Analysis of Azimuthal Variation in Amplitude Factors in Sherman Oaks and Santa Monica During the Northridge Earthquake Aftershock Sequence

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Abstract:

The Northridge earthquake caused unexpectedly high amounts of damage in Santa Monica and Sherman Oaks, two regions far removed from the rupture. My project was to investigate the cause of the anomalous high damage in both locations. Working with data from the Northridge Earthquake Aftershock Recording (NEAR) Experiment, a dependence of high amplitude areas upon source location was investigated. Analysis of data from the twenty-nine seismic stations placed in Santa Monica indicates that there is lens structure at depth which creates the enhanced damaged in the mid Santa Monica region. Using contour plots of amplitudes of the 29 stations in Santa Monica for each event indicated a movement of a "hot zone" where the amplitudes were much higher than the surrounding regions. Tracing rays through a moveable lens from the hypocenter of an event to the surface allows one to pinpoint the location of lens. The finite nature of the lens indicates that the high damage in Santa Monica was dependent upon the location of the main shock. As evidenced from aftershocks in this data set, an earthquake of similar size in a slightly different location would most likely not reproduce this damage pattern. Sherman Oaks produced two regions of concentrated amplification, but no systematic azimuthal pattern as seen in Santa Monica was detected.

Introduction:

The 6.7 M_w earthquake that occurred in Northridge the seventeenth of January 1994 caused anomalous damage patterns throughout the Los Angeles Metropolitan Area. Aside from the regions that immediately surround the rupture zone, the communities of Sherman oaks and Santa Monica experienced some of the highest damage concentrations of any regions. The neighboring regions of both Sherman Oaks and Santa Monica faced considerably less damage. Being that there is no systematic difference in building types, codes, or earthquake resistance between these localities and their surrounding regions, there must be other factors contributing to the damage pattern (Gao, 1996).

I've worked on this research for the six months prior to this internship and plan to continue working on it until some sort of resolution can be reached. It has always been a goal of mine not only to understand earthquakes and how they cause massive amounts of damage, but I also want to share this understanding and disseminate any knowledge, e.g., a seismic hazard model, to prevent public danger due to seismic activity.

Experimental Methods and Procedure:

Between March 29 and April 16, 1994, UCLA deployed 98 seismic stations to record aftershocks of the Northridge Earthquake. They were strategically placed in two clusters (Santa Monica and Sherman Oaks) and along two north/south profiles of approximately 35 km running from the Los Angeles Basin, through the Santa Monica Mountains, to the northern edge of the San Fernando Valley. Over 1500 individual events were recorded by the stations, but a final 32 were selected. All of the waveform data is available from the SCEC Data Center. To obtain maximum P and S Wave amplitudes this data was further processed, by Shangxing Gao, into two separate data files per event. There was a data file for the combination of the two horizontal components (for the S-Wave) and separate vertical component (for the P-Wave) data file. In each data file the station location, station number, and maximum velocity (for the horizontal component, the maximum horizontal velocity was calculated by summing the squares of the North/South and East/West components and taking the square root of it) were recorded. Of these 32 data file sets, there were 4 that were corrupted and therefore unusable, leaving 28 events with which to investigate the damage pattern in Sherman Oaks and Santa Monica.

Chronological Procedure:

Work with Gao's Data for Sherman Oaks

(All work done is with the horizontal components, unless otherwise specified)

The work performed was in search of a pattern which would indicate some form of structure which would create the damage patterns observed. Work on Sherman Oaks began as an investigation into whether there was some form of azimuthal dependence based on source location as Liu (1998) suggested. To do this all the data within Sherman Oaks was normalized for each event with respect to the mean of each event. The average normalized amplitude for each station was then calculated and plotted using GMT and Matlab using amplitude maps (plots which indicate amplitude by an increase/decrease in size of circles located at fixed points). This data was also plotted by hand on top of a damage map (Tan, 1995) to the Northridge Earthquake. To find source location effects, each event had to be plotted separately. A movie format was used to search for some kind of azimuthal dependence. Each event was plotted in its own amplitude map, which were played as stop frames in order with respect to their azimuth to a fixed point in Sherman Oaks. Furthermore, I went on to create something I called a SO-Ratio, which is a ratio between the region of high damage/amplitude versus those regions of lesser damage/amplitude. I also calculated a 3-Ratio (a ratio between the three high stations in Sherman Oaks versus the rest of Sherman Oaks). Both the SO-Ratio and the 3-Ratio were plotted as amplitude maps. I plotted a northerly trending cross section of event depth and latitude versus SO-Ratio. Contour plots, as described in the Santa Monica Methods Section, were also used for analysis in Sherman Oaks.

Work with Gao's Data for Santa Monica

Similar methods as those used for Sherman Oaks, were employed in the work on Santa Monica. The data was normalized with respect to the mean or median for each event, and a movie of the same style as those used in Sherman Oaks was used. The average amplitudes for each station in Santa Monica were plotted in an amplitude map. Again, a ratio was used to test for source location dependency. The ratio was between a region of typically high amplitudes and high damage during the main shock and a region which experienced far lesser amplitudes and damage. This ratio was called the S-Ratio and was comprised of a region similar to the region which both Gao, et al (1996) and Liu (1998) used. The S-Ratio proved to be imprecise for our data, focusing on a fixed region instead of a region which is dynamic, moving counter to movements of the source location.

Regions of high amplitude, instead of point locations, were needed to better visualize the data. This led me to use contour maps, whose variation in color indicates variation in amplitude. The contour plot indicates "hot zones", areas which have high amplitudes relative to the rest of the surrounding regions, a good method for Santa Monica which had very sharp boundaries between areas of extreme damage and areas of inconsequential damage after the main shock. The data for each event for the Santa Monica region (again using normalized amplitude (normalized with respect to the median value)) was contoured. With these 28 plots, I made a movie that plays these plots in order (from West to East) according to their azimuth with respect to a fixed point in Santa Monica.

Using the simplified assumption that the lens was merely a sphere, I began to work on locating the lens. With the contour movie, I located the approximate Latitude and Longitude of the lens. I varied the location of the lens (with respect to its projection onto the surface) and then traced rays from the epicenter through the lens and beyond. Moving the lens around allowed me to attempt to hit most of the regions of amplification with the direct ray. With the approximate location of the lens established, I traced rays from the hypocenter through the lens. To approximate its depth, I chose a point on the surface that I wanted the ray to hit (the center of the region of amplification). Using trigonometry I found the approximate lens depth.

Work with Waveform Data

I first downloaded waveform data from the SCEC DC. Before working on the data I attempted to locate the instrument response information. In this process I emailed Steve Gao (administrator of the experiment), Aaron Martin (he calibrated the instruments), and Hong Liu (wrote her dissertation on this data). While waiting for instrument response data, I investigated the Sherman Oaks triad's waveforms. I made a log of the waveforms from all 28 events for the 3 stations in the triad. The log included: relative amplitudes, similar arrival times, similar waveforms, relative frequencies/dominant frequencies, presence of noise/ringing, and appearance of extra phases. I focused especially on the waveform similarity, using the assumption that because the stations were within 100m of each other their waveforms should be nearly identical. Furthermore from these logs, I made plots of source location versus presence of noise.

Challenges:

Using GMT, Matlab, PQL, SAC, and coding in Fortran 90, I've learned numerous data analysis and visualization techniques. Learning SAC, GMT, PQL, and how to better use Matlab were a challenge for me. I would guess that this slowed the data analysis greatly, but now near the end of my internship I am a much more productive and faster worker with all of these programs. Although SAC and GMT are not the easiest of programs, I learned how to manipulate the software to produce results that fitted my needs. I did this by consulting previous work and examples, consulting others who work in the Seismology Lab, web resources, and software manuals.

Another major challenge I faced and overcome is fear of using and reading literature on the subject. As an undergraduate student, I believed that since articles in scientific journals are written by PhD's they would have too much complex math for me to understand. Occasionally they do have very complex math, but typically I've found that merely taking one's time with any journal article will allow the article to lend itself to you so you can understand. I have found scientific journals to be a great resource, noting what others have and haven't done and attempting to reproduce their results.

Cooperation with others is key in the scientific community. To accomplish something, numerous people need to help you. This includes being willing to learn and accept, as well as challenge, other scientists' ideas. I have learned to work with numerous people in the department, and even outside the department, when I need help and I am always willing to aid in anyone else's problems. Occasionally I've encountered situations when other scientists couldn't help me with my work. When I encountered such situations, I typically found alternate ways to go about what I intended to do. On one occasion, though, when a data set was unavailable, I was forced to abandon a particular aspect of my project.

Results and Conclusions:

In Sherman Oaks, the results are not nearly as simple as had been hoped. Using a method of contouring data by cubic interpolation, we had hoped to find a zone of concentrated amplification that moved with respect to movements of the source, similar to the effect that Gao observed in 1996 in Santa Monica. We used simple ray tracing from the epicenter to a fixed point in Sherman Oaks to identify movement of a concentrated amplified region. The ray tracing proved ineffective and showed that there is no simple systematic movement of a region of enhanced amplitude with respect to ray path.

The study of Sherman Oaks did produce two regions of fairly consistent enhanced amplitude (Figure 1).

Figure 1

One region is found at the base of the north edge of the Santa Monica Mountains. This region was recorded by a triad of stations. The stations were are all within a block of each other on the same street. These stations, although typically having amplitudes approximately twice as large as the surrounding regions, have no apparent dependence on source location, nor do they typify the response of the rest of Sherman Oaks to the events. This was found using the 3-Ratio, the average amplitude of the three stations in the triad divided by the average amplitude in the rest of Sherman Oaks. The 3-Ratio was calculated for the 17 events which all 3 triad stations (c10, c14, c15) recorded. The amplification ratio ranged from a minimum of only 1.12 to 3.29, with a mean of 2.01, standard deviation of 0.70, and a median of 1.96. The 3-Ratio didn't typify the region's amplitudes as it varies greatly, but not systematically with source location (Figure 2).

Figure 2

Furthermore, a source location dependence within the triad was not found. By calculating a ratio between the amplitude measured at each triad station divided by the mean of those three amplitudes, for all 17 events that all 3 triad stations recorded, we found there was no systematic variation in station amplitudes. This was plotted in a bar graph and played in a movie that showed frames in order (from West to East) according to azimuth. This movie indicates that one station (c10) during one event had an amplitude of approximately four times greater than the other two stations but surrounding events didn't produce results of similar amplitudes/amplitude ratios. This anomaly led me to check the waveform data. The waveform data indicated that the station was ringing prior to the P arrival, and it appears that the P and S arrivals merely made the seismometer resonate more. For obvious reasons, the data for this event at station c10 was no longer considered in further calculations.

This led to a more in depth study of the waveform data. As would be expected for stations within 100m of each other, all three stations produced very similar waveforms. In the logging of the waveform data, 3 more events on c10 and 7 events on c14 were found to have unreasonable amounts of noise and ringing. Fortunately, the seven noisy events on c14 were not recorded by all three stations in the triad, so these didn't affect any previous work. No real conclusions can be drawn from the triad region, the results did not lend themselves to locating a consistent pattern, and a pattern due to variation in source location is unlikely.

The other region of high amplitude in the Sherman Oaks area, was located in the Santa Monica Mountains. This region appears to have some sort of azimuthal dependence, getting largest when the events are coming from the north. It does, though, seem to be dominated by one station, which could possibly create erroneous data. This source location dependence wasn't discovered until very recently, due to errors in a program that calculates azimuths. Due to this, little work has been done on this region, but it will soon be further explored.

On the whole, Sherman Oaks is not easily explainable. There is no simple model where a region on concentrated amplification is in a constant location or moving with respect to source location, making a lens or lens-like model unlikely. Possible explanations for the amplitudes in Sherman Oaks include: fault-plane solutions, polarity dependence, or frequency dependence.

Santa Monica, on the other hand is producing some very promising results. After using the same method of ray tracing as was used for the Sherman Oaks data, we have since converted all the data, for Santa Monica, from Latitude/Longitude format to kilometers and re-plotted it. To convert the data, the origin was relocated to 33.8ºN and 119ºW and then degrees lat/long were converted to kilometers by multiplying the difference in longitude by 92.1806 and the difference in latitude by 111.1949. When this data is plotted, the region of enhanced amplitudes appears to have a dependence upon source location, thus supporting the lens model for Santa Monica. With the preliminary location of the lens (lat,lon,dep) found using methods previously describeed, I traced rays from the hypocenter through the lens. Many rays were within one half mile of the desired location, but some were unreasonably far away. The south dipping fault plane created this effect; events that were further north, and thus further from the lens, were also shallower. The focal points for these events would thus be projected to be very distant.

At this point, one must consider that shallow events (deeper than 12km) are typically going to propagate downwards and then back up towards the lens, so the direct ray would produce erroneous results. To address this problem, the 6 events that were 12km or deeper were used in further work. A depth for the lens for each event was then found, and the mean was computed. Using this mean depth, the rays were retraced. Of the 6 events that were deep enough to be used, 5 showed good focusing (Figure 3a-f).

Figure 3a

Figure 3b

Figure 3c

Figure 3d

Figure 3e

Figure 3f

The surface point coincided within one half kilometer of the desired location for these 5. To better locate the lens, I have begun work on placing a Gaussian surface centered at the surface contact of a direct ray.

Applications:

This project aims to resolve the anomalous damage patterns. With a model that explains the reasons why there were such sharp boundaries and anomalous locations of high damage zones, seismic hazard could be better assessed in the future. Knowing the seismic hazard would allow for changing of building codes or even the prevention of construction, similar to the 1971 act that prohibits building on a fault that has been active within the last 11,000 years, for those regions which have a high risk of seismic damage.

If the lens model that I am working on locating does prove to exist, this would be a breakthrough for geology in Southern California. This discovery would aid in making a seismic hazard model and given source locations, one could estimate the location of maximized damage. Furthermore, this could serve as an example for future research and seismic hazard analysis throughout the world, as underground lenses are capable of wreaking major havoc, as evidenced by the extreme damage experienced in the Mid-Santa Monica region following the 1994 Northridge earthquake.

Reference:

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Figure Captions:

Figure 1: Contour Plot of Average Amplitudes In Sherman Oaks

Figure 2: Contour Plot of 3-Ratio plotted versus Epicentral Location

Figures 3a-f: Contour Plots of the Six Events Which Had a Source Depth of at Least 12km; Blue line in the lower left indicates approximate location of the coastline; Bent line coming in from the East indicates approximate location of the Santa Monica Fault; Pink 'X' Indicates approximate location of Lens; Red Diamond Indicates Relative distance of source from lens; Black Diamond indicates the point on the surface where a direct ray would hit the surface, Title (EQ#….) Indicates Day, Time of Event (dddhhmm)

Table 1: Date, Location, and Magnitude of Events Used in This Study

Table 1:
Events Used In This Study

Day_Time_Latitude_Longitude_Depth(km)_Magnitude__90_1136_34.293_-118.636_13.8_2.2_90_2027_34.268_-118.479_9.8_2.2__92_1218_34.304_-118.488_9.2_2__93_909_34.339_-118.616_12.9_2.6__93_1427_34.287_-118.437_5.9_1.8__93_1828_34.235_-118.605_17.9_2.7__94_519_34.304_-118.444_7.9_2.2_94_1006_34.306_-118.442_7.7_2.2__94_1205_34.317_-118.471_7.2_1.9__95_547_34.235_-118.528_13.6_2__96_918_34.347_-118.552_4.6_2.9__96_1051_34.247_-118.493_10.2_2__97_419_34.331_-118.487_5.9_3.5_97_440_34.33_-118.489_5.7_2.6__97_955_34.296_-118.665_7.7_2.4__98_1345_34.325_-118.47_8_2.3__98_1436_34.266_-118.49_9.9_2.4__98_1715_34.307_-118.469_8.1_2.8__99_1229_34.285_-118.696_12.1_2.5_99_1515_34.293_-118.485_9_2.3__99_2118_34.276_-118.455_10.4_2.5__100_829_34.221_-118.517_18_1.7__100_1601_34.336_-118.502_7.1_2.6__102_1127_34.261_-118.491_11.8_1.8__103_157_34.343_-118.614_10.4_3.2_103_1118_34.365_-118.531_2_2.8__103_1529_34.291_-118.499_7.3_2.6__104_642_34.323_-118.57_3.4_2.5__