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Seismological evidence for nonlinear elastic ground behavior during large earthquakes

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Amplification of earthquake-induced seismic waves by soft superficial deposits often causes significant damages in the urban areas. In predicting this effect for large future earthquakes, the linear elastic response of soils is customarily assumed. To check this assumption, we have analyzed surface and downhole acceleration data from the SMART1 and SMART2 strong motion arrays in Taiwan, covering peak accelerations of up to 0·3 g. First, frequency-dependent amplification induced by the alluvial deposits at the SMART1 array was estimated using spectral ratio technique, where the records at rock site were taken as a reference motion. Statistically validated reduction in soil amplification in the strong motion relative to the weak motion in the frequency range between approximately 1 and 9 Hz was detected. Secondly, relative site responses between the Pleistocene and recent sedimentary deposits at the SMART2 array were studied. Relative amplification was shown to be clearly dependent on the excitation level. Thirdly, we compared experimentally recorded uphole/downhole spectral ratios on weak and strong ground motion with the theoretical response yielded by the geotechnical code DESRA2 which assumes hysteretic constitutive relationship of soil. Major symptoms of nonlinear ground behavior predicted by the model were found in the observed data. Back-calculation of the shear wave velocities to the depth of 47 m shows nearly 50% decrease in the strongest quakes, also accounted for by the nonlinear soil behavior.

Key words: strong motion, soil amplification, shear wave velocity, nonlinear deformation, elastic hysteresis.

1 INTRODUCTION

It has long been understood that seismic waves generated by earthquakes are magnified by low-impedance superficial deposits.[1,2] Among the most dramatic recent demonstrations of this effect were the 1985 Michoacan (Mexico) Earthquake and the 1989 Loma Prieta (California) Earthquake, where the extent of damage from soil amplification was catastrophic in Mexico City[3,4] and significant in the areas of San Francisco and Oakland.[5]

Nearly all of the ground motion prediction models employed in seismology assume the linear elastic behavior of the ground during earthquakes; as a result, soil amplification correction is introduced by a mere multiplication of the synthetic seismogram by the corresponding amplification factor.[6-8] These factors are usually empirically deduced from the records of weak seismic events, microtremors, or coda waves.[9,10] It is believed that there is no significant difference in the soil amplification on weak and strong motion.

However, the above commonplace seismological practice is in contradiction with the concept of ground deformation largely adopted in geotechnical engineering, where the dynamics of the structures substantially influenced by the local behavior of the ground is of great concern. On the basis of the results of the cycling loading tests performed on soil samples, geotechnical engineers have recognized that shear deformation in soil deviates from the linear elasticity above a certain threshold acceleration.[11-16] Accordingly, nonlinear site effects have been taken into account in earthquake engineering in modelling soil response to seismic loading.[10] This contradiction has not been resolved hitherto and has remained a subject of continuous debate.[10,17-20] Seismologists are reluctant to accept nonlinear ground response basically because of the lack of compelling evidence of nonlinear effects