Introduction to the Special Section on Advances in Site Response Estimation

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INTRODUCTION

Earthquake-induced ground motions are determined by a combination of source, path, and site effects. As seismic waves propagate along a path from the fault rupture to a given site, they often encounter softer geologic materials as they approach the ground surface. Site response, broadly defined as the effects of near-surface geologic materials on seismic waves, can significantly alter the amplitude, duration, and frequency content of ground motions. Therefore, to properly estimate seismic hazards and design earthquake-resistant infrastructure, it is necessary to accurately assess the effects of site response on ground motions.

Observations of large variations in damage patterns over short distances after many past earthquakes have provided empirical evidence of the effects of local geologic structures on the intensity of ground shaking. Kramer (1996) notes that some of the earliest published observations of site response occurred in the 1800s, during the 1819 Rann of Kutch, western India, earthquake (Macmurdo, 1824) and the 1857 Great Neapolitan (Basilicata), southern Italy, earthquake (Mallet, 1862). Arguably, the first significant earthquake that led to a wide recognition of site effects was the 1906 San Francisco, California, earthquake. In addition to supporting the development of elastic rebound theory, postearthquake observations confirmed the effects of underlying geologic materials on ground shaking intensity (Wood, 1908; Reid, 1910).

Site effects continued to be noted during earthquakes throughout the 1900s, but great strides in the understanding and modeling of site response did not occur until the second half of the century (e.g., Borcherdt, 1970; Seed and Idriss, 1971). The 1950s–1970s saw the development of analytical methods for computing the response of horizontally layered soil deposits to seismic waves, such as the linear Thomson–Haskell matrix method (Thomson, 1950; Haskell, 1953), and the equivalent-linear program SHAKE (Schnabel *et al.*, 1972). These theoretical methods revolutionized the consideration of site response in scientific and engineering practice, and fostered the inclusion of site effects in building codes (Borcherdt, 1994; Building Seismic Safety Council, 1998). Since the 1970s, our understanding of site response and of its damage potential has continued to evolve significantly due to advances in modeling capabilities, more and better seismic instrumentation, and more systematic documentation of relevant observations of damage distributions after earthquakes (e.g., through reconnaissance surveys).

As our understanding of site effects expanded, a significant earthquake that demonstrated a strong linkage between soil conditions, resonant frequencies, and structural damage was the 1967 M_w 6.6 Caracas, Venezuela, earthquake, in which buildings within a specific height range were most severely affected (Seed *et al.*, 1972). Eighteen years later, the 1985 M_w 8.0 Michoacán, Mexico, earthquake produced extreme amplifications in soft lacustrine deposits beneath Mexico City, over 300 km from the earthquake rupture, leading to heavy damage and loss of life (Seed *et al.*, 1988). This earthquake was perhaps one of the most influential events in modern history in terms of broadening the understanding of site response among the general public, underscoring themes that were observed again 4 yr later during the 1989 M_w 6.9 Loma Prieta earthquake (Seed *et al.*, 1991), and in many earthquakes since then (e.g., Chang *et al.*, 1996). Site response now has a significant role in the development and application of ground-motion models (GMMs), seismic hazard mapping, building codes, site-specific ground-response analyses, and probabilistic seismic hazard analyses (PSHAs).

Figure 1 illustrates modeling frameworks for estimating site response and examples of common local (shallow) geologic structures and complex wave-propagation phenomena that impose challenges for accurate site response estimation. Figure 1 also depicts the main components required for numerical estimations of site response, grouped into five categories: (1) subsurface characterization at the site, (2) characterization of dynamic material behavior properties, (3) constitutive model selection, (4) site response modeling framework (i.e., 1D, 2D, or 3D), and (5) characterization and selection of input (bedrock) ground motions. First, a representation of the site profile stratigraphy is necessary, including knowledge of the density (ρ), thickness, and plasticity of the

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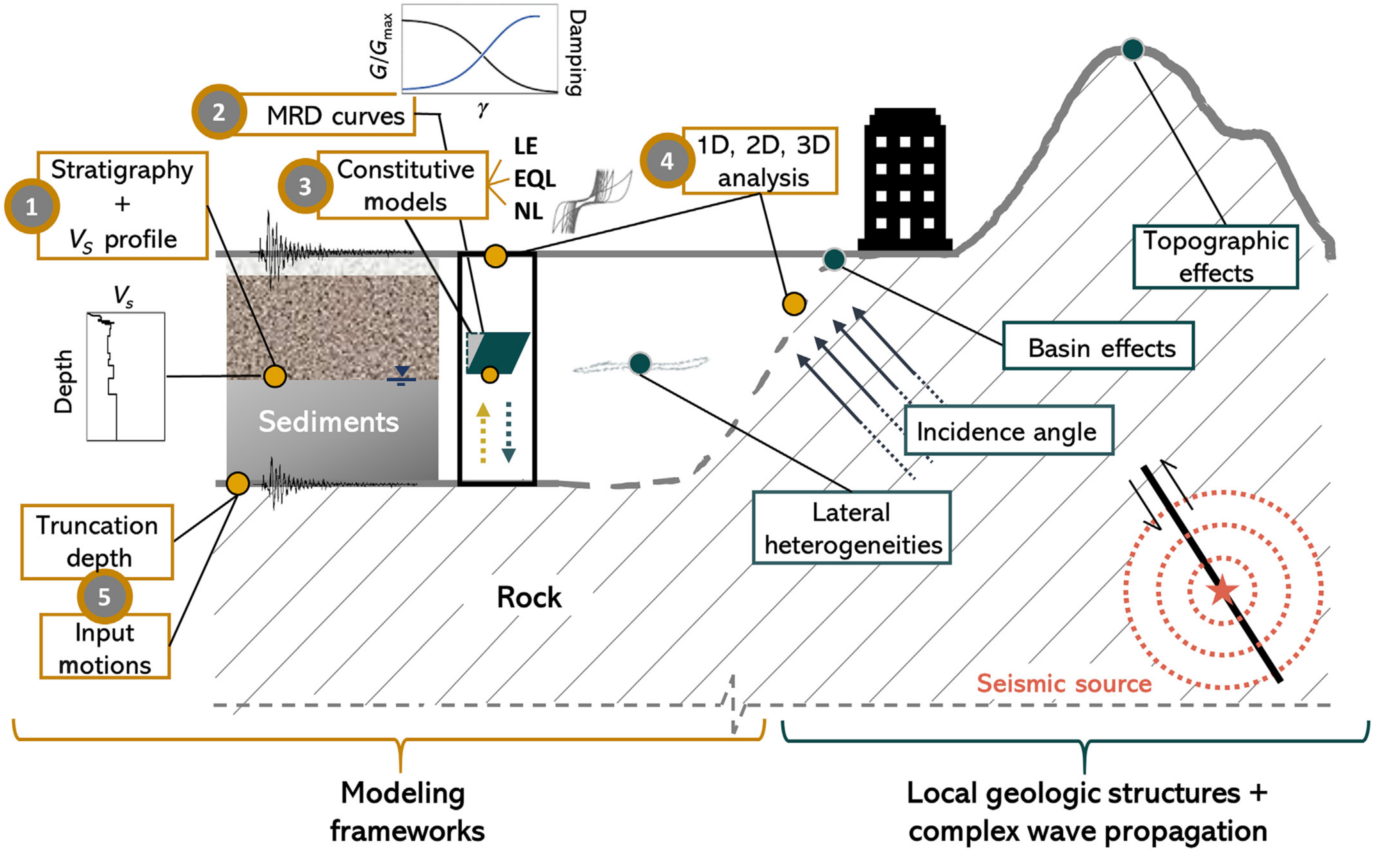

Figure 1. Schematic of components of site response estimation. Modeling frameworks for estimating site response via numerical simulations are grouped into five categories, shown at left: (1) stratigraphy and V_S profile (including the groundwater table, denoted by the triangular symbol in the sediment column); (2) modulus reduction ($G/G_{\max}$) and damping curves (modulus reduction and damping [MRD] curves, as a function of shear strain, γ); (3) constitutive models, including linear-elastic (LE), equivalent-linear (EQL), and fully nonlinear (NL) models; (4) 1D to multidimensional (2D and 3D) site response modeling frameworks; and (5) the characterization of input motions and the truncation depth of the sediment column of interest. Local geologic (shallow) structures and complex wave-propagation phenomena that remain challenging to model in site response analyses are depicted at right: topographic effects, basin effects, nonvertical incidence, and lateral subsurface heterogeneities. The primary output of site response analyses, the predicted ground motion at the surface of the site, is also illustrated. The color version of this figure is available only in the electronic edition.

layers to be included in the numerical model, as well as the location of the groundwater table. Profiles of shear-wave velocity (V_S) and small-strain damping ratio (ξ) are essential for all site response analyses. To incorporate nonlinear effects, strain-dependent dynamic properties must be specified, most commonly using modulus reduction and damping (MRD) curves. In general, available constitutive models for site response include linear, equivalent-linear, and nonlinear models. For equivalent-linear analyses, MRD curves are specified directly as input; for time-domain nonlinear analyses, MRD curves are often used as the target curves for fitting the nonlinear material parameters. Strength parameters are also often required for nonlinear analyses that apply corrections for shear strength of materials at large strains (e.g., Groholski *et al.*, 2016; Shi and Asimaki, 2017).

The site response modeling framework refers to the selection of 1D or multidimensional (2D or 3D) analyses, with simplified 1D analyses being the most widely used in engineering practice. Figure 1 illustrates phenomena that cannot be captured by 1D analyses, such as topographic effects, basin effects (e.g., focusing and 2D resonance), nonvertically incident waves, and lateral subsurface heterogeneities, to name a few. Finally, input ground motions that represent the incoming seismic waves at the base of the soil column must be specified. These ground-motion records can either be obtained as surface "outcrop" motions recorded at sites underlain by hard rock or as downhole "within" motions recorded using vertical seismometer arrays at depth, after appropriate corrections. The specification of the truncation depth of the numerical model of the soil column often implies that an elastic half-space boundary is positioned at the base of the column (i.e., a homogeneous, linear elastic material is assumed beneath the base of the soil column). Importantly, input ground motions must be compatible with the properties assumed for the elastic half-space in the model (soft rock, hard rock, etc.). Ultimately, these five components required for the numerical evaluation of site response assessment, as illustrated in Figure 1, are highly interrelated.

Despite advancements in the understanding of site effects and the prediction of site response, methods for estimating site response still have limitations and are affected by multiple sources of uncertainty. This Special Section brings together 29 studies that represent the state-of-the-art in site response estimation, with the overarching goals of summarizing recent advances in the field and identifying areas with potential for improvement. The studies in this Special Section are grouped into five interrelated themes that span the various components of site response estimation presented in Figure 1: (1) site characterization, (2) observations and predictions of site amplifications, (3) site response analyses and uncertainties, (4) modeling of 2D and 3D effects, and (5) assessment of nonlinear effects and damping. In this article, we summarize some of the key research topics within each of these themes, discuss the significant contributions of each study and how they relate to one another, and provide some perspectives on future research directions and challenges in the field. Although the articles in this Special Section encompass a wide variety of focus areas and research methods, they are unified in their overarching goal of improving our ability to accurately predict earthquake ground motions.

SITE CHARACTERIZATION

Characterization of near-surface geologic properties at a site is essential for predicting site response behavior through numerical simulations. Measurement or estimation of a number of material properties is needed, including seismic velocities, densities, and small-strain damping ratios, as well as strain-dependent dynamic soil properties for the incorporation of nonlinear soil behavior. The articles in the Site Characterization section are centered on the assessment of seismic velocities (in particular, V_S) from site-specific measurements or estimation from ground-motion records, as well as how these velocities are specified in downstream analyses. In addition, some articles in the Assessment of Nonlinear Effects and Damping section discuss the estimation of damping and kappa (κ), the high-frequency spectral decay parameter (Anderson and Hough, 1984).

The Special Section begins with an article evaluating the characteristics of V_S in terms of its assumed probability distribution. Mital *et al.* (2021) address the uncertainty and skewness associated with measurements of V_{S30}, the time-averaged shear-wave velocity in the upper 30 m of the subsurface. A probabilistic framework is presented in which the distribution of V_{S30} measurements can be theoretically approximated by a reciprocal–normal distribution using geostatistics and probability theory. Mital *et al.* (2021) show that a nonnormal and skewed distribution of V_{S30} is to be expected, and it does not necessarily reflect error or sampling bias. However, sampling bias can exaggerate the skewness of the distribution. Results from this work support the use of the mode as the characteristic value of V_{S30} measurements, as opposed to the mean or median value.

A number of in situ measurement techniques are available to characterize seismic velocities, ranging from direct measurements made in boreholes to measurements from noninvasive techniques at the surface. There has been a large increase in the availability and usage of noninvasive methods for rapidly characterizing sites in recent years, allowing for measurements over much broader areas than was previously possible. Two articles in this section, Hobiger *et al.* (2021) and Stephenson *et al.* (2021), focus on V_S measurements at seismic stations. Stephenson *et al.* (2021) analyze multimethod V_S data acquired at three permanent and 25 temporary seismograph stations in Oklahoma. They find a strong agreement between the predicted in situ model and the observed resonant frequencies from horizontal-to-vertical spectral ratio (HVSR) data. Using multiple in situ V_{S30} measurements, Stephenson *et al.* (2021) further quantify the improvement in the accuracies of selected suites of GMMs when compared to predictions using proxy methods for V_{S30} estimation. Hobiger *et al.* (2021) present the results of multiple geotechnical and geophysical subsurface characterization methods at strong-motion stations from the Swiss Seismological Service Network, using detailed analyses at two stations as an example. The fundamental frequency of the site, the polarization of the wavefield, the Love- and Rayleigh-wave phase-velocity dispersion curves, and the Rayleigh-wave ellipticity function are estimated from the diverse in situ data. Inversions at one of the study sites confirm the benefits of including Rayleigh-wave ellipticity information to reduce the range of potential velocity values. The results of this work should help to support improved seismic hazard assessments and magnitude calculations in the region.

An emerging area in site characterization is the estimation of site properties from ground-motion records, which is the focus of two articles in this Special Section, Kim (2021) and Okazaki *et al.* (2021). Okazaki *et al.* (2021) apply a neural network (NN) machine-learning algorithm to construct site-specific GMMs that extract site properties from ground-motion data. The model incorporates one-hot encoding of the site ID, which optimizes the flexibility of the NN to obtain site-specific properties, while avoiding overfitting at sites for which a small number of strong motions have been recorded. Okazaki *et al.* (2021) find that the proposed model produces accurate and robust estimations of peak ground acceleration (PGA) for data-poor sites. The resulting model could be used to derive single-station sigma estimates and be incorporated in site-specific GMMs. Kim (2021) uses ground-motion data from the Kiban–Kyoshin (KiK-net) network of vertical seismometer arrays in Japan to develop a new method of estimating near-surface *P*-wave velocities. Using *P*-wave seismograms recorded on the ground surface, the proposed method is based on the incidence angles of the *P* waves in the subsurface. Inversions for *P*-wave velocity profiles are performed by comparing the epicentral distance implied from Snell's law to the known epicentral distance, allowing for the estimation of

P-wave velocities solely from ground-motion records, source-to-site distances, and focal depths.

The Site Characterization section concludes with an article by Al Atik and Abrahamson (2021) that illustrates the importance of proper V_S characterization in downstream analyses, such as GMM adjustments and site response analyses. This article highlights an application of V_S profiles and GMMs in terms of host-to-target adjustments, in which GMMs constructed for one region (the host) are adapted for application in another region (the target), which has a different velocity structure than the region in which the GMM was derived. The authors propose a methodology (based on the principles of quarter-wavelength linear site amplification) that allows for the derivation of GMM-compatible host 1D V_S profiles and kappa values.

OBSERVATIONS AND PREDICTIONS OF SITE AMPLIFICATIONS

Observations of site amplifications and related parameters are necessary for the development of predictive models for ground-motion amplifications as a function of site parameters (such as V_{S30}, fundamental site frequency f_0, etc.). Data can be obtained from recordings of earthquakes at seismometer stations and/or from in situ ambient-noise measurements. In this regard, there has recently been a significant growth in interest in HVSR measurements (from earthquake signals or ambient noise) for characterizing site amplifications and fundamental frequencies (Parolai, 2012; Kawase *et al.*, 2019; Ito *et al.*, 2020; Zhu *et al.*, 2020), including multiple studies in this Special Section. The eight articles in the Observations and Predictions of Site Amplifications section address various aspects of the measurement and prediction of site amplifications; nonlinear effects are addressed more fully in the Assessment of Nonlinear Effects and Damping section.

Machine-learning techniques, as applied to site characterization by Okazaki *et al.* (2021) in this Special Section, also show significant promise for the prediction of site amplification. Roten and Olsen (2021) apply deep learning to predict surface-to-borehole Fourier amplification functions (AFs). The authors train an NN with observed mean AFs from KiK-net vertical array sites and then perform a blind comparison of the NN-based predicted AFs with predictions based on theoretical 1D linear amplifications. The NN reduces the mean squared logarithmic error between predictions and observations by up to 50%, which suggests that NNs may lead to purely data-driven, accurate predictions of site responses, independently of proxies or simplifying assumptions.

Four studies in this section evaluate ground-motion amplifications in the central and eastern United States (CEUS): Pratt and Schleicher (2021) and Schleicher and Pratt (2021) across the Atlantic Coastal Plain (ACP) in the eastern United States, Chapman and Guo (2021) for the ACP and the Gulf Coastal Plain, and Zhu *et al.* (2021) in western Kentucky. First, Pratt and Schleicher (2021) characterize ground-motion amplification in the ACP strata by means of Fourier spectral ratios from teleseismic and regional earthquakes at 217 sites. Spectral ratios are computed with respect to the average of four bedrock sites to derive AFs versus ACP thickness at specific frequencies. Findings from this work provide evidence of prominent resonance peaks that define the largest amplifications at specific ACP thicknesses for each frequency. As frequencies increase, the resonance peaks migrate to thinner ACP strata and increase in amplitude. The general method used in Pratt and Schleicher (2021) can be used to characterize 1D amplification effects of widespread sediments. Schleicher and Pratt (2021) compare site response estimates on ACP strata derived using both sediment-to-bedrock ratios (SBSRs) from teleseismic signals recorded by regional arrays and HVSRs computed from earthquake arrivals and ambient noise. The authors confirm a close match in f_0 determined by both methods in laterally extensive sediments. Schleicher and Pratt (2021) find that correcting the HVSR amplitudes derived from earthquake arrivals using source-term information from a bedrock site and multiplying the peak by a factor of 1.2 results in amplitude peaks that, on average, match SBSR results within a factor of 2. The authors conclude that the HVSR method may successfully estimate regional linear weak-motion site response amplifications from the ACP, or similar geologic environments, when appropriate region-specific corrections to the amplitude ratios are used.

Chapman and Guo (2021) develop a linear site amplification model for pseudospectral acceleration (PSA) response ratios in the Atlantic and Gulf Coastal Plains in the southeastern United States. The reference site condition is defined as the mean response for stations located outside the coastal plain. Their resulting model for PSA ratios is dependent on the coastal plain sediment thickness, and can be used with existing GMMs to predict motions for linear behavior in the ACP and Gulf regions of the United States. Zhu *et al.* (2021) evaluate site effects in the Jackson Purchase region of extreme western Kentucky, located within the CEUS in the New Madrid seismic zone. Their article addresses the use of f_0 and the corresponding peak amplification as first-order approximations of site effects. Zhu *et al.* (2021) develop a regional 3D V_S model based on seismic reflection and refraction data, mapped geologic units, and digital-elevation-model datasets. From the results of 1D site response analyses, the authors confirm that the depth to bedrock is correlated with the fundamental site period, whereas the average sediment V_S is correlated with the peak amplification.

The three remaining studies in the Observations and Predictions of Site Amplifications section investigate site amplifications in other regions. Klin *et al.* (2021) analyze more than 7300 three-component recordings collected by 67 permanent stations in northeastern Italy. They observe noticeable amplifications at stations located not only on alluvial deposits but also at several stations that were installed on what were assumed to be rock sites, highlighting the challenges in defining reference rock stations for site response evaluation. Their results suggest the possibility of forecasting time-domain peak ground motion values from AFs estimated by generalized inversion. Panzera *et al.* (2021) apply a canonical correlation analysis to predict the site amplifications at 172 free-field sites in Switzerland. Correlations are investigated between horizontal-to-vertical noise spectral ratios (HVNRs) from ambient vibrations and empirical AFs using generalized inversion of earthquake data. Predictions of amplifications at instrumented sites are compared with empirical observations, and the results show a systematic underprediction of amplifications in soft sediment sites and overprediction in hard-rock sites. To mitigate this bias, the authors incorporate geological and geophysical parameters in addition to the HVNRs in the canonical correlation analysis. Using data from Gori, in the country of Georgia, Giallini *et al.* (2021) apply principal component analysis to reconstruct a subsurface model for seismic microzonation purposes. The article focuses on the full exploitation of geological and inexpensive geophysical surveys for seismic characterization, in the frame of microzonation studies in urban areas where economic resources for detailed seismic response analyses may be scarce. The proposed approach allows for a reliable assessment of subsurface structures, geological domains, and the distribution of lithofacies, all of which influence the local seismic response.

SITE RESPONSE ANALYSES AND UNCERTAINTIES

Site response analyses are used to estimate site-specific ground motions using the assumed soil profile properties and dynamic soil behavior properties, the selected constitutive model and analysis framework, and the input (bedrock) motion, which is applied at the base of the profile and propagated upward (as illustrated in Fig. 1). Significant uncertainties exist in site response modeling; blind comparisons of site response predictions with observations at vertical seismometer arrays often show considerable disagreement (e.g., Boore, 2004; Thompson *et al.*, 2012; Kaklamanos *et al.*, 2013). In recent years, a number of studies have evaluated the choice of the site response constitutive model (e.g., equivalent-linear vs. nonlinear; Zalachoris and Rathje, 2015; Shi and Asimaki, 2017; Kaklamanos and Bradley, 2018), uncertainties in the input parameters in site response estimation (such as shear-wave velocity, small-strain damping, MRD curves, and input motions; Rathje *et al.*, 2010; Teague *et al.*, 2018; Bahrampouri *et al.*, 2019; Kaklamanos *et al.*, 2020; Meite *et al.*, 2020; Passeri *et al.*, 2020), and the overall epistemic uncertainty associated with site response modeling (Rodriguez-Marek *et al.*, 2021; Stewart and Afshari, 2021). The studies in the Site Response Analyses and Uncertainties section further our understanding of the aforementioned topics.

Two studies in this section, Aimar and Foti (2021) and Bessette and Yniesta (2021), perform evaluations of constitutive models in site response analyses. Using the results of a large number of 1D site response simulations, Aimar and Foti (2021) develop simplified criteria for selecting between equivalent-linear and nonlinear analyses in seismic design. Equivalent-linear analyses are more computationally efficient and require fewer input parameters, but nonlinear analyses more realistically represent the dynamic soil behavior of the soil. The authors' criteria are based on site and ground-motion parameters such as the average V_S, thickness of the soil deposits, and PGA, and their recommendations are dependent on the period range of interest to the structure. Aimar and Foti (2021) find that equivalent-linear and nonlinear models provide similar results, except for deep (>30 m) and soft soil deposits. Even for PGAs up to $0.1g$–$0.2g$, the authors conclude that the equivalent-linear scheme is still adequate for routine hazard assessments. Using data from five downhole arrays and two centrifuge experiments, Bessette and Yniesta (2021) compare the results of effective-stress nonlinear models with those from more common total-stress nonlinear and equivalent-linear models. The comparison of total-stress and effective-stress nonlinear 1D site response models has not received significant attention in the literature to date. Effective-stress analyses, which incorporate the generation of excess pore pressures, potentially allow for a more rigorous representation of material behavior, but they have not been extensively validated. The authors find that although effective stress models are critical for predicting liquefaction-related phenomena, they should be used with caution for predicting surface response spectra, for which they do not show an improvement over total-stress analyses.

The quantification of uncertainties in site response analyses continues to be a topic of high interest in the community. Dejphumee and Sasanakul (2021) undertake an evaluation of site response behavior at two sites in the South Carolina Coastal Plain—an area of high seismic hazard on the U.S. Atlantic Seaboard. Using equivalent-linear analyses, the authors quantify how uncertainties in the V_S profiles from different measurement methods are mapped into the site amplification factors. By evaluating the characteristics of the velocity profiles that contribute to uncertainty, Dejphumee and Sasanakul (2021) find that the average shear-wave velocity V_{S30}, the velocity contrast at the base of the profile, and the depth to engineering bedrock impact not only the mean amplification factors but also their variabilities.

The final two articles in the Site Response Analyses and Uncertainties section work toward the goal of properly incorporating site effects in PSHAs. Williams and Abrahamson (2021) introduce the V_S profile correction method—an alternative to the soil-over-rock approach often used for site response analyses. The proposed approach requires two site response analyses: the first using the generic profile associated with the GMMs and the second using a site-specific profile. Then, the ratio of the two site response analysis results is used to correct the design response spectrum for the reference site condition developed using the GMMs. Through two example applications, Williams and Abrahamson (2021) show that the standard soil-over-rock analysis can lead to underpredictions of long-period spectral accelerations.

A common method of incorporating epistemic uncertainty in PSHAs, particularly for critical facilities such as nuclear power plants, is to compute an amplification curve as a weighted average of alternative branches of a site response logic tree (accounting for multiple scenarios, such as alternative V_S profiles). Ulmer *et al.* (2021) identify a shortcoming of this standard approach in which statistical smoothing of the amplification curve can occur, resulting in decreased computed hazard as epistemic uncertainty increases (when, in fact, the converse should occur). The authors propose a modified procedure for capturing epistemic uncertainty using a plot of amplification factors versus period, with period-dependent weights. Their method is ultimately consistent with one of the guiding principles of PSHA that higher uncertainty should lead to higher hazard, and their method has the potential to be broadly applied in PSHAs.

MODELING OF 2D and 3D EFFECTS

One-dimensional analyses are, by far, the most common methodology for predicting the effects of near-surface geologic materials on seismic waves. However, a number of studies have shown that the simplifying assumptions and limitations of 1D analyses may significantly affect the accuracy of ground-motion predictions (Bard and Bouchon, 1985; Paolucci, 2002; Raptakis *et al.*, 2004). As illustrated in Figure 1, a number of 2D and 3D effects can influence ground motions, including: (1) 3D subsurface heterogeneity (which produces lateral variations in velocities that can scatter and/or focus seismic waves), (2) topographic effects (interactions of seismic waves with sloping ground, hills, valleys, or 2D earth structures), (3) basin edge effects (surface waves generated from diffraction and interactions at the edge of sedimentary basins), (4) incident angle ground-motion effects (deviating from the common assumption that site response is caused by only vertically propagating shear waves), and (5) 3D soil constitutive response (material behavior that is dependent on stresses and strains in multiple dimensions). Further research on multidimensional site effects, as addressed by the studies in this section, will allow us to better understand the limitations of existing 1D models, incorporate correction factors to the results of 1D models, and undertake more advanced modeling strategies where appropriate (e.g., Asimaki and Mohammadi, 2018; Pilz and Cotton, 2019).

Two studies in this section, Hu *et al.* (2021) and Pitarka and Mellors (2021), evaluate the influence of lateral subsurface heterogeneities on ground motions using 3D wave-propagation simulations. Pitarka and Mellors (2021) apply cross-correlation-based methods to vertical waveforms from an underground chemical explosion to evaluate the statistical properties of small-scale velocity heterogeneities. They compare simulated wavefields from their numerical model with observed wavefields from a dense 2D seismic array. Pitarka and Mellors (2021) recover sets of statistical properties of small-scale velocity perturbations in the velocity model that produce the best fits between the recorded and simulated ground motions. They find that adding a depth-resolved stochastic variability to the geology-based velocity model improves the overall performance of ground-motion simulations. Using 3D subsurface velocity models and linear wave-propagation calculations, Hu *et al.* (2021) propose a framework for modeling 3D site response. At two well-documented vertical arrays (the Garner Valley Downhole Array in southern California and KiK-net site TKCH05 in Japan), they compare the modeled surface-downhole transfer functions with those inverted from recorded ground motions. Compared to standard 1D site response models that assume laterally constant velocity layers and vertically propagating shear waves, their 3D model more accurately represents the scattering of seismic waves by lateral subsurface heterogeneities.

Dynamic rupture simulations have the capability to capture source, path, and site effects using a physics-based approach. Huang (2021) uses 2D dynamic rupture simulations to evaluate the depletion of high-frequency seismic energy at soil sites. Reductions in amplitudes of HVSRs at high frequencies are often attributed to nonlinear soil behavior. Huang (2021) finds that an alternative explanation for the reduction of high-frequency seismic energy is crustal velocity models that are overly smooth. The author concludes that the smoothness of crustal velocity profiles should be more strongly emphasized in the simulation of near-field strong ground motions.

Basin effects can significantly affect site amplifications at long spectral periods. Mascandola *et al.* (2021) analyze observations of amplifications in the Po Plain sedimentary basin of northern Italy to investigate the influence of shallow deposits on long-period ground motions. This study provides a new seismostratigraphic model of the shallow deposits of the entire basin, which is used to estimate site amplification by means of 1D site response analyses. Comparisons with observations demonstrate that the 1D numerical model is not able to capture the amplitude of the actual seismic amplification of the basin in the long-period range. The authors find average underestimations of 30%–60% of the amplification in the basin by 1D analyses. Mascandola *et al.* (2021) recommend the implementation of basin-effects terms from GMMs as correction factors to adjust 1D site response analyses for multidimensional basin effects.

The Modeling of 2D and 3D Effects section concludes with two companion articles (Dafni and Wartman, 2021a,b) that evaluate topographic effects on site response. Both studies present results from a comprehensive geotechnical centrifuge experimental program to investigate topographic effects of single-sided slopes. Dafni and Wartman (2021a) perform a parametric investigation of the results of the centrifuge tests, by evaluating a range of factors that influence topographic effects, including the angle of inclination of the slope, and ground-motion amplitude, frequency content, and duration. The authors find that both frequency content and amplitude are greatly affected by topography, especially for ground motions with high energy at frequencies near the topographic resonant frequency. At the crest of a slope, the measured PGAs range from 50% to 200% of the corresponding free-field PGA and the mean square frequency can be shifted by as much as 55%, compared to the corresponding free-field value. Dafni and Wartman (2021b) further evaluate the mechanisms of how topography can modify ground motions, building on the findings of the parametric investigation. The laboratory results indicate that resonance at the topographic frequency of the slope is the principal driver of topographic effects on ground motions, and that site and topographic effects may combine at a slope crest to produce high levels of overall amplification. Dafni and Wartman (2021a,b) illustrate that new methods and measures of topographic effects may help bridge the gap between numerical modeling of topographic effects and field observations during earthquakes.

ASSESSMENT OF NONLINEAR EFFECTS AND DAMPING

Several previously discussed articles in the Special Section have addressed the influence of nonlinear soil behavior in 1D site response analyses (Aimar and Foti, 2021; Bessette and Yniesta, 2021). The studies in the Assessment of Nonlinear Effects and Damping section address nonlinear site effects in contexts outside of 1D site response analyses, including observations of nonlinear effects during earthquakes, and predictions of nonlinear effects using site amplification factors (for incorporation in GMMs). Also addressed in this section is the accurate characterization of the attenuation and damping of ground motions in near-surface materials, which has been a widely discussed topic in the recent literature (Cabas *et al.*, 2017; Afshari and Stewart, 2019; Tao and Rathje, 2019; Xu *et al.*, 2020).

Thornley *et al.* (2021) undertake an investigation of nonlinear soil behavior observed during the 2018 M_w 7.1 Anchorage, Alaska, earthquake. Using the generalized inversion technique, the authors evaluate site responses at over 20 strong-motion stations, with records from 94 events from 2005 to 2019, including weak to strong ground motions. The authors compare site response differences for multiple National Earthquake Hazards Reduction Program site classes and ranges of V_{S30}, and they observe nonlinear site response for sites with $V_{S30} < 300$ m/s, but not for stiffer sites. A shear-strain proxy (peak ground velocity divided by V_{S30}) supports the observation that sites with lower V_{S30} experienced nonlinear site response.

Nonlinear site amplification models are an important component of GMMs. Loviknes *et al.* (2021) present a transparent framework for testing nonlinear site amplification models against observed ground motions and linear site amplification models. Using a set of records from the KiK-net database with bedrock PGAs less than 0.2*g*, the authors find that the effects of nonlinearity are not significant in this PGA range; linear site amplification models actually perform better than nonlinear site amplification models in the aggregate. In addition to producing a framework for validating future nonlinear site amplification models, the methods of Loviknes *et al.* (2021) allow for an evaluation of the degree of nonlinear effects. For the sites and ground motions considered, their conclusions suggest that a wider-than-expected range of PGAs can be characterized using linear (rather than nonlinear) site amplification models in GMMs and building codes.

The final two studies in the Special Section concern near-surface attenuation (Ji *et al.*, 2021) and damping ratios (Boore *et al.*, 2021). Using sites and ground motions from the KiK-net database, Ji *et al.* (2021) evaluate the effects of nonlinear soil behavior on κ. The authors investigate the behavior of both the Fourier amplitude-based kappa per record (κ_r) and the site-specific component of kappa (κ_0) beyond the linear-elastic regime. They find that the classification scheme used to identify ground motions that trigger soil nonlinear behavior biases estimates of κ_0 in the linear and nonlinear regimes. Ji *et al.* (2021) show that soil nonlinearity affects κ_r and κ_0 estimates, but this influence is station dependent. The authors find that other complexities in the wave propagation (e.g., scattering and amplifications in the high-frequency range) impose challenges to the application of κ_0, including the estimation of negative values of κ_r. Boore *et al.* (2021) determine average damping ratios at 22 sites in the San Francisco Bay and San Fernando Valley areas using surface sources and downhole receivers. The in situ damping ratios are estimated over a range of depths and include values from less than 1% to almost 8%, showing little dependence on grain size. These average damping ratios provide a representation of the cumulative effect of wave propagation over a depth range that is similar to the use of κ. Boore *et al.* (2021) find that damping ratios for sites with average V_S larger than 450 m/s are greater than their counterparts for softer sites. Although nonintuitive, this observation is explained by the combined effects of the attenuation properties of the material and the time spent by seismic waves traveling through such material.

FUTURE DIRECTIONS AND CHALLENGES

Despite substantial progress, there remain many challenges and opportunities for further improvements in site response estimation. In the Future Directions and Challenges section, we provide some perspectives on the adequacy of current site response estimation methods and the major issues that need to be addressed. We present some potential promising future research directions, echoing the themes of this Special Section that may leverage emerging methods and technologies in the field.

Improvements in site characterization and the representation of dynamic soil behavior are vital for accurate site response estimation, as illustrated by many of the articles in this Special Section. There has been a trend in recent years toward site characterization methods involving rapid in situ measurements at the ground surface or using ground-motion recordings. In the future, we expect such methods to rise in popularity, with the potential to perform measurements of a site's behavior in a matter of minutes or seconds. Passive-source measurements using ambient noise are likely to be more heavily used for rapid site characterization.

Extremely efficient measurements of soil behavior subjected to cyclic loading could transform how we think about seismic hazard assessments. To that end, more comprehensive assessments of site response on a regional scale are likely to become much more commonplace, as the availability of data and computational power continues to grow. Systematic site effects, therefore, could be more rigorously integrated into seismic hazard maps (e.g., Pergalani *et al.*, 2020), and this may impact urban planning and seismic design efforts, as well as postevent emergency response. Such efforts will require more effective and frequent communication between scientists, engineers, and the public. Moreover, site responses have the potential to be more broadly incorporated into regional earthquake early warning systems in the future (Hoshiba, 2013; Pilz and Parolai, 2016). As the available data grow, more detailed site response criteria may be integrated in building codes; the state of the practice in most current building codes and design standards (e.g., American Society of Civil Engineers, 2017; European Committee for Standardization [Eurocode 8], 2004]) is to classify sites using V_{S30}. However, changes have been proposed to Eurocode 8 to incorporate additional site variables such as H_{800}, the depth to seismic bedrock ($V_S = 800$ m/s) (Paolucci *et al.*, 2021). Future building codes may explore the potential to incorporate more complex site effects such as basin resonance (Chávez-García and Faccioli, 2000).

Several studies in this Special Section have used ground-motion recordings to extract site properties and amplification behavior. In the years ahead, an increase in the number of seismic recording instruments may foster new methods of estimating near-surface seismic velocities from ground-motion data. The number of instruments has been expanding rapidly, especially with dense networks for earthquake early warning. The growth of smartphone ownership throughout the globe over the past decade can also be leveraged. Nearly every mobile device has the potential to measure ground motions during an earthquake; although the data quality of such recordings may be an obstacle, the vast number of observations may allow for integrating many measurements to increase accuracy. Measurements from nontraditional seismometers could be particularly important in regions that lack dense seismic networks. Recent investigation of the usage of optical fibers seems to be promising for allowing high resolution and repeatable measurements of the subsurface (Ajo-Franklin *et al.*, 2019).

When the next significant earthquake occurs, especially beneath a large urban area, we will obtain a much greater number of recordings over different ground conditions. The number of observations of truly nonlinear behavior will almost certainly increase in ground-motion databases, which will aid in the development and validation of GMMs and site response methods. An increase in near-source strong-motion records will be particularly beneficial to understanding seismic hazards in cities near major faults, such as San Francisco, Istanbul, and Tehran. As the amount of site and ground-motion data continue to grow, we expect that big data analytics and machine-learning technologies (such as those employed by Okazaki *et al.*, 2021; Roten and Olsen, 2021, in this Special Section) to enter the field of site response estimation on a much more robust scale. Such techniques could also support more detailed physics-based analyses of seismograms, which would provide new insights into wave propagation, especially in the shallowest geologic structures.

Increases in available site and ground-motion data may foster lines of research that capture aspects of site response behavior that are currently challenging to represent. Several studies in this Special Section have evaluated the significance of 2D and 3D effects on site response, including lateral heterogeneities in seismic velocities (Hu *et al.*, 2021; Pitarka and Mellors, 2021), basin effects (Mascandola *et al.*, 2021), and topographic effects (Dafni and Wartman, 2021a,b). Multidimensional resonance will often be highly dependent on the direction of the incoming wavefield, and therefore 2D and 3D effects for a specific earthquake can be difficult to predict in advance. Further research into variations of site response with the wave incidence angle and source-to-site azimuth, and perhaps scenario-based (source zone-specific) simulations, may be required to fully capture multidimensional site effects (Wirth *et al.*, 2019; Ramos-Sepúlveda and Cabas, 2021).

Site response is most often envisioned as an earthquake effect on systems located at or near the ground surface, but an emerging research area is the inverse effect: the influence of civil infrastructure on site response. Soil–structure interaction has been investigated for some time, usually on the scale of a single building or foundation. In addition, the influence of large concentrations of structures (on the city scale) on ground motions has been evaluated (e.g., Guéguen *et al.*, 2002; Petrovic and Parolai, 2016). Objects at the ground surface, such as a dense forest of trees (Lott *et al.*, 2020), have recently been found to behave as locally resonant metamaterials for surface waves, producing frequency bandgaps in the seismic wavefield. Multiscale approaches to evaluate the influence of the damping of ground motions by large concentrations of buildings

(Guéguen and Colombi, 2016) may become more common in the coming years for densely populated urban environments, with important implications for seismic hazard assessments in cities. Furthermore, as we incorporate deeper geologic structures into site response estimates, a related topic is understanding the boundary between site and path effects. Seismic-wave propagation is often subdivided into source, path, and site contributions (e.g., Boore, 1983), but there is not always a clear separation at the interfaces of these categories. For example, the influence of crustal structure beneath a site could be conceptualized as either a path effect or site effect. As site response analyses in the future are perhaps truncated deeper in the subsurface, the assumptions of 1D site response and vertically propagating waves will need to be re-evaluated.

In the years ahead, we expect that remote-sensing technologies, including the usage of Global Navigation Satellite System data, will be applied to site response estimation on a broader scale. Such data can be used to analyze permanent soil deformation after earthquakes and detect ground failure due to liquefaction or landslides (Rathje and Franke, 2016). There is a growing interest the interaction of site response with secondary effects, such as liquefaction and landslides, and the incorporation of these secondary effects into seismic hazard maps. Also of interest are temporal variations in site response, which can occur for multiple reasons, such as inelastic soil deformations during a significant earthquake. Temporal changes in the groundwater table and the level of frozen soil (including permafrost) can also have significant effects on site response (Alshembari *et al.*, 2019); research on these temporal effects is inextricably linked to ongoing global efforts to better understand the impacts of climate change. There are many potential avenues through which site response estimation may evolve in the decades ahead. Regardless of the specific problem at hand, interdisciplinary methods and technologies will likely play a tremendous role in the future of site response estimation.

CONCLUSIONS

Although our ability to predict site response behavior has significantly evolved in the past few decades, there remain many challenges associated with site response estimation. Looking back at our significant progress on site response estimation in the past 25 yr gives us a baseline for what can be achievable in the decades to come. For example, consider that V_{S30} was first introduced as a GMM explanatory variable just under 25 yr ago by Boore *et al.* (1997). Although far from perfect, the use of V_{S30} reflected a desire to more quantitatively incorporate site effects in seismic design, and V_{S30} now has a near-universal meaning in the community. Twenty-five years from now, no one can predict exactly how site response estimation will have evolved. Given the recent progress in the field, however, we can presume that the state of site response estimation in 2046 will be significantly improved from 2021, just as the state of the field in 2021 has been improved from 1996. We hypothesize that advances in the estimation of site response could potentially be exponential in nature, leveraging new data and technologies, and global engagement and collaboration of geoscientists and earthquake engineers, which may allow for faster leaps than in previous years.

The articles in this Special Section provide an overall picture on the state-of-the-art of site response estimation and have contributed toward improving how earthquake ground motions are predicted. These continued research efforts will work toward the long-term goal of reducing the loss of life and property during earthquakes, while enabling a path toward the resilience of the built environment and the communities it serves, because, ultimately, this is the common goal that truly matters.

DATA AND RESOURCES

No data were used in this article.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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