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Nonlinearity, Liquefaction, and Velocity Variation of Soft Soil Layers in Port Island, Kobe, during the Hyogo-ken Nanbu Earthquake

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Abstract Clear nonlinear behavior is analyzed from the acceleration records of the 1995 Hyogo-ken Nanbu earthquake at Port Island, Kobe. From four triaxial instruments placed at four different depths, the surficial effects during strong ground motions were compared with those during weak motions before and after the mainshock. We used a spectral ratio technique and a nonlinear inversion for velocity structure to analyze the data. From the spectral analysis, we observed a large variation of the spectral ratios between the surface and different depths during the strong ground motions and during the liquefied state. The spectral ratios after the mainshock (i.e., after the liquefied state) are different from those before the mainshock. The peak frequencies in the spectral ratios after the mainshock are shifted to lower frequencies with respect to those in the spectral ratios before the mainshock. We inverted the *S*-wave velocities using a genetic algorithm technique to determine the velocity structure before, during, and after the mainshock. The *S*-wave velocity structure before and after the mainshock was found to be different. Specifically, the *S*-wave velocity of the second layer (5 m to 16 m depth) after the mainshock was 20% lower than before. Our analysis shows that the liquefied state remains at least 3 hr after the mainshock but no more than 24 hr. The rigidity of the soil decreased close to zero when liquefaction happened and later increases gradually following a trend that resembles a consolidation curve. The strong influence of nonlinearity during the mainshock yielded a big reduction of the horizontal surface ground motions, so that the observed horizontal peak acceleration was only about 25% of the peak acceleration expected from the linear theory. However, the nonlinear effects in the vertical peak acceleration were not significant.

Introduction

Many authors have been studying the amplification produced from the sedimentary soils in order to predict the motions during large earthquakes, as well as to reproduce the ground motions during large earthquakes at sites where the ground motions have not been recorded. The amplification of the seismic waves basically originates from the strong contrast between the physical properties of the rocks and the sediments. To evaluate this amplification, conventionally, the seismic response of the soils has been treated as linear in the seismological community. That means strain and stress are related linearly by a constant rigidity independently of the level of strain. This assumption is acceptable for low levels of strain (for $\gamma_c = 0.0001\%$ and 0.001%, where γ_c is the cyclic shear strain amplitude, Vucetic and Dobry, 1991), from soil laboratory testing results. But for larger stress–strain levels, the soil laboratory testing results showed a nonlinear relation, that is, the nonlinear character of the soil response.

The basic reason that the seismologist conventionally has been using a linear relation is that for the level of strains in most of the seismological observations the shear modulus reduction is small. But, according to the laboratory test results, the nonlinear relation in the case of large strains may play an important role in ground motions at soil sites near the source during large earthquakes. Since the conditions in the laboratory are not the same to those in the field, it is important to investigate the nonlinearity of the soil response for large strain levels through *in situ* observations by separating the soil response from other factors such as source and path effects in seismic data.

Some authors have been trying to find observational proof of the nonlinearity from seismological data and estimate how much it influences strong ground motions (Sugito and Kameda, 1990; Chin and Aki, 1991; Ordaz and Faccioli, 1994; Aguirre *et al.*, 1994; Beresnev *et al.*, 1995; Satoh *et al.*, 1995). One of the problems that they have been facing is the lack of records for large strain levels during the strong ground motions. Also, the mixed influence of the nonlinear