rigorous knowledge of the amount of dissipation phenomena at the site scale, especially for high frequencies. Adopted model in NL analyses for the additional viscous damping, particularly for low periods.	A portion of geometrical damping that is controlled by the global spatial wave propagation

Moreover, for nonlinear analyses, further EUs are due to the numerical approach that is implemented for the addition of the viscous damping to the hysteretic damping (Hashash & Park 2002, Park & Hashash 2004, Phillips & Hashash 2009).

2.2.7 *Summary*

Table 2 summarizes the most common sources of EUs and AVs involved in each parameter of a GRA and discussed in previous sections.

3 EXAMPLES OF IQM METHOD APPLICATIONS

This section illustrates three examples of an application of the identification, quantification, and management (IQM) method. The first regards the shear-wave velocity profile and it is based on the results of the blind test conducted during InterPACIFIC project at Mirandola (Italy). For this example, the use of a new geostatistical model is presented. The second example studied the influence of uncertainties and variabilities included in the MRD curves for the Groningen Gas Field (Netherlands). The last contribution concerns the benchmark conducted within the PRENOLIN project that investigated the influence of the EUs due to different approaches adopted to model the nonlinearity of the material.

3.1 *Shear wave velocity profile*

This study was aimed at validating a new geostatistical randomization model described in Passeri (2019). Ground response analyses were performed for the site of Mirandola (Italy) where multiple V_S profiles by invasive and surface wave methods were available. The geostatistical model is applied to one base-case solution to reproduce the EUs and AVs empirically estimated in situ by the different teams of the InterPACIFIC project (Garofalo et al. 2016a, Garofalo et al. 2016b). To isolate the effects of the V_S profile on the results of the ground response analyses, all other parameters (see Section 2.2) were kept constant. The results of the geostatistical model are compared to the procedures prescribed by EPRI (2013) for the management of the uncertainties and variabilities in V_S profiles. These comparisons are conducted for both the viscoelastic and nonlinear responses. Finally, the study compared the mean and standard deviations of the obtained responses in the light of a hazard-consistent evaluation of the ground motion at the site. The nonlinear analyses and the results for invasive tests are not reported here. The reader can refer to Passeri (2019).

In the following, the results obtained from non-invasive tests are considered. Only the subset of V_S profiles that clearly identified a marked impedance contrast at depth was considered for ground response analyses (Passeri et al. 2019). This selection criterion provided 12 profiles from non-invasive tests. The solution obtained by the University of Texas (UT) at Austin (Griffiths et al. 2016) was considered as the *base-case*.

For critical facilities, the management of EUs and AVs is usually conducted with the procedures proposed in EPRI (2013). The first method prescribes the creation of profiles (termed upper/lower range profiles) shifted by a value of V_S logarithmic standard deviation (i.e., assuming an inter-layer perfect correlation). In this study, the minimum value of 0.25 prescribed by EPRI (2013) was applied to the base-case profile (Passeri et al. 2019). Figure 3a shows that the upper/lower range interval velocity profiles generally bracket the values for the non-invasive V_S experimental profiles. However, Figure 3b illustrates the dramatic alteration of the harmonic average profiles obtained by the upper/lower range profiles. For example, the base-case profile has a $V_{S,30}$ = 213 m/s, the lower range profile has a $V_{S,30}$ = 166 m/s (i.e., even different soil class for NEHRP and EC8), and the upper range profile has a $V_{S,30}$ = 274 m/s.

Figure 3 also shows 1000 profiles obtained by the standard Toro (1995) model around the base-case profile. This method is prescribed by EPRI (2013) for the management of AVs in shear wave velocity profiles. The logarithmic standard deviation of the base-case profile was assumed as suggested by Stewart et al. (2014). The Poisson's model parameters are assumed equal to the ones suggested by Toro (1995), as for the parameters of the inter-layer correlation model. The lognormal distribution of the halfspace depth is included in the randomization with a logarithmic standard deviation equal to 0.1. In this case, both the interval velocity and harmonic average profiles are entirely out of range, compared to the experimental results. Note that this is true even if the reduced V_S standard deviation proposed by Stewart et al. (2014) is adopted (an almost doubled value is suggested in Toro (1995)).

The last set of 1000 profiles presented in Figure 3 (in gray) were obtained from the new geostatistical model (Passeri 2019) around the base-case solution. The results of this second randomization excellently reproduce the EUs and AVs experimentally estimated at Mirandola, especially in terms of harmonic average profiles (Figure 3b).

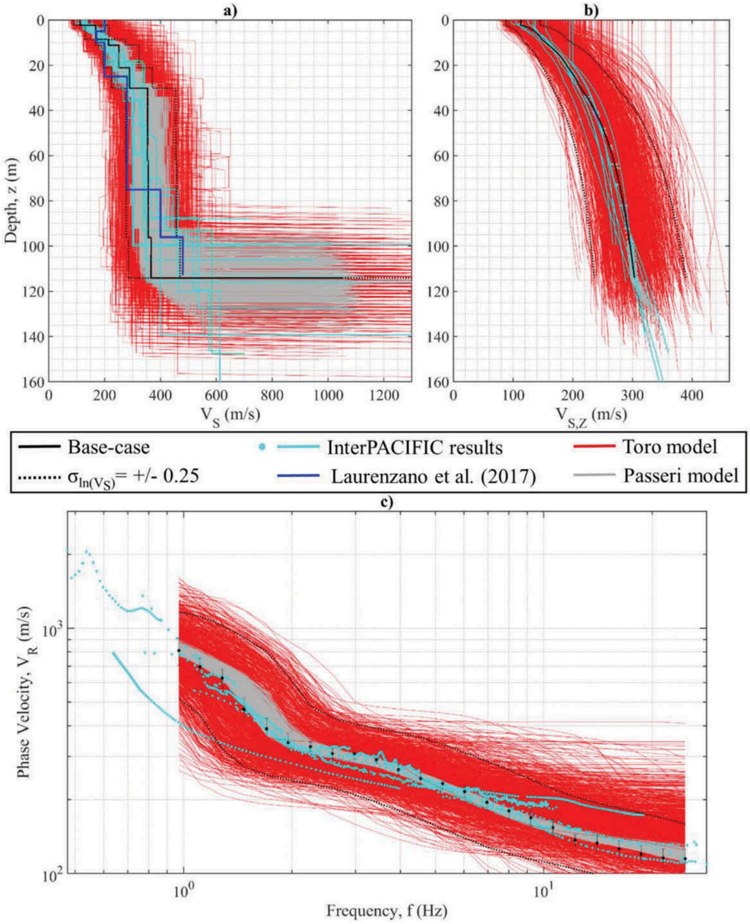

Figure 3. Results obtained for the site of Mirandola. a) Shear wave interval velocity profiles, b) shear wave harmonic average profiles, and c) dispersion curves (modified from Passeri 2019).

A Further confirmation of the problems encountered with the methods proposed in EPRI (2013) is given in Figure 3c. This figure shows the comparison of the Theoretical Dispersion Curves (TDCs) with the Experimental Dispersion Curves (EDCs). The latter can be considered as a specific characteristic of the site. Note that the dispersion curves corresponding to the V_S profiles obtained following the EPRI approaches do not match the experimental dispersion curve (i.e., the available experimental information is not honored). On the contrary, the TDC calculated from the profiles randomized with the new geostatistical model are in excellent agreement with the EDC as estimated by all the participants in the benchmark.

Linear, viscoelastic analyses were conducted for each V_S profile of the study. Figure 4a shows a comparison of the surface-to-halfspace (‘outcrop’ motion) Theoretical Transfer Functions (TTFs). The figure also includes the average HVSR resonant frequency peak (f_0) measured around the site during the InterPACIFIC project (Prof. Brady R. Cox, personal communication) and the Experimental Transfer Function (ETF) as estimated by Laurenzano et al. (2017) by processing the data from the down-hole array installed at the site.

The upper/lower range profiles exhibit f_0 values well outside the range of the measured V_S profiles. The scaling of the base-case profile produces a consequent inacceptable scaling of both TTFs (Figure 4a). Interestingly, the amplitudes of the TTFs are preserved, as the impedance contrasts are also linearly scaled.

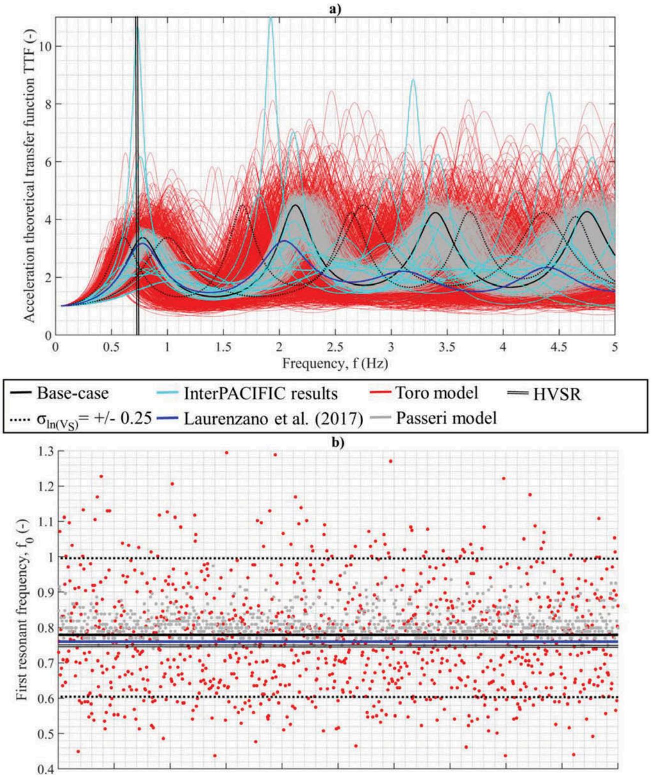

Figure 4. Results of the visco-elastic analyses. a) Theoretical transfer functions and b) scatter of the first resonance frequencies (modified from Passeri 2019).

The profiles obtained with the Toro model (1995) show scattered amplitude peaks concerning the base-case profile. This is further evidence that these profiles do not reproduce well the small strain (i.e., elastic) soil behavior and the site signature corresponding to the resonant frequency of the site (i.e., HVSR f_0). In this context, the V_S profiles are altered, and the visco-elastic response reflects the results of the randomization.

On the contrary, the profiles obtained with the new geostatistical model show consistent results. The agreement is confirmed for both resonant frequencies and amplitude peaks of the ETF.

The observations above are also valid for Figure 4b, where the first resonant frequency of the TTF for each of the 1000 realizations is plotted. Note that these viscoelastic resonant frequencies are a fundamental signature of the profile, and should be in accordance with the independent experimental site signatures (i.e., HVSR peak and the resonant frequency of the ETF). Also, the asymmetric scatter of the results is due to the lognormal distribution that is adopted for the randomization process (i.e., logarithmic distribution as seen on a linear scale).

Similar results are obtained for EQL GRAs (Passeri 2019). Consistency in the viscoelastic behavior is indeed a prerequisite of the consistency also for nonlinear responses.

3.2 *MRD curves*

Bahrampouri et al. (2018) presented a study that investigated in depth the influence of EUs and AVs on the seismic hazard assessment study of the Groningen gas field. The authors systematically investigated the influence of uncertainty in V_S profiles and in MRD curves on the results of EQL ground response analyses. For the purposes of this paper, we focus on the results regarding the influence of the variability of the MRD curves. Figure 5 shows the contribution (as envelope of all the results obtained for 19 zones) of the uncertainty in MRD curves to the final uncertainty in amplification functions (as logarithmic standard deviations, Φ), both for low-intensity (i.e., motions that resulted mostly in linear response) and high-intensity motions (i.e., motions that resulted in non-linear site response). The input motions were accurately generated with a stochastic model that was developed specifically for the seismic hazard project. For low-intensity motions, the contribution of MRD curves uncertainty is significant (i.e., larger than about 0.15 in natural log units) for periods slightly higher than 0.1 s. As expected, the effects of MRD curves uncertainty increase for larger strains and strong nonlinear behavior and are highly site-dependent (Figure 5).

3.3 *Nonlinear method*

Besides the EU and AV due to input parameters, a specific focus on the EUs due to the specific nonlinear adopted approach is given in Régnier et al. (2016) and Régnier et al. (2018). The increasing spread of nonlinear approaches led the authors to a systematic assessment of the performance of the most common GRA nonlinear codes. In Régnier et al. (2018), 19 teams utilizing 23 different codes took part in the international benchmarking project PRENOLIN. They provided a rigorous estimation of code-to-code variability for two real sites in Japan (i.e., Sendai and KSRH10), where in-hole measurements were available (i.e., no influence of the input motion selection). The authors found a variability ranging from 0.05 to 0.25 in $\log_{10}$ units (an average of 0.1 is proposed). This indicates a quite considerable influence of the numerical methods on site-effect assessment and more generally on the seismic hazard. The level of epistemic uncertainties was found to be also dependent on the site characteristics (i.e., thin or thick deposits represented by the two case studies) and the quality of the experimental measurements, especially for V_S profiles and MRD curves. Figure 6 reports the results obtained at the shallow bedrock site (Sendai) using two different recorded input motions that were applied to a rigid-base model. The results are given as transfer functions (upper portion

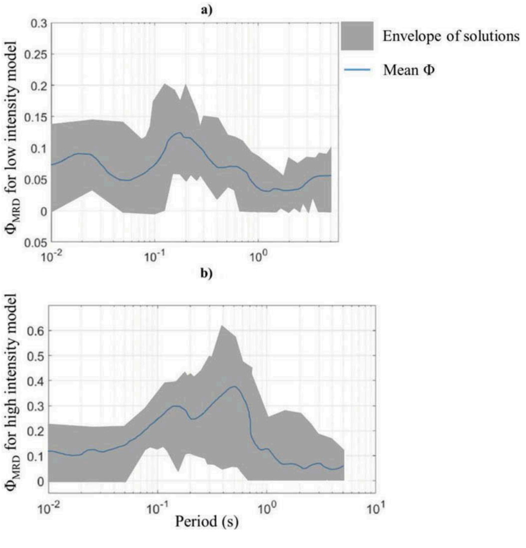

Figure 5. Analysis of the influence of uncertainties in MRD curves for a site in Netherlands including 19 different zones. a) Low-intensity stochastic input motions and b) high-intensity stochastic input motions (modified from Bahrampouri et al. 2018).

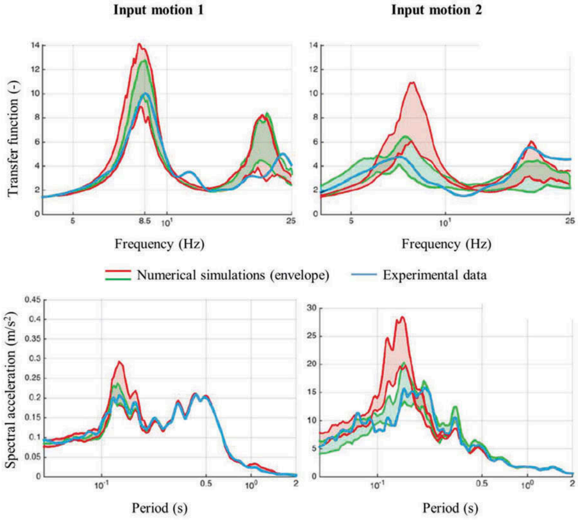

Figure 6. Results obtained during the PRENOLIN project for the assessment of the code-to-code varia-bility of GRA results (modified from Régnier et al. 2018) as transfer functions or surface spectra. The different numerical simulations refer to two different adopted V_S profiles (i.e., different results of the site characterizations).

of the figure) or surface response spectra (lower portion of the figure) for two different site characterizations models. The green envelope is referred to as SC1, while the red envelope is for the profile termed SC2 in Régnier et al. (2018). In addition, the results of the simulations performed by different teams are compared with the experimental data recorded at the Down-Hole array station. Although the general trend of the results is globally in line with the experimental data, the observed variability is not negligible.

4 FINAL REMARKS

The present paper discussed uncertainties and variabilities in seismic ground response analyses. Particular attention was paid to 1D simulation-based ground response analyses (GRAs). In particular, an identification, quantification, and management (IQM) methodology is suggested. This allows a systematic and rigorous analysis of epistemic uncertainties (EUs) and aleatory variabilities (AVs) involved in non-ergodic site response evaluations. The paper presents an exhaustive discussion of the main sources of EUs and AVs and three examples of the IQM method application in the literature.

ACKNOWLEDGMENTS

The first and the second author acknowledge the ReLUIS 3 project, funded by the Italian Civil Protection Agency that partially supported this study.

REFERENCES

Abrahamson, N. A., and Bommer, J. J. 2005. Probability and uncertainty in seismic hazard analysis. *Earthquake spectra*, 21, 603–607.

Afshari, K., and Stewart, J. 2015. Uncertainty of site amplification derived from ground response analysis.

Aki, K. 1993. Local site effects on weak and strong ground motion. *Tectonophysics*, 218, 93–111.

Amorosi, A., Boldini, D., and Di Lernia, A. 2016. Seismic ground response at Lotung: Hysteretic elasto-plastic-based 3D analyses. *Soil Dynamics and Earthquake Engineering*, 85, 44–61.

Anderson, J. G., and Brune, J. N. 1999. Probabilistic seismic hazard analysis without the ergodic assumption. *Seismological Research Letters*, 70, 19–28.

Asimaki, D., and Li, W. 2012. Site-and ground motion-dependent nonlinear effects in seismological model predictions. *Soil Dynamics and Earthquake Engineering*, 32, 143–151.

Asimaki, D., Li, W., Steidl, J., and Schmedes, J. 2008. Quantifying nonlinearity susceptibility via site-response modeling uncertainty at three sites in the Los Angeles Basin. *Bulletin of the Seismological Society of America*, 98, 2364–2390.

Bahrampouri, M., Rodriguez-Marek, A., and Bommer, J. J. 2018. Mapping the uncertainty in modulus reduction and damping curves onto the uncertainty of site amplification functions. *Soil Dynamics and Earthquake Engineering*.

Baise, L., Thompson, E., Kaklamanos, J., and Dorfmann, L. Complex site response: Does one-dimensional site response work. 4th IASPEI (International Association of Seismology and Physics of the Earth's Interior)/IAEE (International Association of Earthquake Engineering) International Symposium on the Effects of Surface Geology on Seismic Motion (ESG4), Santa Barbara, California, 2011. 23–26.

Baturay, M. B., and Stewart, J. P. 2003. Uncertainty and bias in ground-motion estimates from ground response analyses. *Bulletin of the Seismological Society of America*, 93, 2025–2042.

Bazzurro, P., and Cornell, C. A. 2004. Ground-motion amplification in nonlinear soil sites with uncertain properties. *Bulletin of the Seismological Society of America*, 94, 2090–2109.

Bommer, J. J. 2003. Uncertainty about the uncertainty in seismic hazard analysis. *Engineering Geology*, 70, 165–168.

Bommer, J. J., and Abrahamson, N. A. 2006. Why do modern probabilistic seismic-hazard analyses often lead to increased hazard estimates? *Bulletin of the Seismological Society of America*, 96, 1967–1977.

Bommer, J. J., Coppersmith, K. J., Coppersmith, R. T., Hanson, K. L., Mangongolo, A., Neveling, J., Rathje, E. M., Rodriguez-Marek, A., Scherbaum, F., and Shelembe, R. 2015. A SSHAC level 3 probabilistic seismic hazard analysis for a new-build nuclear site in South Africa. *Earthquake Spectra*, 31, 661–698.

Boore, D. M. 2003. Simulation of ground motion using the stochastic method. *Pure and applied geophysics*, 160, 635–676.

Boore, D. M., and Brown, L. T. 1998. Comparing shear-wave velocity profiles from inversion of surface-wave phase velocities with downhole measurements: systematic differences between the CXW method and downhole measurements at six USC strong-motion sites. *Seismological Research Letters*, 69, 222–229.

Brown, L. T., Boore, D. M., and Stokoe, K. H. 2002. Comparison of shear-wave slowness profiles at 10 strong-motion sites from noninvasive SASW measurements and measurements made in boreholes. *Bulletin of the Seismological Society of America*, 92, 3116–3133.

Budnitz, R. J., Apostolakis, G., and Boore, D. M. 1997. Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts. Nuclear Regulatory Commission, Washington, DC (United States). Div. of Engineering Technology; Lawrence Livermore National Lab., CA (United States); Electric Power Research Inst., Palo Alto, CA (United States); USDOE, Washington, DC (United States).

Cabas, A., and Rodriguez-Marek, A. 2018. Toward Improving Damping Characterization for Site Response Analysis.

Cornell, C. A. 1968. Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, 58, 1583–1606.

Darendeli, M. B. 2001. Development of a new family of normalized modulus reduction and material damping curves.

Der Kiureghian, A., and Ditlevsen, O. 2009. Aleatory or epistemic? Does it matter? *Structural Safety*, 31, 105–112.

Faccioli, E., Paolucci, R., and Vanini, M. 2015. Evaluation of probabilistic site-specific seismic-hazard methods and associated uncertainties, with applications in the Po Plain, northern Italy. *Bulletin of the Seismological Society of America*, 105, 2787–2807.

Field, E. H., and Jacob, K. H. 1993. Monte-Carlo simulation of the theoretical site response variability at Turkey Flat, California, given the uncertainty in the geotechnically derived input parameters. *Earthquake Spectra*, 9, 669–701.

Foti, S., Hollender, F., Garofalo, F., Albarello, D., Asten, M., Bard, P.-Y., Comina, C., Cornou, C., Cox, B., and Di Giulio, G. 2018. Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project. *Bulletin of Earthquake Engineering*, 16, 2367–2420.

Foti, S., and Passeri, F. 2018. Reliability and Accuracy of Seismic Tests in Geotechnical Site Characterization. *Geotechnics for Natural and Engineered Sustainable Technologies*. Springer.

Garofalo, F., Foti, S., Hollender, F., Bard, P., Cornou, C., Cox, B., Dechamp, A., Ohrnberger, M., Perron, V., and Sicilia, D. 2016a. InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part II: Inter-comparison between surface-wave and borehole methods. *Soil Dynamics and Earthquake Engineering*, 82, 241–254.

Garofalo, F., Foti, S., Hollender, F., Bard, P., Cornou, C., Cox, B., Ohrnberger, M., Sicilia, D., Asten, M., and Di Giulio, G. 2016b. InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part I: Intra-comparison of surface wave methods. *Soil Dynamics and Earthquake Engineering*, 82, 222–240.

Goulet, C. A., Stewart, J. P., Bazzurro, P., and Field, E. Integration of site-specific ground response analysis results into probabilistic seismic hazard analyses. Proceedings, 4th International Conference on Earthquake Geotechnical Engineering, 2007.

Griffiths, S. C., Cox, B. R., Rathje, E. M., and Teague, D. P. 2016. Mapping dispersion misfit and uncertainty in V s profiles to variability in site response estimates. *Journal of Geotechnical and Geoenvironmental Engineering*, 142, 04016062.

Hashash, Y., Phillips, C., and Groholski, D. R. 2010. Recent advances in non-linear site response analysis.

Hashash, Y. M., and Park, D. 2002. Viscous damping formulation and high frequency motion propagation in non-linear site response analysis. *Soil Dynamics and Earthquake Engineering*, 22, 611–624.

Hollender, F., Maufroy, E., Bard, P.-Y., and Ameri, G. 2018. Are we ready to perform fully site-specific seismic hazard studies in low-to-moderate seismicity areas? A synthesis of the CASHIMA program results. *Conference: 16th European Conference on Earthquake Engineering at ThessalonikiAt: Thessaloniki, Greece*.

Idriss, I. 2004. Evolution of the state of practice. *Int. Workshop on the Uncertainties in Nonlinear Soil Properties and Their Impact on Modeling Dynamic Soil Response, Pacific Earthquake Engineering Research Center, Richmond, Calif.*

Kaklamanos, J., Baise, L. G., Thompson, E. M., and Dorfmann, L. 2015. Comparison of 1D linear, equivalent-linear, and nonlinear site response models at six KiK-net validation sites. *Soil Dynamics and Earthquake Engineering*, 69, 207–219.

Kaklamanos, J., Bradley, B. A., Thompson, E. M., and Baise, L. G. 2013. Critical parameters affecting bias and variability in site-response analyses using KiK-net downhole array data. *Bulletin of the Seismological Society of America*, 103, 1733–1749.

Kim, B., Hashash, Y., Kottke, A., Asimaki, D., Li, W., Rathje, E., Campbell, K., Silva, W., and Stewart, J. A predictive model for the relative differences between nonlinear and equivalent-linear site response analyses. Proceedings of the 22nd International Conference in Structural Mechanics in Reactor Technology, San Francisco, CA, 2013.

Kim, B., Hashash, Y. M., Stewart, J. P., Rathje, E. M., Harmon, J. A., Musgrove, M. I., Campbell, K. W., and Silva, W. J. 2016. Relative Differences between Nonlinear and Equivalent-Linear 1-D Site Response Analyses. *Earthquake Spectra*, 32, 1845-1865.

Kottke, A., and Rathje, E. M. 2008. A semi-automated procedure for selecting and scaling recorded earthquake motions for dynamic analysis. *Earthquake Spectra*, 24, 911–932.

Kramer, S. L. 1996. Geotechnical Earthquake Engineering Prentice Hall. *New York*.

Kramer, S. L., and Paulsen, S. B. Practical use of geotechnical site response models. Proc. Int. Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response, 2004. Univ. of California Berkeley, 10.

Kwok, A. O., Stewart, J. P., Hashash, Y. M., Matasovic, N., Pyke, R., Wang, Z., and Yang, Z. 2007. Use of exact solutions of wave propagation problems to guide implementation of nonlinear seismic ground response analysis procedures. *Journal of Geotechnical and Geoenvironmental Engineering*, 133, 1385–1398.

Papaspiliou, M., Kontoe, S., and Bommer, J. J. 2012. An exploration of incorporating site response into PSHA-part II: Sensitivity of hazard estimates to site response approaches. *Soil Dynamics and Earthquake Engineering*, 42, 316–330.

Park, D., and Hashash, Y. M. 2004. Soil damping formulation in nonlinear time domain site response analysis. *Journal of Earthquake Engineering*, 8, 249–274.

Park, D., and Hashash, Y. M. 2005. Evaluation of seismic site factors in the Mississippi Embayment. I. Estimation of dynamic properties. *Soil Dynamics and Earthquake Engineering*, 25, 133–144.

Passeri, F. 2019. *Development of an advanced geostatistical model for shear wave velocity profiles to manage uncertainties and variabilities in Ground Response Analyses* Ph.D. dissertation, Politecnico di Torino.

Passeri, F., Bahrampouri, M., Rodriguez-Marek, A., and Foti, S. 2018. Influence of the Uncertainty in Bedrock Characteristics on Seismic Hazard: A Case Study in Italy.

Passeri, F., Foti, S., Cox, B., and Rodriguez-Marek, A. 2019. Influence of estimated epistemic uncertainties in shear wave velocity models on ground response analyses. *Earthquake Spectra*, 35, 26.

Phillips, C., and Hashash, Y. M. 2009. Damping formulation for nonlinear 1D site response analyses. *Soil Dynamics and Earthquake Engineering*, 29, 1143–1158.

Rathje, E. M., Kottke, A. R., and Trent, W. L. 2010. Influence of input motion and site property variabilities on seismic site response analysis. *Journal of geotechnical and geoenvironmental engineering*, 136, 607–619.

Régnier, J., Bonilla, L. F., Bard, P. Y., Bertrand, E., Hollender, F., Kawase, H., Sicilia, D., Arduino, P., Amorosi, A., Asimaki, D., Boldini, D., Chen, L., Chiaradonna, A., Demartin, F., Ebrille, M., Elgamal, A., Falcone, G., Foerster, E., Foti, S., Garini, E., Gazetas, G., Gélis, C., Ghofrani, A., Giannakou, A., Gingery, J. R., Glinsky, N., Harmon, J., Hashash, Y., Iai, S., Jeremić, B., Kramer, S., Kontoe, S., Kristek, J., Lanzo, G., Lernia, A. D., Lopez-Caballero, F., Marot, M., Mcallister, G., Mercerat, E. D., Moczo, P., Montoya-Noguera, S., Musgrove, M., Nieto-Ferro, A., Pagliaroli, A., Pisanò, F., Richterova, A., Sajana, S., Paola, M., D'avila, S., Shi, J., Silvestri, F., Taiebat, M., Tropeano, G., Verrucci, L., and Watanabe, K. 2016. International benchmark on numerical simulations for 1D, nonlinear site response (PRENOLIN): Verification phase based on canonical cases. *Bulletin of the Seismological Society of America*, 106, 2112–2135.

Régnier, J., Bonilla, L. F., Bard, P. Y., Bertrand, E., Hollender, F., Kawase, H., Sicilia, D., Arduino, P., Amorosi, A., Asimaki, D., Boldini, D., Chen, L., Chiaradonna, A., Demartin, F., Elgamal, A., Falcone, G., Foerster, E., Foti, S., Garini, E., Gazetas, G., Gélis, C., Ghofrani, A., Giannakou, A., Gingery, J., Glinsky, N., Harmon, J., Hashash, Y., Iai, S., Kramer, S., Kontoe, S., Kristek, J., Lanzo, G., Lernia, A. D., Lopez-Caballero, F., Marot, M., Mcallister, G., Mercerat, E. D., Moczo, P., Montoya-Noguera, S., Musgrove, M., Nieto-Ferro, A., Pagliaroli, A., Passeri, F., Richterova, A., Maria, S. S., D'avila, P. S., Shi, J., Silvestri, F., Taiebat, M., Tropeano, G., Vandeputte, D., and Verrucci, L. 2018. PRENOLIN: International Benchmark on 1D Nonlinear Site-Response Analysis—Validation Phase Exercise. *Bulletin of the Seismological Society of America*.

Rodriguez-Marek, A., Rathje, E., Bommer, J., Scherbaum, F., and Stafford, P. 2014. Application of single-station sigma and site-response characterization in a probabilistic seismic-hazard analysis for a new nuclear site. *Bulletin of the Seismological Society of America*, 104, 1601–1619.

Shi, J., and Asimaki, D. 2017. From stiffness to strength: Formulation and validation of a hybrid hyperbolic nonlinear soil model for site-response analyses. *Bulletin of the Seismological Society of America*, 107, 1336–1355.

Stewart, J. P., Afshari, K., and Goulet, C. A. 2017. Non-ergodic site response in seismic hazard analysis. *Earthquake Spectra*, 33, 1385–1414.

Stewart, J. P., Afshari, K., and Hashash, Y. M. 2014. Guidelines for performing hazard-consistent one-dimensional ground response analysis for ground motion prediction. *PEER Rep*, 16.

Stewart, J. P., and Baturay, M. B. 2001. Uncertainties and residuals in ground motion estimates at soil sites.

Stewart, J. P., and Kwok, A. O. 2008. Nonlinear seismic ground response analysis: Code usage protocols and verification against vertical array data. *Geotechnical earthquake engineering and soil dynamics IV*.

Taborda, R., López, J., Karaoglu, H., Urbanic, J., and Bielak, J. 2010. Speeding up finite element wave propagation for large-scale earthquake simulations. *Parallel Data Laboratory Tech. Rept. CMUPDL-10*, 109.

Thompson, E. M., Baise, L. G., Tanaka, Y., and Kayen, R. E. 2012. A taxonomy of site response complexity. *Soil Dynamics and Earthquake Engineering*, 41, 32–43.

Toro, G. 1995. Probabilistic models of site velocity profiles for generic and site-specific ground-motion amplification studies. *Department of Nuclear Energy Brookhaven National Laboratory, Upton, New York*.

Toro, G. R., Abrahamson, N. A., and Schneider, J. F. 1997. Model of strong ground motions from earthquakes in central and eastern North America: best estimates and uncertainties. *Seismological Research Letters*, 68, 41–57.

Yee, E., Stewart, J. P., and Tokimatsu, K. 2013. Elastic and large-strain nonlinear seismic site response from analysis of vertical array recordings. *Journal of Geotechnical and Geoenvironmental Engineering*, 139, 1789–1801.

Zalachoris, G., and Rathje, E. M. 2015. Evaluation of one-dimensional site response techniques using borehole arrays. *Journal of Geotechnical and Geoenvironmental Engineering*, 141, 04015053.

Zhang, J., Andrus, R. D., and Juang, C. H. 2005. Normalized shear modulus and material damping ratio relationships. *Journal of Geotechnical and Geoenvironmental Engineering*, **131**, 453–464.