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"Site response analysis considering strain compatible site period"

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ABSTRACT

In practice it is common to estimate site effects using a single proxy, or single variable such as 30 m shear wave velocity (V_{S30}) or site period. Many studies have investigated merits of proposed proxies with contradicting recommendations. Yet, most studies indicate the single proxy approach is less than ideal, resulting in large uncertainty. To provide a better understanding of components that drive site response, we performed a parameterized study on 19 shallow soil profiles with V_S ranging from 150 m/s to 400 m/s. We propagated 74 input motions through each soil column using one-dimensional equivalent-linear method to produce 1406 site response analyses. The resulting amplification factors (the ratio of surface to base motion) were then analyzed statistically to identify trends. The mean amplification factor, averaged from 74 records, was used to isolate and quantify the effects of V_S on site response. Based on analysis of record-to-record trends, we identified two separate mechanisms through which nonlinearity affects site response including "damping increase" and "site period shift". The interaction of these two mechanisms makes amplification-shaking intensity models highly depth-dependent. The residual standard deviation of amplification factor based on depth-independent models was found to be up to three times larger than the corresponding standard deviation based on depth-specific models. We found strain compatible site period a promising site parameter that complements the predictive information obtained from V_S. Finally, a simplified procedure providing a five-point estimate of site transfer function is outlined. The proposed procedure can fill the gap in current practice for an intermediate solution between the numerically rigorous solution and the single proxy approach. Implementation of this procedure is demonstrated in an example.

1. Introduction

Two general approaches are used to estimate site effects on ground motion. A "site-specific" analysis is usually performed for sensitive buildings and large infrastructure like highway or railroad bridges, underground subway stations, lifelines, and dams. The site-specific analysis can be conducted using nonlinear or equivalent-linear methods to propagate shear waves from basement rock to the ground surface. Although three dimensional solutions are available for site response, in most cases a one dimensional (1-D) solution based on assumption of polarized upward/downward shear waves and infinite horizontal layers is practiced. Implementation of site-specific analysis requires resources that may not be readily available for small to medium size projects or in conceptual/bid phase of large projects. Alternatively, generic site factors are used for final design of typical buildings, a wide range of small infrastructure, and in conceptual phase design of large infrastructure. Developing site factors has been done by compiling ground motion data recorded at soil and rock sites during past earthquakes and examining dependence of amplification factor on certain site parameter, also known as site proxy, using multivariable regression techniques (e.g., [1,3,5,6,13,16,26]).

The most commonly used site proxies include descriptive geotechnical or geological classification, shear wave velocity (V_S) averaged in top 30 m (V_{S30}), or site period (T_N). Borcherdt [5] analyzed site response data from 1989 Loma Prieta earthquake and suggested a linear relationship between amplification factor and V_{S30} in natural log scale at short and mid periods for two ranges of peak ground acceleration (PGA) of $<0.2g$ and $>0.2g$. Accordingly, a site classification was proposed based on V_{S30} to estimate site factors which were later adopted by the UBC1997 Code [27] and NEHRP Provisions (2009) [17]. Probabilistic seismic hazard analysis (PSHA) practice has gradually evolved to adopt the V_{S30}-based approach by incorporating V_{S30} and various depth-related terms, (e. g. depth to V_S =1000 m/s) in ground motion prediction equations (GMPE) including Next Generation of Attenuation (NGA) models (eg. [2,7,8,12].

The single proxy approach is simple to use but omits several key

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components of site response which leads to large uncertainty of the results. For example, site factors developed from 1989 Loma Prieta earthquake data by Borcherdt [5] have an standard error of regression of 0.5–0.65 in natural log scale. Choi and Stewart [13] developed amplification factors as a continuous function of V_{S30} and shaking intensity with a regression error ranged from 0.45 to 0.69 in natural log scale. Estimation of amplification factor with an error of such magnitude makes the applicability of the developed transfer functions limited.

There have been numerous studies focusing on merits of various site proxies with contradicting recommendations. Rodriguez et al. [20] used site response data from 1989 Loma Prieta and 1994 Northridge earthquakes to examine the accuracy of various site classification systems. They compared the V_{S30}-based classification and a site period-based classification and found the two systems provide similar accuracy in prediction of site response. Stewart et al. [23] used 1828 records from 154 shallow crustal earthquakes and found that a detailed-surface geology classification provides a more accurate prediction of site amplification than either the V_{S30}-based or a site period-based classification system for soil sites. Abrahamson [2] favored V_{S30} as a less subjective site parameter to be used in GMPE for deep soil sites common in California and suggested other site parameters can be added to GMPEs. Site period has been found an adequate site parameter by a handful of scholars (e.g. [29,10,19]). Zhao [30] used 3018 KiK-net downhole array record pairs (surface and borehole) from 95 earthquakes in Japan and developed a model for surface/borehole amplification factors. Based on this study, site period was found a better site proxy with lower standard deviation of inter-site residuals of amplification ratios compared to V_{S30} for spectral periods > 0.6 s. McVerry [19] analyzed the strong ground motion data that was used in developing New Zealand GMPEs and found site period is a more adequate predictor of site effects than V_{S30}, in particular, for deep/stiff sites. Castellaro [9] ran one dimensional equivalent-linear site response simulations for a suite of 585 soil profiles and two simple records including a Ricker wavelet with frequency of 1 Hz and 0.5 Hz and showed a matrix consisting of shear wave velocity of shallower softer layer, site period, and site impedance ratio predicts amplification factor better than V_{S30}.

Although a large number of studies suggested the inadequacy of the single proxy approach in general, and V_{S30} as the single site proxy in particular, no consensus has emerged for an alternative approach. The inconclusive research may be attributed to complexity of site response problem which is inherently unresolvable to a single predictor. This paper presents a parametric study of multiple components that are omitted in single proxy approach. The methodology includes performing 1-D site response analysis by propagating 74 ground motions through a suite of hypothetical soil profiles. The resulting suite of amplification factors is analyzed statistically to identify trends. This study attempts to provide some perspective on "which single proxy? " through a better understanding of the contribution of shear wave velocity, site period, and site period shift due to nonlinear soil behavior.

2. Methodology

The general methodology used here is similar to the approach used by [4], [28], and Castellaro [9]. In particular, this study was performed to build upon findings of [4]. The set of soil profiles used in this study covers a broader condition than the set used in [4]. This study includes 19 soil profiles, with V_S ranging from 150 m/s to 400 m/s and the depth to bedrock ranging from 10 m to 75 m. Two soil types, a generic sand and a generic clay (with plasticity index of 40–80) were used. The shear stiffness degradation and damping versus shear strain models [14,21,22,24] for these materials are plotted in Fig. 1. A summary of soil profiles along with the material type, V_S, and site periods are presented in the Table 1. Bedrock was assumed to have a V_S of 760 m/s to match the boundary between NEHRP B and C classes.

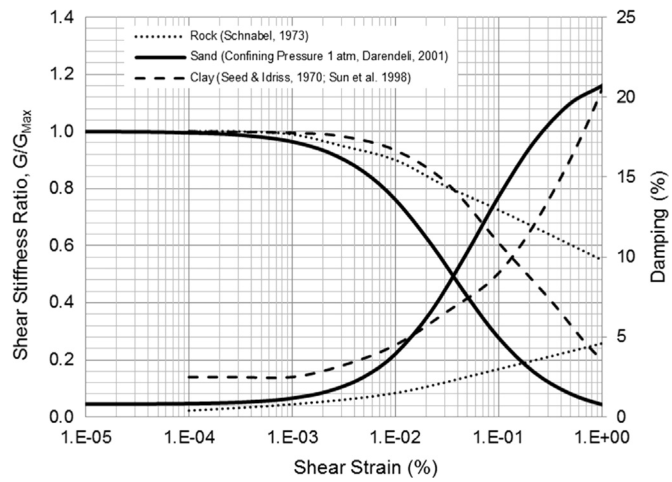

Fig. 1. Stiffness degradation and damping curves for materials used in this study.

Table 1
Hypothetical soil profiles used in this study.

Profile	Soil Type	Depth to bedrock (m)	V_S (m/s)	T_N (s)
S–75–400	Sand	75	400	0.75
S–75–316	Sand	75	316	0.95
S–75–200	Sand	75	200	1.50
S–50–400	Sand	50	400	0.50
S–50–316	Sand	50	316	0.63
S–50–200	Sand	50	200	1.00
S–25–400	Sand	25	400	0.25
S–25–316	Sand	25	316	0.32
S–25–200	Sand	25	200	0.50
C–75–400	Clay	75	400	0.75
C–75–316	Clay	75	316	0.95
C–75–200	Clay	75	200	1.50
C–50–400	Clay	50	400	0.50
C–50–316	Clay	50	316	0.63
C–50–200	Clay	50	200	1.00
C–25–400	Clay	25	400	0.25
C–25–316	Clay	25	316	0.32
C–25–200	Clay	25	200	0.50
S–10–150	Sand	10	150	0.27

A total number of 74 records from 27 earthquakes after [4] were run through each soil profile. Most of the ground motions were recorded at rock sites with average V_S of 760 m/s. The recording at the bedrock level is not equal to the recording at a nearby rock outcrop due to reflections and weathering of surficial rock. Following [4], we did not perform deconvolution for two reasons, (1) the main objective of this study is not to provide the best estimate of amplification factor but to investigate parameters and procedures that will lead to better estimate of amplification factor, (2) deconvolution is expected to impact site response at very short period range. Such period range is not usually of interest for infrastructure projects like bridges and tall buildings.

A list of records used in this study and the corresponding spectral accelerations are provided in the electronic supplement. The earthquake magnitudes range from M5.0 to M7.4 with a median value of M6.7, and *PGA* ranges from 0.01 g to 1.5 g, with median and geometric mean values 0.11 g. The ground motion database used in this study is available at Pacific Earthquake Engineering Research Center website (www.peer. Berkeley.edu; accessed November 2010).

We performed equivalent-linear 1-D site response analysis on each soil profile using SHAKE2000 [18]. The appropriate shear strain range for application of equivalent linear method is investigated in several past studies. Bolisetti et al. [11] conclude that the equivalent linear response is inappropriate when shear strain is greater than 1%. Kaklamnous et al. [15] recommended nonlinear method be used for