Characterization of Representative Site Profiles in PMA through Ambient Vibration Measurement

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Abstract

With a significant increase in the number of high-rise buildings in the Perth Metropolitan Area (PMA) in recent years due to the rapid population growth, the seismic vulnerability of PMA increased substantially. Some previous studies indicated that Perth Basin might amplify the bedrock motion by more than 10 times at some frequencies and some sites. However, due to the limited geological information available for the Perth Basin, it is not possible to perform reliable and quantitative site response analyses to estimate seismic motions on ground surface. Hence, more detailed studies on site characterization and amplification are necessary. In this study, Site response evaluation in PMA is performed using two microtremor measurements, namely SPAC technique and H/V method. The clonal selection algorithm (CSA) is introduced to perform direct inversion of SPAC curves to determine the soil profiles of the representative PMA sites. Using the simulated bedrock motion based on the predicted response spectrum as input, the site response is analysed and the response spectra on soil sites are estimated. They are then compared with the respective design spectrum defined in the Australian Earthquake Loading Code. It is found that the current code may underestimate the spectral acceleration at shallow soil sites in the period range of 0.5 to 3.0 sec.

Keyword: site profile, ambient vibration measurement, clonal selection algorithm

1. INTRODUCTION

Perth is the largest city in Western Australia and home to three-quarters of the state's residents. In recent decades, there have been a lot of earthquake activities just east of Perth in an area known as the South-West Seismic Zone. Amplification of seismic waves in Perth sedimentary basin has been observed in previous seismic events. For example, panic to occupants and minor damage in some of the middle-rise buildings in downtown Perth were caused by the Great Indonesian Earthquake of August 17, 1977, with an epicentral distance of 2000 km. Gaull *et al.* (1995) presented an initial analysis of the site amplification effects of the Perth Basin using microtremor spectral ratios, namely horizontal-to-vertical (H/V) method. They constructed microzonation maps of Perth from microtremor spectral ratios and found that spectral ratios correlated well with geological subsurface layers and provided a tentative assessment of Perth's ground motion. Gaull *et al.* (1995) indicated that the Perth Basin might amplify the bedrock motion by 2 to 10 times. Based on microtremor spectral ratios, more detailed study of site effect was performed in Gaull (2003). The resonance periods throughout the regolith of Perth Metropolitan Area (PMA) were identified using H/V method. McPherson and Jones (2006) investigated regolith thickness, and natural period for PMA by using borehole data, seismic cone penetrometer test (SCPT) data and microtremor data. They divided PMA into 4 soil classes based on the soil properties. By comparing with the shear wave velocity estimated in Gaull (2003) and that in their study, McPherson and Jones (2006) concluded that overall the shear wave velocity estimates presented by Gaull (2003) do not compare favourably with the measured shear wave velocities and should be used with caution in relation to earthquake studies. Furthermore, many studies, Jarpe *et al*. (1989) and Schnabel (1973), have indicated that soil responses will be nonlinear under strong shaking. These studies also showed that the amplification factor derived from microtremor may not give a reliable prediction of strong ground motion response at some sites.

The potential amplification of ground motion in Perth Basin and the limitation of previous site response studies for PMA provide the motivation to perform more detailed study of site responses across the PMA. In this study, a site survey is performed around Perth using two microtremor methods, namely the spatial autocorrelation (SPAC) method and the H/V method. The clonal selection algorithm (CSA) is adopted to perform direct inversion of SPAC curves to determine the soil profiles of the study sites. The shear-wave velocity profiles vs. depth for the top hundred metres of 16 sites are determined using the SPAC method. These shear-wave velocity profiles are compared to available soil profile information obtained in previous studies, i.e. Asten *et al.* (2003). The site vibration frequencies are also estimated using the derived soil profiles and compared with the H/V measurements. Favourable comparisons are obtained. Using the derived shear-wave velocity profiles, detailed site response analyses are carried out to estimate motions on ground surface. The response spectra of ground motions on rock site and on soil sites are derived from the calculated ground motion time histories, and are compared with the respective design spectrum defined in the Australian Earthquake Loading Code (AS1170.4-2007). Discussions on adequacy of the design spectrum are made.

2. SITE TESTING AND ESTIMATION OF SUBSURFACE STRUCTURES

During December 2007 and May 2008, site survey was performed in 16 sites around PMA as shown in Figure 1. The soil profiles of the study sites are estimated using SPAC method and inversion technique of CSA. The SPAC method as described by Okada (2003) with the basic theory developed by Aki (1957) is to extract the Rayleigh wave from observed microtremors and calculate the spatial autocorrelation function of dispersing waves in the observed microtremor array. The phase velocity of subsurface structure is related to SPAC function by Eq (1) which is given as:

$$SPAC(f,r) = J_0(2\pi fr / c(f)) \tag{1}$$

where $SPAC(f,r)$ is the spatial autocorrelation coefficient, f is frequency in Hz, $c(f)$ is the phase velocity, r is the radius of array station separation and J_0 is the Bessel function of the first kind of zero order. These velocities form a phase-velocity dispersion curve, usually considered to be the dispersion curve for fundamental-mode of Rayleigh waves. It is assumed that the spatial autocorrelation coefficient $SPAC(f, r)$, as shown in Eq.(3), is expressed as a function of the subsurface parameters using Eq. (1) and Eq. (2).

$$c = c(f, v_p, v_s, h, \rho) \tag{2}$$

$$SPAC(f,r) = SPAC(f, v, v_s, h, \rho) \tag{3}$$

in which v and v_s are Poisson's ratio and shear wave velocity, v_p is P-wave velocity, h and ρ are layer thickness and density, respectively. The subsurface parameters are estimated by fitting the observed SPAC coherency spectrum directly with a modelled SPAC spectrum using CSA technique. More detailed information about SPAC methodology and CSA technique can be seen in the previous studies (i.e., Aki, 1957, Okada, 2003, Asten *et al.*, 2003 and Liang *et al.*, 2008a).

The deployment consisted of two circular arrays with respective radii of 48 and 59 m. As can be seen in Figure 2, each circular array consisted of three accelerometers, with an additional accelerometer at the center station. Vertical ground accelerations were recorded at 500 samples /sec. Two sets of data were recorded with approximately 15 minutes in each set. In processing the data, each 15-minutes recording is divided into five windows. Synchronized records of 3 minutes long were taken out and baseline corrected and transformed to the frequency domain. A matrix of coherencies between the recorded vertical ground vibrations at the center station and one of the stations on the inner or out ring is constructed. The coherencies calculated from ground vibrations in five 3-minutes time windows in both sets of the recorded data are averaged to get assemble mean of the calculated coherencies. A total of 10 coherency functions are averaged to reduce the effect of random noises.

Figure 1. Location of sites in PMA investigated in this study

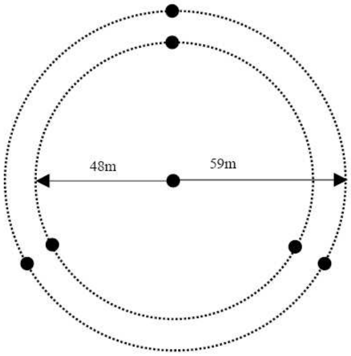

Figure 2. Circular array with 7 measurement locations in field measurements

3. SITE RESPONSE EVALUATION

Using the CSA technique, the subsurface parameters of the study sites are estimated. According to the shear-wave velocity vs. depth profiles, detailed site response analyses with consideration of soil nonlinear behaviour are carried out using SHAKE2000 (Ordóñez, 2000) with the simulated rock motion as input. Owing to lack of nonlinear soil properties in PMA, those derived by Seed and Idriss (1970), Sun et al. (1988) and Schnabel (1973) are used in this study to model the nonlinear soil modulus value and damping ratio for sand, clay and rock, respectively. The input bed rock motion is simulated to match the response spectrum for a 475-year return period defined by Liang *et al.* (2008b). The natural frequency of a given site is also estimated using H/V technique. Due to the length restrictions, only one site, S4, with detailed site survey processing is reported in this paper.

3.1 S4 (Warwick)

The SPAC function as defined by Eq.1 is used to produce a curve to be fitted to the Bessel function of the first kind of zero order which yields the SPAC coefficient. The observed SPAC function for the arrays with radius of 59m and 48m and the curve fitting are shown in Figure 3. As shown, the theoretical function fits the observed SPAC function well in the range of 0.3Hz to 5.0Hz and is a close match above 5.0Hz. The identified shear wave velocity profile for this site is given in Figure 4. It should be noted that Asten, *et al.* (2003) also derived the shear wave velocity profile of this site using the SPAC method. As shown, the three shear wave velocity profiles match reasonably well with each other except in the first layer with a depth of 10m, where this study predicts a significantly lower shear wave velocity than that derived from Asten *et al.* (2003) and

SCPT data. The lower shear wave velocity prediction for the first layer is probably because of different testing location and other uncertainties. Based on the identified shear wave velocity, we suggest the bedrock interface locates at approximately 50m. As the natural site period is greater than 0.6s and the depths of soil exceed 40m, according to the suggested site classifications in Australian code (AS 1170.4-2007), this site is a deep soil site with a soil layer depth of about 50m.

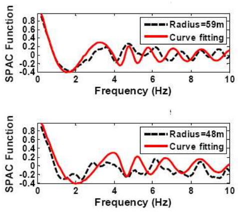

Figure 3. S4: Measured and modelled SPAC function

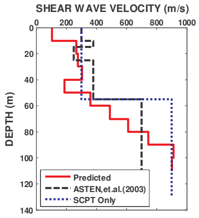

Figure 4. Identified Shear-wave velocity profile of S4

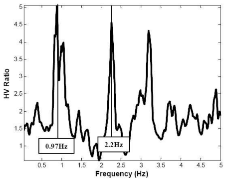

Figure 5. H/V spectrum of S4

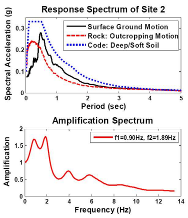

Figure 6. Response spectrum and amplification spectrum of S4

H/V spectrum, calculated response spectrum and amplification spectrum of S4 are shown in Figure 5 and 6. As shown, the first two peaks of H/V ratio occur at 0.97Hz and 2.2Hz, respectively, which correspond to the 1st and 2nd modal frequency of S4. They are reasonably consistent with the peaks at 0.9Hz and 1.89Hz in amplification spectrum. Figure 6 reveals that the current code spectral values for deep soil site are conservative for this site.

3.2 Site Response of PMA

Following the procedure in above example, the site responses of the 16 sites are evaluated. Their natural periods are listed in Table 1.

Table 1. The estimated regolith thickness and natural period for the study sites

Study Sites	Regolith Thickness (m)	Natural Period (sec)	Study Sites	Regolith Thickness (m)	Natural Period (sec)
S1	30	1.47	S9	70	3.70
S2	20	1.47	S10	100	7.14
S3	20	0.62	S11	50	1.64
S4	50	1.11	S12	20	1.35
S5	80	3.70	S13	80	1.64
S6	20	1.64	S14	80	2.94
S7	30	0.62	S15	20	1.85
S8	10	1.06	S16	30	1.85

Figure 7 shows the calculated response spectra of surface ground motions at these sites. As shown, significant deamplification of outcrop motion at periods below 1sec is observed in most sites classified as very soft soil site or deep soil site, which results in the code spectra conservative at these sites for period below 1sec. The spectral acceleration corresponding to the deep soil sites and very soft soil sites lie well below the design spectra specified in Australian code. However, for shallow soil sites, the current code underestimates the spectrum from S3 and S7 at periods between 0.5sec and 1sec, and undervalues the spectrum from S2, S8, S12 and S15 at periods between 1sec and 3sec. This implies that the shallow soil site spectrum in the current code should be used with caution in structure design.

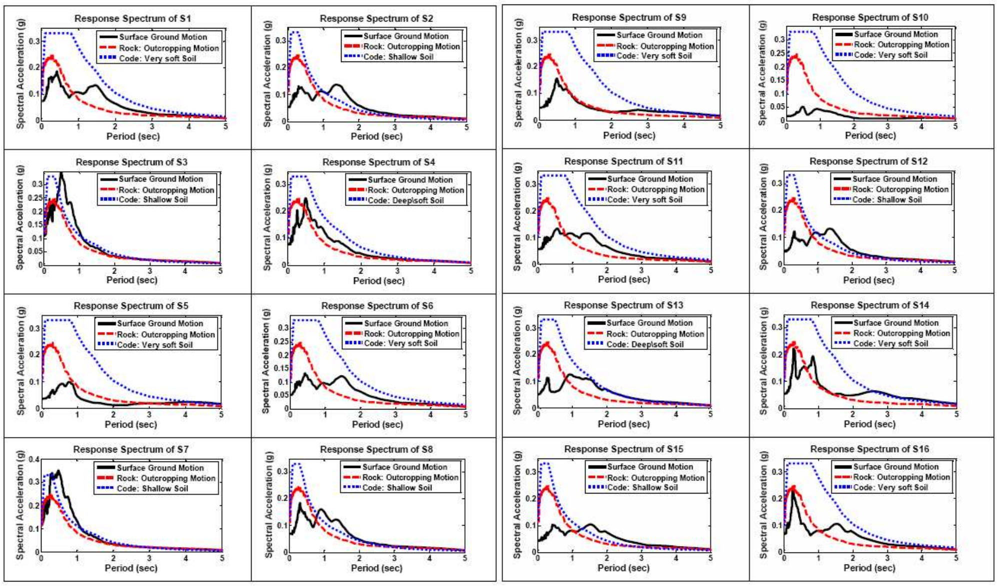

Figure 7. 475-year return period response spectra of the study sites

3.3 Seismic microzonation maps for PMA

As shown from Figure 8 to Figure 13, the natural period and the response spectrum corresponding to the 475-year return period earthquake at frequencies of 0.2, 0.5, 1.0, 2.0 and 3.0sec for the study sites are interpolated and plotted onto maps of PMA. Commenting on each of these contour maps in order, there appear to be two regions in the central and northwest of the mapped area which have long natural periods. These long period features have been known to follow some deep geological feature and provide a predicted boundary of Perth Basin. This observation is consistent with Gaull (1995) in which this region has greatest amplification at long period and is identified as the central basin.

It can be seen that the greatest spectral accelerations for the 0.2sec map in Figure 9 are located at central north and southwest corners of the mapped area, which is due to the short natural period at S7 and S3. The lower value contours of the spectral acceleration run throughout the Perth Basin region, indicating significant deamplification of outcrop motion at short periods. The 0.5sec contours, as seen in Figure 10, have a similar shape to those in Figure 9 except that the lower value contours of the spectral acceleration run throughout not only the Perth Basin region, but also the east regions. The 1sec contours is shown in Figure 11. Again, the general features of the contours on this map are similar to those in Figure 9 and 10. The regions with relatively high value contours of the spectral acceleration located at central north and southwest corners of the mapped area are observed.

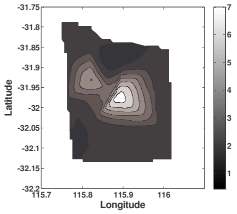

Figure 8. Natural period contours

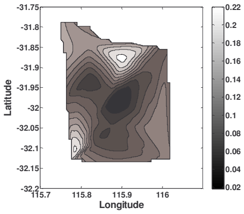

Figure 9. Spectral acceleration (g) contours at 0.2 sec

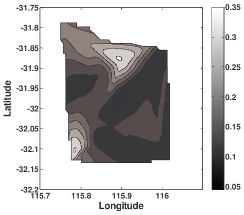

Figure 10. Spectral acceleration (g) contours at 0.5 sec

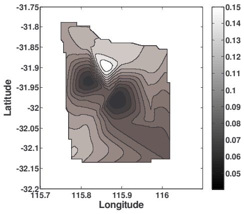

Figure 11. Spectral acceleration (g) contours at 1.0 sec

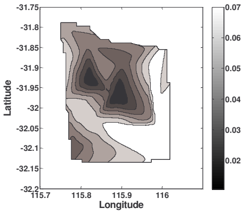

Figure 12. Spectral acceleration (g) contours at 2.0 sec

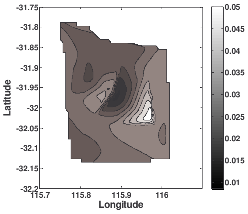

Figure 13 Spectral acceleration (g) contours at 3.0 sec

The high value contours of spectral acceleration associated with long period, starting from the 2sec map (Figure 12), are observed in east of PMA and south of the Perth city. It is possible that the natural periods of around 2sec are recorded in these regions (S13, S14, S15 and S16). The 3sec contour map in Figure 13 shows that the high value contours appear in east of area and a small region around the centre of PMA. According to the above analysis, very soft soil layers or deep soil layers run throughout most of PMA. This might be the reason that amplification of seismic waves at low frequencies in Perth sedimentary basin has been observed in previous seismic events. However, this observation should be further verified as more geology information comes to hand.

4. CONCLUSION

In this paper, a site characterization is performed in PMA. Comparing the calculated response spectra corresponding to the 475-year return period earthquake to that specified in the design code finds that the current code may underestimate the spectral acceleration predicted from SHAKE2000 models at shallow soil sites in period range of 0.5 to 3.0 sec, indicating that the design response spectrum of shallow soil site in the code should be used with caution in structure design. Seismic microzonation maps show that long period (more than 1.0 sec) sites run throughout most of PMA, which results in significant deamplification of bedrock motion at high frequency range. Most of CBD of Perth is located at long natural period sites.

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