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LONG-PERIOD (3 TO 10 S) GROUND MOTIONS IN AND AROUND THE LOS ANGELES BASIN DURING THE Mw7.2 EL MAYOR-CUCAPAH EARTHQUAKE OF APRIL 4, 2010

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ABSTRACT

Mw7.2 El Mayor-Cucapah earthquake of April 4, 2010 is the largest event providing a number of high-quality recordings to study long-period (3 to 10 s) ground motion amplification in and around the Los Angeles (LA) basin. By using 236 records from this event, spectral amplification factors of long-period ground motions were computed with respect to reference hard-rock sites. This evaluation has shown that: (1) At 8 and 10 s spectral periods, the maximum spectral amplification factor is 5 in the central part of the LA basin, where the Vs 3.2 and 2.8 km/s isosurfaces according to the SCEC Community Velocity Model (CVM-H 6.2) are the deepest; (2) In the San Gabriel valley, the maximum amplification factor is about 4 at 8, 6 and 4 s, and it is better correlated with the depths to the Vs 1.5 km/s isosurface than the Vs 3.2 and 2.8 km/s; (3) The largest amplification factor is 10 at 6 s in the western part of the LA basin (Manhattan Beach), where the CVM-H 6.2 fails to provide the feature of underground structure corresponding to the observed high amplification.

INTRODUCTION

The Mw7.2 El Mayor-Cucupah earthquake that occurred in northern Baja California on April 4, 2010 was the first event not only shaking southern California with a magnitude over 7 since the 1999 M_L7.1 Hector Mine earthquake, but also providing the largest number of recordings with long-period (3 to 10 s) content in the region. Graves and Aagaard (2011) used the ground motion data set of this event to test long-period ground motion simulations of scenario earthquakes. Using the same data set, we examined here the long-period ground motion amplification in the Los Angeles (LA) basin. The amplification of long-period ground motions could be critical for structures having long vibration periods; these structures are high-rise buildings, base-isolated buildings, long-span bridges and large-diameter oil tanks. In the LA basin, high-rise buildings are concentrated in downtown LA and Century City, and large-diameter oil tanks are clustered near Manhattan Beach in the western part of the basin and in Long Beach. During the Mw8.0 2003 Tokachi-oki, Japan earthquake, the long-period strong ground motions excited the liquid sloshing in large-diameter oil tanks, and caused severe damage, including tank fire and sinking of the floating roof, to many of them (Hatayama et al., 2007; Hatayama, 2008).

In the sections that follow, we first describe the ground motion data used in this study by comparing the number of records from the El Mayor-Cucapah earthquake with those from significant southern Californian earthquakes. This is followed by the distribution of the observed long-period PGV values to provide an overview of the long-period ground motions. We then show the spectral amplification factors of long-period ground motions in and around the LA basin with respect to selected hard-rock reference sites. Finally, the spectral amplification factors, calculated as the ratio of Fourier spectra of the recorded accelerograms with respect to the reference sites, are overlaid on a 3-D seismic velocity model of the LA basin for their correlation with the LA basin underground structure.

GROUND MOTION DATA

Most of the ground motions used in this study are obtained from the Center for Engineering Strong Motion Data (http://www.strongmotioncenter.org/). Records having a duration less than 60 s were not used, because they are unlikely to contain enough long-period content. Figure 1 shows the location of a total of 359 stations that recorded this event; the epicentral distance of these stations ranges from 20 to 400 km. In this study, data from 236 stations falling into the area denoted by the broken lines in Figure 1 are utilized to evaluate the spectral amplification factors for the LA basin. To emphasize that the El Mayor-Cucapah earthquake has provided the largest number of digital recordings in and around the LA basin, which makes evaluation of spatial variations of the basin amplification possible, the number of stations recording several past significant earthquakes in southern California are compared in Figure 2. It is apparent that fewer stations recorded the 1987 Whittier Narrows earthquake (Mw 5.9), the 1992 Landers earthquake (Mw 7.3), and the 1999 Hector Mine earthquake (Mw 7.1). The 1994 Mw 6.7 Northridge earthquake was recorded at more stations relative to these three past earthquakes, however most of the original seismograms of the Northridge earthquake were analog. Digital recordings are superior to study long period ground motion amplification due their higher resolution. Fourier acceleration spectrum decreases at long period, and thus the higher resolution should allow data at longer periods to be obtained than from analog recordings (Boore, 2005).

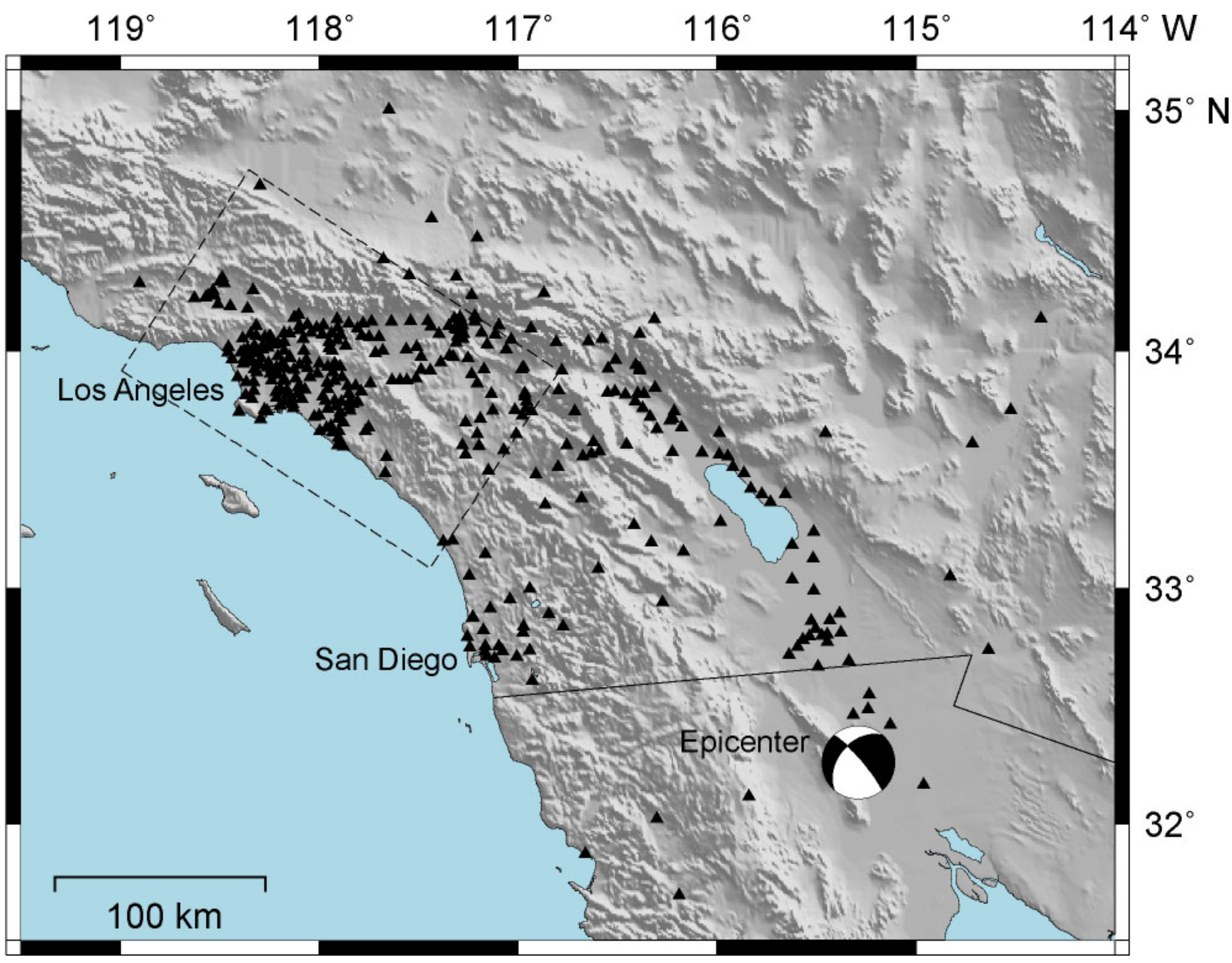

Fig 1. Strong ground motion stations whose records were used in this study (triangles). The beach ball shows the USGS centroid moment tensor solution (http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/ci14607652/ci14607652_cmt.php) with the parameters: epicentral location = 32.237°N, 115.083°W; depth = 10 km; Mo =8.5 x 1019 Nm; strike = 319°; dip = 82°; slip = -135°. The solid line denotes the U.S.-Mexico border. The Fourier spectra of recordings from stations falling into the area denoted by the broken lines are shown in Figure 6.

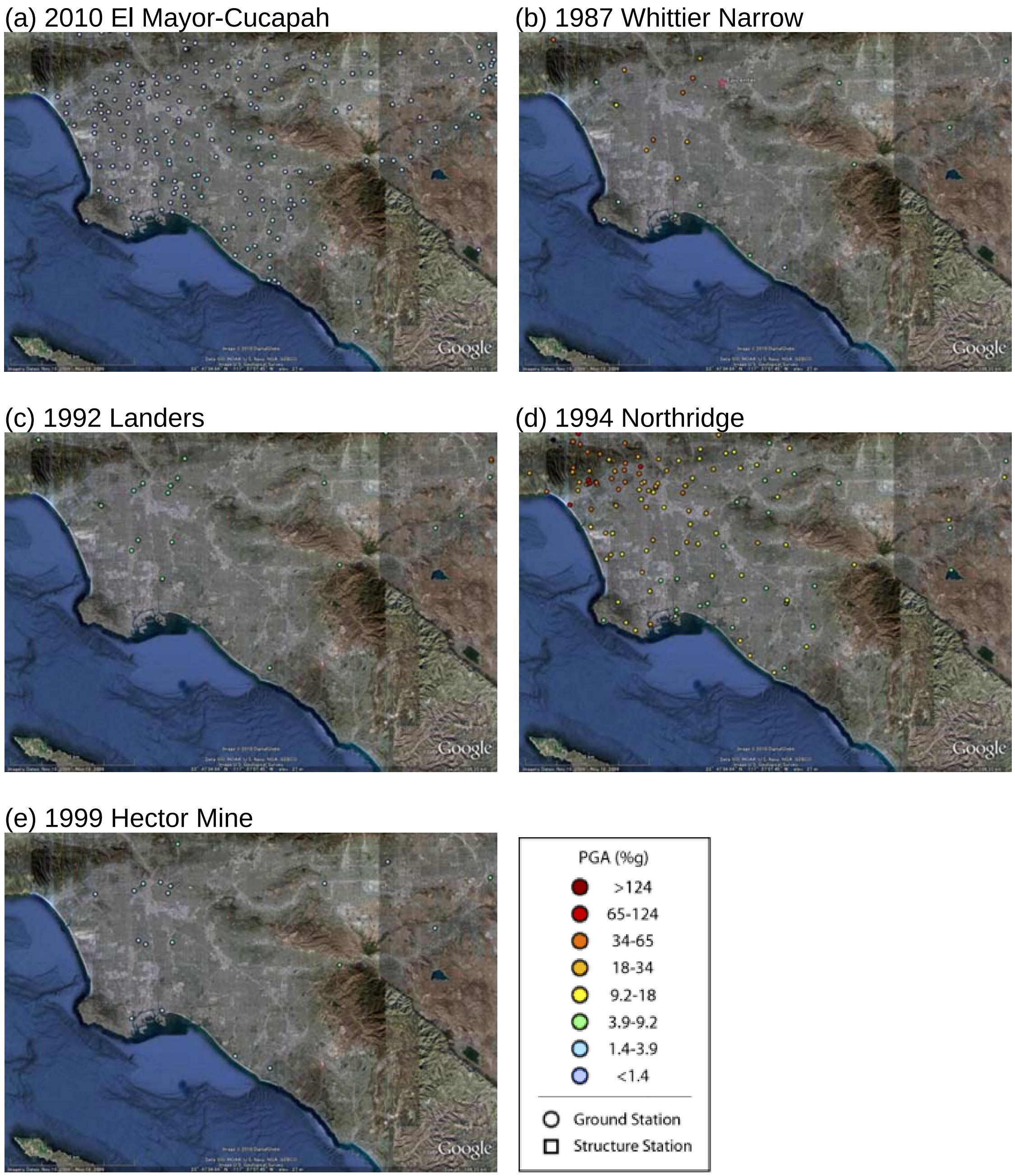

Fig. 2. Significant earthquakes in southern California since 1987, and recorded peak-ground accelerations (PGA); the 2010 El-Mayor Cucapah earthquake has the largest number of recordings.

OBSERVED GROUND VELOCITY

Figure 3 shows the PGV contours computed from the time series of the root mean squares of the two horizontal components of processed velocity records. These records were processed by bandpass filtering with a passing period range of 3 to 16 s. In the LA basin, higher PGV values with long periods, observed relative to its surrounding area, indicate strong amplification of long-period ground motions. Although, the LA basin is about 350 km away from the source, the PGV values were as high as at those stations located 150 km away from the epicenter. Also shown in Figure 3 are the higher PGV values observed in the San Bernardino valley. A detailed map of the PGV contours in and around the LA basin is shown next in Figure 4, which denotes the highest long-period PGV values (0.12 m/s) in the central part of the LA basin (around Downey) and the western part of the basin (around Manhattan Beach). Near Manhattan Beach, there are many large floating roof oil tanks with natural periods at several seconds. Relatively higher PGV values (~ 0.08 m/s) were also observed in the San Gabriel valley (around Baldwin Park).

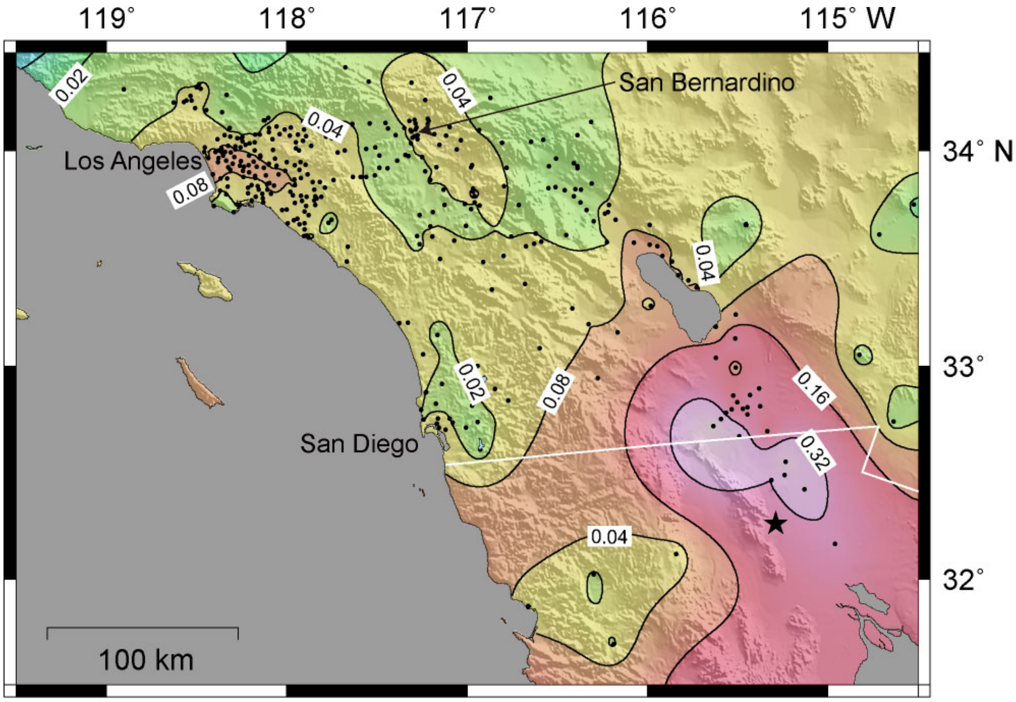

Fig. 3. Contour map of the PGV values (m/s) with a period range of 3 to 16 s observed in southern California during the El Mayor-Cucapah earthquake. The PGV values were read from the time series of the root mean squares of the two horizontal-component velocity records. The star and dots denote the location of epicenter and stations, respectively. The white solid line shows the U.S.-Mexico border.

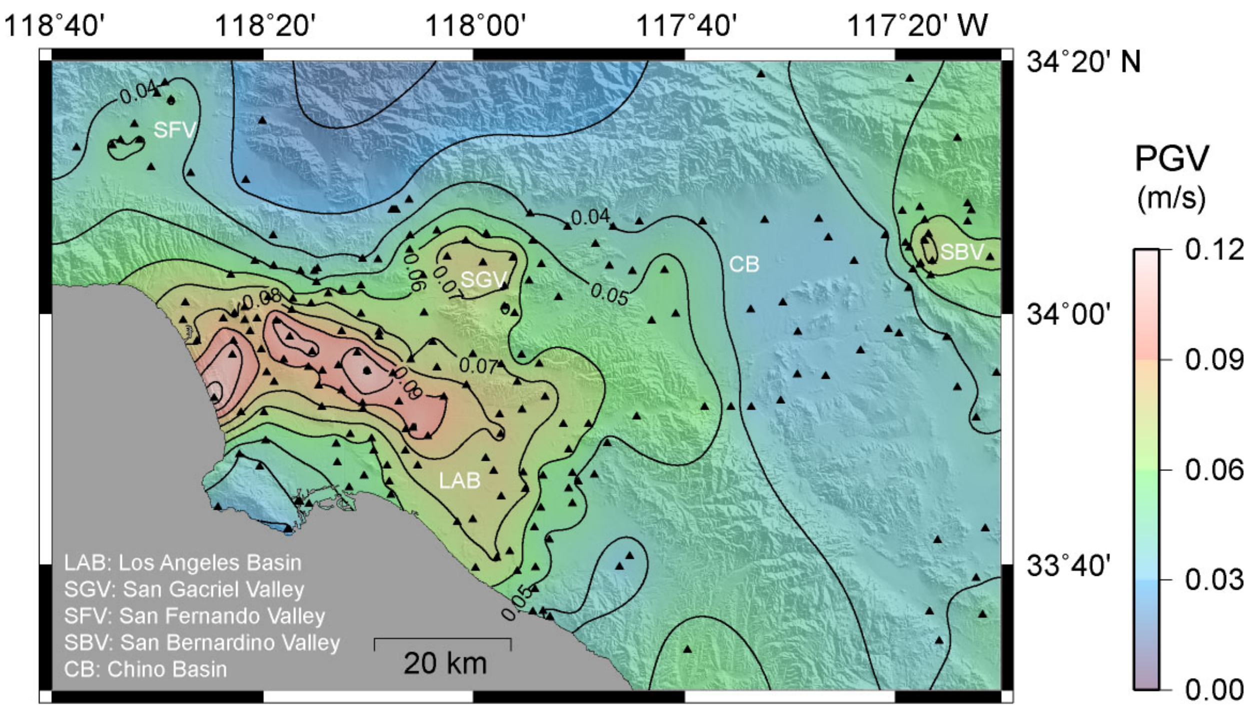

Fig. 4 Contour map of the PGV values (m/s) with a period range of 3 to 16 s in and around the Los Angeles (LA) basin observed during the El Mayor-Cucapah earthquake. The PGV values were read from the time series of the root mean squares of the two horizontal-component velocity records. The triangles denote the stations.

In order to examine the wave propagation within the LA basin, the N303°E- and N213°E-component velocity waveforms are plotted in Figure 5, where the N303°E and N213°E correspond to the radial and transverse directions, respectively, with respect to the one from the source to the basin. Figure 5 (c) identifies the location of corresponding stations along the line passing from the source to the central part of the basin. It is evident that the velocity wave train carrying the PGV values developed significantly with the growth of amplitudes and the elongation of duration as it propagated from the source-side edge (station STG) into the basin. The amplitudes of the wave train reached to a maximum around the central part of the basin (stations 14368 and 14175), and decreased after the wave train passed this location. This figure clearly demonstrates the evolution of long-period ground motions within the LA basin.

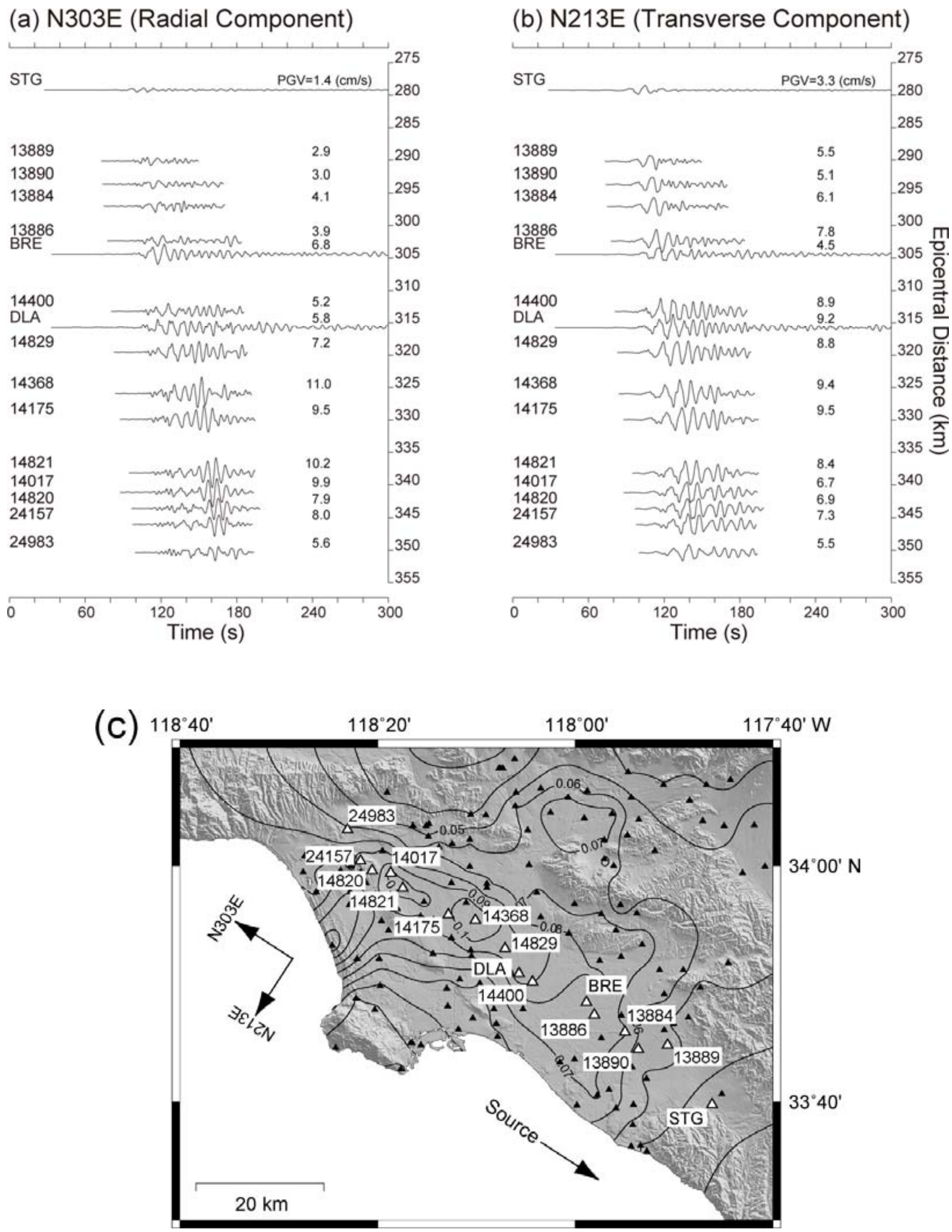

Fig. 5. Velocity waveforms in the LA basin. (a) N303°E-, (b) N213°E-component, (c) The stations whose records are plotted in (a) and (b) (white triangles), along with the same PGV contours (solid lines) and the same stations (black triangles) as shown in Figure 4. The N303°E and N213°E correspond to the radial and transverse directions, respectively, with respect to the one from the source to the basin. The waveforms were bandpass-filtered with a passing period range of 3 to 16 s.

OBSERVED AMPLIFICATION FACTORS OF FOURIER SPECTRA

Figure 6 shows the Fourier acceleration spectra from the 236 stations located in and around the LA basin (the gray and orange lines). The spectral ordinates plotted are the geometric mean of the two-horizontal-component spectra. At periods over 3 s, a group of spectral peaks between 5 and 9 s is evident, indicating that a number of recordings in and around the basin has dominant long-period components. The maximum peak, reaching 0.12 m/s at the station 14221 (Manhattan Beach), has the highest PGV value.

To evaluate the spectral amplification factors for the LA basin, a set of reference stations on hard-rock were selected first and then the spectral ratios at other stations with respect to those stations were computed. The reference stations were selected according to the following three criteria: (1) the record length should be long enough; (2) the basin underground structure model does not suggest that the station is located on sediments; (3) the observed spectral accelerations should be relatively small. Regarding criterion (1), we selected the stations with a record length longer than 300 s. Figure 7 shows the stations following criterion (1) by white triangles. To apply criterion (2), we calculated the surface-wave phase velocities by using the Southern California Earthquake Center Community Velocity Model (CVM-H 6.2), and then selected those stations from the sites where the surface-wave phase velocities are high enough that they cannot be considered to be located on sediments. The colors in Figure 7 show the phase velocities of the fundamental-mode Love waves at a period of 4 s. Because the CVM-H 6.2 is a continuous model, where the material parameters such as S-wave velocities vary continuously in both lateral and vertical directions, we assumed a 1-D layer-wise velocity model based on the CVM-H 6.2 for each site where the surface wave phase velocities were calculated. We supposed that the contour line of the phase velocity of around 2.2 km/s indicate the boundary between the sediment sites and the rock sites in this model, and we selected the stations from those sites where the phase velocity is mostly over 2.2 km/s. Applying criterion (3), we finally identified 17 reference stations denoted by the squares in Figure 7.

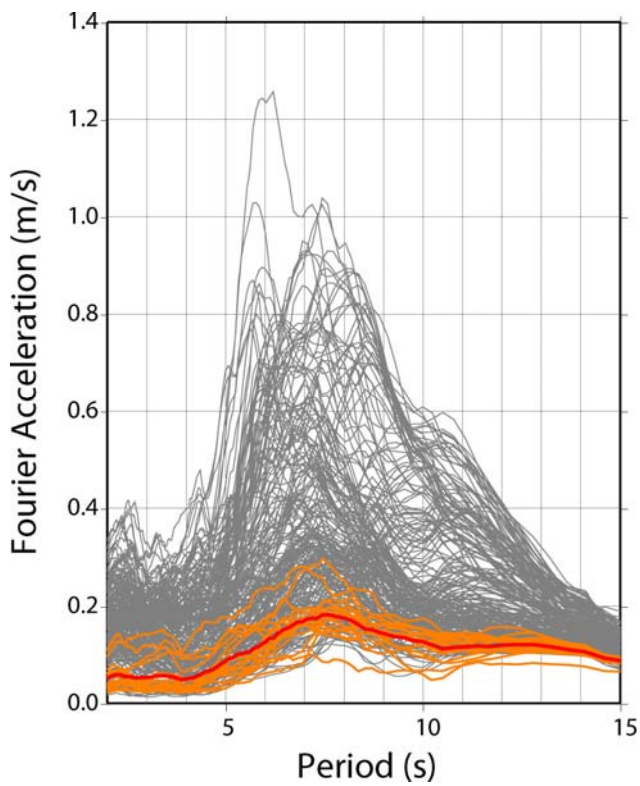

Fig. 6. Fourier acceleration spectra of processed ground motion data from the stations located in and around the LA basin (gray and orange lines). The stations plotted are the ones located in the area denoted by the broken line in Figure 1. The plotted spectral ordinates are the geometric means of the two-horizontal-component spectra. The orange lines represent the spectra from the reference stations. The red line denotes the arithmetic mean of the spectra from the reference stations.

The orange lines in Figure 6 represent the spectral ordinates from those 17 reference stations, and the red line shows their arithmetic-mean. We divided the Fourier spectra of all the stations by the arithmetic mean, and then obtained the amplification factors with respect to the reference hard-rock sites as shown in Figure 8. In the period range between 3 and 11 s, large amplification factors over 5 are observed at a number of stations, and high peaks appear at periods of 4 and 6 s. The maximum amplification factor exceeding 10 is observed at station 14221 (close to Manhattan Beach), where the highest Fourier acceleration spectral ordinate was observed (cf. Figure 6). The amplification factors decrease beyond 11 s.

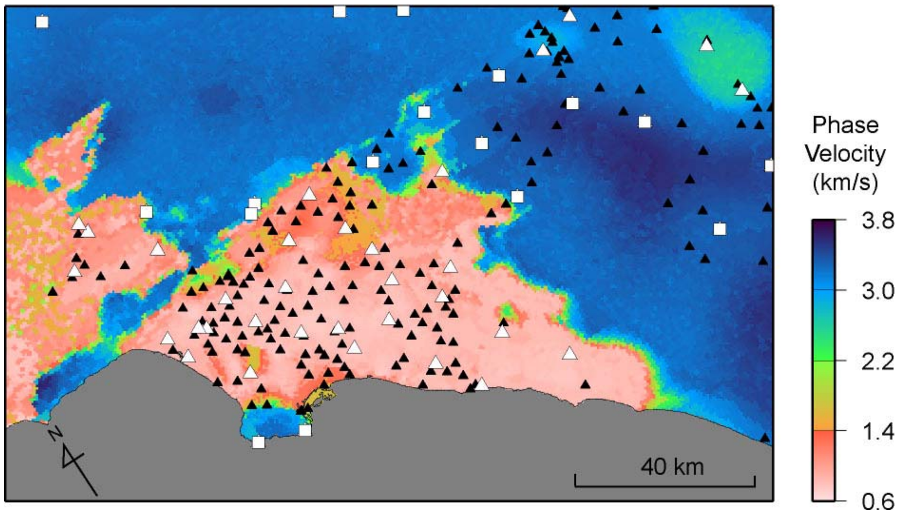

Fig. 7. Phase velocity of the fundamental-mode Love waves at a period of 4 s. The phase velocities were calculated based on the CVM-H 6.2. The black triangles denote all stations, and the white triangles denote those stations whose record length is longer than 300 s. The white squares show the reference stations with respect to which the spectral amplification factors were computed.

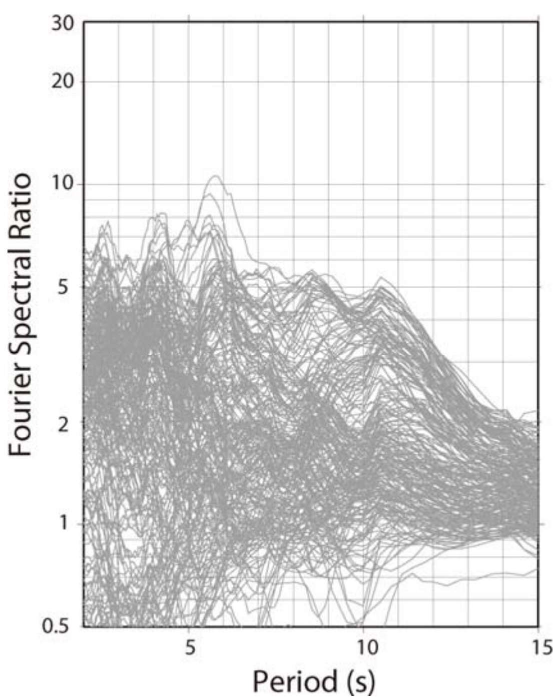

Fig. 8. Amplification factors of the Fourier spectra in and around the LA basin with respect to the reference hard-rock stations surrounding the basin. The amplification factors plotted are the ratio of the Fourier acceleration spectra (the gray lines in Figure 6) to the one averaged among the reference stations (the red line in Figure 6).

Figure 9 shows the maps of spectral amplification factors at 10, 8, 6 and 4 s. In these maps, the spectral amplification factors calculated for each station, shown in Figure 8, are interpolated geometrically without considering the underground structure. For a period of 10 s, the largest amplification factor of about 5 occurs in the central part of the LA basin. For a period of 8 s, larger amplification factors are evident in the San Gabriel valley and the central part of the LA basin. For a period of 6 s, the largest amplification is observed not in the central part of the LA basin but in the western part of the basin (Manhattan Beach), although the amplification in the central part is also large. Around Manhattan Beach, the ground motions with this period are amplified by a factor of 10. For a period of 4 s, the largest amplification factor of about 8 occurs in the central part of the LA basin.

In the San Gabriel valley, large amplification does not occur for a period of 10 s, but does for periods of 8, 6 and 4 s. In the central part of the LA basin, however, large amplification is observed for all these periods. This implies that the sediments in the San Gabriel valley are not as soft and/or thick as the ones in the central part of the LA basin. Looking at the south-eastern part of the LA basin, large amplification occurs only for a period of 4 s, indicating that the sediments in the south-eastern part of the LA basin are thinner and/or harder than the ones in the central part of the LA basin.

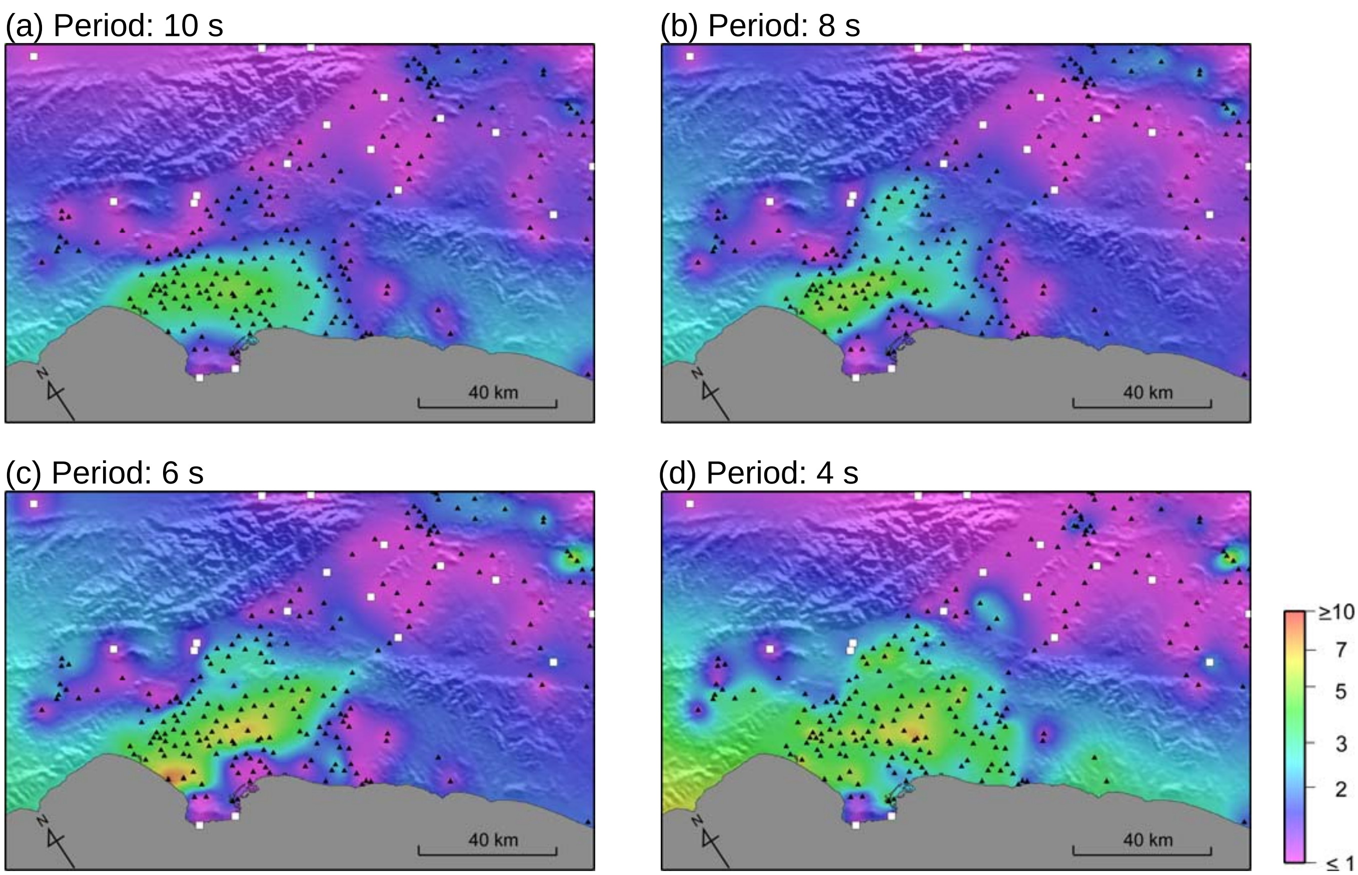

Fig. 9. Maps showing period-specific [(a) 10s, (b) 8 s, (c) 6 s, (d) 4 s] amplification factors in and around the LA basin with respect to the reference hard-rock stations surrounding the basin. The amplification factors depicted are the ratio of the Fourier acceleration spectra (the gray lines in Figure 6) to the one averaged among the reference stations (the red line in Figure 6).

RELATION BETWEEN OBSERVED AMPLIFICATION FACTORS AND BASIN UNDERGROUND STRUCTURE

To correlate the observed amplification factors with the LA basin underground structures, we superimposed the spectral amplification factors for the four periods on the maps of depths to isosurfaces above which the S-wave velocities are less than a given value. Figure 10 shows the contour lines of amplification factors for periods of 10, 8, 6 and 4 s overlaid on the maps of depths to the isosurfaces (colors) for S-wave velocities of 3.6, 3.2, 2.8, 2.0, 1.5 and 1.0 km/s. The contour lines depict the same amplification factors as shown in Figure 9. The depths to isosurfaces are from the CVM-H 6.2. The isosurface for S-wave velocities of 2.8 or 3.2 km/s can be regarded as the basement of the basin. Large amplification generally correlates well with the depths to the basement, as such large amplification occurs in the central part of the LA basin where the basement is the deepest, or where the sediments are the thickest. For periods of 10, 8 and 4 s, the largest amplification is observed in the central part of the basin, but for a period of 6 s, it occurs in the western part of the LA basin (around Manhattan Beach). Around Manhattan Beach, the basement is not very deep according to the CVM-H 6.2, which fails to explain the high amplifications in terms of the depth to the basement. In the San Gabriel valley, high amplifications are observed for periods of 8, 6 and 4 s (cf. Figure 9); in the valley however, the CVM-H 6.2 suggests that the basement is not as deep as in the central part of the LA basin. The high amplifications in the San Gabriel valley cannot be explained in terms of the depth to the basement.

Looking at the isosurface for an S-wave velocity of 1.5 km/s, we find that this surface is the deepest in the San Gabriel valley. In other words, the soft sediment with S-wave velocities under 1.5 km/s is thicker in the San Gabriel valley than in the LA basin. Therefore, the CVM-H 6.2 is able to explain the high amplification observed in the San Gabriel valley because of this soft and thick sediment that is localized in the shallower part beneath the ground surface. We can see an interesting contrast causing the high amplification between the central part of the LA basin and the San Gabriel valley; in the central part of the LA basin, the sediment is firm relative to the one in the San Gabriel valley, but it is thick enough that long-period components with periods from 4 to 10 s can be largely amplified. In the San Gabriel valley, however, the sediment is thinner, but it is soft that the long-period components with periods from 4 to 8 s can be largely amplified. If we considered only the thickness of the sediment in the LA basin and in the San Gabriel valley or the depth to the basement, we would fail in explaining the high amplification in the San Gabriel valley caused by the relatively soft sediments. This suggests that not only the total thickness of sediment or depth to the basin basement but also the detailed velocity profile of the sediment should be taken into account for more precise prediction of long-period ground motions.

In Manhattan Beach, the sediment with S-wave velocities under 1.5 km/s is not thick according to the CVM-H 6.2, therefore we could not find any feature of basin underground structure that can explain the observed high amplification in Manhattan Beach using the CVM-H 6.2.

According to the isosurfaces for S-wave velocities under 2.0 km/s, almost the same thickness of soft sediment is deposited in the south-eastern part of the LA basin as in the central part of the LA basin. However, except for 4 s, the large amplification is limited to the central part of the LA basin and does not extend to the south-eastern part; this is one of the major disagreements between the observations and the velocity model. In other words, the CVM-H 6.2 leads to overprediction of long-period ground motions in the south-eastern part of the LA basin. Graves and Aagaard (2011) pointed out that the CVM-H 6.2 significantly overpredicted the PGV values in their simulations particularly in this part of the LA basin where the simulated PGV values were generally two to three times larger than the observed ones from the El Mayor-Cucapah earthquake. We have also obtained similar results in our numerical simulations, which will be reported in another publication.

CONCLUSIONS

The Mw7.2 El Mayor-Cucapah earthquake of April 4, 2010 was recorded at 236 strong ground motion stations in and around the Los Angeles (LA) basin that is about 250 km away from the source. This earthquake is the largest event providing a large number of high-quality recordings to study spatial variation of long-period ground motion amplification in and around the LA basin. The PGV in the basin reached to 0.12 m/s within a period range of 3 to 16 s. The ground motions in and around the basin were dominated by long-period components; their Fourier acceleration spectra have a peak around 6 s. In this paper, spectral amplification factors of long-period ground motions in and around the LA basin were evaluated with respect to the 17 reference hard-rock sites surrounding the basin. This evaluation has led to the following conclusions:

1. At 8 and 10 s spectral periods, the maximum amplification factor is 5 in the central part of the LA basin, where the Vs 3.2 and 2.8 km/s isosurfaces according to the CVM-H 6.2 are the deepest in the basin.
2. In San Gabriel valley, the maximum amplification factor is 4 at periods of 8, 6 and 4 s, and it is better correlated with the depths to the Vs 1.5 km/s isosurface than the depths to the Vs 3.2 and 2.8 km/s.
3. The largest amplification factor is 10 at a period of 6 s in the western part of the LA basin (Manhattan Beach), where the CVM-H 6.2 failed to provide the feature of underground structures corresponding to this observed high amplification. Manhattan Beach houses many large-diameter oil tanks for which amplified ground motion may adversely affect their seismic performance during strong shaking.
4. We found a contrast causing the large ground motion amplification between the central part of the LA basin and San Gabriel valley. The large amplification in the central part of the LA basin is considered to be the result of firm but thick sediment relative to the San Gabriel valley, while the high amplification in the San Gabriel valley is considered to be the result of thin but soft sediment relative to the LA basin. This contrast suggests that detailed velocity profile of the sediment should be also considered in addition to the total thickness of sediment or depth to the basin basement for more precise prediction of long-period ground motions.

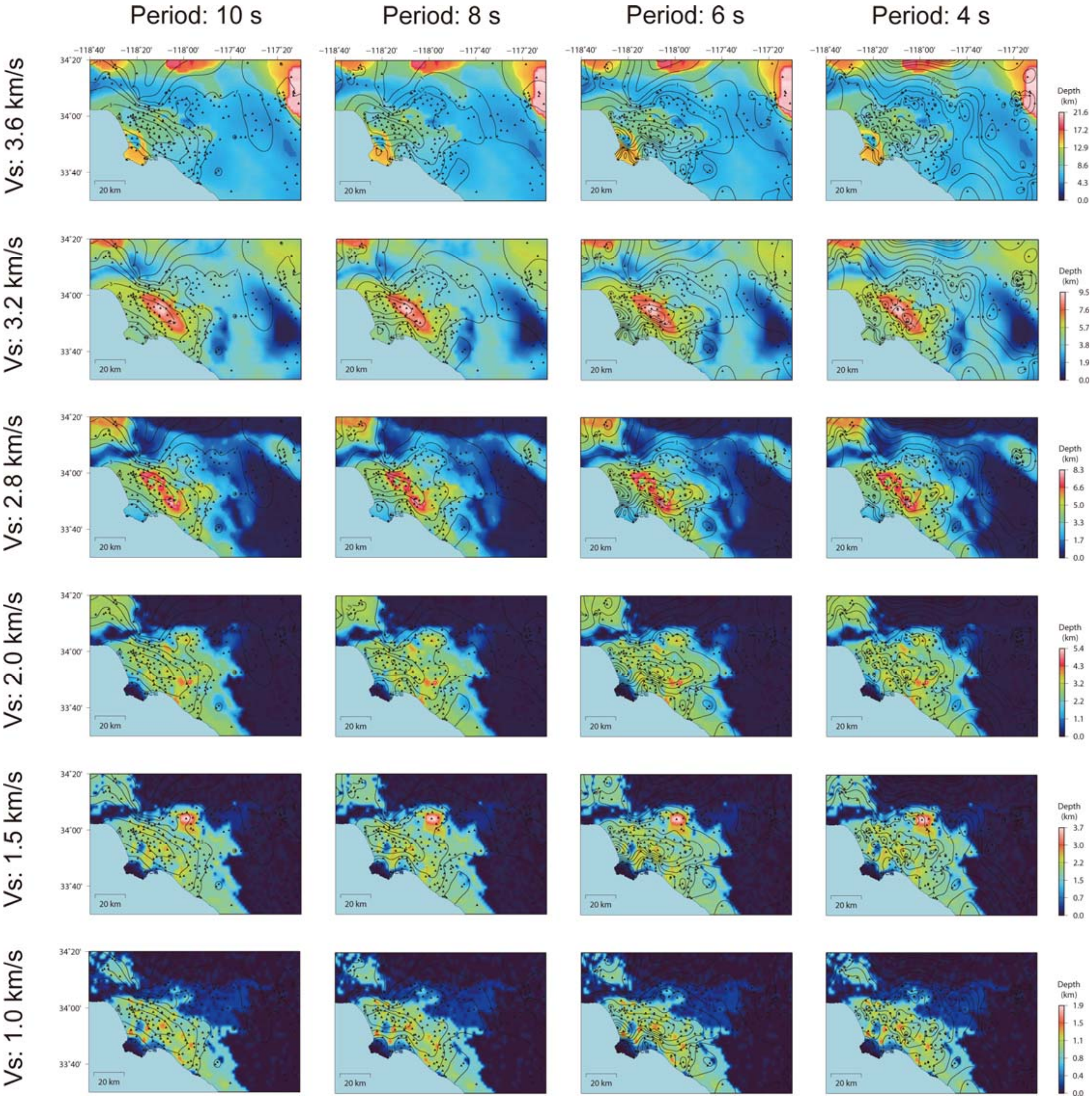

Fig. 10. Comparison of period-specific amplification factors (contour lines) with depths (colors) to isosurfaces above which the S-wave velocities are less than a given value. The contour lines of the amplification factors for periods of 10, 8, 6 and 4 s are superimposed onto the six maps showing depths to the isosurfaces above which S-wave velocities (Vs) are less than 3.6, 3.2, 2.8, 2.0, 1.5 and 1.0 km/s. The amplification factors are the ratio of the Fourier acceleration spectra (the gray lines in Figure 6) to the one averaged among the reference stations (the red line in Figure 6). The depths to the isosurfaces are after the CVM-H 6.2.

DATA AND RESOURCES

The Southern California Earthquake Center (SCEC) Community Velocity Model (CVM-H 6.2) is available online at *http://structure.harvard.edu/cvm-h/*. Most of the accelelograms were downloaded from the Center for Engineering Strong Motion Data (CESMD) at *http://www.strongmotioncenter.org/*. Maps showing the spectral amplification factors in and around the LA basin can be downloaded in high-resolution at *http://nsmp.wr.usgs.gov/ekalkan/Long_Period/index.html*.

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