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DIRECTIONAL SITE RESONANCES AND THE INFLUENCE OF NEAR-SURFACE GEOLOGY ON GROUND MOTION

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Abstract. We examine the horizontal motions at close stations from earthquakes in the Loma Prieta and Whittier Narrows sequences to study the shear wave polarizations. We use a dense, six station array recording 10 aftershocks for the former, and use two events and 11 stations across the Los Angeles area for the latter.

We compute the average azimuth of strongest shaking in the shear wave as a function of frequency from 1 to 18 Hz for each record of each earthquake. The direction of shaking at a given frequency often correlates much better with an empirical site resonance direction than with the direction of shaking expected from the focal mechanism of the earthquake. The effect tends to be greatest at the frequencies that are the most amplified. This phenomenon can complicate determination of the earthquake source at frequencies higher than 1 Hz.

Further, since sites only 25 meters apart show different preferred directions, very near-surface geology is probably responsible. Estimation of directional site resonances may prove useful for seismic design.

Introduction

Near-surface geology is known to be an important factor in the motion of the surface of the earth during earthquakes. This importance is most directly seen by comparing surface seismometer records with seismograms written by instruments in boreholes. Amplification, frequency-dependent attenuation, and an extended duration of shaking are more pronounced in the surface records (Malin *et al.*, 1988, Hauksson *et al.*, 1987, Fletcher *et al.*, 1990, Aster and Shearer, 1991) than in the borehole records. The correlation between unconsolidated surficial deposits and large amplitude motions is a well-established and useful concept in earthquake engineering (e.g., Joyner and Boore, 1981).

The modeling of strong motions generally assumes flat-layered geologic structures. The response of these flat-layered structures is simpler and faster to compute, and can explain many features of strong ground motions. In addition, a one-dimensional estimate of geologic structure is simpler to determine from geotechnical methods than the more realistic three-dimensional structure.

We present observations that contradict the flat-layered model prediction that the site response should be azimuthally symmetric. We compare observed shear wave polarizations to those predicted from the focal mechanisms. Most of the sites studied have a preferred direction of shaking that does not depend on the focal mechanism. We term this phenomenon *directional site resonance.*

Directional Resonances Observed in the Santa Cruz Mountains

Our analysis of the 1989 Loma Prieta, California, aftershock sequence is based on seismograms collected by 2 Hz 3-component geophones during the IRIS-PASSCAL Loma Prieta Aftershock Project. The selected dataset includes 10 events recorded at the ZAYA array and other stations of the network (see Table 1).

Table 1

Julian Day	Time	Lat.	Long.	h [1]	D [2]	M_d	Dip Dir. [3]	Dip	Rake
318	00:02	37° 06'	-121° 52'	4	17	1.6	145°	80°	50°
318	04:50	37° 10'	-121° 58'	5	7	2.3	215°	40°	130°
318	08:41	37° 14'	-122° 09'	8	16	2.1	230°	30°	120°
318	17:33	36° 48'	-121° 34'	6	58	3.1	90°	15°	-130°
318	20:41	37° 05'	-121° 51'	4	19	2.8	220°	35°	100°
318	21:16	37° 04'	-121° 51'	6	20	3.4	165°	50°	10°
319	10:04	37° 03'	-121° 54'	12	15	2.6	275°	40°	-50°
319	10:08	37° 04'	-121° 53'	12	16	2.4	260°	35°	-50°
320	04:59	37° 10'	-122° 04'	11	5	3.0	240°	45°	160°
320	14:07	37° 11'	-122° 03'	10	5	2.5	200°	65°	100°

[1] Hypocentral depth in km.
[2] Epicentral distance in km.
[3] The dip direction is the strike direction increased by 90°.
Mechanisms were provided by D. Oppenheimer (pers. comm.)

The ten selected aftershocks are characterized by different locations and focal mechanisms. All data have good signal-to-noise ratios and clear P-wave onsets. This paper focuses on S-wave data recorded at the six station ZAYA array (see Figure 1). Figures 2a and 2b show records of the 14 November 1989 (00:02 GMT) aftershock filtered in two different passbands (0 to 2 Hz and 3 to 5 Hz) and rotated in the direction of polarization observed for the first arrival and the orthogonal direction. This direction is consistent with that expected from the focal mechanism, however, the array is near the S-wave node, so the polarization direction is very poorly constrained. In the 0 to 2 Hz passband the component in the direction of the observed polarization starts with a half-second pulse, followed by a scattered coda characterized by a lower amplitude. The orthogonal component is quiet at the time of the pulse, but shows a series of scattered waves in the coda whose amplitude is comparable with the coda of the other component. This phenomenon is evident for all the six sites confirming that the polarization direction of the first 0.5 second pulse is consistent across the array. This initial coherence has been observed for P-waves (Menke *et al.*,

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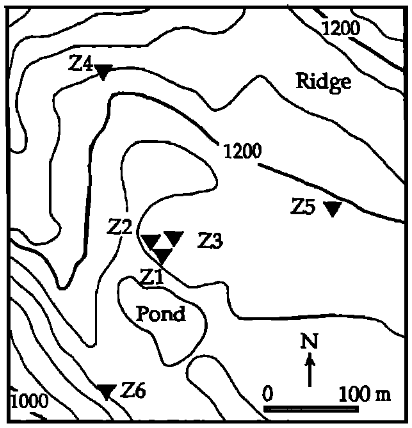

Fig. 1. Topography and location of the six three-component stations comprising the ZAYA array. The array has the geometry of an inner and an outer triangle whose sides are approximately 25 and 300 meters, respectively.

1990). In the 3 to 5 Hz passband (Figure 2b), a directional resonance is observed for station Z1. The signal recorded at Z1 shows that the first pulse is present in the top seismogram and almost absent in the orthogonal direction as expected. The coda, however, shows peak amplitudes larger than in the first 0.5 seconds of the signal. This coda can be interpreted as a resonance effect that generates the strongest shaking in the signal and whose preference for a particular direction is evident in our polarization analysis below. The variation between the stations in Figure 2b motivates our investigation of the shear waves in order to analyze the spatial coherence of the seismic signal.

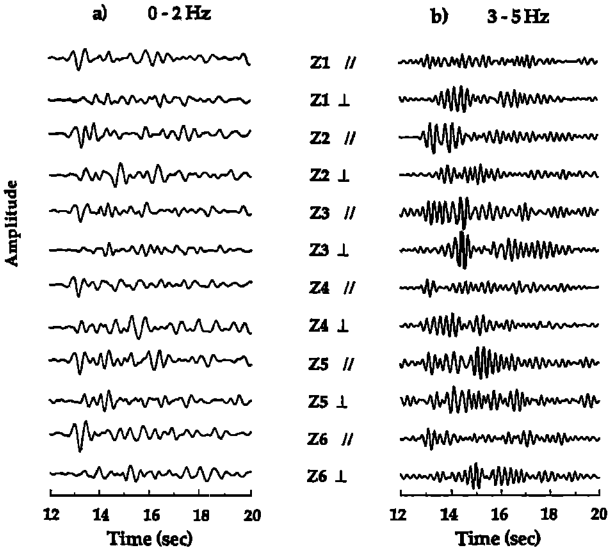

Fig. 2. S-wave records for the 14 November 1989 (00:02 GT) aftershock. The horizontal components recorded at the 6 sites of the ZAYA array have been rotated parallel to observed direction of polarization in the first arrival Z //) and the orthogonal direction (Z⊥). a) The data have been filtered in the 0 to 2 Hz passband. b) same as in a), except that the seismograms have been filtered in the 3 to 5 Hz passband. The traces in each column have been plotted with a common vertical scale.

We considered the direct and scattered shear waves, using a five-second window starting at the shear wave arrival. We filtered the signals in the frequency domain using 2 Hz wide cosine-bell-shaped windows from 1 to 20 Hz. Polarization directions were estimated following Montalbetti and Kanasewich (1970), and Vidale (1986). The eigenvector associated with the largest eigenvalue of the covariance matrix of the real signal points in the direction with the largest amount of ground motion; the azimuth of this direction is the polarization direction used here. These observations indicate that 4 of the 6 sites show a preferred direction of motion. These results are summarized in Figures 3a and 3b. For each site the arrows indicate the preferred direction of motion at the indicated frequencies. The polarization bears the usual two-

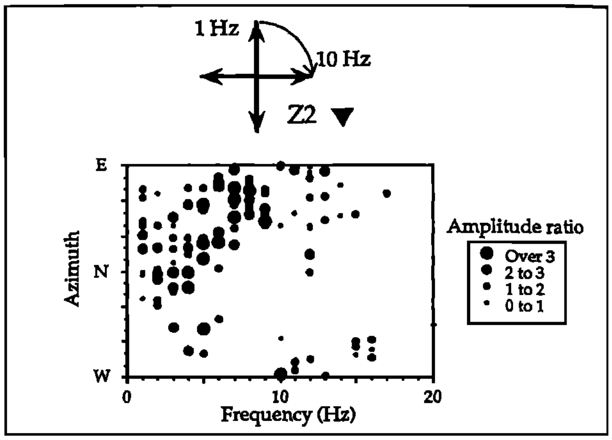

Fig. 3a. Azimuth of strongest polarization plotted against frequency for the station Z2. 0° indicates N-S motion. Data from the 10 aftershocks are shown. For each event we have estimated the polarization direction of the shear waves in different pass-bands. For the ideal case of polarization direction determined exclusively by the focal mechanism and coherent with frequency, we would observe that the dots would align for each event at a given value of polarization azimuth. The symbol size is proportional to the amplification at that frequency relative to the average spectra computed from stations outside the ZAYA array. The top figure summarizes the observation using an arrow to indicate the preferred direction, while the thin curved arrow shows its dependence on frequency.

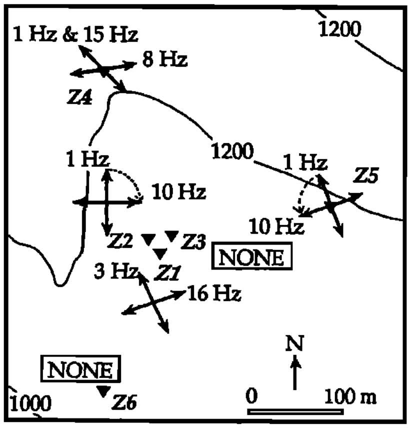

Fig. 3b. Directions and frequencies of consistent polarizations observed at the ZAYA array in Santa Cruz Mountains from aftershocks of the Loma Prieta earthquake.

fold ambiguity; for example, north-south vibration has a direction of either north or south. We therefore plot polarization in the 180° range centered about north. Stations Z2 and Z5 show a preferred direction of motion that changes fairly smoothly with frequency as indicated by the thin curved arrows.

No clear correlation between topography and resonance effects has been found (compare Figure 2 and Figure 3b). Surface geology does not offer any means to differentiate between stations: the six sites straddle the trough of the San Lorenzo syncline in a geologically homogeneous area of Tertiary age. Nevertheless, deeper geological features may still play a significant role.

It is remarkable that the direction of preferred motion changes across the inner stations which are only 25 m apart (Figure 3b). Furthermore, these directions at each station remain relatively constant from just after the shear wave onset through the coda.

The presence of a directional resonance suggests that information about the focal mechanism may be obscured by the site response. However, the polarization direction of the array in the low-frequency passband (0-2 Hz) obtained by averaging the covariance matrix of the six sites (Jurkevics, 1988) exhibits a strong agreement with the polarization direction expected from the focal mechanism. In addition, the initial 0.5 sec of the shear wave arrival shows good agreement with the expected direction of motion, although later arrivals are often larger and in different directions.

Directional Resonances Observed in the Los Angeles Area

We have also analyzed the frequency content and the polarization characteristics of the 1 October 1987, Whittier Narrows, California, mainshock and the 4 October aftershock to understand the relative contributions of source and site to the observed ground motions. The mainshock hypocenter was located at 14.6 km depth. The focal mechanism is that of a gently dipping thrust (Hauksson and Jones, 1989). Based on teleseismic body wave analysis, Bent and Helmberger (1989) suggested that the moment was released by two distinct sources. The second source is 11 km deep and 5 times larger than the first with a slightly different mechanism. In this paper we use the depth and mechanism of the second and largest source to represent the mainshock. The 4 October aftershock was located 2 km northwest of the mainshock at a depth of 13.3 km, with a strike-slip mechanism on a vertical plane (Hauksson and Jones, 1989).

The California Division of Mines and Geology digitized strong motion records for both the mainshock and the aftershock at 11 stations. Stations range from almost directly above the hypocenters to 50 km away. We processed the Whittier Narrows strong motions similarly to the Loma Prieta records. The two data sets are intrinsically different in that digital records exist for many Loma Prieta aftershocks, whereas only records of the Whittier mainshock and largest aftershock have been digitized. Hence, the presentation of the results is different because it is tuned to the features that are best resolved for each data set.

The polarization directions do not agree particularly well with the directions predicted by the focal mechanisms (Figure 4), but in each passband and for the unfiltered signal there is a tendency for the polarization directions of the two events to agree with each other (further details can be found in Vidale, Bonamassa, and Houston, 1991). This tendency is particularly strong at stations 157, 303, 399, 400, and 461, but also is present at stations 368 and 401. At stations 402 and 436 the observed directions for the two events lie closer to each other than to the predicted directions. Thus 9 of 11 sites show evidence for directional resonances.

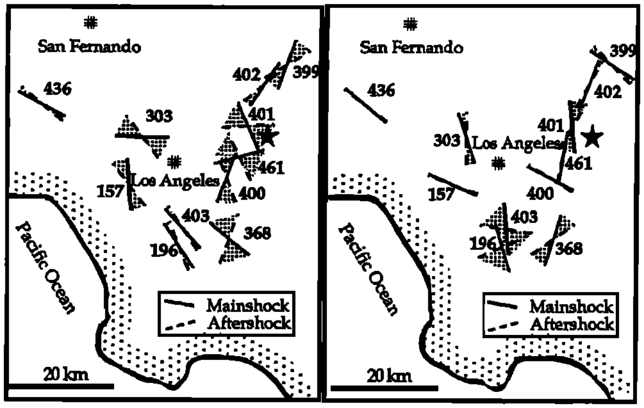

Fig. 4. Directions of shaking observed and predicted from the 1 October 1987 and 4 October 1987 Whittier Narrows earthquakes. Left: directions of shaking expected from earthquake focal mechanisms. Right: predominant directions of observed shaking.

These observations suggest that the polarization of the shear waves at high frequencies is not controlled by the earthquake source. Previous work (Vidale, 1989) on the Whittier Narrows sequence suggests that the focal mechanism influences *peak acceleration* at a specific site, but the data presented here indicate that in many cases, the *azimuth of polarization* of the motion in the range 1-16 Hz depends on the site. In addition, in several cases, the most similarity between the mainshock and aftershock polarizations is in the passband where spectral peaks appear, suggesting that the geologic features that enhance amplitudes in a particular frequency band also have a preferred direction of particle motion. The 11 stations span a wide range of surficial geology from hard rock to soft sediment suggesting that these directional resonances are probably a feature common to differing geologic settings.

Interpretation of Directional Resonances

Our results may be summarized as: i) the polarization of shear waves is affected by the site and depends on frequency; ii) this is not evident in the first 0.5 s pulse. Thus anisotropy or similar phenomena cannot explain the observations because they would act on the whole wave train. The observed site effect acts on the reverberations or scattered energy. Hence we term the effect directional resonance. We interpret the observed directional resonances as the result of some geological feature along the ray-path to the surface that is able to amplify the particle motion in selected frequency bands in particular directions compared to motions in other directions. This direction-dependent amplification alters the particle motion.

The actual geological features that cause this amplification are not known: lateral gradients in near-surface shear wave velocity are likely to cause these resonances that change across short distances. Since the Loma Prieta data show that the preferred direction can change on a scale of 25 m, and that it remains constant through the shear wave onset and coda, these features must be very close to the receivers, probably within a few tens of meters.

The presence of specific geological features that can alter the particle motion direction leads to the alignment of shear body wave polarizations. This phenomenon can be described as a directional site effect and may be relevant in seismic design. Even if the mechanism is not yet fully understood, the predictability of the directional resonances should prove useful to earthquake engineers. If the preferred direction of strongest shaking can be measured in advance, then structures can be appropriately reinforced.

Conclusions

Strong motion data recorded during the Whittier Narrows and Loma Prieta earthquake sequences show the presence of directional site resonances. In the frequency range from 1 to 16 Hz a majority of sites studied exhibit a preferred direction of ground motion of shear waves that does not depend on the polarization expected from the focal mechanism and location of the event. For the Whittier Narrows earthquakes, the coincidence of the polarization directions from the two events with different focal mechanisms was greatest for the frequencies at peaks in the spectra, suggesting that site amplification and directional resonances are linked. For the Loma Prieta study, the analysis of ten aftershocks recorded at the small-aperture ZAYA array has shown that the preferred direction for the ground motion can change within 25 m. Furthermore, the observed directional site effect is not easily correlated with either topography or surficial geology. Understanding these observations of directional site resonances will contribute to earthquake hazard mitigation as well as to basic knowledge of seismic wave propagation.

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