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Nonlinear Soil Amplification: Its Corroboration in Taiwan

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Abstract Nonlinear ground response at two strong-motion arrays in Taiwan is studied using the spectral ratio technique. At the SMART1 array, we calculate the frequency-dependent soil amplification functions as a ratio of the spectra at alluvium to rock sites, and study their dependence on the excitation level. Horizontal components of shear waves are considered. We compare (1) the average spectral ratios on weak and strong motions, (2) the ratios for the mainshocks and aftershocks, and (3) the ratios for the strong shear waves and their coda. At the SMART1 array, "weak motions" have a peak horizontal acceleration (PHA) less than 30 Gal. "Strong motions" are in the range of 100 to 267 Gal. Comparison of the average weak- and strong-motion spectral ratios shows a significant deamplification of strong motion between 2 and 9 Hz, exceeding the error margin estimated by the standard deviations. The maximum deamplification occurs at approximately 6.5 Hz where the average weak-motion amplification is 2.9 versus 0.40 in the strong motion. A similar pattern is exhibited by the ratios calculated for the mainshocks and the aftershocks, as well as for the shear waves and their coda. The spectral ratio calculated from a single realization of coda is identical to the average ratio obtained from many small earthquakes. At the SMART2, we analyze spectral ratios between the stations on Pleistocene terrace deposits and recent alluvium, which characterize the relative response at these two types of sediments. Weak motion is PHA less than 13 Gal, while strong motion extends from 100 to 295 Gal. Strong-motion spectral ratios between terrace and alluvial sites are consistently reduced in the frequency range from ~1 to 10 Hz, compared with the weak motion. This effect is insensitive to the variation in distance between stations from 7.9 to 11.4 km, as well as the azimuthal change of up to 80° in the station pair strike. We attribute the observed discrepancies between weak- and strong-motion amplifications to the differential nonlinear response occurring at terrace and alluvial sites. Our results document a significant nonlinear ground response at both arrays.

Introduction

Nonlinear effects in ground motion during large earthquakes have long been a controversial issue between seismologists and geotechnical engineers. Nonlinear effects have been routinely taken into account in earthquake engineering in the evaluation of seismic wave amplification by superficial deposits. However, seismologists rarely considered the possibility of these phenomena playing an important role (Aki and Richards, 1980, p. 9).

Explicit indications of the significance of nonlinear site response in seismological observations have appeared in the last years, owing to the progressive increase in the number of permanently operating strong-motion arrays and improvement in data quality. These findings have increased seismological interest in the study of nonlinear seismic phenomena worldwide.

Linear and Nonlinear Amplification of Seismic Waves

That the amplitude of seismic waves approaching the earth's surface is magnified by superficial low-impedance layers is well understood. Works by Kanai *et al.* (1956) and Gutenberg (1957) started a quantitative study of this phenomenon. The importance of soil amplification effects has been clearly demonstrated by the great recent Michoacan (Mexico) earthquake of 19 September 1985 (Celebi *et al.*, 1987; Seed *et al.*, 1988) and the