Coherency Variation With Depth
at Different Strong Ground Motion Arrays

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SUMMARY:
Strong ground motion coherency variation with depth, both in horizontal and vertical directions, is studied by utilizing 303 recordings in three arrays of CSMIP, USA. New coherency model is suggested in this paper, which indicates that the epicenter distance and site condition can affect the coherency variation with depth obviously.

Keywords: Average periodogram algorithm; Coherency function; Epicenter distance

1. GENERAL INSTRUCTIONS

The earthquake is of a complicated motion process reflecting different characteristics and state of the movement at different places. Actually, with the development of a variety of engineering structures, the coherency relationship of ground motions among these points in an earthquake is one of the most important problems that must be considered for key engineering structural design and other aseismic analysis, like long bridges, large span and high-rise structures. However, many present studies on ground motion coherency focus on the horizontal components of the earthquake waves. Even so, due to the constraints of the arrays and recording numbers that are needed for analyzing, most of research can only utilize recordings acquired by SMART-1 array or synthetic time-histories, the university of the findings are subject to certain constrains. Research on vertical (downward from the surface) coherency is very rare although it is acknowledged that ground motion changes obviously along depth and many researchers understand the importance of this aspect. After all, because of a few arrays laid along the depth all over the world, little progress has been made and achieved on the vertical seismic coherency, i.e., almost in blank status now, we try to change such situation through this research.

The aim of this work is to analyze and compare the impact of site conditions, earthquake epicenter distance and depth on ground motion coherency variation with different frequency, based on many actual observed recordings from three strong seismic arrays laid along depth in California, USA. This paper compares the difference of vertical and horizontal ground motion coherency and suggests a new proper coherency model that can show out the typical variation of coherency along depth.

2. DATABASE

As mentioned above, many observed recordings acquired by three arrays---Treasure Island, La Cienega and Eureka Samoa of California Strong Motion Instrumentation Program (CSMIP), are utilized for our analysis.

Treasure Island array is laid in a site with soft deposit on upper part and bedrock on lower part, and located on an artificial island (Treasure Island) with an area of 400 acres in the San Francisco Bay, California. The soils from top to bottom are as follows: about 12 meters of hydraulic filler, sand and gravel; about 15 meters hard Holocene mud, dense sand and hard Pleistocene silt; and then sandstones and shale under 91 meters. The distribution of seven accelerographes is: surface, -7 meters artificial soil layer, top of -16 meters silt layer, -33 meters dense sand layer, top of -44 meters silt layer, and -104 meters and -122 meters below the bedrock layer. The position of the instruments and wave velocity are shown in Fig.2.1.

La Cienega array is located next to the Santa Monica Freeway. The first layer of this site is thick sediments about 30 meters, the lower part are sand, silt, clay and gravel. The near-surface S-wave velocity is 140m/s, and the velocity reaches about 600m/s when the depth is 100 meters, belonging to the thick soft alluvial sites. Four accelerographes are emplaced in different depths in borehole: on ground surface, -18 meters, -100 meters and -252 meters respectively. The positions and site velocity are shown in Fig.2.2.

The site of Eureka Samoa array is similar with that of La Cienega array. Eureka Samoa array is in Eureka, northwest of California and the site is representative thick soft alluvial sites. Five accelerographes are emplaced on ground surface, -19 meters, -33 meters, -56 meters and -136 meters respectively along different depths in one borehole.

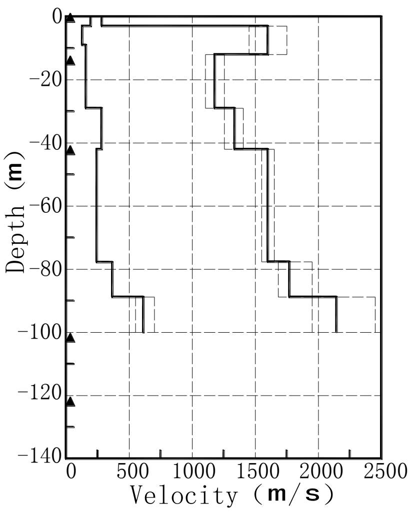


Figure 2.1. P and S wave velocity at Treasure Island array

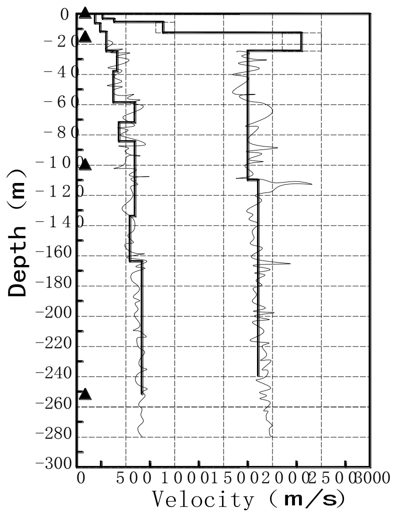


Figure 2.2. P and S wave velocity at La Cienega array

The information of earthquake of three stations, Treasure Island, La Cienega and Eureka Samoa, is shown in Table 2.1, Table 2.2 and Table 2.3 respectively.

3. ANALYSIS OF SEISMIC COHERENCY ALONG DEPTH

3.1. Calculation of Theoretical Coherency Function

Currently, the average periodogram algorithm (Welch method) is widely used for the calculation of frequency response function, ground motion coherency function and power spectral density function. In this paper, this method is used to calculate seismic coherency function and the exact calculation steps are as follows:

(1) Specify the sampling frequency of random vibration signal fs, generally 3-4 times higher than analysis frequency.

(2) Set the data length of FFT (Fast Fourier transform) NFFT, according to the needed bandwidth of the frequency resolution Δf. NFFT=fs/$\Delta f=2^q$（q is based on the value of fs/Δf and it must be an

integer）, then divide the random vibration signal into L segments (total segments of the data), and each has a length of NFFT. Two segments can share overlap data for about 50% of the data length generally. Take Hanning window as the smoothing window in order to eliminate the trend of each data segment.

(3) Calculate the self-power spectral density and cross-power spectra with formula below:

$$\mathrm{S_{xx}}(k) = \frac{1}{LN_{FFT}} \sum_{i=1}^{L} X_i(k) X_i^*(k) \tag{1}$$

$$\mathrm{S_{xy}}(k) = \frac{1}{LN_{FFT}} \sum_{i=1}^{L} X_i(k) Y_i^*(k) \tag{2}$$

where *Xi (k)* is the Fourier transform of the i-th data segments, *Xi※(k)* is the conjugate complex numbers of *Xi(k)*; *L* is the total number of segments; N_{FFT} is the data length of FFT.

(4) Calculate the coherency function:

$$\rho_{\mathrm{xy}} = \frac{\left|S_{xy}(k)\right|}{\sqrt{\mathrm{S}_{xx}(k) S_{yy}(k)}} \tag{3}$$

where *Sxx(k), Syy(k)* and *Sxy(k)* are calculated using equation (1) and (2).

The ground motion coherency function here is the hysteresis coherency function, such as Eqn.3, which eliminates the influence of phase angle difference brought by the traveling wave effect. Its value varies between 0 and 1, 0 means the two components are independent of each other and 1 means two components are totally relative and the earthquake wave is the same. The bigger the coherent value is, the stronger the coherency of the two components.

3.2. Empirical Coherency Function Model

Some researchers have suggested different ground motion coherency function models, like Harichandaran, Vanmarcke, etc., Nakamura, Yamazaki, etc., Luo Junxiong from other countries, and Qu Tiejun, Feng Qiming, Hu Yuxian, etc, Ding Haiping, Liu Qifang, etc from China. All of above models can basically describe the coherency of the horizontal ground motion after comparative analysis in this paper. However, there exist lack of the coherency along depth variation due to very limited recordings from arrays in depth and the impact of the epicenter distance on coherency models that shows a significant impact on the coherency by analyzing many recordings recorded during different events at the same array.

To solve such problems in coherency analysis, 114 recordings obtained by Treasure island array in 6 earthquakes, 144 recordings obtained by La Cienega array in 14 earthquakes and 45 recordings obtained by Eureka Samoa array in 3 earthquakes are selected carefully to study the coherency variation in detail in this paper. Firstly calculate the ground motion coherency between surface (0 meters) and the lower parts at different depths in different earthquakes of three arrays respectively, then after comparison considering many factors in detail, the following new coherency model along depth variation is suggested.

$$\rho_{\mathrm{ik}}(f,h) = \exp(-(a + bR^c h^D (f - f_1)^2)h) \tag{4}$$

$$f_1 = \alpha \exp(\beta R)(1 - \exp(\delta h^2) \quad (5)$$

where *a, b, c, d, α, β, δ* are constants; *f* is frequency; *h* is the distance between i-th and k-th points at different depths in the soil; *R* is the earthquake epicenter distance; the values of the parameters are shown in Table 3.1. f_1 is a typical function representing the frequency moving with event epicenter distance and interval between two recording points. Such function is the first time to be introduced into the coherency model in this paper and the results below show it is necessary to do so.

Table 2.1. Earthquake Recording Information At Treasure Island Array

NO.	Date	M	Depth(km)	R(km)	Latitude	Longitude	Recording NO.
1	1993.01.16	4.8	7.9	120.4	37.02	121.463	18
2	1994.06.26	4.0	6.6	12.6	37.92	122.286	18
3	1998.08.12	5.4	9.2	143.8	36.75	121.462	18
4	1998.12.04	4.1	6.9	13.0	37.92	122.287	18
5	1999.08.18	5.0	6.7	29.0	37.91	122.687	21
6	2000.09.03	5.2	9.4	61.4	38.38	122.414	21

Table 2.2. Earthquake Recording Information At La Cienega Array

NO.	Date	M	Depth(km)	R(km)	Latitude	Longitude	Recording NO.
1	1995.06.26	5.0	13.3	47.6	34.39	118.67	9
2	1997.03.18	5.1	1.8	176.7	34.97	116.82	9
3	1997.04.04	3.3	4.2	6.7	33.98	118.35	9
4	1997.04.05	2.5	4.1	6.4	33.99	118.36	9
5	1997.04.26	5.1	16.5	45.8	34.37	118.67	9
6	1997.04.27	4.9	15.2	45.7	34.38	118.65	9
7	1998.01.12	3.4	11.3	19.1	34.19	118.47	9
8	1998.04.15	3.2	9.2	13.0	34.10	118.26	9
9	1999.06.17	3.0	8.5	15.2	34.01	118.22	12
10	1999.10.16	7.1	6.0	203.6	34.60	116.27	12
11	1999.10.16	5.8	5.8	205.0	34.68	116.29	12
12	2000.08.01	3.0	15.9	12.2	33.93	118.36	12
13	2000.09.16	3.3	12.2	7.9	33.98	118.42	12
14	2001.09.09	4.2	4.9	2.7	34.06	118.39	12

Table 2.3. Earthquake Recording Information At Eureka Samoa Array

NO.	Date	M	Depth(km)	R(km)	Latitude	Longitude	Recording NO.
1	2000.03.16	5.9	5.0	106.4	40.38	125.28	15
2	2000.09.22	4.4	13.1	25.4	40.85	124.46	15
3	2000.12.27	4.0	28.7	45.7	40.47	124.45	15

Table 3.1. Model Parameters

Array	Direction	*a*	*b*	*c*	*d*	*α*	*β*	*δ*
Treasure Island	horizontal	0.01006	0.00059	0.63960	-1.28480	14	-0.00800	-0.00045
	vertical	0.01032	0.00091	0.75664	-1.57840	40	-0.01290	-0.00108
La Cienega	horizontal	0.00441	0.00017	0.63086	-0.94755	16	-0.00667	-0.00100
	vertical	0.00929	0.00080	0.64861	-1.39879	17	-0.00474	-0.00088
Eureka Samoa	horizontal	0.00700	0.00002	0.82835	-0.79356	18	-0.00720	-0.00030
	vertical	0.01226	0.00001	1.56014	-1.52885	20	-0.01313	-0.00057

4. COHERENCY ANALYSIS AND COMPARISON

To the three arrays, coherences of the surface and lower parts of -10 meters, -30 meters and -100 meters with epicenter distance of 10 km, 30 km, 60 km and 100 km are calculated. Fig.4.1. and Fig.4.2 show comprehensive change characteristics of horizontal and vertical components with different depth, different epicenter distance and different site conditions. The horizontal axis is frequency (Hz), the ordinate axis is coherency value between surface and different depth below ground.

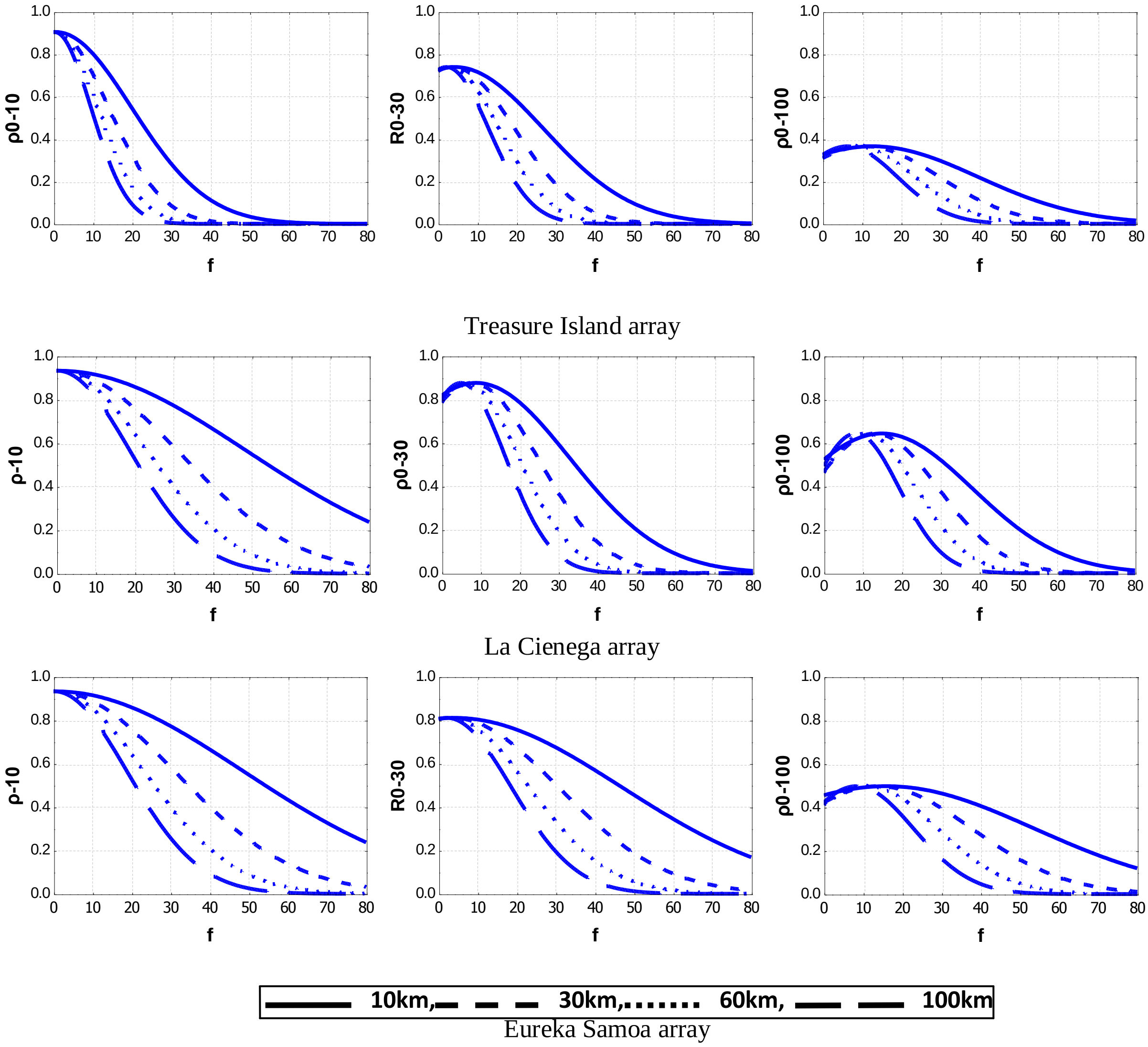
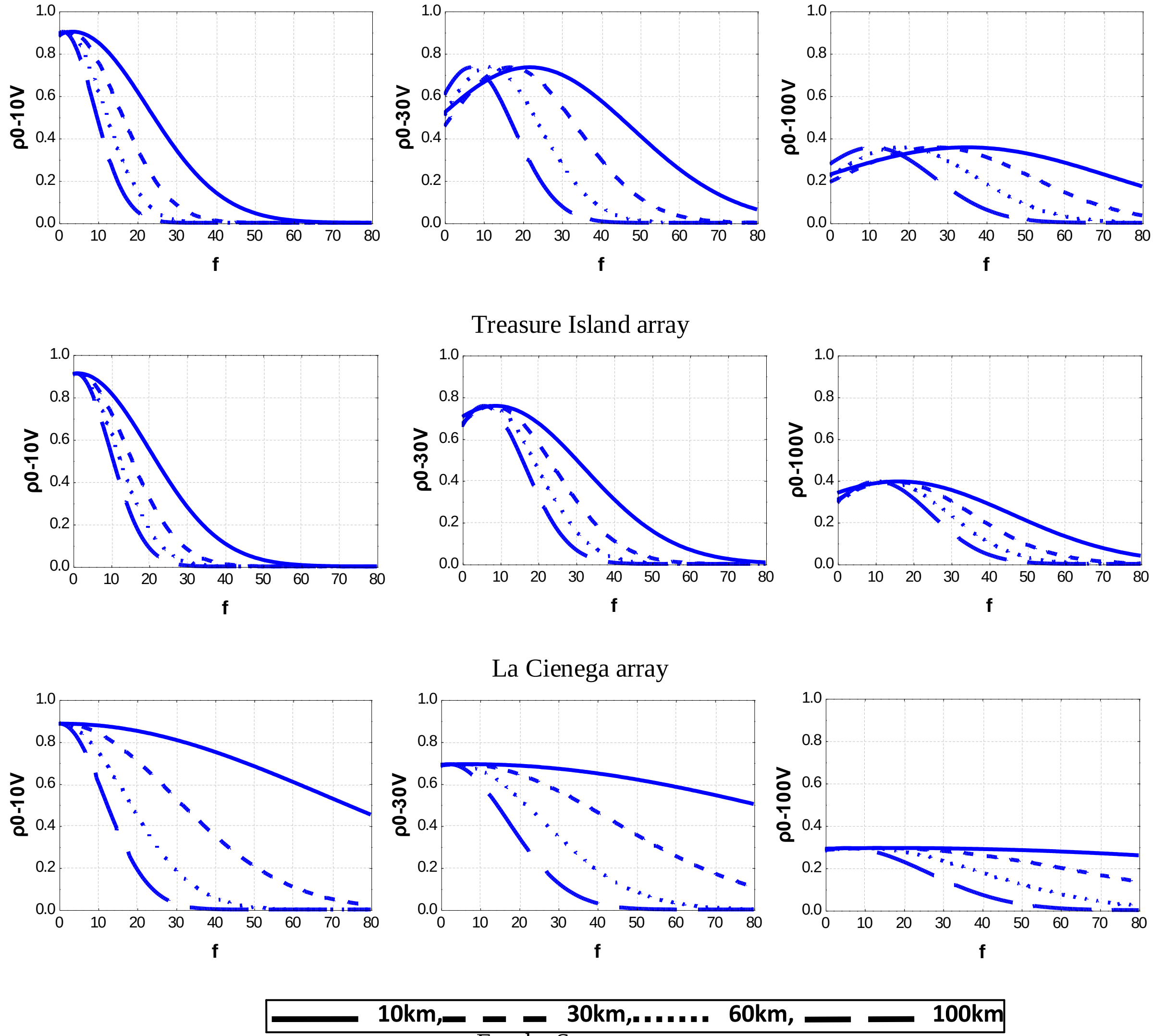


Figure 4.1. Coherency in horizontal direction at different epicenter distances



Eureka Samoa array

Figure 4.2. Coherency in vertical direction at different epicenter distances

5. CONCLUSION AND DISCUSSION

Some features can be seen and summarized through the result of this paper:

(1) Earthquake epicenter distance has great influence on the ground motion coherency varying with depth, and basically the ground motion coherency attenuates quickly with the epicenter distance increasing. The epicenter distance is one of the main influencing factors that cannot be ignored for both horizontal and vertical ground motion coherency. The statistical data of the three array stations verify this characteristic.

(2) The common features of the ground motion coherency of the 3 arrays are: In the circumstance that other conditions are the same, the coherency drops as epicenter distance and depth to the ground surface increases; and it drops quickly with low frequency while slowly with high frequency generally.

(3) Given that the site conditions of the 3 arrays are different, the statistical analysis results show that the influence of the site conditions on coherency cannot be ignored. Due to limitation of number of

arrays available and data, how to consider the site condition influence on coherency is a valuable issue.

(4) Comparatively speaking, the rules of the horizontal ground motion coherency variation reflect good coherency in the three array stations. As frequency increases the attenuation velocity of vertical coherency function in Eureka Samoa array is less than that of the other two arrays. On the one hand this phenomenon shows the influence of site condition. On the other hand, the limited record data of this array station is also one of the factors.

(5) The coherency function model in this paper shows the variation rules of coherency varying with depths well, and the statistical results of different arrays are well consistent with actual situation. This indicates that our suggested new model can illustrate the primary features of coherency variation along depth. The studying results filled the gaps of ground motion coherency varying with depths.

(6) Throughout the statistical results of the 3 arrays, if define the coherency function less than 0.4 as weak related, then the ground motions with depth lager than 100 meters away from the surface can be regarded as weak related.

(7) The spatial changes of ground motion are greatly affected by such factors as seismic source, path and site condition. In this paper, the influence of space, frequency and epicenter distance on ground motion coherency is considered in the study. Other factors, such as depth of seismic source or magnitude, etc. were not considered, which will be studied in our following research.

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REFERENCES

Qu Tiejun. (2003). Study on variation of the earthquake ground and sub-ground motion. Master's Degree Thesis Institute of Engineering Mechanics China Seismological Bureau, Harbin , P.R.C.

Wang Ji, Hu Xiao. (2006). MATLAB Application in Vibration Signal Processing .China Water Power Press, P.R.C.

Hu Yuxian. (1998). Earthquake Engineering . Seismological Press, P.R.C.

Nakamura H, Yamazaki F. (1995).Spatial variation of earthquake ground motion based on dense array records. *Transaction of the 13th International Conference on Structure Mechanics in Reactor Technology* **3:**19-24.

Harichandran R S and Vanmarcke E H. (1986). Stochastic variation of earthquake ground motion in space and time. *Eng. Mech.* **Div112:**154-17.

Loh C H ,Lin S G. (1990). Directionality and simulation in spatial variation of seismic waves. *Eng. Struct*. **12:** 134 -14.

Qu Tiejun, Wang Junjie, Wang Qianxin. (1996).Practical model of spatial variation of ground motion power spectral. *Acta Seismological Sinica of China* **18:1,**55-62.

Feng Qiming, Hu Yuxian. (1981). The mathematical model of the spatial correlation of ground motion. *Earthquake Engineering and Engineering Vibration* **1:2,**1-8.

Ding Haiping, Liu Qifang,Jin Xing, Yuan Yifan. (2003). A coherency model of ground motion on base-rock corresponding to dip-slip fault. *Earthquake Engineering and Engineering Vibration* **23:2**, 8-11.

Zheng Fei, Ye Jihong. (2009). The study of spatial coherency of ground motion. *Journal of Vibration and Shock of China* **28:9**,23-28.

Liu Xianming,Ye Jihong, Li Aiqun. (2004). Spatial coherency model of ground motion. *Engineering Mechanics* **21:2,**140-144.

Zhong Jufang, Hu Xiao, Qu Tiejun, Wu Shengxing. (2005). Spatial coherency analysis of different ground motion components at the same observational station. *Earthquake Research of China* **28:4,**378-383.