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STUDY ON THE INFLUENCE OF BEDROCK INPUT MOTION UNCERTAINTY TO SOFT SITE SEISMIC RESPONSE

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Abstract

Numerous evidences show that the earthquake ground motions are affected by the local site conditions significantly. In addition to strong ground motion records, site seismic response analysis is the most effective approach to catch the dynamic response characteristics of layered soil sites under earthquake shaking. One-dimensional calculation methods (e.g., Equivalent linear program SHAKE2000) are widely used to carry out the prediction of earthquake effect in engineering practice, which is very important for the seismic fortification of various structures, especially for major projects. The bedrock strong-motions are always stochastic, hence the numerical simulation results definitely have a strong relationship with the input acceleration time histories. About 310 strong motions of 179 earthquakes were carefully selected at NMRH04 site. The peak accelerations were adjusted to 5, 20, 50, 100, 150, 200 cm/s^2 after routine processing. A large number of calculations were completed to take the uncertainty of bedrock input motion into consideration, and then the distribution of ground motion parameters (e.g., the average PGA amplification factors and its standard deviations) were studied.

Keywords: seismic response analysis, uncertainty, amplification factor, standard deviation, dynamic shear strain

1. Introduction

A large number of seismic damages in previous great earthquakes have fully shown that the local site condition has a significant effect on seismic responses [1-5]. When incident bedrock motions propagate from bedrock to the soil surface, the soil deposit changes characteristics of the ground motions, such as the vibration amplitude and the effective shaking duration. The amplification effect caused by deep sedimentation is one of the most important concerns. An important task in geotechnical earthquake engineering is to predict the ground response caused by earthquake shaking. One-dimensional (1-D) equivalent-linear (EQL) site response analysis is the most common approach in the current practice to estimate the site-specific ground response in a deterministic manner, which was introduced by Idriss and Seed [6] and implemented by Schnabel et al. [7] in the SHAKE software. 1-D EQL site response analysis requires only a reasonable number of soil parameters (i.e. shear wave velocity profile, unit weight of the soil layers, modulus degradation and damping curves), the consequences of various factors can be easily distinguished.

The seismic downhole array, which consists of accelerometers located at the surface and at one or more depths in the ground, has been widely used to assess and calibrate 1D site response models. Downhole arrays are used because they have the advantage of separating the local site effects from other seismic processes such as earthquake source and path effects. Thus, downhole arrays provide the most direct observations of how the seismic waves are modified by the properties of the geological material between a location in the ground and the surface. Ground motions recorded at various depths are used to compute how seismic waves are amplified or attenuated as they travel from bedrock to the ground surface. The Kiban Kyoshin strong-motion seismograph network (KiK-net) in Japan is one of the most commonly used downhole array networks, which are always utilized to evaluate the capabilities of different seismic response analysis methods, such as the equivalent linear method in frequency domain and the completely nonlinear method in time domain. These procedures generally use ground motions recorded at some reference condition within the borehole array as input into a ground model for seismic site response. Then, the surface ground motions predicted from site response analyses are compared to those actually recorded at the site. However, effect of the selected time series on the analysis results is significant [8-11], in other words, the amplification model of a specific site needs to take the input motion uncertainty into consideration. NMRH04 site in KiK-net was chosen as a typical soft site to track the uncertainty propagation from input bedrock motion to the response estimation model.

In view of the simulation-based ground response analysis, several factors can influence the calculation results. The shear-wave velocity profile and soil nonlinearity curves (e.g., modulus reduction and damping curves) have associated aleatory uncertainties that produce different site responses [12]. A velocity profile represents the dynamic properties of soil at very small strains and significantly influences the wave propagation under weak motion. Meanwhile, soil nonlinearity represents the large strain behavior under moderate-to-strong motions. In addition to the material variability, the uncertainty in ground motion characterization is a dominant source of aleatory uncertainty in the estimation of seismic site response [9]. The objective of this study is to develop a probabilistic framework to account for the uncertainties of site amplification factors on soft sites due to the input bedrock motion uncertainties.

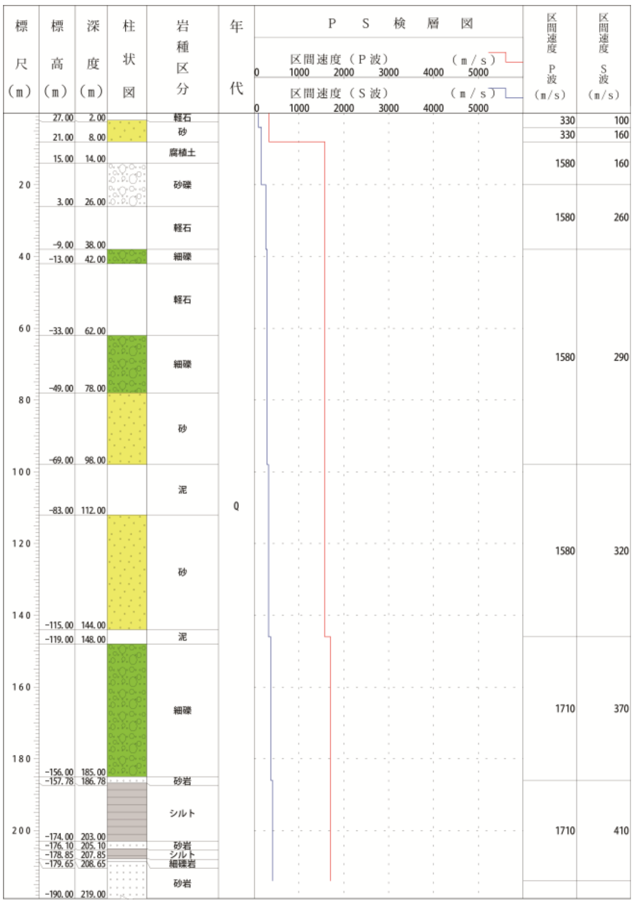
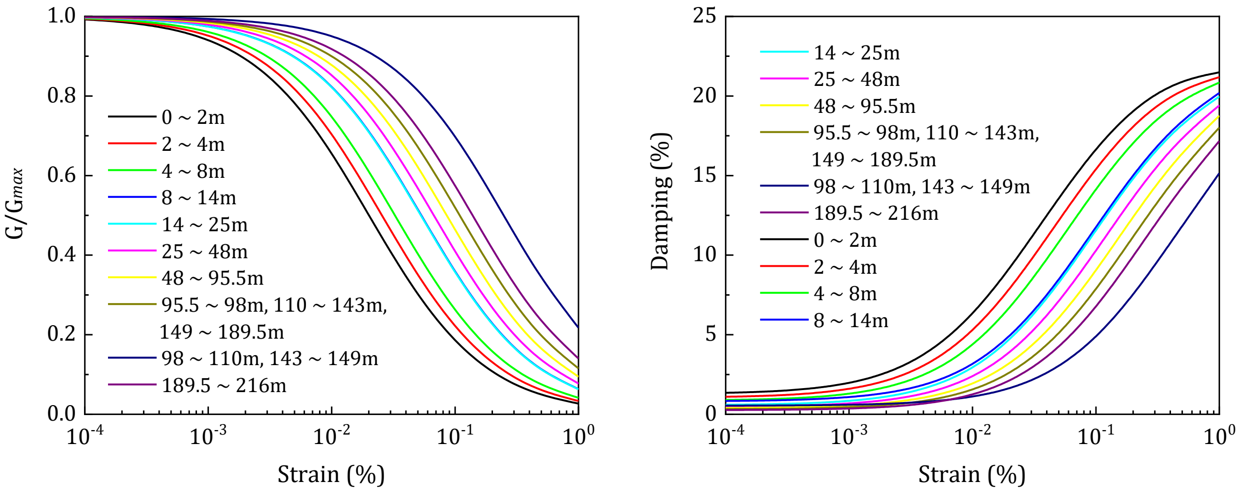


Fig. 1 – Soil layer and wave velocity profile of NMRH04 station site

2. Model and Soil Nonlinearity

The selected typical soft site NMRH04 is one of the Kiban-Kyoshin network (KiK-Net, http://www.kyoshin.bosai.go.jp/) downhole arrays. The KiK-net consists of more than 1,000 observation stations, of which 700 have downhole and surface high-quality seismographs. Since 1996, the stations have recorded thousands of strong ground motion data at different sites, including the records of the Great East Japan Earthquake on March 11, 2011. The shear-wave velocity profile is illustrated in Fig. 1, from which we can see the thickness of the sediments is more than 200 m. Time averaged velocity of the top 30 m depth (V_{S30}) is 168 m/s and the approximate fundamental period is about 3 s. According to the 2015 NEHRP provisions, the site class of NMRH04 is class E.

Although the soil layer profile and the shear-wave velocity data are provided online, the non-linearity parameters are not available. However, strain-dependent shear modulus reduction and damping ratio curves are essential parameters for equivalent linear program SHAKE to calculate the site seismic response. According to Darendeli [13], the normalized modulus reduction and material damping curves are not only related to the soil type (expressed by PI, Cu, D_{50}) and shearing strain amplitude (γ), but also related to the effective confinement (σ_0'), number of cycles (N), loading frequency (f) and overconsolidation ratio (OCR). We estimated the strain-dependent G/G_{max} and damping ratio of each soil layers, which can be seen in Fig. 2. We divided the total 216m depth into 84 sublayers and assigned them with 10 pairs of non-linearity parameters as shown in Fig. 2.



(a) Shear modulus reduction curves (b) Damping ratio curves

Fig. 2 – Estimated nonliearity parameters used for equivalent linear response analysis

3. Input Strong Motions

863 sets strong motion data were recorded on NMRH04 station due to May 2018. Each set of data consists of a pair of 3-component records (NS, EW and UD), one of which is on the ground surface, and the other is in the downhole. All the NS and EW direction time histories in the downhole constitute a raw input motion dataset. The following data processes mainly include baseline correction and Butterworth band-pass filtering. The low-cut corner frequencies were taken 0.01 Hz and the high-cut corner frequencies were taken 25 Hz. Then, records with peak acceleration less than 2 cm/s^2 were deleted to ensure sufficient signal-to-noise ratio and several outliers were cut out. Finally, 310 recordings during 179 earthquake events were selected to form the ultimate input motion database.

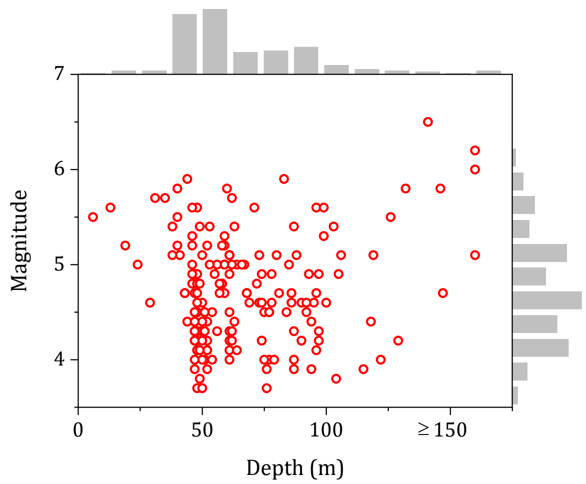


Fig. 3 – M_L-D plots of the selected recordings

Fig. 3 shows M_L-D plots of the selected recordings, in which M_L is the magnitude of earthquake event and D is the focal depth. Most recordings were obtained from earthquakes of M_L = 3.5 ~ 6.0. The focal depth mainly covered the range 30 ~ 100 km, and the maximum is larger than 150 km. All the 310 normalized acceleration spectra are shown in Fig. 4, from which we can infer that the selected input motions represent quite rich frequency components. The prominent periods of the 310 recordings range from 0.04 ~ 0.44 s.

As is well known, site response, not only in terms of amplitude but also in relation to fundamental frequency, can show significant variation because of soil non-linearity caused by strong ground shaking [14, 15]. Thus, In the calculation process, the selected data will be scaled to simulate different shaking level. The time series will be proportionally scaled to match the peak accelerations equal to 5, 20, 50, 100, 150 and 200 cm/s^2, representing weak-to-moderate-to-strong motions. The nonlinearity influence is negligible under weak vibration. While the PGA is equal or larger than 100 cm/s^2, the nonlinearity contribution will be significant.

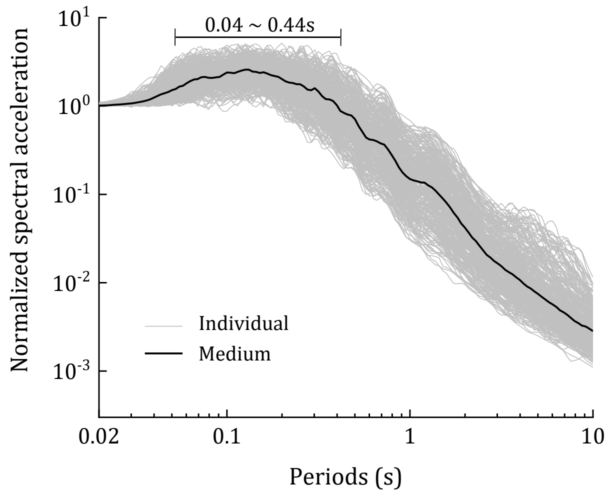
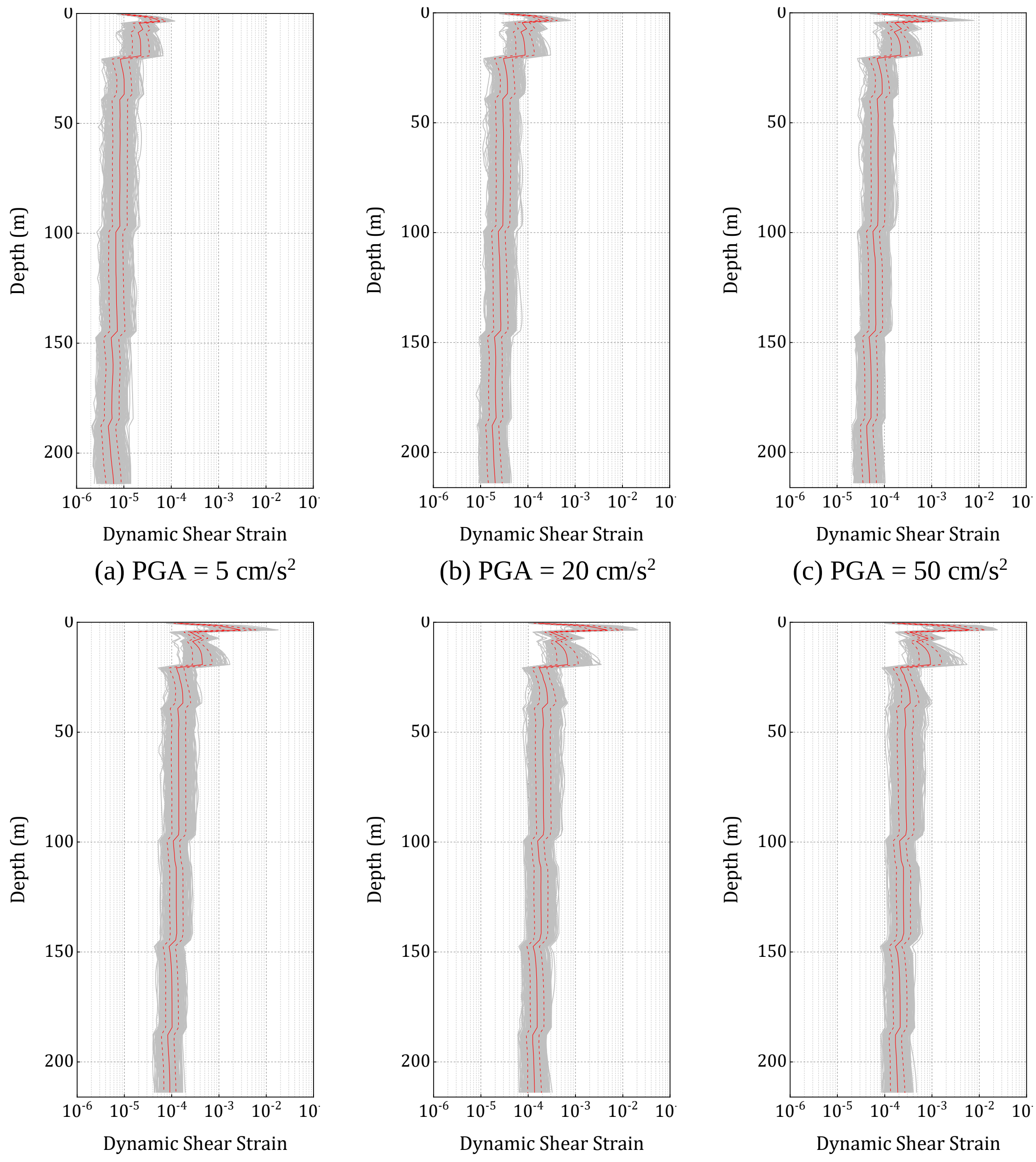


Fig. 4 – Normalized accelaration spectra of the selected dataset

4. Soil Response

In site seismic response analysis, dynamic shear strain of soil is one of the most crucial parameters, which directly reveals the mechanical state of site soil. Under different intensity strong-motion inputting, the distributions of dynamic shear strain are shown in Fig. 5. The medium values under PGA equals 5, 20, 50, 100, 150 and 200 cm/s^2 are 7x10^{-6}, 3x10^{-5}, 7x10^{-5}, 1x10^{-4}, 2x10^{-4} and 2.5x10^{-4}. From this point of view, the dynamic shear stains and seismic intensities are almost proportional. However, the maximum shear strain almost does not increase any more when the input PGA reaches 100 cm/s^2. Under every shakeing level, the distribution of dynamic shear strain spans two order of magnitude.



(a) PGA = 5 cm/s^2 (b) PGA = 20 cm/s^2 (c) PGA = 50 cm/s^2

(a) PGA = 100 cm/s^2 (b) PGA = 150 cm/s^2 (c) PGA = 200 cm/s^2

Fig. 5 – Distributions of dynamic shear strain under different shaking level

5. Site Response

The distributions of calculated predominant periods of outputted surface ground motion are shown in Fig. 6. Increasing tendency of the mean period along with the seismic intensity is very clear. Meanwhile, the standard deviation of the predominant periods increases with the seismic intensity. With the increase of input seismic intensity, the nonlinear effect of the site becomes more obvious. By comparing the situations with PGA equals 5 and 20 cm/s^2, we can see that the nonlinear effects still exist even under weak motion input.

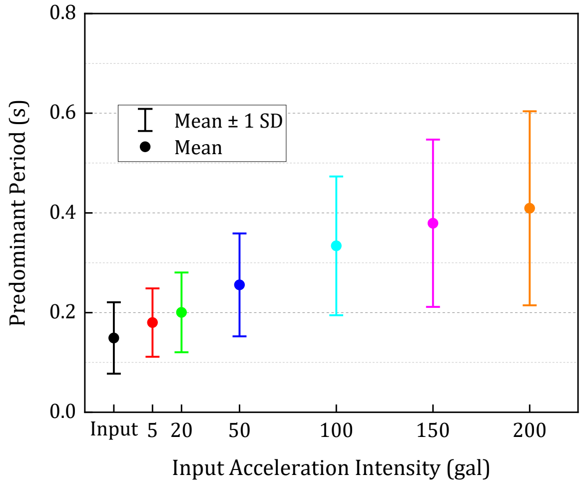


Fig. 6 – Distributions of the predominant periods

The distributions of calculated peak ground accelerations are shown in Fig. 7. With the increase of input seismic intensity, the mean calculated PGAs increase. In all cases, the site always behaves an average amplification effect. In other words, the amplification factor is larger than 1.0 on the average meaning. The standard deviations of calculated PGAs present consistent increases trend with the input motion intensity. If considering the mean minus one standard deviation range, the amplification factor for certain individual records may smaller than 1.0.

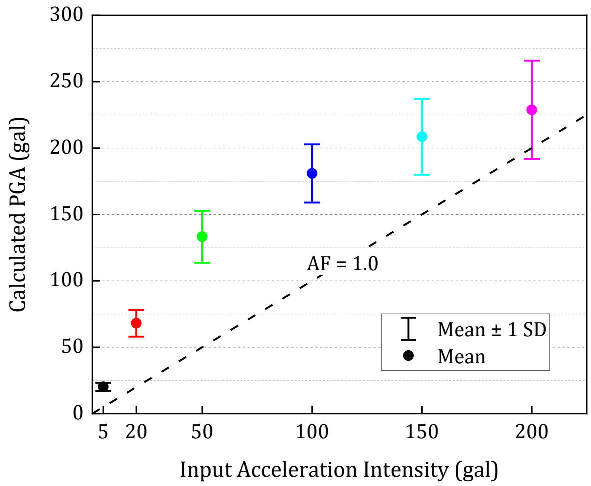


Fig. 7 – Distributions of the calculated peak accelerations

The distributions of the amplification factors are shown in Fig. 8. Here, the amplification factor is defined as the ratio of calculated PGAs divided by the inputted peak acceleration. A regular decrease tendency can be clearly seen with the increase of input seismic intensity. When the input peak acceleration equals 5 cm/s^2, the average amplification factor is about 4.0. While the seismic intensity is 100 cm/s^2, the amplification factors mainly cover the range from 1.6 to 2.0. When the input peak accelerations reach 200 cm/s^2, the corresponding amplification factors locate in the range from 0.9 to 1.3. With the increase of input seismic intensity, the standard deviations of the amplification factors gradually decrease. When input peak accelerations reach larger than 100 cm/s^2, the standard deviation seems no longer changing.

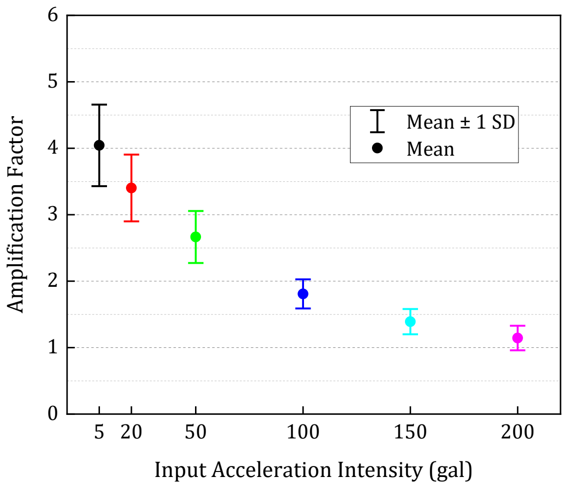


Fig. 8 – Distributions of the amplification factors

6. Conclusion

In order to study the uncertainty propagation from the bedrock input motion to soft site seismic response, 310 strong motions recorded on the NMRH04 station during 179 earthquake events were selected to establish the input motion database. The shear modulus reduction and damping ratio curves were estimated for assigning nonlinearity parameters corresponding to the soil layers of NMRH04 site. One-dimensional equivalent-linear site response analysis program SHAKE was used to carry out the calculations. Analysis results indicate that:

(1) The dynamic shear stains and seismic intensities are almost proportional. Under every shakeing level, the distribution of dynamic shear strain spans two order of magnitude.

(2) Average prominent periods and its standard deviations increase with the seismic intensity. Nonlinear effect of the site still exists even under weak motion input, and it became more obvious with the seismic intensity increase.

(3) With the increase of input seismic intensity, the mean calculated PGAs increase. In all cases, the site always behaves an average amplification effect. The standard deviations of calculated PGAs present consistent increases trend with the input motion intensity

(4) A regular decrease tendency can be clearly seen with the increase of input seismic intensity, but the amplification factor is always larger than 1.0 on the average meaning. With the increase of input seismic intensity, the standard deviations of the amplification factors gradually decrease.

7. Acknowledgements

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