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BROADBAND WAVEFORM MODELLING OF ANOMALOUS STRONG GROUND MOTION IN THE 1989 LOMA PRIETA EARTHQUAKE USING THREE-DIMENSIONAL GEOLOGIC STRUCTURES

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Abstract. Strong motion recordings of the 1989 Loma Prieta earthquake show a large, coherent SH wave displacement pulse across much of the San Francisco Bay area. This distinctive ground motion has been modelled using approximate, broadband synthetics for a double-couple centroid source in a 3-D crustal model for the region. The synthetics indicate that (1) horizontal bending and focusing of SH waves by the lateral crustal velocity contrast across the San Andreas fault and (2) the source radiation pattern, contribute significantly to the observed azimuthal variation of the SH pulse and hence to the regional variations of strong ground shaking in the period range of 1 to 8 sec. In addition, the scattering of surface-reflected shear waves by deep basins under the Santa Clara Valley may contribute to increased coda amplitude and duration observed for sites around Oakland.

The wave modelling also supports the earlier conclusion that an increase in intensity in portions of San Francisco and Oakland is in part the result of energy reflected from the base of the crust [Somerville and Yoshimura, 1990].

Introduction

The damage pattern and strong motion recordings from the 1989 Loma Prieta California earthquake (M_S=7.1) show significant spatial variations in intensity of ground motion around the San Francisco Bay (SF Bay). Explanations for these variations include soil amplification site effects [Hanks and Brady, 1991; Borcherdt and Glassmoyer, 1992] and reflections of high-frequency waves from horizontal interfaces in simplified crustal models [Somerville and Yoshimura, 1990]. The present analysis of broadband wave propagation through the major geological structures in the Bay Area indicates that lateral wave refraction was also a significant cause of spatial variation of intensity.

In the northern SF Bay (Figure 1), at an epicentral distance $\Delta \approx 100$ km, there was significant damage in the Loma Prieta earthquake in a localized region between San Francisco and Oakland about 10 km wide by 15 km long [Hanks and Brady, 1991]. Somerville and Yoshimura [1990] and Somerville and Smith [1991], using a layered model to analyze higher frequency ($f > 2$ Hz) acceleration records, attributed observed amplification of strong ground motion in this region to a path effect consisting of the near simultaneous arrival of direct shear waves (S) and shear waves (SmS) reflected from the base of the crust. However, this mechanism (S+SmS) does not explain some of the observations, namely: (1) increased ground motion occurred over a smaller range in epicentral distance than is predicted by higher frequency, one-dimensional analyses, and (2) within the distance range of increased intensity, there were significant azimuthal variations of the waveforms, including a decrease in amplitude of S+SmS waves and an increase in coda amplitude and duration from west to east.

We use an approximate numerical method for synthesizing broadband wave propagation in complex, 3-D structures to extend the path effect hypothesis of Somerville and Yoshimura to longer periods and laterally varying structure.

Strong Motion Observations

Figure 2 shows transverse component, strong-motion displacements from 19 sites (17 rock or alluvium and 2 soft soil) around the SF Bay from the Loma Prieta earthquake. The dominant feature is an impulsive, WSW motion at about 4 to 5 sec reduced time with duration less than 2 sec. We interpret this pulse as a combination (S+SmS) of direct SH waves (S) and SH waves (SmS) reflected from the Moho as suggested by Somerville and Yoshimura [1990]. The sense of motion of this pulse is compatible with SH radiation from the oblique-slip mechanism for the Loma Prieta event. Although the pulse is present on most records in the North Bay, its shape varies significantly with azimuth and distance from the

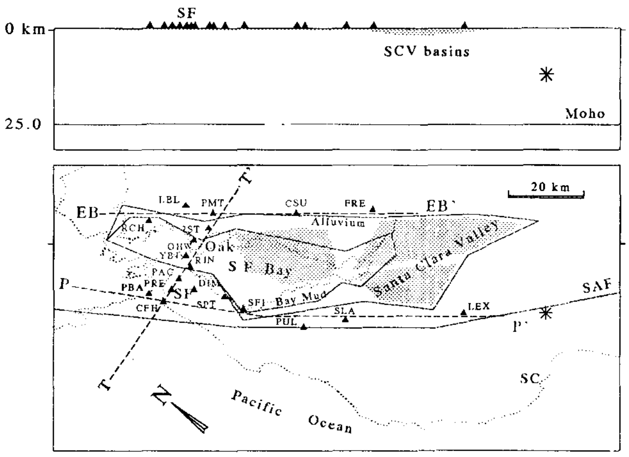

Fig. 1. (upper) cross section and (lower) map view of the SF Bay region showing the Loma Prieta source (star), strong motion stations (triangles), San Andreas Fault (SAF), San Francisco (SF), Oakland (Oak), Santa Cruz (SC) and limits of 3-D velocity model elements. Dashed lines show synthetic seismogram lines. The surface extent of low velocity alluvium and bay muds is indicated by the outer and inner polygons around the SF Bay, respectively; the three shaded areas indicate low velocity basin regions deeper than 300 m. The shaded region on the cross-section indicates the depth extent of the alluvial basins under the Santa Clara Valley (SCV basins).

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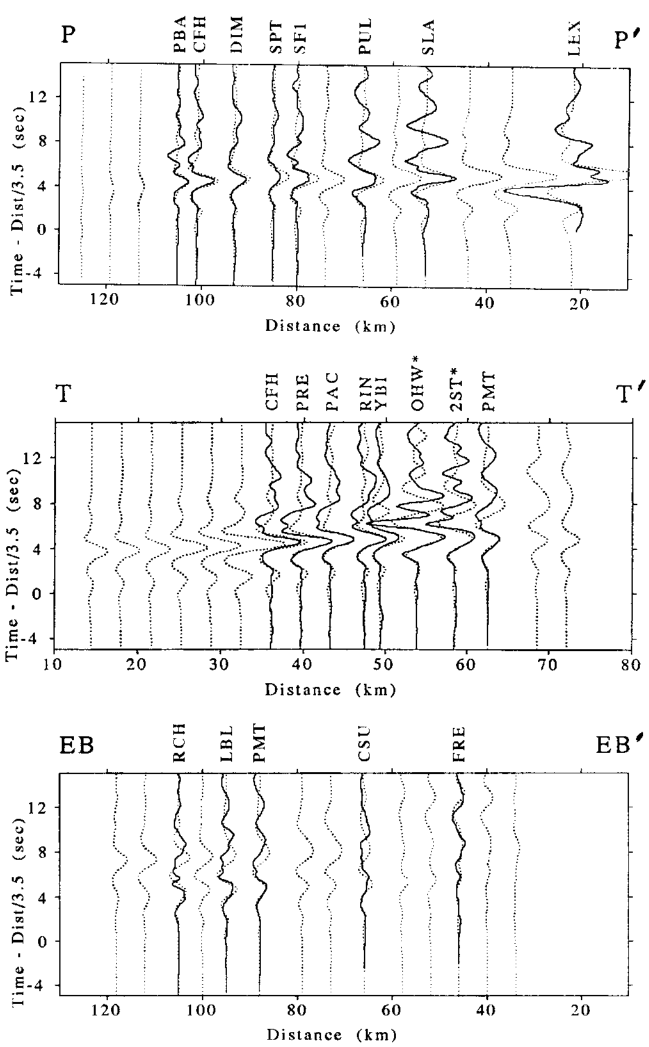

Fig. 2. Observed strong motion transverse displacement recordings (solid) and waveray synthetics (dotted) shown along three lines: San Francisco peninsula (P-P'), Transverse (T-T') and East Bay (EB-EB'). Traces are plotted as a function of distance along section; travel time is reduced with respect to epicentral distance. Trace distance on section P-P' only is identical to epicentral distance. All amplitudes on each section are plotted to the same scale; the observed traces are band-pass filtered from 1 to 8 sec and shifted in time to align the interpreted direct SH arrival with the direct SH arrival on the synthetics. (*) indicates soft-soil sites. Station LEX is shown only for comparison of peak to peak amplitudes; this record is distorted by the double integration of truncated near and intermediate field signals that begin before the trigger time.

source. On the records at CFH and PRE in San Francisco (Figure 2) the pulse is greatly amplified relative to sites such as SPT about 15 km *closer* to and PBA about 5 km *farther* from the epicenter. About 20 km to the east around Oakland, the same pulse is reduced in amplitude and lacking in higher frequencies (e.g. PMT, LBL in Figure 2) and this pulse is barely visible on records at sites farther south in the East Bay (e.g. CSU, FRE in Figure 2).

Also, just west of Oakland at soft soil sites OHW and 2ST (Figure 2) there is a strong, almost monochromatic coda of about 1.5 sec period and 5 sec duration [c.f. Hanks and Brady, 1991]; such a coda is not apparent at stations a few kilometers to the west (e.g. YBI, RIN) or to the east (e.g. PMT, LBL). Although the amplified motions at OHW and 2ST are characteristic of soft soil sites, these records are included to determine if any wave features on them can be explained with 3-D path effects.

Three-Dimensional Modelling Method

Far-field, broadband wave propagation from the Loma Prieta source was modelled using a numerical method which tracks *wavepaths* as they refract through 3-D velocity structures. This approximate method, called the *waveray* method [Lomax, 1992] invokes Huygens' principle to propagate wavefronts using a frequency-dependent velocity function defined as the elastic phase velocity smoothed over local wavelength across the wavefront. Because the smoothing of the velocity structure differs at each frequency the wavepaths and travel times also are functions of frequency. The waveray technique is an implementation of the concept that waves of a given wavelength are not influenced by features that have characteristic dimensions much smaller than the wavelength. A number of numerical validation tests of the method have been performed [Lomax, 1992]. The current implementation of the waveray method does not include high angle reflections or wavetype conversions at velocity discontinuities except at the free surface.

3-D velocity model. The 3-D S-wave velocity model for the SF Bay area incorporates different crustal structures on each side of the San Andreas fault (SAF) and surficial, low velocity regions representing younger sediments (Figure 1 and Table 1). The two crustal columns consist of gradient layer over half-space generalizations from P velocity models for the east and west sides of the SAF [Walter and Mooney, 1982]. The 3-D structure has a sharp velocity jump at the base of the crust (Moho) at 25 km depth and a crustal velocity contrast of up to 8% across the SAF, with higher velocities to the southwest (Table 1).

Principal alluvial deposits are represented by a low velocity region above a basement contact surface defined by planar polygons (Figure 1). The depth to basement, obtained from subsurface stratigraphy [Rogers and Figuers, 1991] and from well and refraction data [Hazlewood, 1976], is everywhere less than 0.5 km except under the Santa Clara Valley. There, two negative gravity anomalies [Oliver, 1980] are most likely caused by deep alluvial basins (D. L. Jones, personal communication, 1992) which are here inferred from the gravity anomalies to be over 1.5 km thick.

Table 1. San Francisco Bay Area Three-Dimensional Velocity Structure

3D Element	Depth Range (km)	S Velocity (km/sec) *	Density (gm/cm^3)
Bay Muds	0 - 0.1	$0.1 + 6.0d$	1.2
Alluvium	0 - 2.0	$0.3 + 0.5d$	2.0
Crust NE of SAF	0 - 25	$3.2 + 0.03d$	2.6
Crust SW of SAF	0 - 25	$3.45 + 0.02d$	2.7
Mantle	25 +	$4.4 + 0.005d$	3.3

* Velocity given by $A + Bd$ where A is velocity at top of element, B is velocity gradient and d is depth below top of element.

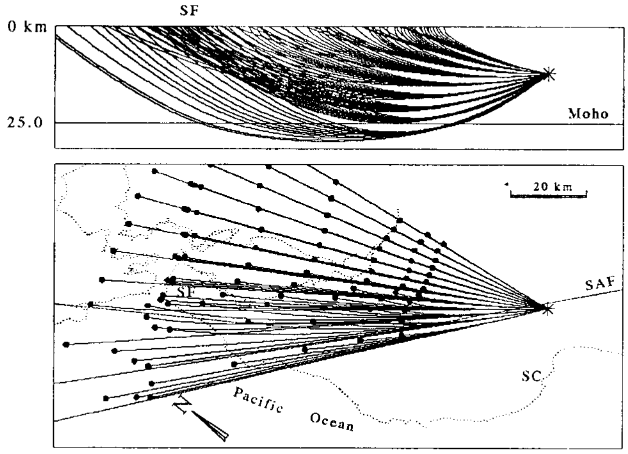

Fig. 3. Waveray results for 12 vertical fans of 9 wavepaths each at a period of 2 sec in (upper) section and (lower) map view. The horizontal distribution of wavepaths ranges clockwise from near the SH radiation maximum to near the SH radiation node. Each wavepath is terminated at the surface (solid circles) to emphasize the direct S and SmS arrivals. The wave focussing caused by the SAF and the Moho is indicated by the large number of arrivals along a southwest-northeast trend through San Francisco.

Younger bay muds are approximated by a 0.1 km thick layer with a very low S wave velocity of 0.1 to 0.16 km/s [Rogers and Figuers, 1991]. The lateral extent of bay muds and alluvium at the surface (Figure 1) is generalized from the soil type map of Hall (ND).

Source. The Loma Prieta rupture is approximated with a double-couple point source (strike 130°, dip 70°, rake 135°, $M_0 = 2.0\text{x}10^{19}$ Nm; see Wallace et al. [1991] for references) located updip of the hypocenter of Dietz and Ellsworth [1990] at a depth of 12 km. The source time function is adapted from Wallace et al. [1991] with an increase in amplitude and decrease in duration of their largest sub-event. A distributed slip solution is not used in this study because it is not required to fit at longer periods the strong S+SmS displacement pulse.

225 wavepaths from this source were mapped using the waveray method at 21 periods between 1 and 8 sec. This period range brackets the apparent short period limit of coherent and deterministic energy in the strong motion records (Figure 2) and the long period high-pass filter corner at about 6 sec used in processing the records [Hanks and Brady, 1991]. Broadband SH synthetic seismograms for a given site were constructed by summing the contributions at each period from wavepaths that reach the surface near the site.

Modelling Results

Figure 2 shows broadband synthetic seismogram sections along the San Francisco peninsula (P-P'), along the East Bay (EB-EB') and transverse from west of San Francisco to east of Oakland (T-T'). On the transverse section (T-T', Figure 2), the direct (S+SmS) arrival forms the impulsive first arrival on all traces; its amplitude is greatest near location 35 km, corresponding to station CFH, and decreases to the west and east. This lateral variation in amplitude has two main causes. First, there is lateral distortion of the direct S+SmS wavepaths caused by the crustal velocity contrast across the SAF. The lower velocities on the northeast side of the fault refract towards the east waves that pass along the boundary. This lateral bending of the wavepaths forms a region of focused energy and increased wave amplitudes that passes through San Francisco and a region of de-focusing offshore to the west (Figure 3). This lateral refraction and focusing is a horizontal analog of vertical refraction and focusing caused by the Moho contrast (Figure 3).

A second cause of lateral amplitude variation is the modification to the source SH radiation pattern as it is mapped along the wavepaths in the 3-D velocity structure; the marked decrease in S+SmS amplitude southeast of Oakland (EB-EB', Figure 2) is mainly due to the wave take-off angles approaching the SH radiation node at the source.

The synthetics along the peninsula section (P-P', Figure 2) are dominated by the direct S+SmS body wave pulse. The amplitude of this phase decreases with increasing Δ to about 60 km, is nearly constant for $60 < \Delta < 90$ km, rapidly increases to a peak about $\Delta = 100$ km, and then decreases. This behavior matches both the variation in the observed S+SmS displacement pulse along the San Francisco peninsula (Figure 2) and the observed peak acceleration attenuation behavior [Campbell, 1991]. The strong amplitude peak at about $\Delta = 100$ km is caused by vertical focussing of waves by the velocity contrast across the Moho, combined with the horizontal focussing due to the contrast across the SAF.

Another striking wave feature on the transverse section (T-T', Figure 2) is the development of a wave coda eastward of station YBI. The coda duration in the synthetics is about 5 sec near station OHW in the West Oakland region. Farther east, the coda amplitude varies and its dominant period increases. Qualitatively, these changes in coda character between San Francisco and Oakland match the observed displacements. The coda in the synthetics is caused by sS and higher multiple surface reflections that initially reflect above, and are scattered by, the deep, low velocity basins under the Santa Clara Valley. Additionally, because the western basin lies between the epicenter and Oakland (Figure 1), it acts as a lens and focuses waves into the region near Oakland.

The coda in the synthetics is formed mainly by waves of 1 to 2 sec period. Wave scattering and focusing at these periods under the Santa Clara valley is sensitive to details of the geometry of the deep basins. Consequently, an exact match to the phase and amplitude of the observations cannot be expected. However, the results suggest that focusing and scattering of waves by thick alluvium near the source region contributed to the large amplitude and duration of strong ground motion in West Oakland.

Discussion

The results presented here indicate that scattering and vertical and lateral focusing of SH waves by the 3-D crustal structure of the SF Bay area contributed significantly to the ground motion variations. Horizontal bending and focusing of waves by the velocity contrast across the SAF together with the SH source radiation pattern can account for most of the observed azimuthal variation in the dominant, direct S+SmS displacement arrival in the period range of 1 to 8 sec. Increased coda amplitude and wave duration for sites around Oakland may be caused partially by scattering and focusing of sS and other surface reflection phases by deep basins under the Santa Clara Valley.

This modelling supports the argument that an increase in amplitudes recorded in San Francisco and Oakland is due in part to energy reflected off the Moho [Somerville and Yoshimura, 1990]. However, in agreement with the observations, the 3-D, broadband modelling predicts that significant amplification occurs only in a narrow epicentral range of about 10 km.

In this work, a close fit to the observations is obtained using a numerical algorithm which neglects energy from high angle reflections at major discontinuities such as the Moho and the SAF. Thus, there is a suggestion that in the SF Bay area these two boundaries may be gradational or rough at scale lengths corresponding to the wavelengths of 1 to 2 sec waves in the crust. Either of these conditions might be expected to suppress the coherence and strength of high angle reflections.

In the 3-D modelling, the synthesized wavefield becomes more complex and increasingly sensitive to details of the model parameterization as the wave frequency increases. However, the major conclusions reached here concerning wavepath distortion, focusing and scattering appear fairly robust, because they are controlled primarily by the gross model features.

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