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FROM RESEARCH TO PRACTICE IN NONLINEAR SITE RESPONSE: OBSERVATIONS AND SIMULATIONS IN THE L.A. BASIN

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ABSTRACT

There exists nowadays agreement between the earthquake engineering and seismological community that the assessment of local site effects is of great significance, both for mitigating seismic hazard and for performing detailed analyses of earthquake source characteristics. Nonetheless, there still exists large degree of uncertainty concerning the site categorization scheme to be used for quantifying the susceptibility of soil profiles to nonlinear effects, the mathematical model to be employed for the computationally efficient evaluation of these effects, and the site investigation program to ensure cost-effective predictions given the target level of design sophistication. Despite the fact that seismic observations of site response can provide critical constraints on interpretation methods for surface observations, the lack of a statistically significant number of in-situ strong motion records prohibits statistical analyses to be conducted and uncertainties to be quantified based entirely on field data. For this purpose, we here combine downhole observations and broadband ground motion synthetics in the Los Angeles Basin and present preliminary results of a comprehensive parametric study, which focuses on investigating the variability in ground-motion estimation introduced by nonlinear site-response methodologies and their associated input parameters. In particular, we address the uncertainty introduced in the assessment of seismic hazard by the selected site-specific ground motion analysis methodology, low-strain velocity and attenuation profiles of the near-surface and the deeper sediment structure, dynamic soil properties and nonlinear constitutive model input parameters. The long-term goal of this work is the establishment of a cost-effective and computationally-efficient framework for site parameterization and nonlinear site response simulation.

Keywords: equivalent linear, nonlinear, site effects, amplification, inversion, uncertainty

INTRODUCTION

Strong motion ground response analyses are currently required in the engineering practice for the design of new components of the civil infrastructure on soft soil profiles. In these cases, it is necessary to arrive at realistic predictions of the nonlinear soil behavior to enable the rational design of earthquake-resistant structures, and these predictions require elaborate nonlinear analyses to be conducted. The selection of the appropriate methodology for the prediction of soil nonlinearity in strong ground motion is based on the anticipated strain amplitude; and while nonlinear methods are indeed necessary to capture large-strain phenomena such as permanent deformations or liquefaction, the accuracy of nonlinear analyses depends on the constitutive model used: elaborate models require

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numerous parameters which must be determined through lab and/or field tests, and the additional cost and effort involved in the parameter acquisition and time-domain simulation often limits their frequency of use.

The bottleneck in technology transfer of nonlinear methods, to the engineering design practice and seismology alike, arises from the uncertainties that exist regarding the conditions under which nonlinear analyses are necessary, the complexity of the nonlinear model to be employed, and the development methodology of the input model parameters for implementation. These difficulties, further aggravated by the lack of well-documented validation studies, have thus far prohibited the wide adoption of the nonlinear analysis procedures by members of both disciplines.

Clearly, there exists a pressing need for the establishment of guidelines that will allow credible predictions of nonlinear site response based on an efficient and cost-effective framework, and this framework is indeed the long-term goal of this work. Applied on a regional basis for the Los Angeles sedimentary site conditions, we here present preliminary results of a comprehensive uncertainty assessment study opting to determine: (i) the site conditions and ground motion characteristics under which nonlinear analyses should be conducted; (ii) the adequate complexity of the nonlinear model to ensure computationally-efficient simulations; and (iii) the geotechnical site investigation and input parameter development methodology, to ensure cost-effective parameter acquisition. At the interface of seismology and engineering, the overarching goal of this study is to advance the state-of-the-art in seismic hazard assessment by developing an efficient and cost-effective framework for the prediction of nonlinear site effects.

PREDICTION OF SITE EFFECTS AND THE ROLE OF DOWNHOLE ARRAYS

Realistic ground motion predictions of future earthquakes implies advancement of the understanding and characterization of seismic ground motion, which can be only achieved by combining source, wave-propagation, and site-response models. Among others, an important step towards this goal is the consensus that exists nowadays between the earthquake engineering and seismological community that the response of soft sediments to strong ground motion can significantly aggravate the catastrophic consequences of large earthquakes, while the increasing number of observations has contributed towards the improved understanding of nonlinear site effects.

Strong motion ground response analyses refer to either ground amplification or ground failure problems, distinguished on the basis of permanent deformations: while the former involve insignificant residual deformations and may be addressed by means simplified methodologies, the latter require nonlinear analyses to be conducted, which are, however, associated with considerable cost and effort since they require both detailed site characterization and significant computational time for analysis. Therefore, if this expense is to be incurred, the expectations are that the use of elaborate nonlinear methodologies reduces the bias and/or uncertainty of predicted ground motions relative to what would be obtained from approximate procedures.

Nonlinear models are necessary when large strains and permanent displacements are expected, and their prediction accuracy depends on the constitutive material law that governs soil behaviour: elaborate constitutive laws require numerous parameters that need to be determined through laboratory and field techniques. Currently, uncertainties still exist regarding the methodology to be employed, the level of sophistication required that determines the number of input parameters, and the development of these parameters for implementation. These difficulties are further aggravated by the lack of well-documented validation studies that have thus far prohibited the wide adoption of the nonlinear analysis procedures in design practice.

For the engineering and the seismological community, a major impediment towards understanding and modelling sediment nonlinearity in-situ has been until recently the shortage of strong-motion observ-ations. Resolving the physics requires a good estimate of the input motion, and by far the best source of information on input motion is provided by downhole arrays. Downhole array records have allowed direct in situ evidence of nonlinearity; they have invited a re-evaluation of the use of surface-rock recordings as input motion to soil columns, and they have provided basic information about scaling and alluvium sites located at the surface (e.g. Wen et al. (1994); Zeghal & Elgamal (1994); Iai et al. (1995); Satoh et al. (2001a)). The amount and quality of information from downhole arrays in seismically active areas is the key both to improve the understanding of in-situ soil behaviour and to assess the modelling and parametric uncertainty of employed methodologies for site-specific response analysis; and this type of validation involving full-scale, in-situ data that only strong motion arrays can provide, is the only one that will be accepted by engineering practitioners and seismologists alike, and result in successful technology transfer. Nonetheless, comprehensive validation and sensitivity analysis and uncertainty investigation of approximate and elaborate nonlinear site response methodologies on the basis of downhole geotechnical array data involves a two-fold impediment: (i) the scarcity of near-surface geotechnical information, the error propagation of laboratory and in-situ measurement techniques, and the limited resolution in the numerical representation of the continuum, usually result in predictions of surface ground motion that poorly compare with weak motion observations, while this discrepancy is even further aggravated for strong ground motion, usually associated with hysteretic, nonlinear, and potentially irreversible material deformations, and (ii) even further, the lack of a statistically significant number of strong motion downhole recordings, the paucity of design-level records in the Southern California, and the uncertainty involved in the deconvolution of ground surface strong motion data, necessitate the use of synthetic ground motions to enable the investigation of a wide spectrum of site conditions and ground motion characteristics and ensure reliability of the target design framework.

Site conditions in the Los Angeles basin

Accounting for the lack of geotechnical and strong motion data recordings alike, a statistically significant number of 3-component broadband ground motion time-histories have been simulated for the purpose of this study for strike-slip fault rupture scenaria at 33 discrete points on a 100x100km^2 square grid (**Figure 1a**).

The alternative 1D-crustal velocity and density models have been compiled using available near-surface geotechnical site investigation data, downhole array seismogram inversion profiles (Assimaki et al. 2006a), and data extracted from the Southern California Earthquake Centre (SCEC) community velocity model (CVM) at the locations of 7 downhole geotechnical arrays in the Los Angeles basin. The location of the arrays and the crustal models used in the ensuing for synthetic ground motion simulations are shown in **Figures 1b** and **1c** correspondingly.

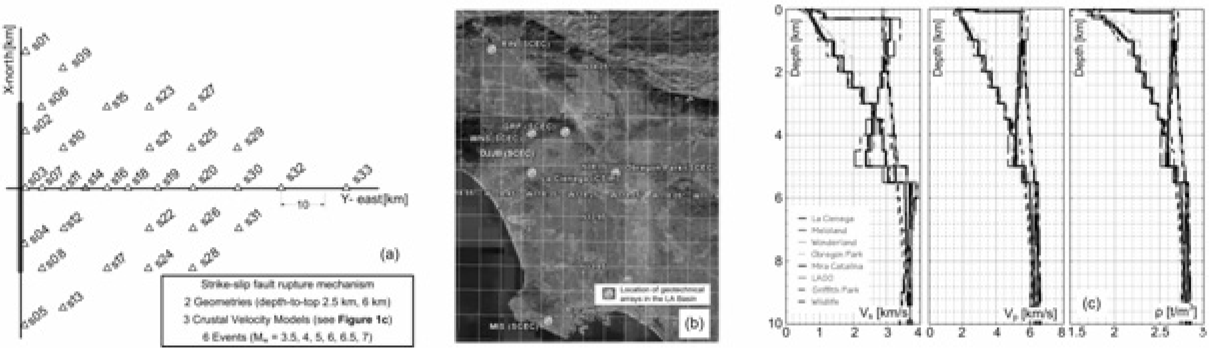


Figure 1. (a) Plan view of station locations where 3-component broadband seismogram synthetics are computed for the purpose of this study; (b) Downhole array stations in the Los Angeles basin, where seismogram inversion has been employed; and (c) 1D crustal velocity and density models, extracted from the SCEC community velocity model

In particular for the near-surface site conditions, high-resolution velocity, attenuation and density profiles were estimated by means of waveform inversion of downhole array recordings, using the optimization technique developed by Assimaki & Steidl (2006a, 2006b). Referred to as hybrid globallocal optimization, the numerical scheme comprises a genetic algorithm in the wavelet domain coupled in series to a nonlinear least-square fit in the frequency domain, which improves the computational efficiency of the former while avoiding the pitfalls of using local linearization techniques for the optimization of multi-modal, discontinuous and non-differentiable functions. The parameters estimated for the purpose of this study are stepwise variations of the shear wave velocity, attenuation and density with depth, for horizontally layered media with predefined layer thickness, while the equality constrains imposed on the vector of unknowns to truncate the search space are based on independent geological and geotechnical site characterization data. The best-fit variation of shear wave velocity, attenuation and density with depth in the near-surface for the stations of interest is depicted in **Figure 2**.

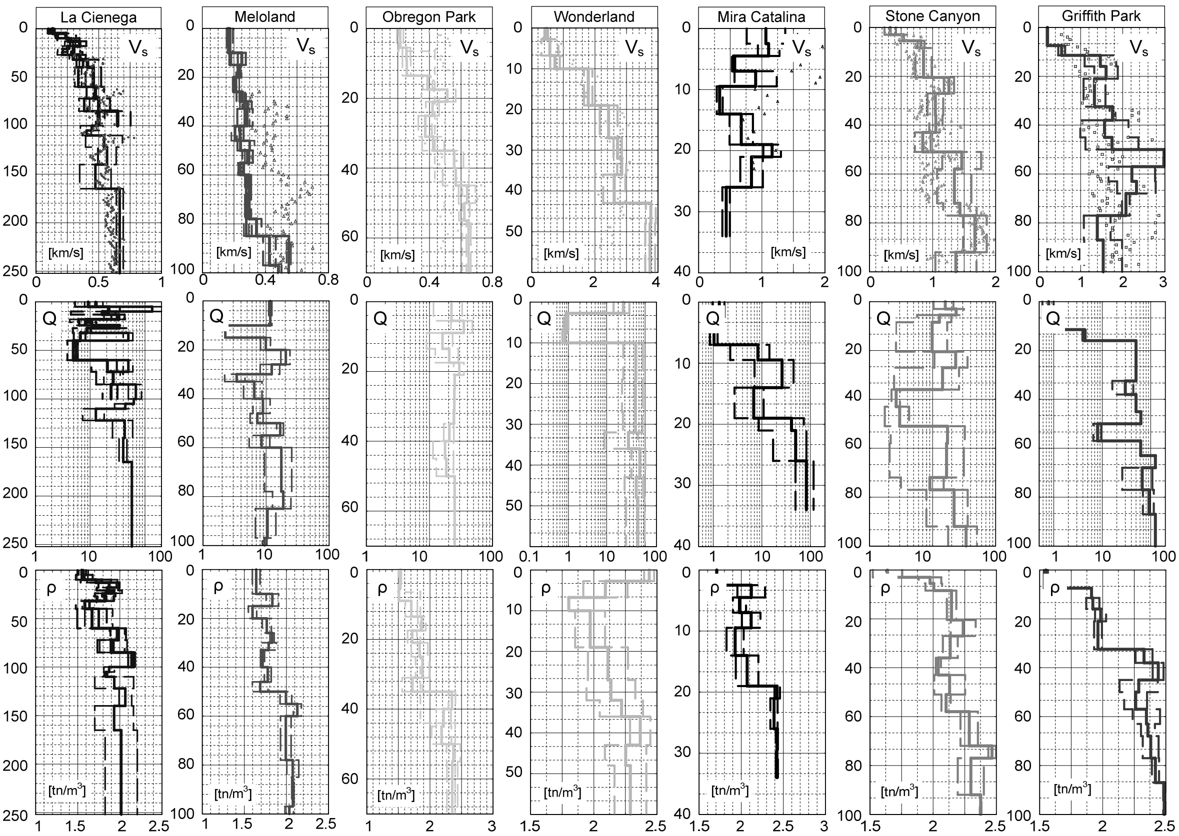


Figure 2. Velocity (top), attenuation (middle) and density (bottom) profiles, evaluated by means of downhole array seismogram inversion at 7 stations in the LA basin (depicted in Figure 1)

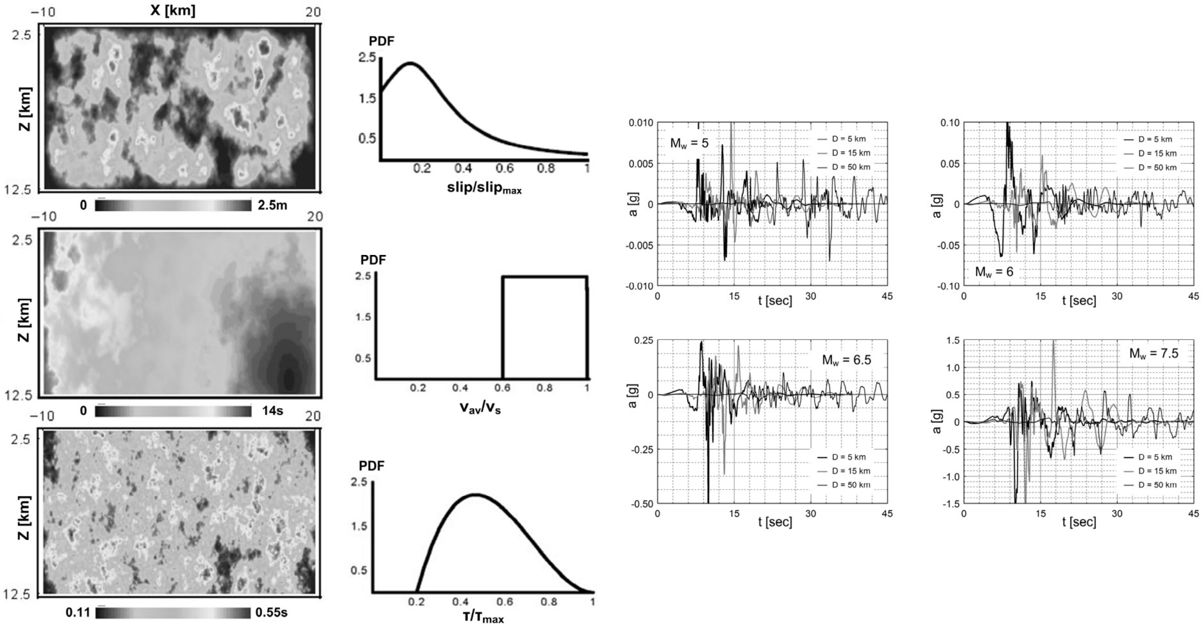
Broadband ground motion synthetics

Successively, broadband ground motion time-histories have been computed for the alternative 1D crustal velocity models and a wide spectrum of strike-slip fault rupture scenaria corresponding to events of magnitude M_w = 3.5-7.0 and depth-to-fault geometry d=2.5-6 km; for each scenario, 3-component time-histories have been evaluated by means of the hybrid low/high frequency method with correlated random source parameters (Liu et al, 2006).

In the complete formulation of the hybrid low/high frequency method, the evaluation of low-frequency synthetics (< ~1Hz) is based on 3D-velocity structures, and the broadband synthetics are evaluated for 1D models, while the two frequency ranges are combined using matched filtering at a cross-over frequency of 1Hz. The source description, common to both the 1D and 3D synthetics, is based on correlated random distributions for the slip amplitude, rupture velocity, and rise time on the fault. A typical realization of the normalized slip distribution, rupture and rise time for a strike-slip event of magnitude M_w=6.5 are shown in **Figure 3**.

This source description allows for the specification of source parameters independent of any a priori inversion results. The correlation introduced between slip amplitude, rupture velocity, and rise time in the broadband modelling is selected in accordance with the one suggested by dynamic fault modelling. A realistic attenuation model is common to both the 3D and 1D-velocity-based broadband simulations resulting in the low- and high-frequency components of the broadband synthetics. The value of Q is a function of the local shear-wave velocity. To produce more accurate high-frequency amplitudes and durations, 1D-synthetics are corrected using a randomized, frequency-dependent radiation pattern.

For the purpose of this study, broadband ground motion synthetics are initially computed by means of the hybrid low/high frequency method with correlated random source parameters on the surface of the linear elastic 1D crustal velocity models. Successively, the ground surface motion is deconvolved to the level of the lowermost downhole instrument (typically ≈ 100 m) and finally, the incident waveform is propagated to the surface by means of the alternative approximate and elaborate nonlinear constitutive models investigated. Typical crustal ground surface linear elastic synthetics are depicted on **Figure 3b**.



(a) (b)

Figure 3. (a) Random realization and corresponding probability distribution functions for slip (top), rupture time (middle) and rise time (bottom) for ground motion simulation of event with M_w = 6.5 and depth-to-fault 2.5 km; (b) Fault-parallel broadband ground motion synthetics at stations (see Figure 1a) s7 (D= 5 km), s14 (D = 15 km) and s 30 (D = 50km) computed on the surface of the crustal velocity model extracted from the SCEC CVM at the location of La Cienega SMGA (see Figure 1b)

Note that this approach allows the computationally-efficient integration of nonlinear site response methodologies in three-dimensional deterministic rupture simulations, conditioned –however- on the existence of well-defined criteria that determine the nonlinearity susceptibility of near-surface site conditions; acknowledging that currently established site classification schemes often fail to describe the anticipated soil behaviour as a function of the incident ground motion characteristics, the target guidelines of our work involve the refinement of currently established site classification schemes to quantify the level of anticipated strain and the required nonlinear model as a function of the soil profile variability and ground motion amplitude and frequency content.

UNCERTAINTY ASSESSMENT IN STRONG MOTION SITE RESPONSE ANALYSES

In the ensuing, the ensemble of ground motion synthetics was used for the assessment of the relative modelling and parametric uncertainty introduced in strong motion site response analyses, which comprised the following steps: (i) the input parameters of each model were initially identified; (ii) fixed- and free-parameters were defined for the use of each model in the parametric investigation; (iii) the models were validated for small ($<10^{-4}$) and medium ($\sim10^{-3}$) strain conditions by comparison with available in-situ downhole array data; (iv) their relative modelling uncertainty was evaluated for large-strain conditions (synthetic ground motions) by comparison with the most elaborate nonlinear formulation (here, the multi-yield plasticity model); and (v) the parametric uncertainty of each model will be finally evaluated by systematically randomizing the low-strain properties and nonlinear input parameters.

Nonlinear site response: Approximate vs. elaborate models

The effects of a soil column upon strong ground motion have been well documented and studied analytically for many years. The engineering community has long believed that sediment nonlinearity is significant, a perspective that has been widely confirmed based on laboratory studies where observed stress-strain loops implied a reduced effective shear modulus and an increased material energy absorption (damping) at higher levels of strain. Currently, two approaches are conventionally used to model cyclic soil response: equivalent-linear and nonlinear.

Equivalent-linear models

In the equivalent-linear (EQL) approach, originally proposed by Seed and Idriss (1970), viscoelastic simulations are performed in each iteration, a characteristic level of strain is defined as a fraction of the peak strain exerted by each layer of the profile, the material properties are selected in the beginning of each iteration to be consistent with the levels of strain computed in the previous iteration, and the algorithm progresses until convergence. This stepwise analysis procedure was formalized into a one-dimensional, vertically propagating shear-wave code termed SHAKE, which currently is the most widely used analysis package for one-dimensional strong motion site response calculations. The advantages of the EQL approach are that the mathematical simplicity of linear analysis is preserved and the evaluation of nonlinear constitutive parameters is avoided. In addition, this frequency-domain (FD), linear formulation is frequently the first step of soil-structure interaction (SSI) simulation chains, and incorporation of FD amplification spectra in FD SSI models improves the computational efficiency of the process. Nonetheless, the linear stress-strain material behavior and total stress approach associated with EQL models, entirely prohibits their use for calculations of permanent deformations or pore pressure built-up, namely for problems that involve large levels of strain (e.g. near-fault motions); deep and/or soft and very soft sedimentary sites; or liquefiable profiles.

Nonlinear models

Results of an informal, international survey conducted by Kramer and Paulsen (2004) indicated that EQL analyses represent the most commonly employed procedures (~80%) for site response analysis in the US, while uncertainties involving ground motion characteristics and material property acquisition strongly influence the results of site-specific analyses in practice. Nonetheless, the users did express concerns about the applicability of EQL analyses for the cases when site-specific response analyses are indeed most useful, namely soft sites, liquefiable sites, and sites subjected to very strong shaking. The adoption of nonlinear analyses, however, appeared to be restrained […by uncertainty in what nonlinear model to use, how to develop the input parameters required for the nonlinear models, and by the lack of well-documented validation studies for those models].

In the nonlinear formulations of soil behavior, the wave equation is directly integrated in the time-domain and the material properties are adjusted to the instantaneous levels of strain and loading path according to the mathematical description of nonlinear stress-strain model and hysteretic (loading and unloading) soil response. Nonlinear constitutive models can simulate soil behavioral features unavailable in the equivalent linear formulation such as updated stress-strain relationships, pore-pressure generation, and/or cyclic modulus degradation, which are critical for the prediction of large strain and ground failure problems. Early nonlinear site response analyses used models based on a hyperbolic shape, cycled in accordance with what are commonly referred to as the Masing rules. Nonetheless, the complexity of soil stress-strain relationships cannot be represented by a plain hyperbola, and additional parameters were gradually introduced to modify the original hyperbolic shape. Early nonlinear soil models include among others the Ramberg-Osgood model, the Iwan-type model and the modified hyperbolic model (Hayashi et al, 1992). Each of these models has certain limitations and advantages in describing the response of soils to seismic loading. Typical examples of the performance of equivalent linear and nonlinear formulations for the strong motion analyses of near-fault sites is shown in **Figure 4**, where the deviation in the predicted surface ground motion increases with increasing ground motion intensity; it is noteworthy that the site illustrated is located 5 km from the surface projection of the fault, and when subjected to incident motion generated by a M_w = 7.5 event, linear elastic (or EQL) formulations overestimate the predicted PGA by 150% relatively to the nonlinear formulations.

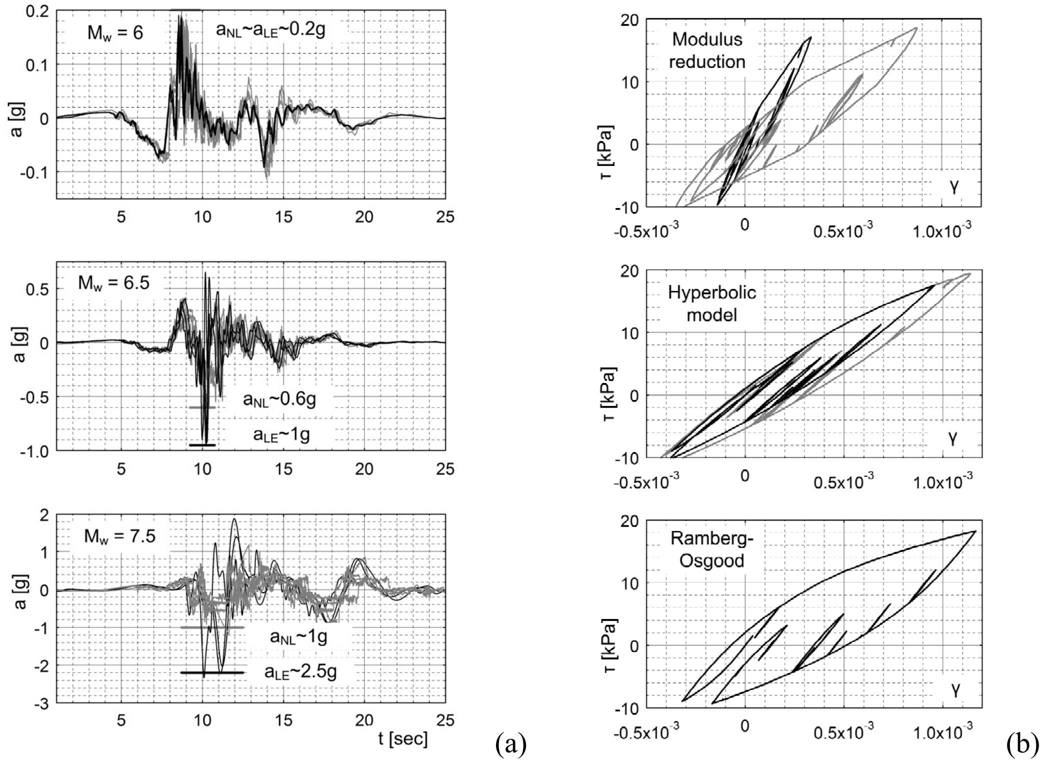


Figure 4. (a) Comparison of the ground surface response evaluated at station s7 (D = 5 km) for three rupture scenaria by means of the linear elastic, equivalent linear and nonlinear formulations; (b) Comparison of the stress-strain hysteresis loops predicted by alternative nonlinear formulations at 7.5m depth at the same station during an event of magnitude M_w = 6 (gray lines correspond to loading-unloading loops formulated by means of the generalized Masing rules)

STATE-OF-PRACTICE & FUTURE RESEARCH

Selection of the appropriate methodology for prediction of soil nonlinearity in strong ground motion is based on the anticipated strain amplitude, and while EQL formulations have been shown to produce reasonable results for strain amplitudes on the order of 10^{-5} to 10^{-3}, nonlinear methods are necessary to capture phenomena such as irreversible deformations, pore pressure coupling, cyclic mobility etc. The accuracy of nonlinear site-response analyses, however, depends on the constitutive model used, and elaborate constitutive models require numerous parameters which must be determined through lab tests and/or field tests; in turn, this additional effort involved to develop the required parameters, often limits their frequency of use. Currently, semi-empirical procedures are deeply rooted and still dominate the geotechnical engineering practice, while there is a clear lack of consensus on what nonlinear material model should be employed –if dictated by the anticipated levels of strain- and how the required input parameters should be estimated. As stated by C. Desai: […*Soil models are like religion. Everyone believes in his own but not in anyone-else's*…].

In this paper, we have presented the preliminary steps of a comprehensive uncertainty assessment study on nonlinear site response methodologies. The long-term objectives of this work include advancement of the understanding of nonlinear effects through model validation based on in-situ data, comprehensive investigation of the uncertainty associated with nonlinear simulation methodologies, as well as the development of guidelines addressing the issues that have been identified to prohibit the adoption of nonlinear ground response analyses in practice, which will allow the optimal integration of nonlinear methods both in broadband ground motion simulations and in the engineering design practice.

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