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PREDICTION OF SEISMIC GROUND MOTION IN PERTH WESTERN AUSTRALIA FOR ENGINEERING APPLICATION

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SUMMARY

Perth is located in the south west of Western Australia (SWWA) and is the capital city of Western Australia. It is one of the few large cities in Australia with a population of more than 1.5 million. Seismic risk in Western Australia is relatively low since population is small and scattered and large-magnitude earthquakes are infrequent. However, the 1968 Meckering earthquake of M_L 6.9 and epicentral distance 130 km caused moderate damage in Perth Metropolitan Area (PMA), for example Lay [1] and Everingham [2]. Since then much effort has been spent on seismic risk analysis of PMA.

With rapid population increase in the last three decades in PMA, many high-rise RC frame structures have been constructed as compared to 1968, at that time most structures were of low-rise masonry type. The seismic vulnerability of PMA is clearly different and an analysis of seismic risk is deemed necessary.

Because only a very limited number of strong ground motion records are available in Western Australia, there is no reliable attenuation model to predict ground motion spectrum or time history, other than some attenuation models for peak ground acceleration and peak ground velocity derived based largely on small magnitude events recorded in Western Australia Gaull [3]. Gaull and his co-authors [4] also spent effort on investigating the site amplification effects of the Perth Basin using microtremor spectral ratios, and found that the Perth Basin might amplify the bedrock motion by 2 to 10 times.

None of the previous studies, however, estimated ground motion time histories and performed site response time history analysis. Reliable prediction of ground motion time histories is

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essential in conducting nonlinear dynamic structural response and damage analysis. This paper evaluates the suitability of using the seismic ground motion models developed for east Northern America (ENA) for SWWA because the seismological conditions of ENA are quite similar to SWWA conditions, namely a stable continent and intraplate seismic events. Modifications are made on ENA model to best fit the recorded strong ground motions in Western Australia. The modified ENA model with SWWA parameters is then used to simulate ground motion time histories on base rock site from an M_L=7.5 and epicentral distance 50 km event. The simulated base rock motions are assumed consisting of either SH wave or combined P-SV wave and used as input in nonlinear response analysis of a typical soft soil site in Perth. Discussions on characteristics of the estimated ground motion time histories on rock site and on the soft soil site, as well as their possible effects on structures are made. The simulated ground motions will be used as input in a subsequent structural response analysis.

INTRODUCTION

Perth is one of the few large cities in Australia with a population of more than 1.5 million. It is located in southwest Western Australia (WA). On the basis of numbers of M_L>4.9 earthquakes, Michael-Leiba [5] demonstrated that an increase in seismicity in the nearby South West Seismic Zone (SWSZ) started around 1949. But it was the major earthquake in 1968 that occurred 130 km east of the city that attracted much engineering interest. Intensities up to MMIX were experienced at the epicentral town of Meckering and more than MMVI in Perth CBD and Metropolitan area. Figure 1 shows the location map of the seismic zone 1 in Western Australia and PMA. As shown, the shortest distance between the seismic zone 1 and PMA is about 50 km. Gaull and Michael-Leiba [6] performed an analysis of the seismic risk of southwest WA in 1987. That study estimated that the maximum earthquake for the seismic zone 1 is M_L7.5. It also predicted that the ground motion intensity with a 10% probability of exceedance at Perth during a 50 year interval is greater than MMVI, which is equivalent to a peak ground velocity (PGV) or acceleration (PGA) of 48 mm/s or 0.44 m/s^2 respectively. The latter study recommended investigation of the seismic wave amplification in the Perth Basin.

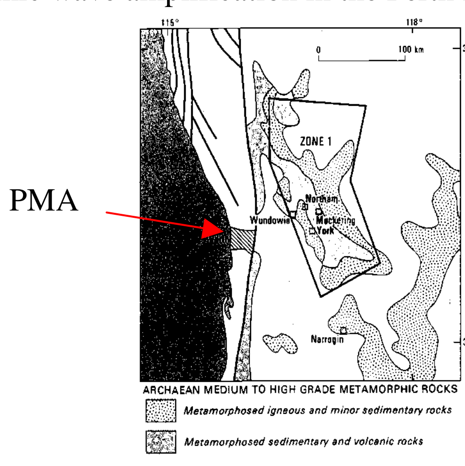


Fig. 1 Map of seismic zone 1 and PMA (after Gaull and Michael-Leiba 1987)

Gaull and his co-authors [4] also conducted spectral ratio analyses of microtremors and minor earthquakes in the Perth Basin and concluded that spectral amplification on the basin sediments is typically 2 to 10 times those on a hard rock site for frequencies 0.2 to 5 Hz. Using the Nakamura method [7], Gaull [8] has reported on the natural resonance frequencies of the upper sediments in the Perth Metropolitan Area (PMA).

As compared to 1968, the current population of PMA has been more than doubled, and many high-rise RC frame structures have been constructed, whereas in 1968, most structures were masonry type low-rise buildings. Therefore, it is necessary to further investigate the seismic effect on structures in PMA.

Only a few significant strong ground motion records are available in WA, thus it is not possible to derive a reliable and unbiased ground motion model based on these few records. But many strong motions have been recorded in eastern North America (ENA), and a few seismic models have been derived based on those records. Since the seismological conditions of ENA are quite similar to WA conditions, namely a stable continent and intraplate seismic events, in this study, the intraplate seismic models developed for ENA earthquakes are used with the WA geophysical parameters. The response spectra of the ground motions on rock site are estimated first using the various models. These response spectra are then compared with the response spectra of a few available strong motions recorded in WA. Modifications on the ENA model is made to make it best predict WA seismic ground motions.

Then, the response spectra of a ground motion on a rock site corresponding to a M_L 7.5 event located as an epicentral distance of 50 km will be estimated using the modified ENA model with SWWA parameters. Ground motion time histories are stochastically simulated according to the estimated response spectra representing horizontal and vertical ground motion components.

A typical soil site in the Perth area will be selected. The soil site amplification of the seismic wave is estimated by using wave propagation method and assuming the simulated time histories consisting of P and SV waves or SH wave. Ground motion time histories on surface of the soil site will be calculated. This paper will present the predicted ground motion time histories on surfaces of rock and soft soil site, and discuss their implications on engineering structures. The predicted ground motion time histories will be used in the subsequent structural response analysis.

RECORDED STRONG GROUND MOTION TIME HSITORIES IN WA

Only a few strong ground motion records are available, Gaull [9]. There are 10 such records are on hard sites which are chosen in the study. They are listed in Table 1.

Using limited strong ground motion data for the SWWA region of Western Australia, Gaull [3] derived the following mean peak horizontal acceleration (PHA) and peak horizontal velocity (PHV) attenuation relations for this region:

$$\text{LogPHA} = [(5\log R+3)/20](M_L-6) - 0.77\log R - 0.0045R + 1.2 \tag{1}$$

$$\mathrm{LogPHV} = 0.60M_L - 1.14\log R - 0.0050R - 0.33 \quad (2)$$

where PHA and PHV are in m/s^2 and mm/s respectively at a site of slant distance $5<R<200$ km and whose ground periods are $0.1<T<0.5$s, from earthquakes of magnitude $4.5<M_L<7$. This period window was chosen, as ground periods shorter than this are generally of little engineering interest. It was found that 1) When these shorter periods were removed from the acceleration data using a band pass filter, the PHA amplitudes approximately halved; and 2) By assuming the data were log-normally distributed around the adopted mean curve, it was estimated that the standard deviation of the residuals was 0.10. This meant that two-thirds of the residuals (observed results) were within 26% of the estimate using relation (1) above.

Table 1 WA Strong Ground Motion Records Used in the Study

No	M_L	Epicent	E Dis Km	Dep Km	Site Condition	PGA (mm/s2) EW	PGA (mm/s2) NS	PGA (mm/s2) VE	PGV (mm/s) EW	PGV (mm/s) NS	PGV (mm/s) VE
1	6.2	Cadoux	87	6	Hard granite outcrop	150.0	128.1	93.3	6.6	4.1	6.8
2	6.2	Cadoux	93	6	Thin alluvium/granite	293.1	305.7	245.5	19.3	21.1	27.2
3	6.2	Cadoux	96	6	Thin alluvium/granite	219.9	170.3	148.6	26.9	12.2	10.0
4	4.5	Cadoux	6	5	Weathered bedrock	2611.9	2888.4	920.8	27.6	27.8	15.7
5	4.5	Cadoux	8	5	Granite outcrop	1542.7	1008.3	938.9	26.1	11.4	9.3
6	4.5	Cadoux	13	5	Weathered bedrock	439.2	473.5	558.3	9.7	8.9	10.5
7	5.5	Meckering	78	6	Hard granite outcrop	98.7	26.1	31.4	1.4	0.5	0.6
8	4.5	Cadoux	70	2	Hard granite outcrop	71.6	48.8	39.2	0.7	0.4	0.4
9	4.1	Meckering	25	6	Hard granite outcrop	138.8	116.0	47.8	1.2	0.7	0.3
10	4.1	Meckering	90	6	Weathered bedrock	5.5	12.6	8.0	0.2	0.3	0.1

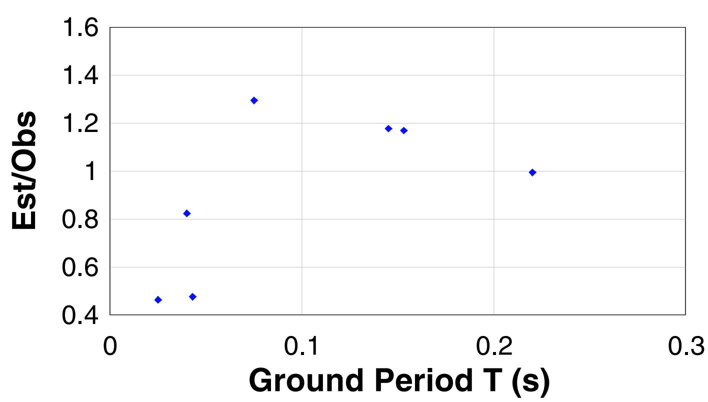
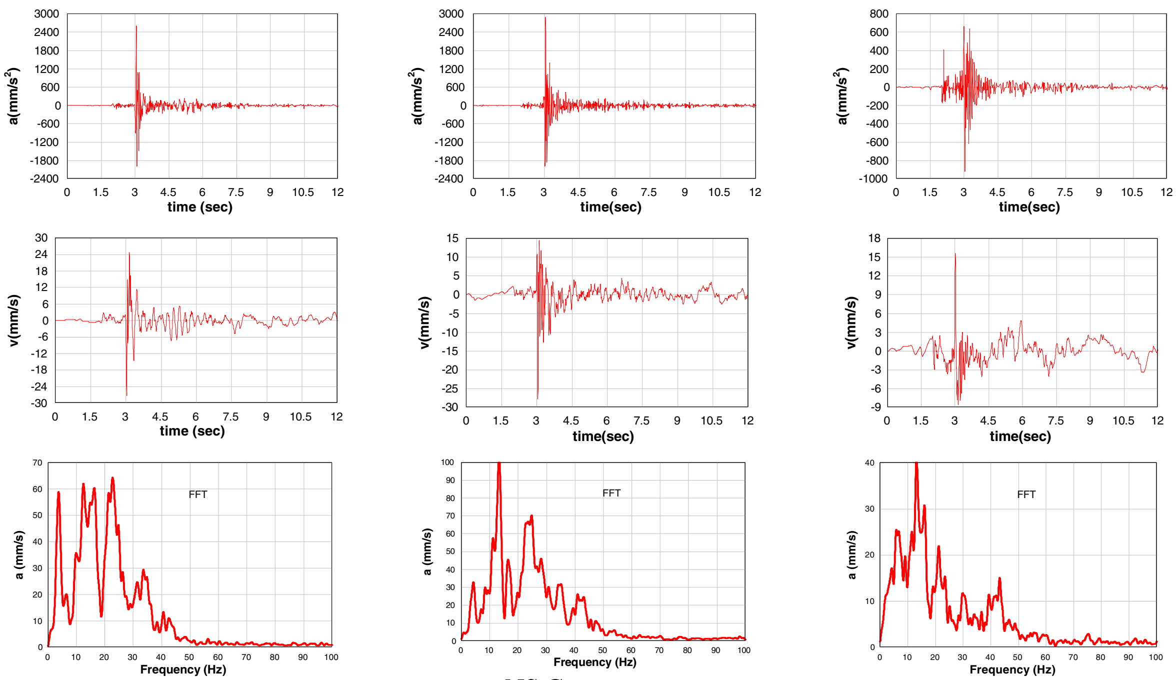


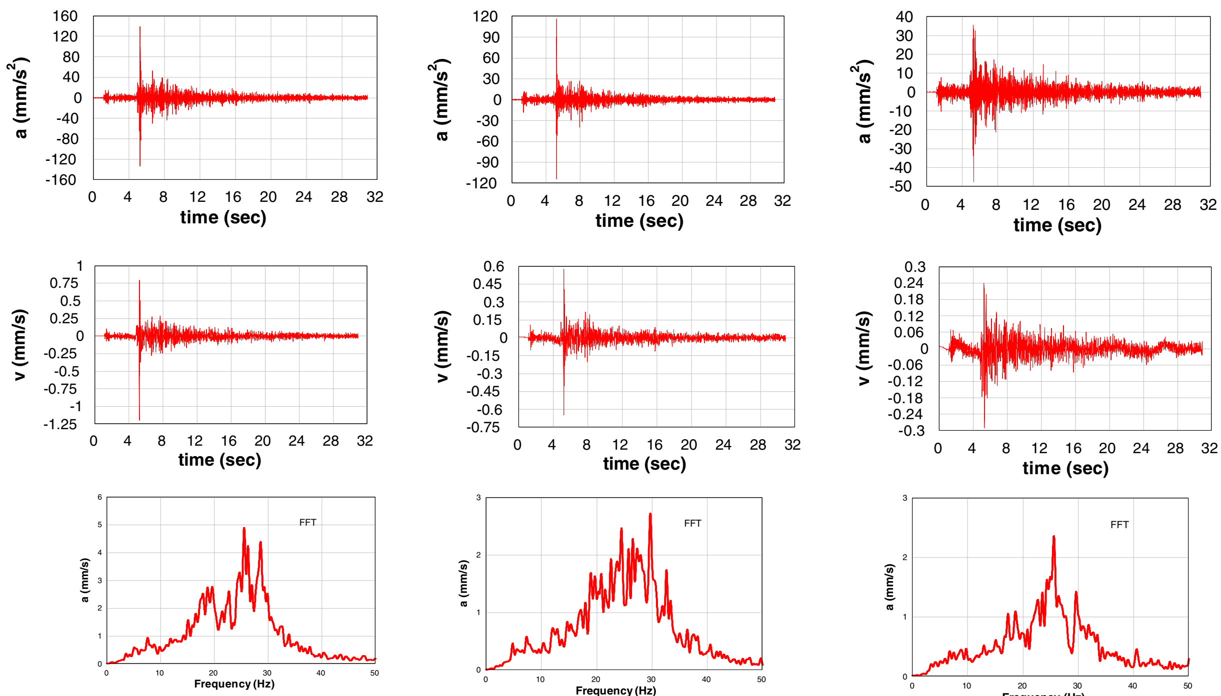
Fig. 2 Ratio of estimated PHA from Eq. (1) to observed PHA

In Figure 2, the SWWA PHA data recorded since the adoption of Relation (1) provides further evidence to support both these findings. For example, if the said allowance for filtering to observed amplitudes of $T<0.1$ data is applied, 5 out of 7 of the data points are within the said margin of the mean.



EW Component NS Component Vertical Component

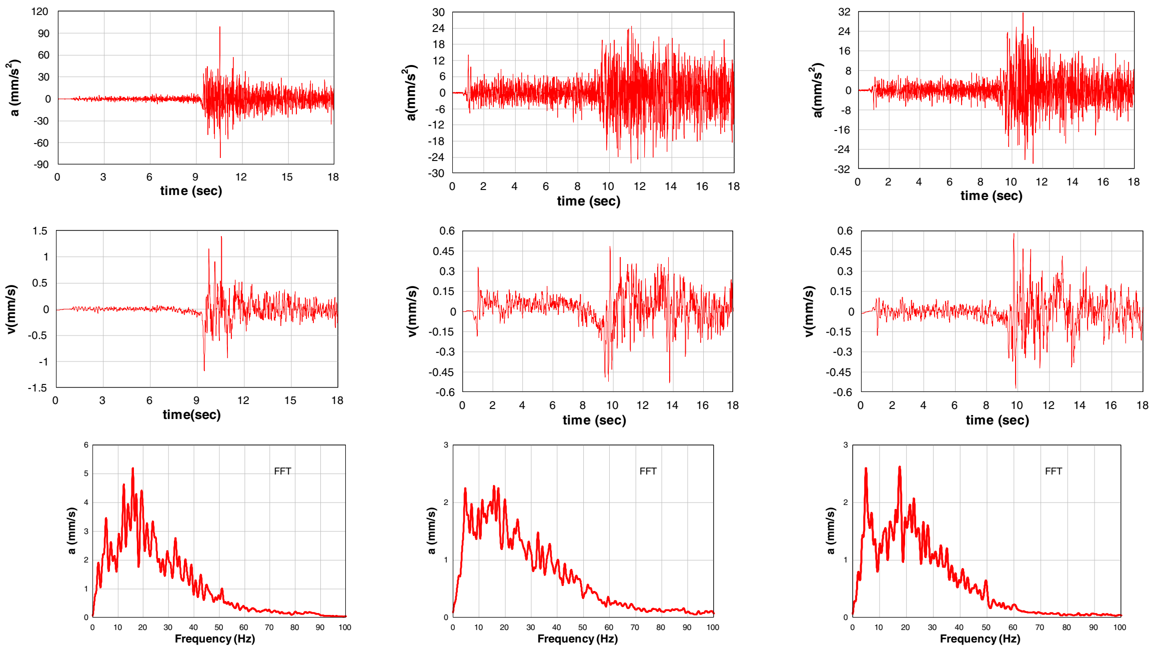
Fig. 3 Recorded time histories and their FFT spectrum at CAA during Event 4 of Table1



EW Component NS Component Vertical Component

Fig. 4 Recorded motions and their FFT spectrum at GOO during Event 9 of Table 1

Figures 3 to 5 show some corrected strong ground motion records in WA. They are events 4, 9 and 7 in the above table 1, representing ground motions from near source (epicentral distance 6 km), and intermediate distance (25 km and 78 km) earthquakes.



EW Component NS Component Vertical Component

Fig. 5 Recorded motions and their FFT spectrum at DOW during Event 7 of Tbale 1

COMPARISON OF ENA MODEL WITH WA RECORDS

No seismic model describing ground motion time history in Western Australia (WA) is available. But several seismic spectrum models for ground motions in eastern North America (ENA) are available. Since the geophysical conditions of WA and ENA are quite similar, this study intends to use ENA model to simulate ground motion time histories in WA. Because the ENA models differ significantly in their assumptions of the spectrum of energy radiation from the earthquake source Atkinson [10], comparative study of the available ENA model is performed first to identify the one that best fit the WA data.

The Fourier spectrum of seismic ground acceleration can be expressed as, Atkinson [10],

$$A(f) = S(M_0, f)D(R, f)P(f) \tag{3}$$

in which $S(M_0,f)$ is the earthquake source spectrum with a seismic moment M_0, and it has the form

$$S(M_0, f) = C(2\pi f)^2 M_0 S_a(f) S_b(f) \tag{4}$$

where M_0 is seismic moment, $C=R_pFV/(4\pi\rho\beta^3)$, with $R_p=0.55$ is the average radiation pattern, $F=2.0$ is the free-surface amplification factor, $V=0.71$ for partition on to two horizontal components, ρ is the crustal density and β the shear wave velocity at the seismic source region. For WA condition $\rho=2750\ kg/m^3$, and $\beta=3910\ m/s$, Dentith [11]. Different authors gave very different spectral shapes of $S_a(f)$ and $S_b(f)$. For example, Atkinson and Boore [12] gave

$$S_a(f) = \frac{1-\varepsilon}{1+(f/f_a)^2} + \frac{\varepsilon}{1+(f/f_b)^2}, \qquad S_b(f) = 1.0 \tag{5}$$

Whereas those given by Haddon [13] are

$$S_a(f) = \frac{1}{[1+(f/f_a)^8]^{1/8}}, \qquad S_b(f) = \frac{1}{[1+(f/f_b)^8]^{1/8}} \tag{6}$$

in which ε is a relative weighting parameter and f_a and f_b are two corner frequencies. Their values are also very different in models proposed by different authors. A detailed comparison study of those models was made by Atkinson and Boore [10].

In Equation (3), $D(R, f)$ describes the spectral amplitude attenuation with hypo distance R from the seismic source. It is expressed as

$$D(R,f) = Ga(R)An(R,f) \tag{7}$$

where $Ga(R)$ is the geometric attenuation and is estimated by

$$Ga(R) = \begin{cases} 1/R, & R \le 1.5D \\ 1/1.5D & 1.5D < R \le 2.5D \\ (1/1.5D)(2.5D/R)^{1/2} & R > 2.5D \end{cases} \tag{8}$$

in which D in km is the earth's crust thickness. In SWWA, the earth's crust thickness is about 33 km to 38 km Dentith [11]. It is taken as $D=35$ km in this study.

$An(R, f)$ is the anelastic attenuation factor,

$$An(R,f) = e^{-\pi f R/Q\beta} \tag{9}$$

The Q value is usually taken as $Q=680f^{0.36}$ in most ENA models, except the model proposed by Haddon [13], in which $Q=1350$ is a constant.

The $P(f)$ in Equation (3) is a high-cut filter. It has the form either Atkinson [10]

$$P(f) = [1+(f/f_{\max})^8]^{-1/2} \quad \text{or} \quad P(f) = \exp(-\pi\kappa f) \tag{10}$$

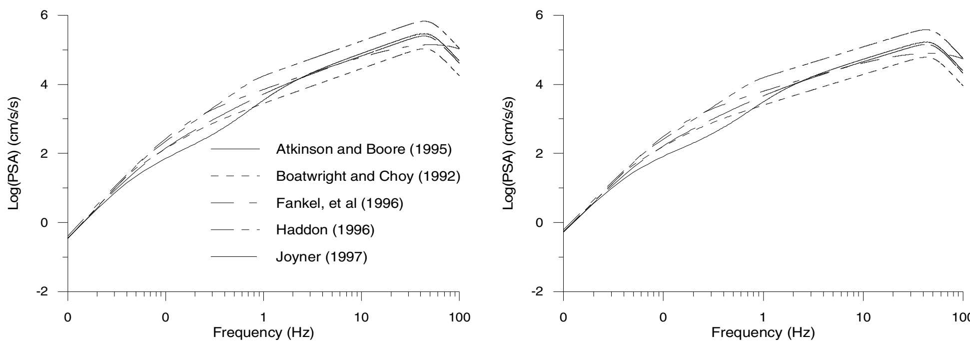
For ENA, f_{max} and κ are taken as 50 Hz, 0.0, or 100 Hz, 0.006. In this study, only the first $P(f)$ function with f_{max}=50 Hz is tested against the WA records.

The vertical component is related to the horizontal component by

$$log_{10} H / V = 0.0519 + 0.117 \, log \, f \tag{11}$$

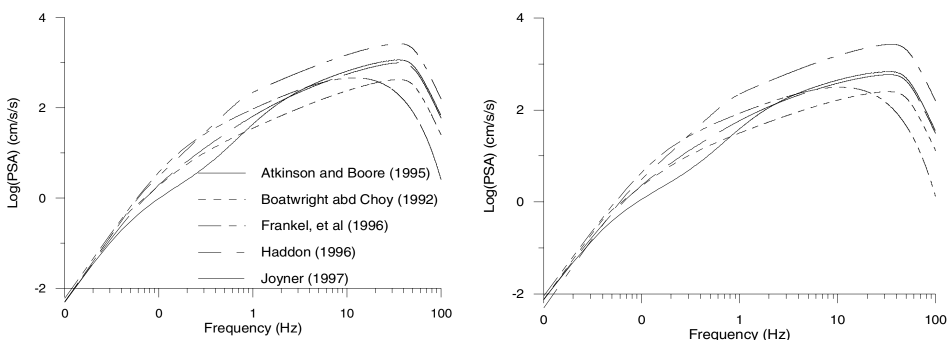
The seismic moment is related to seismic magnitude through the relation Atkinson [10]

$$Log_{10} M_0 = 1.5 M_w + 16.05 \tag{12}$$



Horizontal Component　　Vertical Component

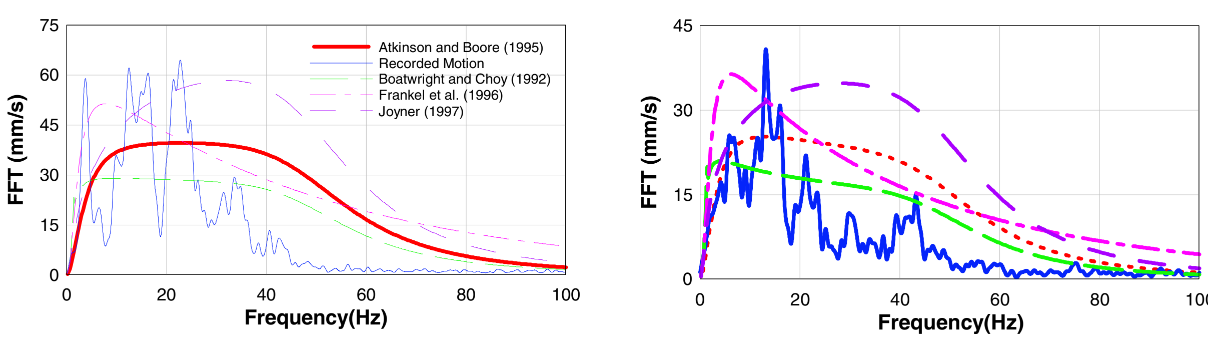
Fig. 6 Comparison of ENA spectra (R=1 km, m_b=7.0)



Horizontal Component　　Vertical Component

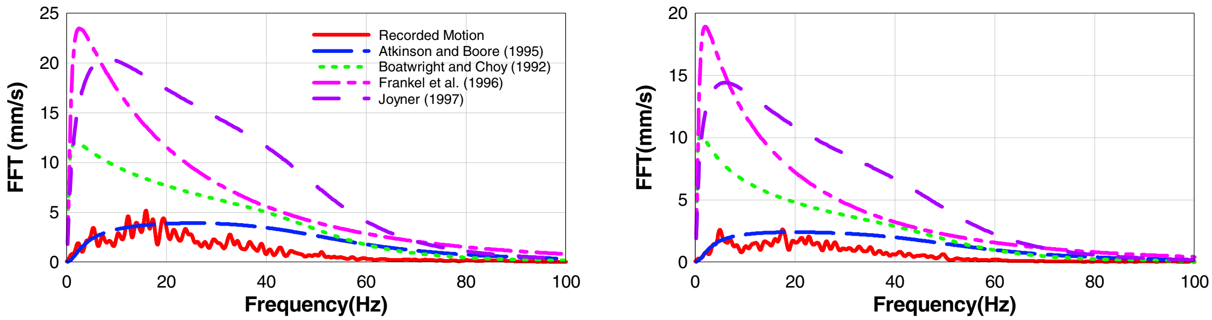
Fig. 7 Comparison of ENA spectra (R=100 km, m_b=7.0)

Figures 6 and 7 compare the earthquake ground motion spectrum at R=1 km and 100 km respectively generated using the various ENA model. As shown, the available ENA model gives very different ground motion spectrum, especially at large focal distance R.



Horizontal Component　　Vertical Component

Fig. 8 Comparison of ENA spectra with the recorded motion (M_L=4.5, Epicentral distance 6km, focal depth 5 km)



Horizontal Component Vertical Component

Fig. 9 Comparison of ENA spectra with the recorded motion (M_L=5.5, Epicentral distance 78km, focal depth 6 km)

Figures 8 and 9 show comparison of the ground motion spectrum estimated from ENA models and the actual recorded motions at 6 km and 78 km from the epicenter. As shown, none of the ENA model gives very satisfactory prediction of ground motion spectrum in WA, especially when the epicentral distance is large. Among them, the model by Atkinson and Boore [12] gives relatively better prediction at both near source and large epicentral distance. Therefore this model is chosen in the present study. It should be noted that the ENA model by Haddon [13] gives very different prediction of ground motion spectrum as compared to those shown in Figures 8 and 9, thus it is not included in the above two figures.

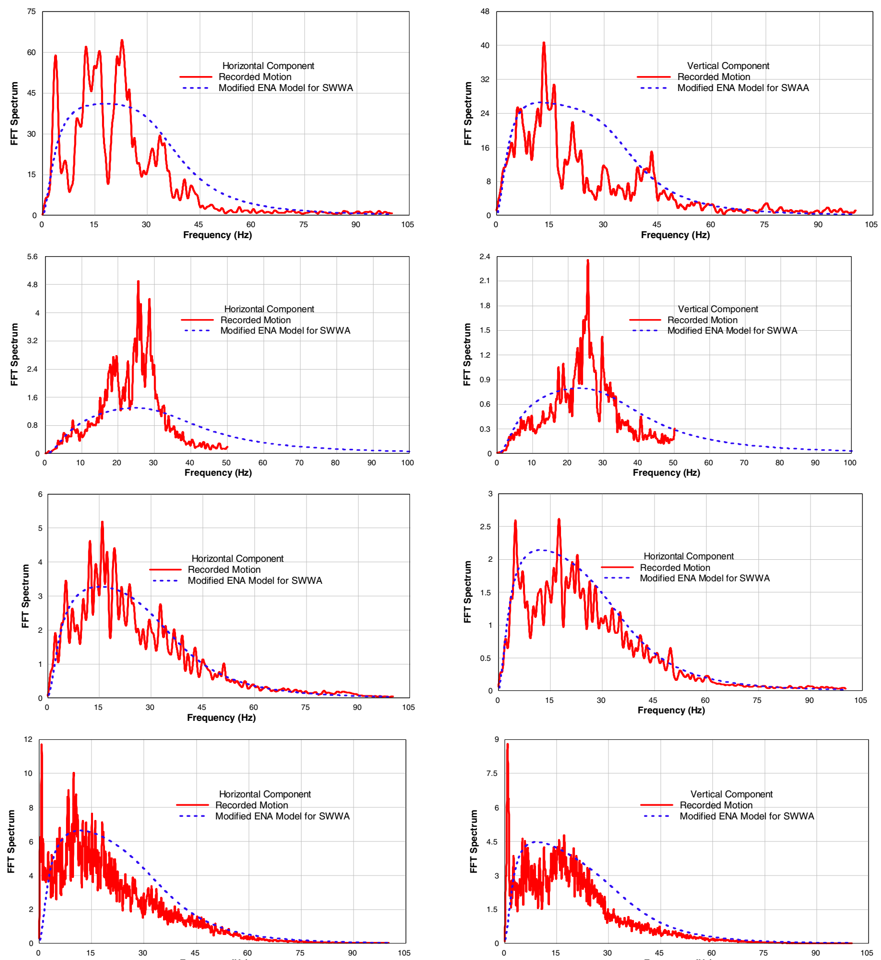
MODIFICATIONS OF ENA MODEL TO FIT WA RECORDS

The above comparison indicated that although the Atkinson and Boore model [12] gives relatively better prediction of the WA strong ground motions than other ENA models. None of the ENA model, however, can be directly applied to represent WA strong ground motion since they all overestimate ground motion spectral value at frequencies larger than about 20 Hz.

Modifications on the high-cut filter function and the anelastic attenuation parameters for ENA conditions are made to fit the WA records. Since only very few strong ground motion records are available, no attempt is made to find the best fit equations, rather trial-and-error adjustment of the filter function and the attenuation parameters are performed. It is found that the Atkinson and Boore model with the modified filter function

$$P(f)=\begin{cases} \dfrac{0.5}{\sqrt{1+(f/f_{max})^8}}, & R \le 10km \\ \dfrac{1}{7000.0}\sqrt{\dfrac{fR}{1+(f/f_{max})^6}}, & R > 10km \end{cases} \tag{13}$$

and the high-cut frequency f_{max}=*35* Hz, and Q=$700f^{0.25}$ gives the reasonable prediction of the strong ground motions recorded in WA. Figure 10 shows the comparison of the Fourier spectrum of the recorded motions in WA and that estimated from the modified Atkinson and Boore model.



M_L=4.5, Dis=6 km, Depth=5 km, Weathered Bedrock (7/3/1987 Cadoux Earthquake)

M_L=4.1, Dis=25 km, Depth=6 km, Rock Site (21/6/1996, Meckering Earthquake)

M_L=5.5, Dis=78 km, Depth=6 km, Granite Outcrop (17/1/1990 Meckering Earthquake)

M_L=6.2, Dis=96 km, Depth=6 km, Thin Alluvium Over Granite (2/6/1979 Cadoux Earthquake)

Fig. 10 Comparison of Fourier spectrum of the recorded earthquake ground motion in WA with the modified Atkinson and Moore Model

BASE ROCK GROUND MOTION TIME HISTORY SIMULATION

It was predicted in a previous study that the largest possible earthquake in seismic zone 1 in SWWA area is expected to be M_L 7.5 Gaull [6], and the shortest distance between seismic zone 1 and PMA is 50 km. In this study, such an event is assumed and ground motion simulated. It should be noted that the ENA model uses seismic moment magnitude M_W. There is no reliable relation between M_L and M_W for Western Australian events. Because M_L saturates after it is larger than 6.5, a rough estimation, with conversion from M_S, gives M_W=8.0 for M_L=7.5. However, more accurate estimation of equivalent M_W and M_L is needed in the future.

A stationary time history is simulated first to be compatible with the modified Atkinson and Boore model. A shape function of

$$w(t) = at^{b} \exp(-ct) \tag{14}$$

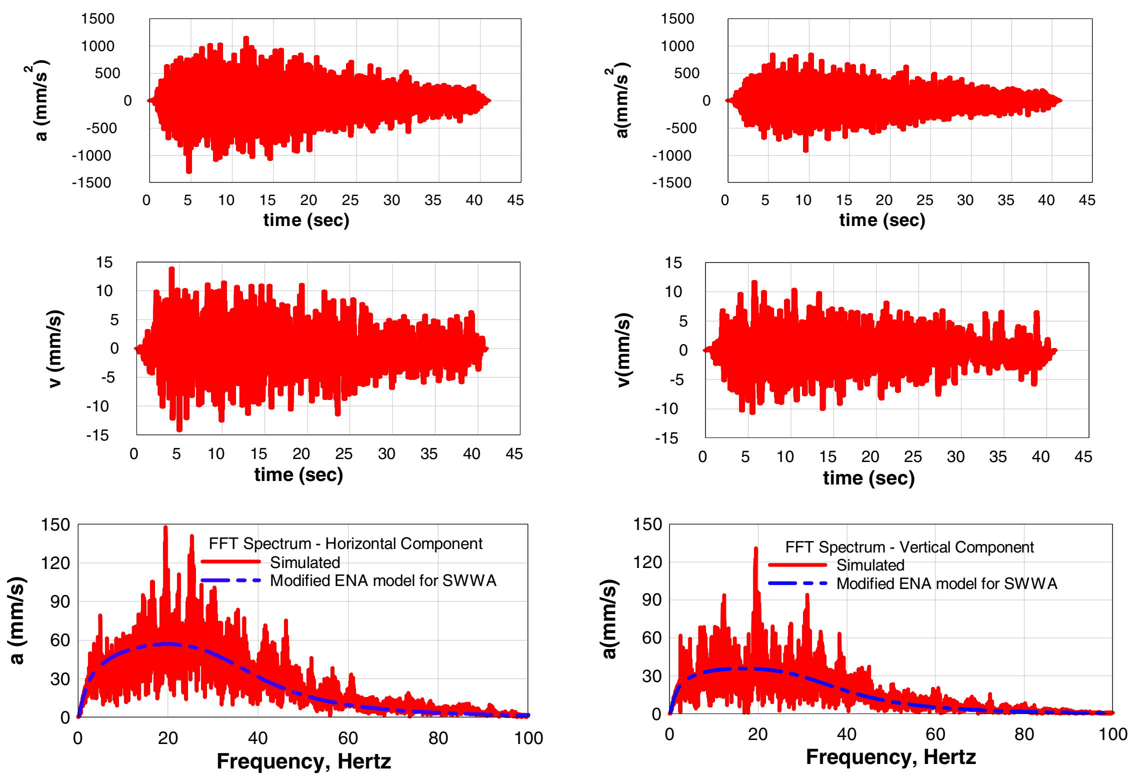
is applied to the simulated stationary time history. Assuming peak value occurs at 20% of the total duration, and amplitude of the signal is about 20% of the peak value at the end of the duration considered, it has $a=5.79T^{-b}$, $b=0.673$ and $c=3.37/T$, in which T is the strong motion duration. A few relations are available to estimate the strong ground motion duration. In the present study, the relations developed by Atkinson and Somerville [14] is used. It has

$$T = 1/2f_a + bR \tag{15}$$

in which the first term is the source duration and the path duration is

$$bR = \begin{cases} 0.0 & R \le 10km \\ 0.16(R-10) & 10km < R \le 1.5D \\ 9.6 - 0.03(R-1.5D) & 1.5D < R \le 2.5D \\ 7.8 + 0.04(R-2.5D) & R > 2.5D \end{cases} \tag{16}$$

in which D is the earth's crust thickness.



Horizontal Component

Vertical Component

Fig. 11 Simulated ground motion time histories on hard rock site and their FFT spectrum

Figure 11 shows the simulated ground motion time history and the corresponding Fourier spectrum. As shown the Fourier spectrum of the simulated ground motion is compatible with the target ground motion spectrum model. The simulated ground motion time histories will be used as input in the study of soft site responses to estimate ground motions on surface of the soil site at Perth basin.

SITE RESPONSE ANALYSIS

Perth Metropolitan Area (PMA) is founded on a very large and deep sedimentary basin, Gaull [8]. Site amplifications of seismic wave were observed in previous occasions. For example, the August 17, 1977 earthquake in Indonesia, which is 2000 km north, caused panic to occupants and minor damage in some of the middle-rise buildings in downtown Perth, Gregson [15]. During two minor earthquakes, Gaull et al. [4] also recorded larger PGA and PGV on the sedimentary basin in the PMA than simultaneous observations that had been recorded on nearby hard rock.

A previous study used microtremor measurement to determine the ground vibration period of the Perth Basin Gaull [4]. It was found that the basin can be divided into four zones with natural vibration period of ground varying between 0.1 sec and 0.3 sec in zone 1, between 0.3 sec and 0.7 sec in zone 2, 0.7 sec and 1.7 sec in zone 3, and 0.1 sec and 2.0 sec in zone 4. In this study, a site with detailed soil investigation data, and is located in zone 3 near the downtown Perth Lehane [16], is used in site amplification study. Figure 12 shows the schematic view of the site and the initial soil properties, in which G is shear modulus, ρ density, ξ damping ratio and ν Poisson's ratio. The ground water level is 1.9 m below the ground surface.

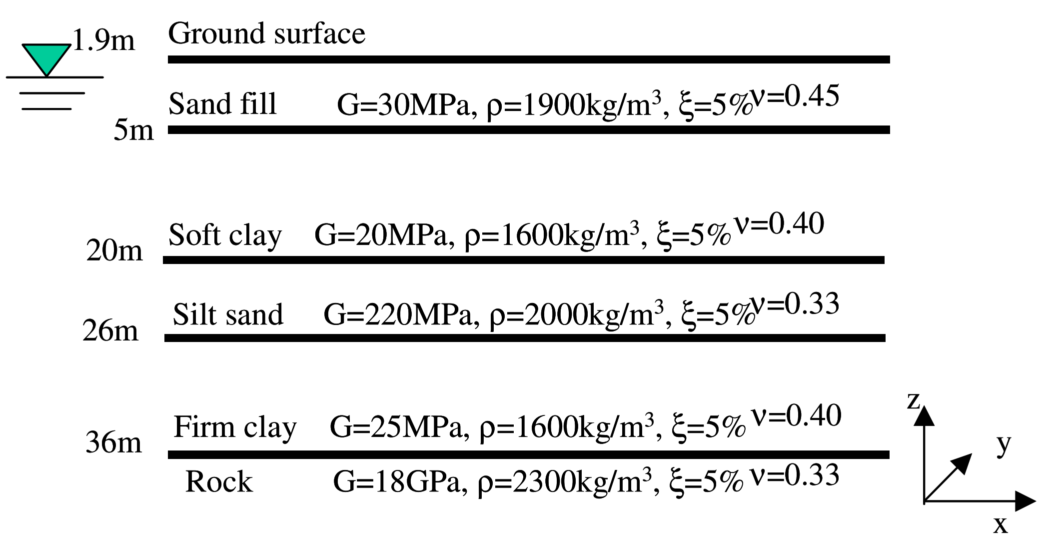
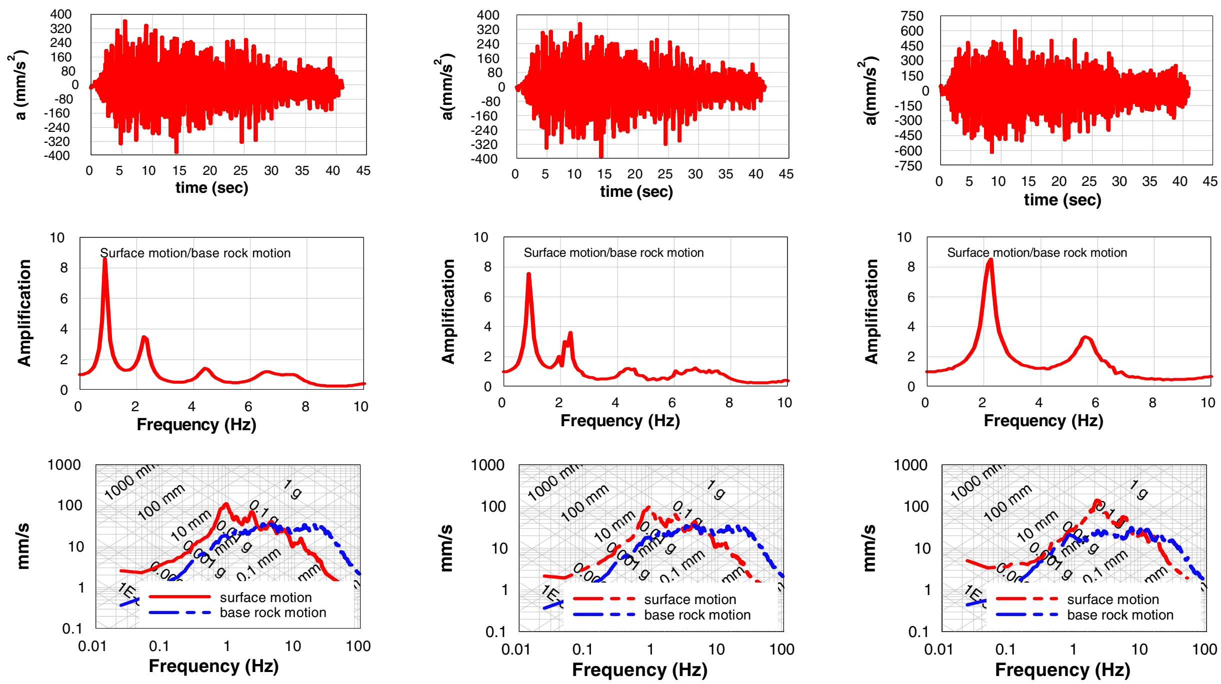


Fig. 12 Schematic view of the layered soil site (not to scale)

The simulated ground motion time histories on rock site given above are assumed consists of SH wave (horizontal component, y-direction) or combined P and SV wave (both horizontal and vertical component, x- and z- direction). The P wave incident angle is assumed to be 30° and that of S wave 60°. Site response is calculated by a computer program developed before Hao [17]. Nonlinear properties of clay and sand obtained by Seed et al [18] are used to account for the nonlinear site responses. The response is solved in the frequency domain and equivalent linearization method is used in the solution process. It is calculated that the average P and S wave velocity of the site are 356.2 m/s and 152.5 m/s, and the fundamental vibration frequency is 1.059 Hz and 2.474 Hz in the horizontal and vertical direction, respectively.

Figure 13 shows the calculated acceleration time histories on ground surface in the three directions, the corresponding amplification spectrum of the surface ground motion to base rock motion and the comparisons of the response spectrum of the surface and base rock motion.



y-component SH wave   x-component combined P and SV wave   z-component combined P and SV wave

Fig. 13 Calculated surface ground motion

As shown, the soft soil site amplifies the base rock motion at its various vibration modes. The horizontal components are greatly amplified at frequency 0.879 Hz, slightly lower than the first horizontal vibration frequency, as expected for a layered site. The largest amplification spectrum value is 8.58 for SH wave assumption, and 7.75 for combined P and SV wave assumption. The vertical component is greatly amplified at 2.246 Hz corresponding to the vertical fundamental vibration mode of the site, and the largest amplification value is 9.10. This is also shown in the comparisons of the base rock and surface motion response spectra. The site amplifies horizontal ground motion response spectrum in the frequency range less than 3.0 Hz, deamplifies it when frequency is higher than 3.0 Hz. It amplifies the vertical component when frequency is less than 8.0 Hz, but deamplifies it at higher frequencies. Because the peak ground motion of the base rock is associated with high frequencies, the soft soil site reduces the horizontal base rock PGA from 1321.88 mm/s^2 to 384.09 mm/s^2 in the y-direction, and 391.40 mm/s^2 in the x-direction, and reduces the vertical base rock motion PGA from 926.56 mm/s^2 to 616.90 mm/^{2}. However, the soil site causes an increase of the base rock motion PGV from 13.97 mm/s to 26.83 mm/s in y-direction and 24.07 mm/s in x-direction, and from 11.58 mm/s to 28.50 mm/s in the vertical direction.

The above calculated PGA for motions on both rock and soil sites at PMA is larger, but PGV is smaller than those predicted in a previous study Gaull [6], which gave a prediction of PGA=440 mm/s^2 and PGV=48 mm/s for a 475-year return period earthquake. Some recent studies, however, predicted PGA about 800 mm/s^2. The above estimated ground motion time histories on rock site represent the worst-case scenario rock site motions in PMA. More studies, however, are needed to investigate the site amplifications at Perth Basin, especially sites in other zones that are stiffer than the one analyzed above. Because the base rock motion has relatively high frequency contents, a stiffer site might amplify base rock motion more significantly. If this is the case, then low-rise and medium-rise structures in PMA with fundamental vibration frequencies higher than 2.0 Hz might be equally vulnerable to earthquake ground motion as the flexible high-rise buildings. More studies are deemed necessary before any solid conclusion can be drawn.

CONCLUSIONS

This study intends to predict earthquake ground motions in Perth Metropolitan Area in Western Australia. Because only very few strong ground motion records are available, ground motion models derived for east Northern America were used to model ground motions in Western Australia. A few ENA models were compared. It was found that the Atkinson and Boore Model, among the ENA models studied, with a modified filter function and Q value for anelastic attenuation can best predict strong ground motions on rock site in Western Australia. The modified Atkinson and Boore model was used to estimate the ground motion spectra corresponding to a M_L 7.5 and epicentral distance 130 km event. Stochastic simulation of time histories representing horizontal and vertical component of the ground motion on rock site was carried out. The simulate time histories were compatible with the estimated ground motion spectra. The simulated time histories were then used as input to a soft soil site to calculate ground motion time histories on surface of the soil site. The base rock motion was assumed consisting of SH or combined P and SV waves in site response calculation. It was found that the soft soil site amplifies base rock motion in the low frequency range corresponding to the site fundamental vibration frequency. Because the base rock motion has high frequency contents, the PGA of the horizontal component of the surface ground motion is smaller than that of the horizontal base rock motion, but PGA of the vertical component of the surface motion is larger than the vertical base rock motion. PGV of the surface motion is, however, always larger than the corresponding PGV of the base rock motion. Brief discussions on the effects of earthquake ground motions on structures in PMA were also made.

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