Bulletin of the Seismological Society of America, Vol. 86, No. 3, pp. 627–635, June 1996

Site Amplification at Five Locations in San Francisco, California: A Comparison of *S* Waves, Codas, and Microtremors

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Abstract We compare microtremor data to weak-motion *S*-wave and coda recordings at sites in San Francisco in order to clarify the range of applicability of microtremor data to ground-motion prediction. We also compare *S*-wave results to coda results. For each type of data, we compute spectral ratios of motions from two soil/rock station pairs and from an uphole/downhole pair in the Marina district. We compute horizontal/vertical ratios (Nakamura's method) at a soil site, a rock site, and the surface and borehole instruments. In the station-pair analyses, microtremor data show amplifications at the same fundamental frequency as *S* waves, but the frequencies of other peaks do not agree. The amplification at frequencies higher than 2 Hz is greater in the microtremor data. Station-pair ratios of coda data generally show spectral peaks occurring at the same frequencies, but with levels varying from one to four times the amplification from *S*-wave ratios. Nakamura's method of analyzing microtremors agrees better with *S*-wave station-pair results than the microtremor station-pair method over a limited frequency band that varies from station to station.

Introduction

Local site conditions are major factors in the distribution of earthquake damage. Two of the more dramatic and familiar cases in recent history are the Marina district of San Francisco in 1989 (Boatwright *et al.*, 1991) and the lake bed in Mexico City in 1985 (Anderson *et al.*, 1986; Singh *et al.*, 1988). Mainshock and aftershock recordings can be analyzed to identify the frequency content and amounts of soil amplification at the recorder sites. The most commonly used method of analyzing aftershocks, or weak motions, compares a soft-soil site to a nearby hard-rock reference site. Studies employing this method can analyze either the *S* wave or the coda. A recent study indicates that results from the two methods yield different amplitudes (Margheriti *et al.*, 1994).

Unfortunately, we must wait for earthquakes to occur in order to predict amplifications of ground motion using earthquake *S* wave or coda recordings. One of the methods currently used to circumvent this dilemma is the study of microtremors (also known as ambient seismic noise).

Microtremor and aftershock studies generally use similar methods to look for spectral peaks, which are thought to represent resonant frequencies in the response of a site. Some researchers (e.g., Lermo and Chavez-Garcia, 1994) have found that microtremors provide a rough approximation of earthquake site amplification, while others (e.g., Field *et al.*, 1990; Field and Jacob, 1993) consider them less reliable in this capacity. The use of microtremors to study the resonant frequency of sites is a long-standing tradition in Japan (see for example Kanai *et al.*, 1954; Kanai and Tanaka, 1961; Akamatsu, 1984). Microtremors have been used to analyze site conditions in many other regions as well, among them Mexico (Lermo *et al.*, 1988; Kobayishi *et al.*, 1991), Spain (Morales *et al.*, 1991), New York (Field *et al.*, 1990), and the San Francisco Bay area (Akamatsu *et al.*, 1991; Dravinski *et al.*, 1991; Kameda *et al.*, 1991; Seo *et al.*, 1991a, 1991b).

While the use of microtremors for site-response investigation is increasing, studies comparing their results with those from other approaches have produced mixed results. Favorable comparisons of earthquake and microtremor investigations were reported in Japan (Akamatsu, 1984; Kanai and Tanaka, 1961), Mexico (Celebi *et al.*, 1987; Lermo *et al.*, 1988; Lermo and Chavez-Garcia, 1994), and the San Francisco Bay area (Kameda *et al.*, 1991; Seo, 1991a). Some of these studies, however, infer better agreement than the data warrant. Figure 4 in Kameda *et al.* (1991), for example, can be interpreted as showing that microtremor and Loma Prieta mainshock amplifications are independent of each other. Other researchers looking at studies conducted in Mexico (Gutierrez and Singh, 1992), the San Francisco Bay area (Borcherdt, 1970), and El Centro (Udwadia and Trifunac, 1973) have concluded that microtremors do not accurately predict the amplification observed from earthquakes.

Recently, Nakamura (1989) has proposed a single-station method of analyzing microtremors that compares the