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Side-effect of using response spectral amplification ratios for soft soil sites—Earthquake source-type dependent amplification ratios

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ABSTRACT

Our previous studies show that site effects (amplification of rock motions), source and path effects are coupled when response spectra are used to characterize the amplification ratios for a soil site modelled as nonlinear or elastic. The coupling is referred to as a "side effect" of using response spectral amplification ratios. In the present study we use a suite of rock site records, well distributed with respect to magnitude and source distance, from crustal, subduction interface and slab earthquakes to evaluate the response spectral amplification ratio for soft soil sites. We compare these side-effects for ground motions generated by three types of earthquakes, and we find that, at periods much shorter or much longer than the natural period of a soil site modelled as elastic, the average amplification ratios with respect to rock site ground motions from three types of earthquakes are moderately different and are very similar for other spectral periods. These differences are not statistically significant because of the moderately large scatter of the amplification ratios. However, the extent of magnitude- and source-distance-dependence of amplification ratios differs significantly. After the effects of magnitude and source distance on the amplification ratios are accounted for, the differences in amplification ratios between crustal and subduction earthquake records are very large in some particular combinations of source distance and magnitude range. These findings may have potential impact in establishing design spectra for soft soil sites using strong motion attenuation models or numerical modelling.

1. Introduction

Site effect, the amplification of earthquake ground motions by soil layers, has long been recognized and is generally considered not to be coupled with earthquake source (characterized by moment magnitude) and path (characterized by source distance) effects for soil sites where soil nonlinear deformation is not significant (Rosenblueth and Arciniega [1]). For engineering applications, response spectral amplification ratios are often used to estimate the displacement demand of soil-site ground motions compared to that of rock-site motions. Due to the nature of response spectra (the peak response of a single-degree-of-freedom structure), response spectral amplification ratios have considerable scatter (Zhao et al. [2], Ni et al. [3], Zhang and Zhao [4] and Bazzurro and Cornell [5]), and they are magnitude- and source distance-dependent for soil sites modelled as nonlinear or elastic [6]. The variability and magnitude- and source-distance-dependence of response spectral ratios are a possible result of apparent randomness of excitation spectra, contribution to the response spectrum at a given period from energy associated with the other periods and different spectral shapes from earthquakes with different magnitudes and different source distances [6].

Response spectra estimated from attenuation models, for example, the models of Zhao et al. [7], Youngs et al. [8] and Atkinson and Boore [9], differ significantly for records from shallow crustal, subduction interface and slab earthquakes. At short and intermediate spectral periods, response spectra estimated for crustal and subduction interface events are generally similar (from Zhao et al. 2006 model [7]). At long spectral periods, the response spectra from subduction interface events are considerably smaller than those from crustal event and the difference increases with increase in spectral period. For example, at 4 s spectral period, the response spectra of interface events are about 60–70% that of crustal events. The response spectra of records from subduction slab events with a moderate focal depth are much larger than those of crustal and subduction interface records (with the same magnitude at the same source distance) at short and intermediate spectral periods, and decrease quickly with increase in spectral periods at long spectral periods. These different characteristics of rock site response spectra from different types of earthquakes would affect the response spectral amplification ratios of soft soil sites but the extent of these effects has not been systematically studied.

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As a follow-up study by Zhao et al. [6], we investigate the effects of earthquake tectonic source types (shallow crustal, subduction interface and subduction slab earthquakes) on the spectral amplification ratios of simple 1-dimensional soil sites. When a soft-soil site is subject to strong ground shaking from these types of earthquakes, significant soil nonlinear response will be likely to develop. In order to separate the effect of soil nonlinear response from the effect associated with different types of earthquakes, we adopt the simplest soil site model, a single soil layer modelled as elastic, following the approach used by Zhao et al. [6]. The effects associated with earthquake types are referred to as the "side effects" of using response spectral ratio to characterize soil site amplification (Zhao et al. [6]).

Using elastic sites can be justified and the results derived from elastic models can be useful for empirical attenuation models for response spectra—a vital part of a probabilistic seismic hazard study— because

(1) the majority of strong-motion records used in deriving attenuation models are too small to induce any significant soil nonlinear response;
(2) the site terms in attenuation models for response spectra are controlled by elastic to moderately nonlinear responses of soil sites (Zhao et al. [7] and Abrahamson and Silva [10]) and
(3) the prediction errors of attenuation models are usually large, in the range of 0.6–0.8 on natural logarithm scale, with the 84 percentile spectrum being the median value multiplied by a factor about 1.8–2.2. The large prediction errors can obscure magnitude-, distance- and earthquake-type-dependent parts of the soft-soil site terms. The results presented in the present study may be used as constraints for the linear soil-site terms in developing attenuation models, in a similar manner as that used for nonlinear soil-site terms in the NGA models (Abrahamson and Silva [11] and Boore and Atkinson [12]).

Using elastic models, we can identify the variation in amplification ratios with magnitude and source distance for three different types of earthquakes, due to effects other than soil nonlinear deformation, as done by Zhao et al. [6] for subduction slab earthquakes. Zhao et al. [6,13] show that these side effects observed from elastic models are also found in the modelling of 2-dimensional nonlinear soil basins.

To assess the first order effect of nonlinear soil response, we attempt to use "equivalent linear" model, by increasing the damping ratios for the elastic model to mimic the energy dissipation due to nonlinear soil deformation.

We will also propose a simple model to account for the effect of nonlinear soil response and the side-effects presented in the present study and the study of Zhao et al. [6].

2. Strong motion dataset

To systematically investigate the possible dependence of response spectral amplification ratios on earthquake magnitude and source distance from different types of earthquakes, we need a large number of records from rock or stiff soil (classified as rock in attenuation models for response spectra for Japan, such as the Molas and Yamazaki model [14] and the Zhao et al. model [7]). The records should also be well distributed with respect to magnitude and source distance for each earthquake type (i.e. crustal, subduction interface or slab earthquakes) and the recording stations should be reasonably reliably classified (Zhao et al. [15]). For the present study, we selected strong motion records from crustal events from California and Japan, and subduction interface and slab events from Japan. The main reason for using Japanese data is that all records have been consistently processed and hypocenters for all events have been relocated by special studies (Zhao et al. [7]). Source distance for all large events is the shortest distances from the site to a known rupture plane, and hypocentral distances are used for smaller events. The magnitude–distance distribution of the dataset is shown in Fig. 1, where the data are well distributed with respect to magnitude within a source distance of 180 km for all three types of earthquakes. The subduction interface and slab records from M_w=6.5 or larger are well distributed across all source distance ranges. These data are all from SC I sites that have a dominant site period less than or equal to 0.2 s (Zhao et al. [15]). The corner frequency of the high-pass filter (used to eliminate low-frequency noise) is less than 0.25 Hz for all records, and so the comparison of response spectral ratios up to 4 s period should not be severely affected by the high-pass filter.

3. Response spectral amplification ratio of single layer elastic soil sites

All soil sites in the present study have a single layer modelled as 1-dimensional and elastic with assumed natural periods of 0.5, 0.75, 1.0, 1.5 and 2.0 s. Sites with long natural periods such as 1.5 and 2.0 s are not common and these sites are mainly used for comparison. Material damping ratios of 5%, 10%, 15% and 20% of critical were used together with an equivalent damping ratio of 5% from energy leakage back to the underlying bedrock (Zhao [16]). The soil surface response was calculated from a frequency–domain analysis. Response spectral ratios of the soil-site surface motions with respect to the excitation ground motion were calculated. The geometric mean of spectral ratios, R_{mean}, and the residuals $\log_e(R_{SA}/R_{mean})$, where R_{SA} is the spectral ratio for a particular record, were calculated for 13 spectral periods.

Fig. 2 shows the mean amplification ratios of 5 soil sites with natural periods of 0.5, 0.75, 1, 1.5 and 2 s for three types of earthquakes, i.e., crustal, subduction interface and slab events. Fig. 2a shows peak ground acceleration (PGA) and the spectra at 0.1 s spectral period, and Fig. 2b shows amplification ratios at long spectral periods (3.0 and 3.5 s). Fig. 3 shows the standard deviation of the amplification ratios in natural logarithm scale and the 84 percentile amplification ratios are given by the median values shown in Fig. 2 multiplied by the exponential of the standard deviations presented in Fig. 3. Fig. 2 shows that the differences in the amplification ratios among the three different types of earthquakes are not large enough to be statistically significant because of the relatively large standard deviation. The amplification ratios from slab events are the smallest at short spectral period (Fig. 2a), and the largest at long spectral period (Fig. 2b) compared with the other two types of earthquakes. At short spectral periods, the mean amplification ratios tend to decrease with increasing site natural period, while at long spectral period the mean amplification ratios increase rapidly with increasing site natural period. However, to make a fair comparison of amplification ratios between the three types of earthquakes, the bias associated with magnitude and source distance should be corrected, as described in the later section of this manuscript.

Fig. 3 shows that the standard deviation at short spectral period in Fig. 3a is much larger than that at long spectral period for a site with a long natural period, and the standard deviation for PGA and long spectral period spectra is reasonably similar for all three types of earthquakes. However, the standard deviation for a spectral period of 0.1 s differs significantly among the three earthquake types, with the slab records having the smallest standard deviation and the crustal records having the largest value. We do not have plausible explanation for the differences