Uncertainties in seismic site characterization

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ABSTRACT: Site characterization for seismic projects requires additional information on top of those which are required for any geotechnical design. Specifically, the investigation of the response of soil deposits to cyclic and dynamic actions has been recently included in the draft of the new generation of Eurocode 7 part 2 on ground properties. In this context geophysical tests play a role of paramount importance in site investigation. Moreover, seismic tests provide the opportunity to estimate the small strain elastic moduli which can be useful for several geotechnical applications. 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 can then be used to manage these uncertainties and evaluate their impact on modeling of site response and soil-structure interaction.

Keywords: shear wave velocity, geophysical tests, geostatistical models, small strain stiffness

1. Introduction

Site characterization for seismic projects requires additional information on top of those necessary for any geotechnical project. In this respect, the new draft of EC7 – part 2 introduces a new clause on "Cyclic, dynamic, and seismic properties". However, the limited availability of testing standard calls for the necessity of specific attention to the state of the practice, especially for some categories of tests.

Specifically, the elements that play the most relevant role for modeling the response to seismic action are: the response of soils to cyclic loading accounting for the level of strain, often reported in terms of Modulus Reduction and Damping (MRD) curves; and the small strain values of stiffness and damping ratio. In respect of the latter, the reliability of geophysical methods is a crucial aspect that deserve specific attention [1].

Moreover, these tests are more and more used for other geotechnical applications (e.g. evaluation of settlements, advanced numerical modeling, representativeness and disturbance of laboratory specimens, effectiveness of ground improvement).

In this note, after a general discussion on the uncertainties related to geophysical tests, derived from [2], the results of a recent benchmark test between different methods are reported. Finally, in the view of improving the standard of practice, available testing standards and international guidelines are listed.

2. Seismic methods

Geophysical surveys provide powerful tools for geotechnical site investigation. Indeed, they cover the whole range of soils and rocks, independently of particle size, and provide data in the natural state for the characterization at different scales. On the other side, the main issue is related to the necessity of adopting a non-trivial framework for the interpretation of the measured quantities and the need for adequate expertise. Indeed, very often, geophysical methods rely on the solution of inverse problems, which are inherently ill-posed according to the Hadamard's definition [3]. The consequence is the solution non-uniqueness, i.e., several solutions honor equally well the available experimental data and it is not possible to identify a single set of model parameters [4].

Specifically, seismic tests play a fundamental role as they allow the direct estimation of the subsoil mechanical properties and stratigraphic conditions. Indeed, the velocity of propagation of seismic waves is directly linked to the mechanical response of the medium. In the most common interpretation framework (i.e., wave propagation in a linear elastic continuum), the velocity of propagation is directly linked to the elastic parameters.

2.1. Uncertainties

In general terms, we define the accuracy of a method as its capability to provide an estimate that is as much as possible close to the "true" value of the investigated parameter.

On the other hand, the precision of a given method is associated with the possibility of getting consistent and repeatable measurements of the parameter of interest. Indeed, the precision aims at obtaining similar results with a repetition of the same test on the same sample (i.e., repeatability).

In this respect, the accuracy is very difficult to assess since the true value of the parameter is unknown. For this reason, very often the performances of a given geophysical method are studied with synthetic cases in which the benchmark is a numerical simulation with a set of known model parameters. However, this strategy is not fully satisfactory, as the uncertainties in data acquisition are not considered, and they can be very relevant. The other possibility is given by a comparison of the results by different techniques, although such comparisons are rarely fully representative of the actual accuracy. Indeed, one of the techniques has to be assumed as the ground truth. Moreover, most often it is not possible to derive general conclusions from such comparisons as different techniques explore different portions of the subsoil. This is, for example, the case when in-hole and surface measurements are compared one to the other (e.g., [5]).

The precision in terms of repeatability of a given measurement is in principle easier to assess than accuracy. However, several blind tests performed in the past have shown that it is difficult to assure that measurements are actually performed in exactly the same conditions, especially when dealing with natural systems.

Moreover, an assessment of a representative statistical sample is typically prevented by the limited possibility to get repeated and consistent measurements, due to the cost of each acquisition and interpretation.

In terms of uncertainty that affects the reliability of a geophysical test, it is important to clearly separate two broad categories: epistemic uncertainty and aleatory variability [6-7]. The former is associated with an incomplete knowledge of the system, with the hypotheses that are introduced during the interpretation (i.e., adopted model), and with measurement errors. The second represents the natural randomness of subsoil conditions, for example, in terms of lateral heterogeneities of ground properties across the site of interest footprint. Epistemic uncertainties can be handled and reduced with additional data/knowledge, but they are difficult to be properly quantified. Aleatory variability are intrinsically linked to natural system heterogeneities and phenomena unpredictability that cannot be reduced.

A clear separation of the two contributions is unfortunately very difficult to be implemented and a lumped uncertainty is therefore typically considered. However, for some specific issues, the observed uncertainty can be referred to a predominant category of the two above. A full discussion is reported in [1].

Seismic surveys can be grouped into two broad categories depending on the position of measuring equipment:

– Invasive tests;
– Non-invasive tests.

The first category is often addressed as borehole methods since receivers and/or sources are placed in the subsoil, typically within holes. However, invasive measurements can be performed by taking the receivers into the subsoil with the rods used for cone penetration tests of dilatometer tests (respectively in the so-called Seismic Cone SCPT and Seismic Dilatometer SDMT tests).

Non-invasive tests are also addressed as surface tests; however, this name can be associated with surface wave analysis, which actually is only a specific type of non-invasive tests. Surface wave methods (SWM) include indeed all the geophysical method which are based on the spectral analysis of the propagation of surface (Rayleigh, Love or Stoneley) waves such as SASW (Spectral Analysis of Surface Wave), MASW (Multistation Analysis of Surface Waves), CSSW (Continuous Source Surface Wave), AVA (Ambient Vibration Analysis).

Table 1 reports a summary of the most relevant sources of uncertainties for the most popular methods in the geotechnical and seismic applications: cross-hole tests (CHT), down-hole tests (DHT), P-S suspension logging, and surface wave methods (SWM).

Seismic Cone and Seismic dilatometer share the same acquisition scheme of Down-hole tests therefore the related considerations apply.

2.2. Comparison of uncertainties

A blind test for site characterization was recently carried out within the InterPACIFIC project [4, 8]. Specifically, three sites have been characterized using repeated realizations of invasive and surface wave tests.

The sites were selected to be representative of different stratigraphic conditions (Figure 1):

- Mirandola: soft soil overlying a bedrock;

- Grenoble: stiff soil extending to significant depths;

- Cadarache: rock outcrop.

For each site, down-hole, cross-hole, seismic dilatometer, and suspension logging tests were repeated by different analysts.

Furthermore, a surface wave dataset was distributed to 14 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.

A comparison of the shear wave velocity profiles obtained using invasive and non-invasive seismic tests, is reported in Figure 2.

Interestingly the level of uncertainty associated to the two categories of tests are similar as shown in Figure 3, which reports the coefficient of variation inter-method (invasive vs. non-invasive) which is broadly the same, with some notable exceptions related to specific stratigraphic features:

- the inaccuracy in bedrock identification in Mirandola (Figure 2-c) causes large uncertainty for depth larger than 90m in surface wave analysis (Fig. 3-a);
- the presence of a softer layer between 25m and 35m depth in Grenoble is difficult to identify for surface wave tests (Figure 2-c).

It is also to be mentioned the large uncertainty close to the ground surface in Cadarache (Figure 3-d) for both invasive and non-invasive tests. It is likely associated to weathering and fracturation of the rock close to the ground surface and to the consequent lateral variability.

Table 1a. Major sources of uncertainty for invasive seismic tests (modified after [9]).

Test	Sources of uncertainty
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)
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
P-S 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

Table 1b. Major sources of uncertainty for non-invasive seismic tests (modified after [9]).

Test	Sources of uncertainty
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)
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 - 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) - Model error in the interpretation of the test (1D assumption not consistent with actual geometry at the site)
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)

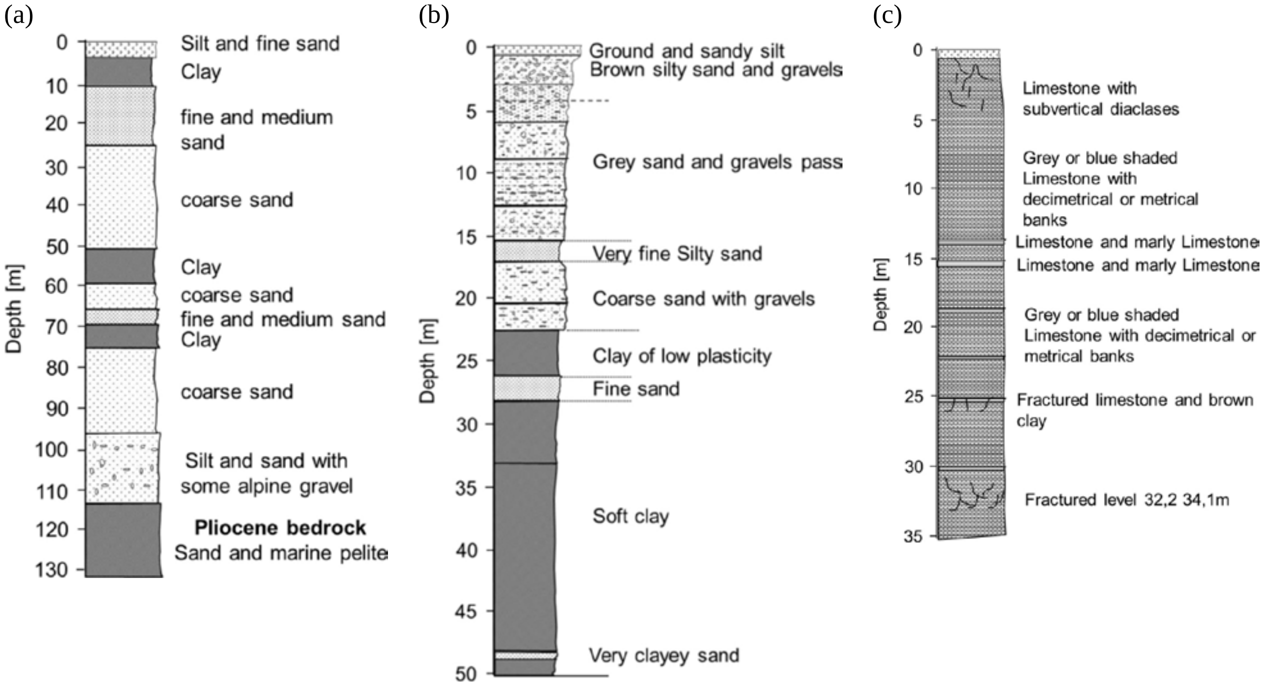

Figure 1. Interpacific blind test - stratigraphic logs [4]: (a) Mirandola; (b) Grenoble; (c) Cadarache

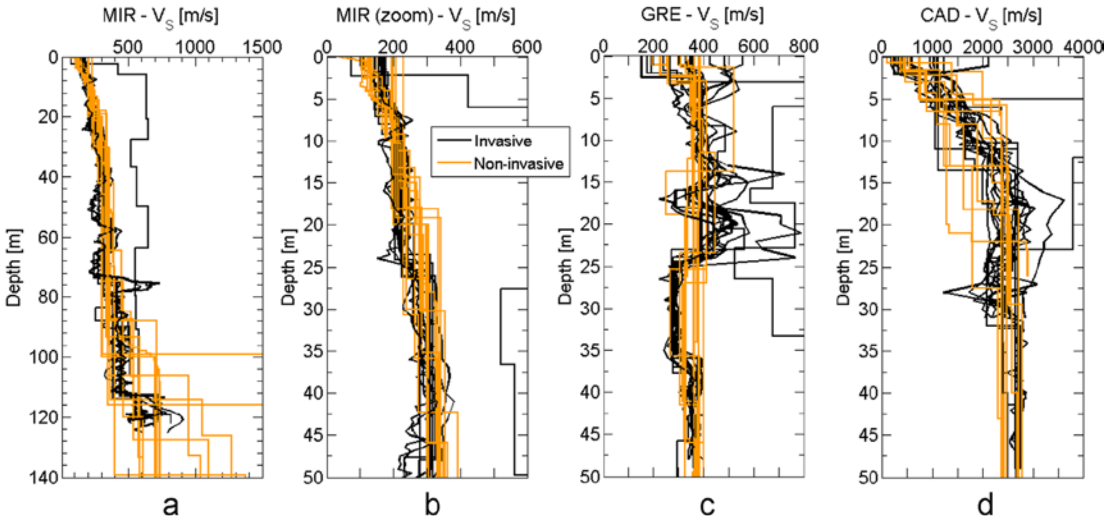

Figure 2. Interpacific blind test - Shear wave velocity profiles [4]: (a-b) Mirandola; (c) Grenoble; (d) Cadarache

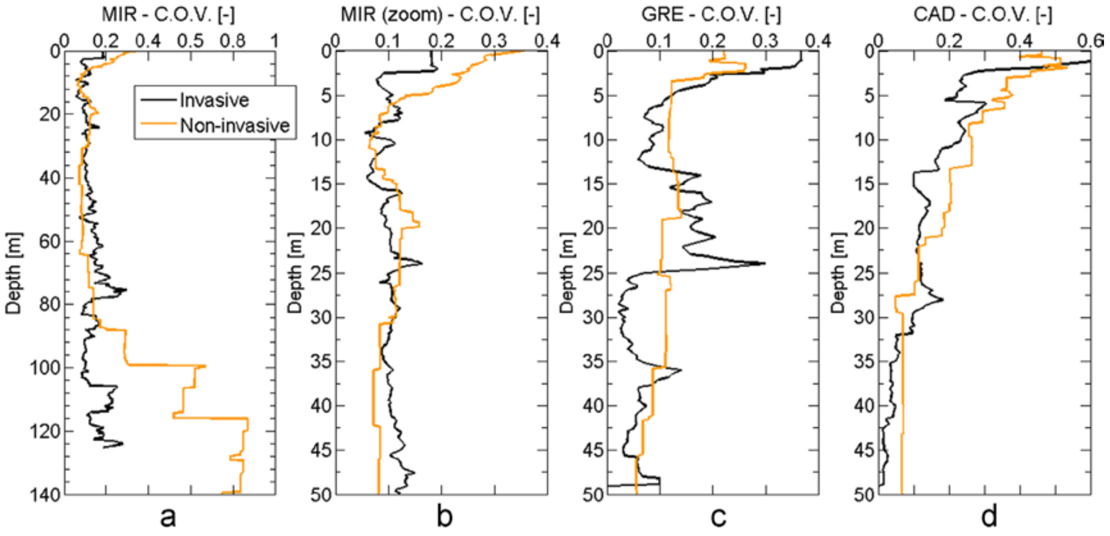

Figure 3. Interpacific blind test - Coefficient of variation of V_S [4]: (a-b) Mirandola; (c) Grenoble; (d) Cadarache

2.3. Modeling uncertainties

Uncertainties associated to site characterization should always be included in modeling in order to assess the reliability of the results for the target application. This principle applies to any geotechnical problem. For static loads it is usually sufficient to considering conservative values of characteristic values of each parameter, even if this approach can lead to overconservative design. For seismic problems however, it is typically not possible to identify a-priori which is the conservative assumption. For example, in seismic site response analysis, a lower bound of ground stiffness cannot be considered straightforwardly as a conservative assumption. Indeed, it will lead to large strains in the numerical simulations and therefore to an overestimation of the damping ratio, resulting in an overdamped solution and an underestimation of expected ground motion. A possible strategy is therefore based on randomization of the shear wave velocity profile and multiple numerical simulations.

A geostatistical model for uncertainties associated to the shear wave velocity profile obtained from surface wave testing has been recently proposed in [10]. The model is an evolution of the Toro model [11] and it is based on the statistical analysis of a large database of surface wave tests at several sites in Italy [12]. Starting from a single deterministic shear wave velocity profile, the geostatistical model allows for the generation of a population of profiles which are representative of the uncertainty. They can be used to propagate the uncertainty into the final boundary problem of interest (e.g. the estimate of local seismic effects from non-linear site response analysis or the modeling of soil-structure interaction). Compared to previous approaches, this model allows for the consistency with site signatures (experimental dispersion curve and transfer function) to be preserved in the generation of the profiles [10]. An example is reported in Figure 4, where the set of randomly generated profiles is reported together with the base case profile that represent the results of a deterministic inversion of surface wave analysis. The model can be also applied to shear wave velocity profiles obtained with other geophysical tests (e.g. down hole tests).

3. State of practice

Considering the increasing role of seismic tests in site characterization, it is of paramount importance to improve the quality level for the state of the practice. In this respect testing standards provide fundamental terms of reference. However testing standards are not available for all the seismic methods. Recently some guidelines have been developed by international experts to partially cover this gap.

3.1. Testing standards

Testing standards are available for the following seismic tests:

- Cross-Hole Test [13]
- Down-Hole Test [14]
- Seismic Refraction [15]
- Seismic Reflection [16]

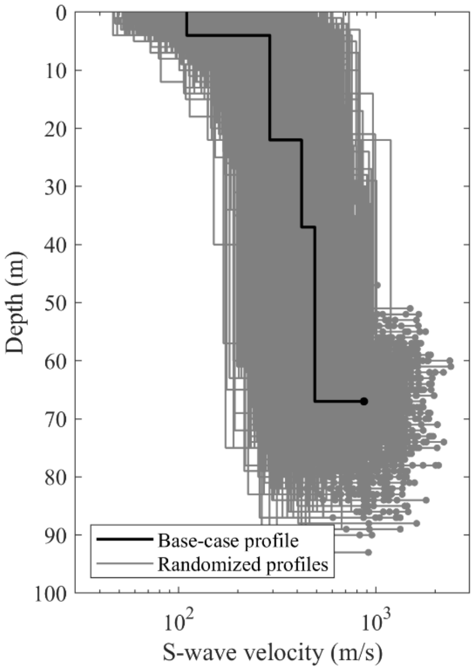

Figure 4. Example of randomization of a shear wave velocity profile with the geostatistical model proposed in [10]

3.2. SCPT/SDMT Guidelines

As mentioned before, the same measurement strategy adopted in Down-Hole tests can be implemented for rod-push methods, such as seismic cone (SCPT) and seismic dilatometer (SDMT). Guidelines for these measurements reported in [17].

3.3. SWM Guidelines

Standardization of surface wave testing is a complex task. Indeed, surface wave analysis can be implemented successfully with a large variety of possible strategies. The latter differ in terms of implementation of each of the three steps: data acquisition; processing of the experimental dispersion curve; solution of the inverse problem for the identification of the shear wave velocity profile. In fact, no testing standard is currently available at a national or international level.

In order to provide guidance on execution and interpretation of surface wave testing a set of guidelines has been recently published by a team of international experts [18]. They are mainly addressed to non-expert users in an attempt to improve the state of the practice in this field. Moreover, they can provide a useful term of reference for final users of the site characterization to check the procedures followed by providers and the obtained results. However, guidelines are not a substitute for experience and a detailed knowledge of the background theory [19] is always necessary. A brief summary of the guidelines is provided hereafter.

The Interpacific guidelines are restricted to fundamental mode analysis. Indeed, when higher modes are relevant in the propagation, the processing and interpretation of surface wave tests require appropriate approaches which are typically not implemented in commercial codes used by non-expert users. Readers are referred to Appendix 5 of the guidelines [18] for an overview of possible strategies to deal with higher modes.

The guidelines cover both active-source tests and passive tests based on the analysis of ambient vibrations. The combined use of both approaches is indeed a common strategy to overcome the limitation of investigation depth of active-source tests, especially when using light impact sources such as sledge-hammers and small weight-drop systems. Guidance on the choice of the experimental setup is provided.

For ambient vibration analysis the use of 2D array configuration on the ground surface is strongly recommended and a minimum of 4 receivers is suggested, even is a larger number (8-10) is recommended to provide quality results.

Most surface wave methods require the evaluation of an experimental dispersion curve which describe the frequency dependency of phase or group velocity. The processing is typically based on transform-based methods (e.g. frequency-wavenumber or frequency-slowness) of the wavefield for active-source data. Frequency-wavenumber beamformer and SPAC are the most widely adopted tools for the analysis of ambient vibrations (passive data). The basics are reported in textbooks (e.g. [19]).

Finally, the experimental dispersion function is compared to the analytical dispersion curve to set a target function for the solution of the inverse problem. The algorithms for inversion can be divided into two broad categories: local search methods (e.g. the least square algorithm) and global search algorithm (e.g. Montecarlo methods). The latter allows for the mitigation of the risk of being trapped into a local minimum. They also provide a population of equivalent solutions which can be used to assess the consequences of solution non-uniqueness in the target application. For example the consequences in site response analyses have been studied in [4].

4. Conclusions

Seismic tests play a major role in site characterization and the associated uncertainties should be properly considered. Geostatistical models provide in this respect the possibility to propagate the influence of such uncertainties in specific geotechnical and seismic applications.

In any case it is of foremost importance to guarantee adequate quality standards and existing international guidelines may provide useful terms of reference for tests which are not yet standardized, such as surface wave methods.

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