THE VARIATION OF STRONG GROUND MOTION OVER SHORT DISTANCES

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SUMMARY

This study, based on digitally recorded ground motions across the strong-motion array in Taiwan (SMART 1), addresses two problems related to input motions for structural design. First, the average coherence of high amplitude wave motions over distances of a few hundred meters is measured as a function of frequency. High resolution wave-number spectra, computed for sub-sets of the array in the range of 0.5 to 10 Hz, indicate significant dependence of coherence on frequency. Above about 5 Hz, spacially incoherent ground accelerations dominate, probably from scattering. Secondly, changes in direction of approach of body and surface waves in the accelerograms across the array are measured using wave number spectra and ground particle motions. The structurally important ratio of coherent vertical to horizontal wave energy is determined as a function of frequency. Spacial averages of response acceleration (N. Newmark's "tau effect") are computed suggesting tau between 0.6 to unity.

INTRODUCTION

The results presented here are based on recordings of strong ground acceleration obtained with the large-aperture array of digital accelerometers (SMART 1) in northeast Taiwan (Ref. 1). The array consists of 37 three-component force balanced accelerometers arranged in three concentric circles of radii 200 m, 1 km, and 2 km with one station at the center. Each station is triggered independently and the accelerations are recorded digitally on cassette tape. Absolute time is kept accurate to 1 msec.

During the first three years of operation (1980-1983), the array has recorded 25 earthquakes with local magnitudes between 3.8 and 6.9 (Ref. 2). The largest accelerations were recorded during the January 29, 1981, $M_L = 6.9$ earthquake. During this earthquake, all twenty-seven installed instruments triggered and the maximum horizontal acceleration recorded was 0.24g. The epicenter was located 30 km from the center of the array at an azimuth of 154°. The depth of the focus was 11 km. In order to simplify the presentation all calculations for the present paper use SMART 1 recordings from the January 29, 1981 earthquake.

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SPACIAL COHERENCE OF GROUND MOTION

The variability of wave energy across the whole array can be conveniently measured by using a frequency-wave number decomposition (Ref. 3). Such azimuthal spectral plots have been calculated using all 27 recording elements of the array, and for the four sub-arrays defined by the principal quadrants. Comparison between the five power spectra then provides a measure of changes in total wave power, wave scattering and direction and speed of approach of the coherent waves.

Example plots for the radial component of ground motion are given in Figure 1 for a 5 sec time window including the main S waves for the north-east (top) and south-east (bottom) quadrants at a frequency of 2.0 Hz. It is clear that the average coherent power in this earthquake is significantly different in the two quadrants. The peak power (peaks labelled A) has changed by a ratio of 1.75 over a distance of 1.5 km. In the north-east quadrant the coherent wave has an apparent velocity of 6 km/sec and azimuth 19° E of S; in the south-east quadrant the values are 2.6 km/sec at 23° E of S. The peripheral power-peaks in Fig. 1 arise from scattered strong wave motion and differ by quadrant. For the whole array (not shown) these outlying peaks diminish significantly.

Similar calculations of wave number plots at other frequencies and components show coherent wave motion with similar variabilities between sub-sections of the array for frequencies up to 3 Hz on the horizontal components and for frequencies up to 5 Hz on the vertical component. Above these frequencies, there is little coherent motion.

GROUND PARTICLE MOTIONS

One way to identify seismic waves is to plot the orbits of particles of the ground during the passage of the waves. These particle motions have loci of different geometries (straight lines, ellipses, etc.) depending on the wave type (P, SV, SH, Rayleigh, etc.). The orbits, which can be computed from the three orthogonal ground displacement components recorded by SMART 1 accelerometers, also can be compared across the array to measure the spacial variability in the ground motion. Fig. 2 shows the ground displacement orbits for a time interval of 3 sec from the January 29, 1981 earthquake recorded at 3 collinear stations of SMART 1. Although double integration of the accelerograms has greatly smoothed the ground motions, significant differences in the orbits are distinguishable.

First, consider the RT orbits. The arrival of the initial S wave pulse corresponds to the loop in the upper right hand corner. The shape and orientation of the loop is fairly constant for all three stations. There are some small differences in the sharpness of the cusps, but the overall orientation is the same. However, the second swing of the S waves (loop in the lower left hand corner) rotates 15° in a counterclockwise manner from I-06 to I-12, indicating a sharply bending wavefront over a distance of 400 m. Secondly, the particle motion in the

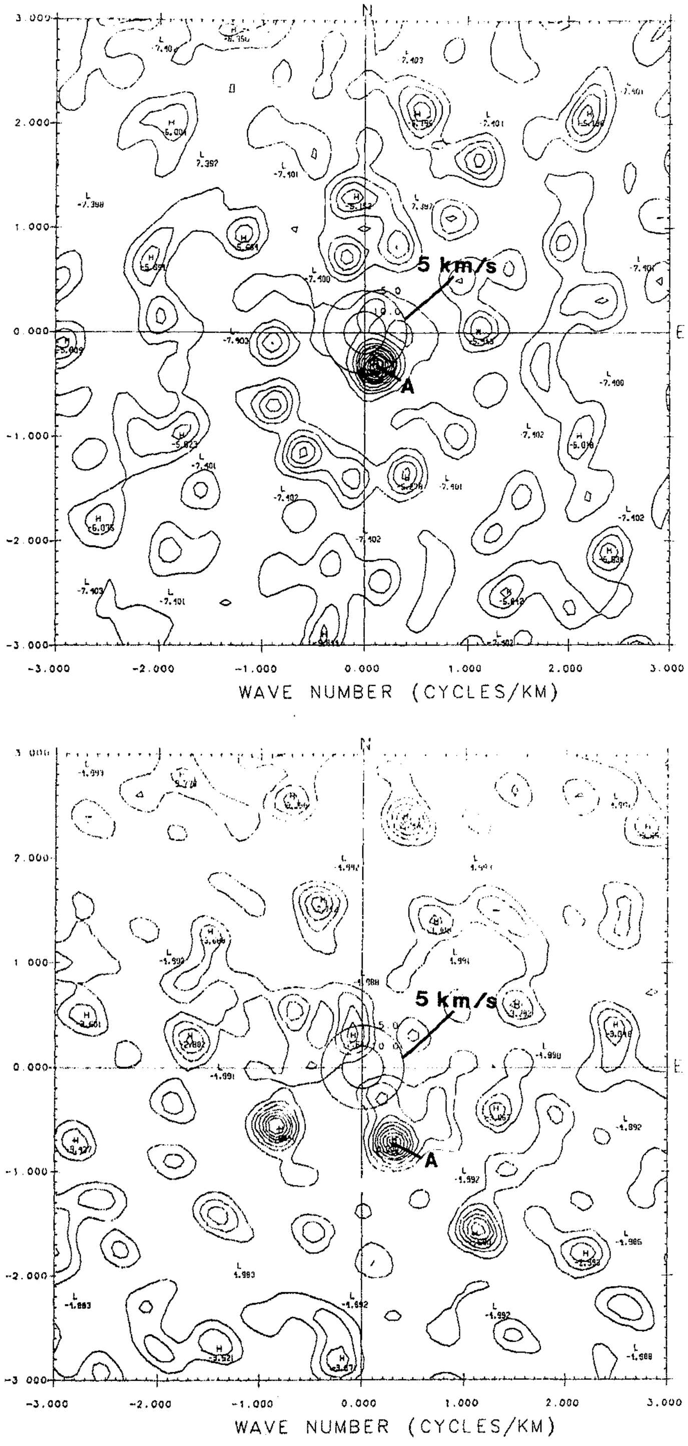

Figure 1. Azimuthal plot of coherent seismic wave power of the radial component at frequency 2 Hz. Power is contoured as a function of db down from the maximum. The vertical and horizontal axes are wave number in the north (N) and east (E) directions. Wave velocity (km/s) is marked on the central circles.

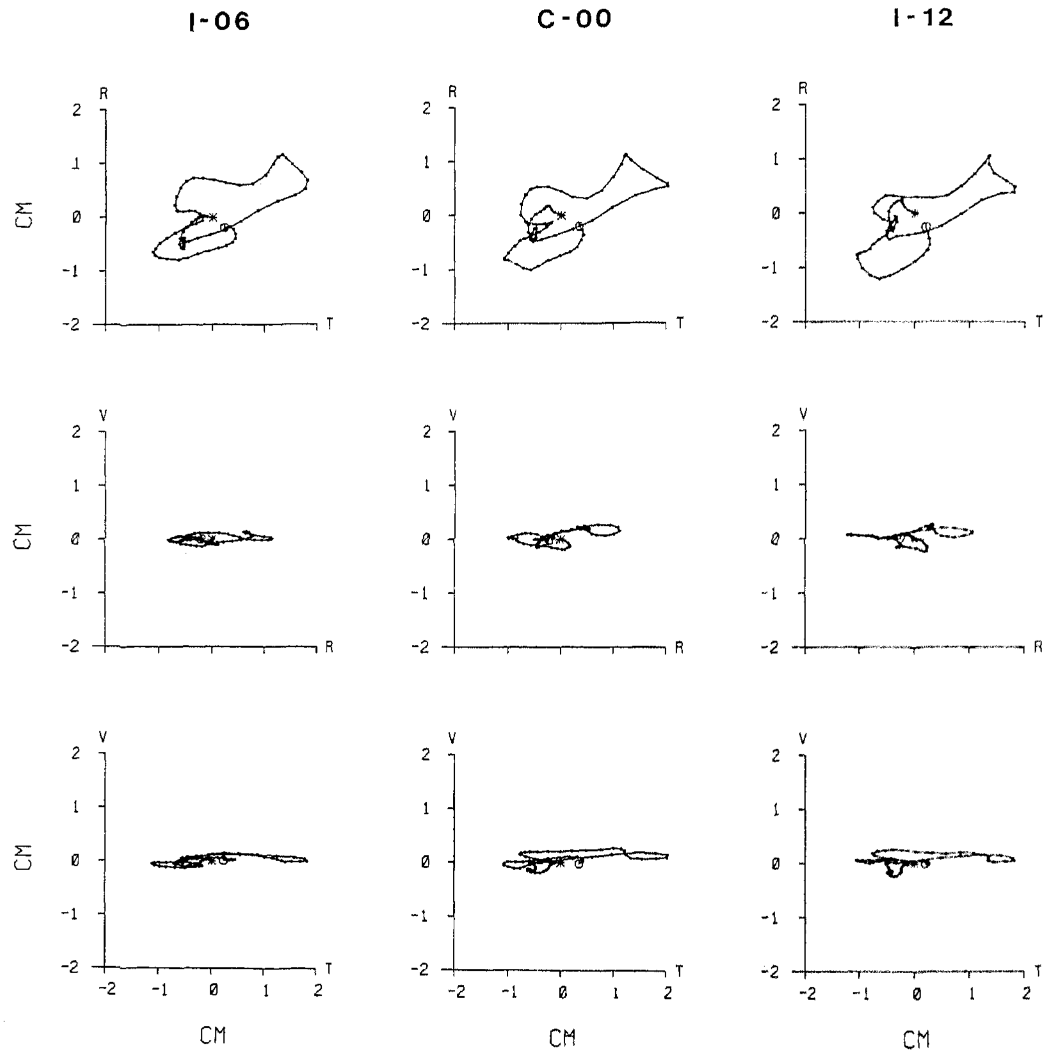

Figure 2. Particle motions of ground displacement (starting at the asterisk and ending at the circle) recorded at 3 array stations (I-06, C-00, I-12) spaced 200 m apart. The selected 3 secs of time history include the main S waves. R, T, and V denote radial, transverse and vertical directions.

VR plane is almost linear at all three stations. Because Rayleigh wave motion is generally retrograde elliptical this motion is probably mainly scattered P and direct SV waves. Variability of over 20 per cent is present in both principal axes.

Finally, the VT diagrams confirm that vertical displacements are relatively small and the ground particles are moving predominantly in a horizontal plane with the largest amplitudes in the transverse direction (SH or Love waves).

RATIO OF VERTICAL TO HORIZONTAL POWER

Wave number spectra for the whole array were analyzed from 1.0 to 8 Hz for a 4 sec time window about the P waves and a 5 sec time window about the S waves. The ratio of the peak power of the vertical to horizontal wave number spectra at various frequencies is shown in Table I. For the P wave window, the vertical power dominates above 4 Hz and for the S wave window the horizontal power dominates up to 5 Hz. Above 5 Hz in this window, the ratio of vertical to horizontal coherent power increases but, as mentioned earlier, there is very little coherent energy at these frequencies.

TABLE I

	Ratio of coherent power V/H	
Frequency	P waves	S waves
1.0	0.78	0.02
2.0	0.85	0.13
4.0	1.37	0.17
5.0	10.60	0.31
6.0	13.60	0.59
8.0	9.60	1.20

SPACIAL AVERAGES OF RESPONSE SPECTRA

A crucial proposal of N. Newmark was that when ground motions are spacially averaged over a structure with a large foundation, there is a decrease in peak (high frequency) acceleration. The reduction results essentially from interference dependent upon the phase lags of the Fourier components of the (horizontally) propagating waves. Array analysis allows a field measurement of this effect.

Consider the transverse ground motion at the adjacent stations C-00 and I-12 with separation comparable to large structural dimensions. Simple addition of the time histories shows a reduction of wave amplitudes for some (but not all) peaks and small phase shifts, particularly for the later (surface) waves. A more meaningful measure of Newmark's average (the "tau effect") is to compute the response of a single degree

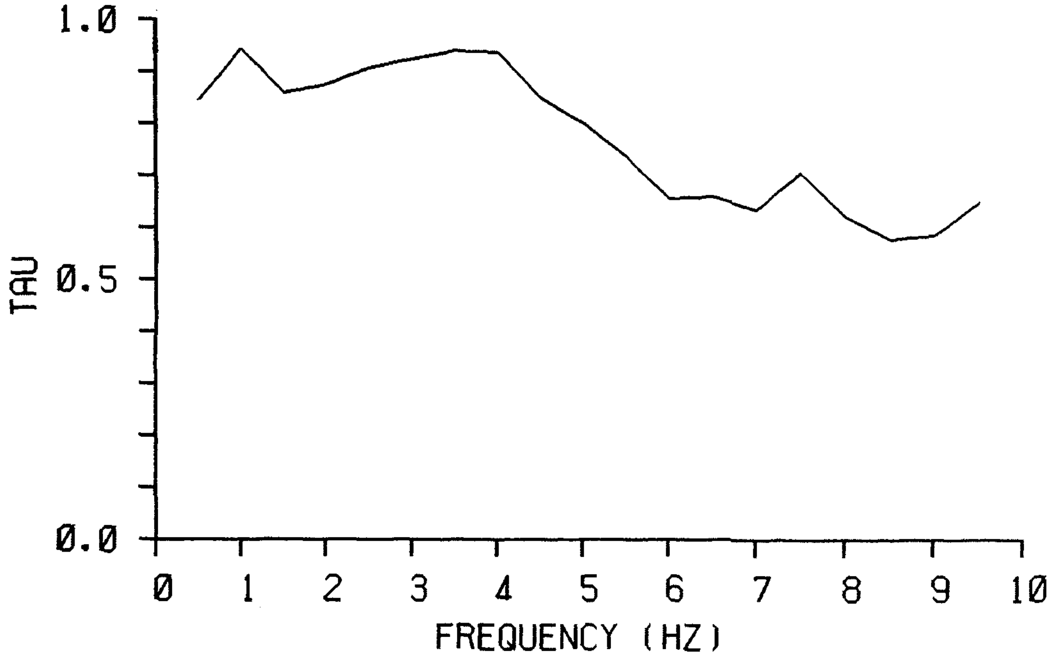

Figure 3. Response spectral ratio (tau) for the averaged response from stations C-00 and I-12 (separated by 200 m). The transverse component was used with a damping of 5 per cent.

of freedom damped oscillator at each station and average the resulting time histories at each oscillator frequency.

The reduction of the response spectrum due to such spacial averaging was computed and is shown in Fig. 3. For each oscillator frequency, the ratio of the averaged response spectrum to the maximum of either input response spectrum is plotted. Below 5 Hz the reduction is about 10 per cent. Above 5 Hz, the response spectrum is reduced by 30-40 per cent.

CONCLUDING REMARKS

The case examined indicates that coherent strong motions are present only up to 3 Hz for S waves and 5 Hz for P waves. An important conclusion is that subsurface structures can produce large changes in the apparent velocity (i.e. changes in angle of emergence) of waves over short distances. This can make prediction of the ratio of vertical to horizontally propagating waves difficult. Significant differences in wave propagation directions occur over short distances with significant rotational motion present. Further detailed results on ground rotation, wave scattering and spacial averages will be presented elsewhere.

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