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INTEGRATION OF NON-ERGODIC SITE RESPONSE INTO NEHRP PROVISIONS & ASCE-7

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ABSTRACT

Site response effects are accounted for in the development of risk-targeted maximum considered earthquake (MCE_R) ground motions in two ways: (1) as site factors incorporated within ground-motion models, as implemented in the National Seismic Hazard Model, and (2) from the use of site response analyses that model wave propagation through a geotechnical model of the project site. Site response analyses are the subject of Section 21.1 in the NEHRP Provisions and the ASCE-7 Standard. As part of a provisions update cycle concluding in Fall 2026 for the NEHRP Provisions and 2028 for ASCE-7, Section 21.1 was rewritten to permit the use of probabilistic methods for combining site response with reference site ground motions, as well as to incorporate significant improvements related to parameter selection, uncertainty evaluation, and analytical approaches. Included within the updates are procedures that allow for the use of non-ergodic (site-specific) site response, including guardrails.

Keywords: Site response, non-ergodic, seismic design, building codes

INTRODUCTION

Site response effects are accounted for in the development of risk-targeted maximum considered earthquake (MCE_R) ground motions in two ways: (1) as site factors incorporated within ground-motion models, as implemented in the U.S. Geological Survey's National Seismic Hazard Model (NSHM), and (2) from the use of site response analyses that model wave propagation through a geotechnical model of the project site. Site response analyses are the subject of Section 21.1 in the NEHRP Provisions and the ASCE-7 Standard.

Site response analyses performed using the procedures in Section 21.1 are intended to capture the effects of site geotechnical conditions on ground-motion amplification and resulting surface ground-motion spectra. They require a much greater degree of site characterization effort and engineering analysis than the use of relatively simple site amplification models that are integrated into ground-motion models (GMMs), which in turn provide the ground-motion characterization components of the NSHM.

As part of a nearly completed provisions update cycle, Section 21.1 was rewritten to permit the use of probabilistic methods for combining site response with reference site ground motions, as well as to incorporate significant improvements related to parameter selection, uncertainty evaluation, and analytical approaches. This paper provides a brief overview of two alternative approaches that now appear in Section 21.1 for performing such analyses.

ALTERNATE PERMITTED PROCEDURES

The updates to Section 21.1 permit use of *site-specific* (partially non-ergodic) site-response methods that incorporate aleatory variability reduction in hazard calculations. The updates also allow for continued use of traditional methods in which MCE_R spectra for a reference site condition are adjusted through simple multiplication by ground motion amplification factors derived from ground response analyses. However, some adjustments to the traditional procedure are provided that mitigate different sources of bias that can lead to under-prediction of ground motions. Those traditional methods, with adjustments, are referred to as providing *hybrid ground motions* in the updated Section 21.1. Separate requirements are provided for the two general methods of analysis (site-specific and hybrid).

Site Specific Site Response

The site amplification models used with ground motion models (GMMs) are *ergodic models* in the sense that they are derived from large global or regional data sets and capture average responses conditioned on site parameters such as V_{S30} and isosurface depths ($z_{1.0}$, $z_{2.5}$). Ergodic models' main advantage is the ease of use – the site parameters are simple and can generally be obtained with relatively inexpensive investigations, and the computation of site amplification only requires using those parameters with the ergodic model. A disadvantage is large uncertainty in the predicted site response, which is quantified with standard deviation terms. The practical impact of that uncertainty is that actual site amplification for a particular site can differ substantially from the mean estimate of an ergodic model. Procedures that aim to quantify site-specific effects have been referred to in literature as *non-ergodic site response* (Stewart et al. 2017), but the more familiar term *site-specific site response* was selected for use in the Provisions and Commentary.

The application of site-specific site response involves five general steps:

1. Reference site motion: A *reference site* is defined as the site condition associated with baseline ground motions against which ground motions for other site conditions are compared to evaluate site amplification. As a result, site amplification is by definition 1.0 at the reference site condition (or null in natural log units). The reference site condition can be defined in a variety of ways including with a V_{S30} value, a reference profile, or a firm horizon within a site profile. Reference site ground motions are defined differently for alternate reference site definitions.
2. Site properties model: A site properties model should include information on shear wave velocities, modulus reduction and damping vs shear strain (MRD) relationships, and unit weights. Shear strength may also be required for applications in which large strains develop. Specific requirements for each are provided – for example, passive surface wave methods (i.e., without a controlled vibration source) in which a single-direction linear array is applied are not permitted for the evaluation of shear-wave velocities.
3. Modeling of mean site response: The analysis of site-specific site response requires the development of a median site amplification model and a model for aleatory variability of site amplification. The mean site response in natural log units for site-specific analysis can be expressed as:

$$\mu_{lnAF} = f_1 + f_2 \ln \left(\frac{x_{IMr} + f_3}{f_3} \right) \quad (1)$$

where μ_{lnAF} is the mean site response expressed in natural log units, $f_1 - f_3$ are coefficients to be established using either the interpretation of site response from ground motions at the site (Approach I) or ground response analyses (Approach II), and x_{IMr} represents the intensity of ground shaking (in engineering units, such as fraction of g) for the reference site. In Eq. (1), the f_1 coefficient represents the linear site amplification (i.e., the level of site amplification that would apply for very small values of x_{IMr}) and the second term on the right side of the equation represents the effects of nonlinearity. As shown in Figure 1, the f_2 coefficient represents the slope of the log amplification with the log of x_{IMr} and f_3 (in the same units as x_{IMr}) represents a transitional level of x_{IMr} between linear and strongly nonlinear response.

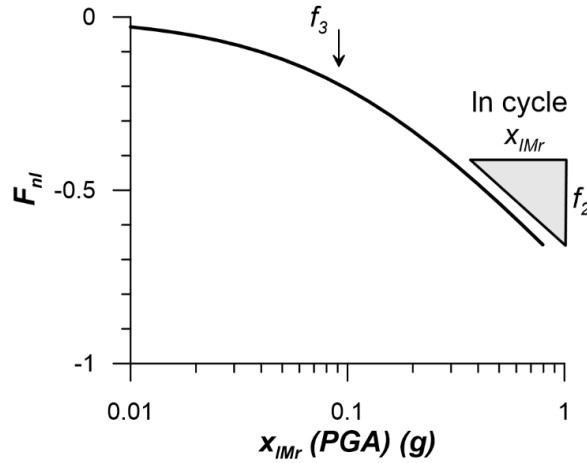


Figure 1. Nonlinear site amplification term showing the physical meaning of f_2 and f_3

4. Ground motion variability and uncertainty: Aleatory variability is modified to remove site-to-site standard deviation. Epistemic uncertainty is required to be evaluated in consideration of soil property uncertainty (Rodriguez-Marek et al. 2021) and model error (Stewart and Afshari 2021), the latter of which represents uncertainty in the applicability of ground response analyses for a given site.
5. Ground motion analysis including site response: For applications of the site-specific site response modeling approach, the median site amplification model (Step 3) is combined with reference site ground motions (Step 1) using procedures that account for variability and uncertainty (from Step 4) to derive site hazard curves that represent the relationships between rate of exceedance and ground-motion level. Those procedures are permitted to include convolution (Bazzurro and Cornell 2004) or running PSHA calculations with the site-specific amplification function and its aleatory variability incorporated within the GMM.

Hybrid Ground Motions

The *hybrid ground motions* approach in Section 21.1 is modified from the traditional approach, i.e., one similar to that of Sect. 21.1 in ASCE 7-22 and prior editions, to address their limitations. The hybrid ground motions approach follows the same five general steps as the site-specific approach but with the following modifications:

1. Reference site motion: A horizon is identified within the site profile, below which is the reference site condition. The reference site condition should correspond to firm-ground conditions such that the effects of site response nonlinearity below the horizon will be negligible. The depth to the reference horizon is $z_{h,ref}$ and the reference site condition time-averaged velocity ($V_{S30,ref}$) is defined over the depth interval $z_{h,ref}$ to $z_{h,ref} + 30$ m. The reference site spectrum is developed using $V_{S30,ref}$ in conformance with standard requirements in Chapter 11 of the provisions for developing MCE_R spectra. An additional target spectrum with reduced amplitudes corresponding to $\frac{2}{3}$ of MCE_R is also required, so as to provide for larger short-period site amplification for profiles that experience nonlinearity.
2. Site properties model: Requirements for the site properties model align with those for the site-specific approach.
3. Modeling of mean site response: The site properties model is used in ground response analyses to compute site amplification relative to the reference site condition (Step 1). A soil-over-reference site approach can be used to derive the mean site amplification that is applicable from short periods to the soil column period (T_{cot}). It is required to consider uncertainties by performing simulations for a suite of at least seven input motions compatible with the reference site spectrum (Step 1) and a reduced spectrum with ordinates of $\frac{2}{3}MCE_R$. For each input motion, at least five alternate values of soil properties should be considered to account for the effects of

their statistical uncertainties on site amplification. Fitting of a site amplification model (Eq. 1) is not required.

4. **Ground motion variability and uncertainty:** The hybrid ground-motion approach makes several approximations in the implementation of site response with the reference site hazard. These approximations align this method of analysis reasonably closely with earlier Provisions in Section 21.1 and are easier to apply. However, they also cause the hazard and risk levels of the resulting ground motions to become mismatched from those of the reference site. Consequently, the aleatory reduction associated with removing ϕ_{S2S} is not permitted. The site-response uncertainty considered in the site-specific approach is not directly quantified but it is indirectly considered by using at least seven single-component input motions for each target spectrum and alternate realizations of soil properties from the soil properties model.
5. **Ground motion analysis including site response:** For each set of reference site ground motions (Step 1), the mean amplification ratio is calculated at each period based on the input ground motion and soil property realizations considered in the analysis. The mean amplification ratios obtained from each set of reference site ground motions (MCE_R and $\frac{2}{3}MCE_R$) are enveloped as shown for an example site in Figure 2. For each period, the enveloped amplification ratios are multiplied by the reference site MCE_R ordinates to obtain the ground surface MCE_R .

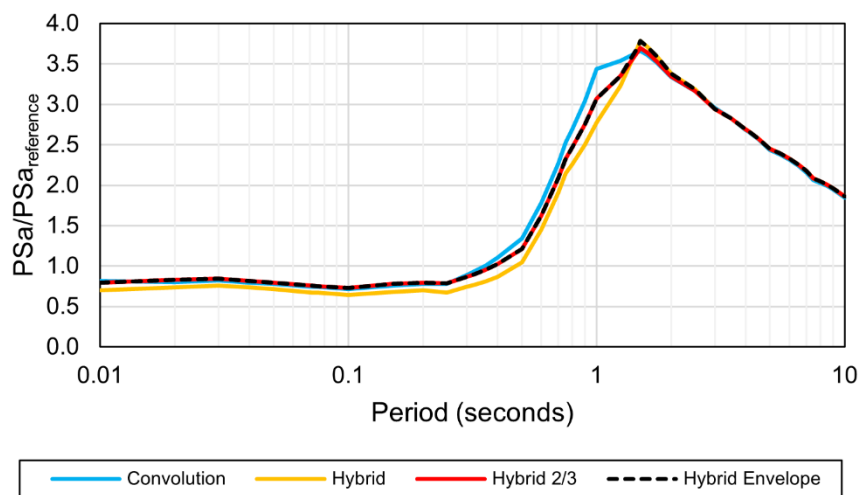


Figure 2. Illustration of hybrid ground-motion approach showing for an example site the period-dependent site amplification as derived using x_{IMr} (labelled “Hybrid”) for a 2475-year return period (0.68 g) and $\frac{2}{3}$ of 0.68 g, along with enveloped site amplifications. The site amplification derived using a convolution approach is shown for comparative purposes.

CONCLUSIONS

The procedures outlined in this brief paper are approved for the NEHRP Provisions and Commentary and will be published in Fall 2026. Final approval is pending for ASCE 7-28.

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