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Nonlinear Behavior of Soils Revealed from the Records of the 2000 Tottori, Japan, Earthquake at Stations of the Digital Strong-Motion Network Kik-Net

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Abstract Acceleration records of the Tottori earthquake (6 October 2000), provided by stations of the Digital Strong-Motion Network Kik-Net, show clear evidence of the nonlinearity of soil response at sites located in near-fault zones. In this study, records of the mainshock of the Tottori earthquake are analyzed, and stresses and strains, induced by the strong motion in the upper 100 or 200 m of soil, are reconstructed at sites located within 80 km from the fault plane. For reconstructing stresses and strains, the method is applied, which we developed and used previously for studying the response of soils during the 1995 Kobe earthquake. Nonlinear time-dependent stress–strain relations in the soil layers are estimated based on vertical-array records. A good agreement between the observed and simulated accelerograms of the Tottori earthquake testifies to the validity of the obtained vertical distributions of stresses and strains in the soil layers. We also evaluated variations of the shear moduli of the soil layers, caused by the strong motion, at stations located at different distances from the fault plane. Changes in the rheological properties of the upper soil layers were found at the stations closest to the fault-plane. A similarity in stress–strain relations, describing the behavior of similar soils during the 1995 Kobe earthquake and the 2000 Tottori earthquake, was obtained, indicating the possibility of precasting soil behavior in future earthquakes at sites where profiling data are available.

Introduction

Experimental data provided by recent large earthquakes, such as the 1994 Northridge earthquake (M_W ~6.7), the 1995 Kobe (M_W ~6.8) and the 2000 Tottori (M_W ~6.7) Japanese earthquakes, the 1999 Chi-Chi (M_W ~7.7) Taiwanese earthquake and others, have shown clear evidence of the nonlinear behavior of subsurface soils in near-fault zones. During the Kobe earthquake, nonlinear soil behavior was identified at sites located within ~16 km from the fault plane, and the content of nonlinear components in the soil response was estimated. It turned out to be rather high, up to ~60% of the whole intensity of the response, at ~2 km from the fault plane and about 10–15% of the intensity of the response at ~16 km from the fault plane (Pavlenko and Irikura, 2005).

This type of analysis and estimations became possible because of the availability of vertical-array records of the Kobe earthquake. Seismic vertical arrays usually contain two, three, or four three-component accelerometers, installed on the surface and at depths down to ~100 or ~200 m, one of the primary motivations for observations with borehole arrays is to understand nonlinear soil response.

Numerical simulation of accelerograms of the Kobe earthquake at depths of the recording-device locations has shown that (1) at least within ~8–10 km from the fault plane, the nonlinearity in the soil response was substantially higher than that stipulated by conventional computer programs of the nonlinear ground-response analysis, and (2) stress–strain relations of different types, depending on the composition of soil layers, their saturation with water, and depth, describe the behavior of the layers. In particular, the behavior of sandy, water-saturated or wet subsurface soils is described by stress–strain relations of "hard" type, declining to the stress axis at large strains. In such soils, amplification of large-amplitude oscillations occurs, which is related to the "hard-type" nonlinearity of the soil response, as at SGK site during the 1995 Kobe earthquake (Pavlenko and Irikura, 2003).

Acceleration records of the Kobe earthquake gave a good illustration of the fact that in strong ground motion, maxima of energy of oscillations at soil sites shift to a lower-frequency domain. This fact was explained by the nonlinearity of the soil response: mutual interactions of spectral components of seismic waves propagating in soil layers lead to redistribution of the energy of oscillations over the spec-