PRELIMINARY ANALYSIS FOR EVALUATION OF LOCAL SITE EFFECTS IN LIMA CITY, PERU FROM STRONG GROUND MOTION DATA BY THE SPECTRAL INVERSION METHOD

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ABSTRACT

The present study applies the spectral inversion method, proposed by Iwata and Irikura (1986, 1988), to separate the source, propagation path, and local site effects from observed strong motion records in the frequency range from 0.5 to 10 Hz for the analyses of the relationship between the local subsurface conditions and the local site amplifications in some areas of Lima city, Peru. The analyzed data are S-wave portions of accelerograms in horizontal components observed at 5 stations for 11 events recorded along the Pacific coast of Lima city. These events are superficial and intermediate earthquakes with local magnitudes (ML) from 4.0 to 5.7 and with hypocentral distances from 40 to 180 km. From the spectral inversion, solutions for source spectra, inelasticity factor of propagation path for S-wave (Q_S-value), and site amplification factor at each site are obtained. The factors of site amplification *Gj(f)* obtained in the present study are compared with the results obtained by Cabrejos (2009) for stations CSM, CAL, MOL and CDLCIP employing the standard spectral ratio (SSR) method, which support our results especially at frequencies below 5 Hz. Q_S-value obtained shows frequency dependency of the form $Q_S(f)=80.4f^{0.63}$. In addition, the influence of non-linearity on the site response is evaluated during the Pisco earthquake which it is concluded that nonlinear response of the soils was not detected at acceleration levels below 115.2 gal (the maximum peak ground acceleration recorded in Lima city). The study also proposed relationships between the amplifications with average S-wave velocity in top 30 meters of the S-wave profiles for some stations at each frequency.

Keywords: Spectral Inversion Method, Lima city, Site Amplification, Q_S-value, Pisco earthquake.

1. INTRODUCTION

Lima city, Peru has been continuously affected by several earthquakes that have caused slight, considerable and severe damages. This city is prone to this kind of natural disaster due to the subduction of the Nazca plate underbeneath the South American plate. In the last 60 years, according to the earthquake catalog compiled by the Geophysical Institute of Peru (IGP), the city of Lima has been subjected to earthquakes with the biggest Mw of 8.1. It is during the earthquake of October 3, 1974 (Mw=8.1) that a few areas outside of Lima center were severely damaged, such as La Molina and Callao – La Punta (Repetto et al. 1980). Works described by Husid et al. (1977), Espinoza et al. (1977) and Repetto et al. (1980) refer that these areas were affected by the influence of local subsurface conditions.

The spectral inversion proposed by Iwata and Irikura (1986) is applied in this study for estimating local site effects in some areas of Lima city. This approach utilizes the direct S-waves.

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2. DATA & DATA PROCESSING

The analyzed data are the S-wave portions of 30 accelerograms from 11 events observed at 5 strong ground motion recording stations (CSM, CAL, MOL, CDLCIP and LMO stations). The seismic events are superficial and intermediate earthquakes (depth < 140 km) from 40 to 180 km in hypocentral distance. The observed peak ground accelerations (PGA) range from 5.5 to 109.0 gal. Besides, the ML is ranging from 4.0 to 5.7. Table 1 exhibits the geological period at each station and the average shear-wave velocity to 30 meters (Vs_{30}) for some stations.

Table 1. Surface geology of the stations and Vs_{30}.

Code Station	Geological period	Geology	Vs_{30} (m/s)
CSM	Quaternary	Alluvial	533.23
CAL	Quaternary	Alluvial	104.79
MOL	Quaternary	Alluvial	---
CDLCIP	Quaternary	Alluvial	565.82
LMO	Cretaceous	Santa Rosa Granodiorite	---

The S-wave portions of two horizontal components (NS and EW) of seismic ground motions are analyzed. To recognize the onset time of S-wave, particle motion plots and Husid plots are realized. After the onset time of S-wave has been determined, the S-wave portion of accelerograms (*to*) is extracted. A cosine-type tapered data-window has been applied to S-wave portion to improve the problem of finite record length using the same criterion took by Takemura et al. (1990). Fourier acceleration amplitude spectra of two horizontal components are computed and summed vectorially. Before using the inversion scheme, the Fourier acceleration amplitude spectra were smoothed with seventeen-point moving average method.

3. METHOD OF ANALYSIS

3.1. Spectral Inversion

One of the big advantages of the spectral inversion is separated source, propagation path, and local site effects from observed seismic waves to examine the relation between local site effects and surface geology (Takemura et al. 1991). In the present study, we adopt the inversion method proposed by Iwata and Irikura (1986, 1988). They assume the quality factor of the wave propagation is independent from the path and only depends on frequency (i.e., Q=Q(f)). Then the observed S-wave Fourier amplitude spectrum is expressed by

$$O_{ij}(f) = S_i(f)G_j(f)R_{ij}^{-1}\exp\left(-\pi R_{ij} f \Big/ Q_s(f)Vs\right) \tag{1}$$

where, $O_{ij}(f)$, observed S-wave Fourier amplitude spectrum of *i*-th event at *j*-th station; $Si(f)$, source amplitude spectrum of *i*-th event; $G_j(f)$, factor of site amplification at *j*-th station; R_{ij}, hypocentral distance between *i*-th event and *j*-th station; $Q_S(f)$, average Q_S-value along the wave propagation path; V_S, average S-wave velocity along the wave propagation path (=3.7 km/s) (Kato et al. 1992).

To separate source, path, and site effects simultaneously from spectra of observed seismic waves as described hereafter, the first step is to take the logarithm of Eq. (1) to obtain simultaneous logarithmic equations in the form.

$$\log O_{ij}(f) = \log S_i(f) + \log G_j(f) - (\pi f / Q_S(f)V_S)R_{ij} \tag{2}$$

These equations have unknown parameters of I (source terms) + J (site amplification terms) + 1 (Q_S – value), which can be determined by the least squares method from IxJ data for $O_{ij}(f)$ at each frequency. However, there is still one unconstrained degree of freedom. Therefore, a constraint condition is needed to determine the unknown parameters.

As a result of this need, Iwata and Irikura (1988) set up a constraint conditions that the site amplification factor must be 2 or over considering the free surface amplification. The constraint condition taking account is explained in the following subchapter.

3.2. Choice of Reference Site

The CDLCIP accelerometer station is used as a constraint condition for the inversion analysis, and the station is located on a shallow, dense to very dense coarse gravel. So, for inversion the factor of site amplification at a reference station CDLCIP is assumed to be the same as that of theoretical amplification of S-wave. This constraint condition represents the free surface amplification effect.

4. RESULTS AND DISCUSSION

4.1. Site Amplification Factor and Standard Spectral Ratio

Figure 1 shows the site amplification factor obtained by the spectral inversion method $G_j(f)$ represented by the solid blue line. The $G_j(f)$ is compared with the standard spectral ratio (SSR) obtained by Cabrejos (2009) represented by the solid green line in Figure 1. Cabrejos (2009) estimated the amplifications of ground motions for the same stations evaluated in this study. Since the spectral ratio is not necessary to know the S-wave velocity structure of the reference site, he used the LMO station, a station located on intrusive rock as reference site.

Figure 1 explains that there is a good agreement between both results, especially in low frequencies, which support our results although different techniques for estimating site response have been applied and different reference sites have been used, as previously mentioned.

It is noted from Figure 1, that $G_j(f)$ has large values at frequencies above 5 Hz compared with the SSR values, because the amplification at the reference site (CDLCIP station) becomes large in this frequency range.

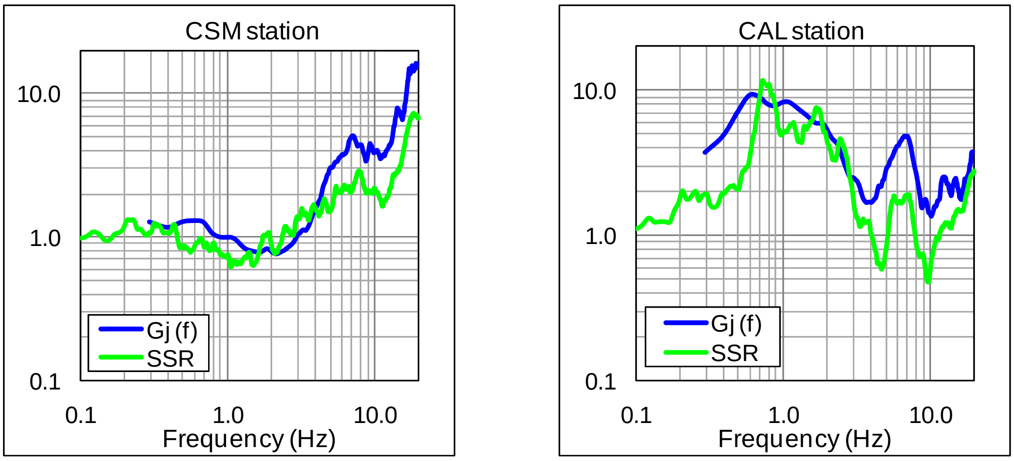


Figure 1. Comparison of site response with different techniques. The *Gj(f)* and the SSR are represented by the blue and green lines, respectively (Continue).

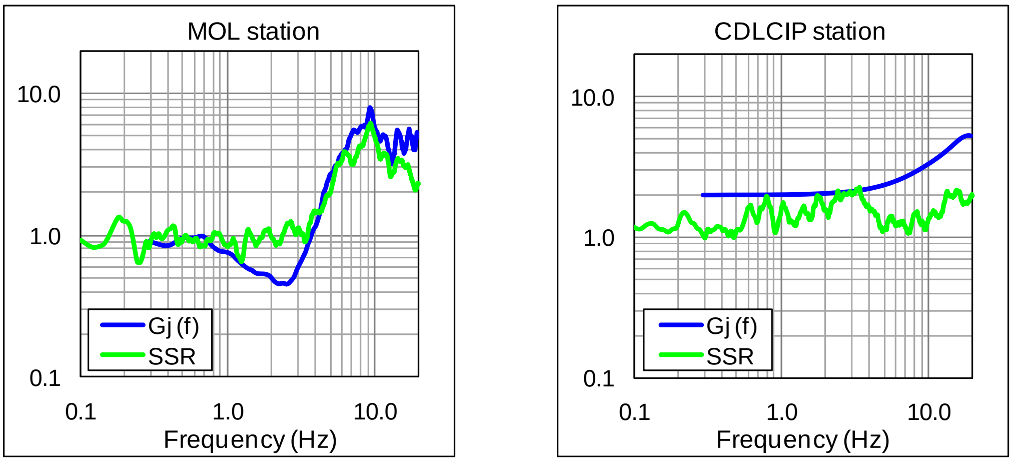


Figure 1. Comparison of site response with different techniques. The *Gj(f)* and the SSR are represented by the blue and green lines, respectively.

4.2 Surface Geology and Local Surface Conditions

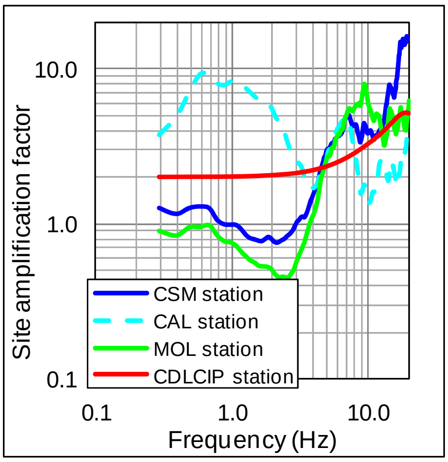


Figure 2. Comparison of $G_j(f)$ for CSM, CAL, MOL and CDLCIP stations.

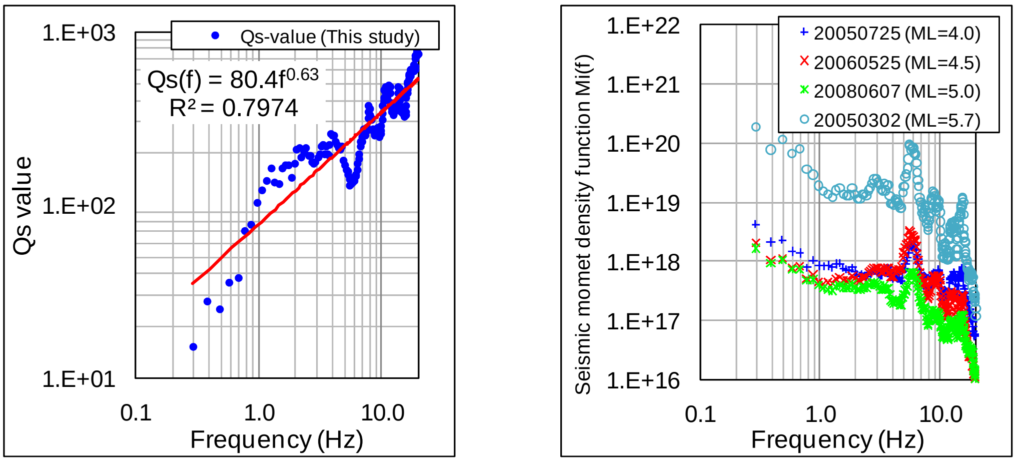
According Table 1, CSM, CAL, MOL and CDLCIP stations are located on Quaternary alluvial deposits. Figure 2 shows the comparison of site amplification factors $G_j(f)$ for these four stations. It is noted that $G_j(f)$ for CSM, MOL and CDLCIP stations have larger amplifications at frequencies above 4 Hz (represented by solids lines), but nevertheless a considerable variation is observed in CAL station (represented by a broken line), located also in Quaternary deposits, in which the amplification values are much higher at frequencies below 4 Hz.

According to the soil type map of Lima city developed by CISMID in 2003 with the support of the recognized Peruvian geologist Alberto Martinez Vargas (Aguilar 2005), CSM, CDLCIP and MOL stations are located on alluvial gravel overlying the denser Lima Conglomerate. Alluvial gravel covers a large portion of Lima city, and presents a good geomechanic behavior (Aguilar 2005). On the other hand, CAL station is located on soft soil, which is conformed by a 5 to 15 m thick layer of soft saturated clay and organic soil (Aguilar 2005).

4.3 Source Spectra and Q_S-values

The source acceleration amplitude spectra are obtained from the inversion technique. It is divided over ω^2 to obtain the source displacement spectra and to replace in the equation proposed by Kanamori (1972) to get the seismic moment density *M(f)*. The shear-wave velocity of 4.0 km/s, density of 3.0 g/cm^3, and the average point-source radiation coefficient of 0.6 are assumed. Figure 3 (a) shows examples of the source spectra for events with ML from 4.0 to 5.7. Figure 3 (b) shows the Q_S-values obtained by the inversion and a model of $Q_S(f)=80.4f^{0.63}$ which fits the results.

In Figure 3 (a), there is a conspicuous trough in the frequency range between 5 and 6 Hz. As known, higher frequency values provide close surface depth data whereas lower frequency values shed light on deep sections of the ground. In the analyzed data, there is not enough data in the shallow part that can provide information in higher frequencies. In Figure 3 (b), a conspicuous peak in the same frequency range is also observed, and this occurs because the Q_S-value along the wave propagation path influences the form of the source spectrum.



(a) (b)

Figure 3 (a) Examples of seismic moment density functions. (b) Q_S-values.

4.4 Analysis of Non-linearity of the Soil

On August 15, 2007, a strong offshore earthquake hit the coast of Central Peru. This earthquake, also known as the Pisco earthquake, had a magnitude of 8.0 Mw (USGS http://earthquake.usgs.gov/eqcenter/eqinthenews/2007/us2007gbcv/). The maximum peak ground acceleration recorded in Lima city was of 115.2 gal in La Molina district (Bernal and Tavera 2007). In the present study, the influence of non-linearity on the site response is evaluated during the Pisco earthquake.

From the spectral inversion method, Q_S-value and $G_j(f)$ at reference site are already known. To analyze the influence of the soil's non-linearity on the $G_j(f)$ at CSM, CAL, MOL and LMO stations, first the source amplitude spectrum $S_i(f)$ of the Pisco earthquake is calculated applying Eq. (1). After that, Eq. (3) is applied to get the site amplification factor during this strong ground motion where another amplification factor $G_{ij}(f)$ is newly defined for avoiding confusion

$$G_{ij}(f)=\frac{O_{ij}(f)R_{ij}}{S_i(f)\exp\left(-\pi R_{ij}f/Q_S(f)V_S\right)} \tag{3}$$

where, $O_{ij}(f)$ is obtained by the vectorial of two observed horizontal components, $S_i(f)$ is the source spectrum and $Q_S(f)$ is the Q_S-value (Takemura et al. 1991).

No systematic change is found for the difference between $G_j(f)$ obtained by the inversion analysis and $G_{ij}(f)$ for this strong ground motion, namely there is not found explicit evidence of strong-motion deamplifications, accompanied by changes in resonant frequencies (Beresnev and Wen 1996). Thus, it is concluded that nonlinear response of the soils was not detected at acceleration levels below 115.2 gal during the Pisco earthquake.

4.5 Average S-wave Velocity and Site Amplification

The site amplifications are compared with average S-wave velocity in top 30 meters of the S-wave profiles (Vs_{30}) for CSM, CAL and CDLCIP stations, and proposed linear relations between them at each frequency (0.5 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz, 10.0 Hz and 20.0 Hz). We know that Vs_{30} is only available for a few stations so far, but we want to know the possible relationships between Vs_{30} and SAF, and to improve our results for the future researches in the same area of interest.

These relationships illustrate that Vs_{30} can be considered as a good indicator to estimate site amplification for frequencies less than 10.0 Hz; however for frequencies above 10.0 Hz is observed the trendline can not fit the calculated data well because the data are dispersive.

5. CONCLUSIONS

From the spectral inversion method, the site amplification factors for some areas of Lima city were evaluated from strong motion records at 5 accelerometers. Out of the five stations used in this study, four stations (CSM, CAL, MOL and CDLCIP stations) are located on alluvial soil deposits belonging to the Quaternary Holocene. It is noted that $G_j(f)$ for CSM, MOL and CDLCIP stations have larger amplifications at frequencies above 4 Hz compared with CAL station, in which the amplification values are much higher at frequencies below 4 Hz. These differences between CAL station and other stations are due to the local subsurface conditions. CSM, CDLCIP and MOL stations are located on alluvial gravel overlying the denser Lima Conglomerate and CAL station is located on soft soil.

The obtained results were confirmed with the results obtained by Cabrejos (2009) employing the Standard Spectral Ratio (SSR) in his study. There is a good agreement between both results, especially at frequencies below 5 Hz, although different techniques for estimating site response have been applied and different reference sites have been used.

About the Q_S-value obtained in this study, there is a conspicuous trough in the frequency range between 5 and 6 Hz because there is not enough data in the shallow part that can provide information in higher frequencies. So it is recommendable that we should reanalyze these results with new data so that we should be able to get and improve our results.

The influence of non-linearity on the site response is evaluated during the Pisco earthquake, and it is concluded that nonlinear response of the soil was not detected at acceleration levels below 115.2 gal during this strong ground motion.

Relationship between site amplifications obtained from spectral inversion and Vs30 are proposed for frequencies 0.5 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz, 10.0 Hz and 20.0 Hz using the few data that it is currently available. So it is strongly recommendable to get information of another accelerometer stations located in Lima city to estimate better relationships for evaluating the local site effect.

AKNOWLEDGEMENT

I am really indebted to Dr. Toshiaki YOKOI – Building Research Institute – who sincerely advised and guided me during this work. I thank Ms. Elsie Benedit Jaimin, Mr. Roberto Armando Torres Corredor and Mr. Hussam Eldein Zaineh Adel Wasfieh whose comments improved the paper, and Mr. Jonathan Cabrejos Hurtado for providing information personally collected.

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