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ANALYSIS OF THE OBSERVED LAGGED COHERENCY OF CHLEF CITY (ALGERIA) DEPENDING ON V_{s30}

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ABSTRACT: The assumption that the seismic ground motion imposed on the supports of extended structures is uniform is no longer valid. Especially those which are generally constructed at sites with different soil characteristics. Among the causes which contribute to the non-uniformity of the seismic ground motion is the site effect. However, several coherency models which estimate this spatial variability of seismic ground motion do not consider this effect. In addition, these models have concentrated only on the horizontal direction while neglecting the vertical direction. The work at hand is an analysis of the observed lagged coherency by taking into account the site effect, which is often estimated by the average shear wave velocity over the upper 30 m of depth V_{s30}. This analysis tackles the three directions of the seismic ground motion. In this context, this study relies on fifteen seismic events recorded by nine seismological stations located in different sites in Chlef city from December 2014 to October 2015. As expected, the observed lagged coherency decreases with the increase of the separation distance d between two recording stations. The results prove that V_{s30} affects the observed lagged coherency. Thus, the tendency of the observed lagged coherency decreases with the decrease of V_{s30} defined for one or both recording stations. Therefore, the observed lagged coherency is influenced significantly by the site effect. Comparing three components of the observed lagged coherency indicates that the Vertical component is more significant than those of the East-West and North-South components.

Keywords: Spatial variability, Observed coherency, Site effect, V_{s30}, Chlef city

1. INTRODUCTION

During an earthquake, the induced ground motions can vary greatly from one point to another on the surface as well as in the depth of the ground [5] in terms of amplitude, duration and frequency content. This variation is known as the spatial variability of seismic ground motion (SVGM). The latter has an important effect on the response of extended structures such as pipelines, bridges and tunnels [15]. The SVGM can induce significant additional forces in extended structures compared to those obtained if it is assumed that the movements at all supports are identical. In fact, the causes contributing to SVGM are the wave passage effect, the incoherence effect and the site response effect [19]. The latter has significant effects on SVGM [6]. Moreover, it has an immense effect on seismic ground motion and can increase damage during an earthquake [3,4].

SVGM is often measured by the lagged coherency. There is a multitude of expressions of coherency models in literature: empirical models, semi-empirical models and analytical models [18-26]. Since empirical coherency models are dependent on the site parameters in which they are developed, they cannot be extrapolated to other sites. On the other hand, analytical or semi-empirical coherency models can extrapolate from one site to another, but these models assume that the site is laterally homogeneous, yet for extended and multi-support structures they are generally built on sites with lateral heterogeneity.

Many authors have demonstrated that site response effects influence the shape of the coherency function [8-10]. They studied the effect of local site condition on SVGM [12]. In this paper, the researchers aim at analyzing the observed lagged coherency based on the average shear wave velocity over the upper 30m of depth V_{s30} which is one of the most convenient parameters to describe site effects [1]. This analysis describes the spatial variability of the horizontal (EW and NS) and vertical (VER) directions of the seismic ground motion. The study was conducted in Chlef city, northwest of Algeria, which has a high seismic activity. A temporary array was installed in Chlef city by Layadi, K., Semmane, F. and Yelles-Chaouche, A. K [13]. A correlation was made between the acceleration records obtained during the 15 events to have the observed lagged coherency, then they were analyzed depending on the average shear wave velocity over the upper 30 m of depth V_{s30}.

2. CHLEF TEMPORARY SEISMIC ARRAY AND V_{s30}

In order to analyze the observed lagged coherency, a database was collected for this objective. Since the influence of the site effect on the SVGM, or in other words, the dependence of the lagged coherency on V_{s30} is needed, a database collected on an array where the recording stations are located at sites with different V_{s30} had to be utilized. In this study, the similar seismic database of Layadi, K., Semmane, F. and Yelles-Chaouche, A. K [13] is considered. It consists of 15 local and regional seismic events for the analysis of the observed lagged coherency based on V_{s30} for Chlef City, previously known as El Asnam, is at a high seismic risk. More details on the database including the spatial distribution of events, properties of earthquakes, selected signal segment and soil profile models of each station in term of V_s are available in the study established by Layadi, K., Semmane, F. and Yelles-Chaouche, A. K [13,14].

The temporary seismological array consisted of nine recording stations as well as the spatial distribution of recording stations are shown in Fig. 1, equipped with Omnirecs CUBE3 24-bit digitizers and Mark Products L22 sensors ($f_0 = 2Hz$). Instrumental response corrections were applied on the recorded waveforms measured in m/s for East-West (EW), North-South (NS) and vertical (VER) components. In the present analysis, a sequence of signal processing was performed to select the useful segment (details are given in Layadi, K., Semmane, F. and Yelles-Chaouche, A. K [13]).

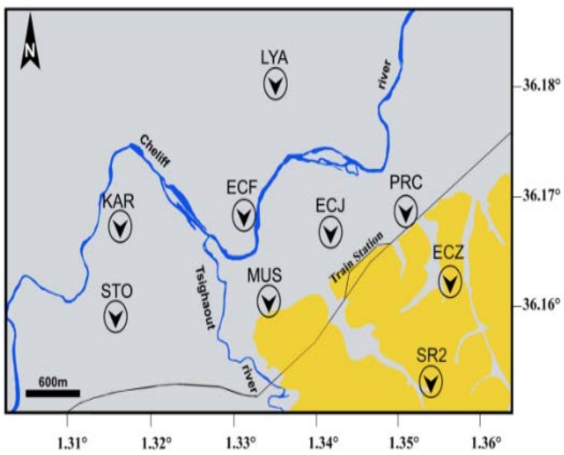


Fig. 1 Locations of the temporary seismological recording stations of Layadi, K., Semmane, F. and Yelles-Chaouche, A. K [13]

For the calculation of V_{s30}, the results of the near surface V_s structure of Chlef city obtained by Layadi, K., Semmane, F. and Yelles-Chaouche, A. K [14] for nine sites of the temporary seismological array as shown in Fig. 2 have been taken into account.

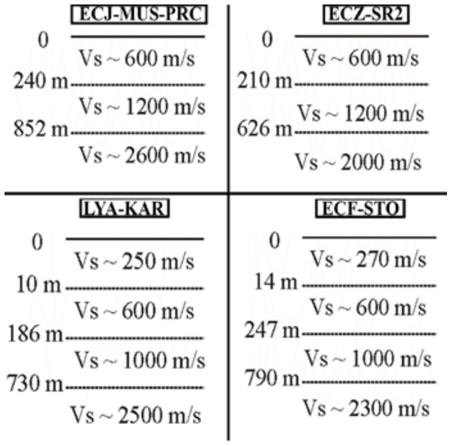


Fig. 2 Soil profile models of each station in term of Vs and depth modified from Layadi, K., Semmane, F. and Yelles-Chaouche, A. K [14]

To compute V_{s30}, the following formula will be applied:

$$V_{s30} = \frac{30}{\sum_i^n \frac{h_i}{V_{si}}} \tag{1}$$

Where $\sum_i^n h_i = 30$; and V_{si} is the shear wave velocity in layer i from the top, h_i is the thickness of layer i. The results are listed in Table 1.

Table 1 V_{s30} of each recording station

Station	V_{s30} (m/s)
ECF	380
ECJ	600
ECZ	600
KAR	410
LYA	410
MUS	600
PRC	600
SR2	600
STO	380

3. COHERENCY ANALYSIS FROM SINGLE EVENTS

3.1 Introduction

The covariance function is used for the derivation of the coherency function. For engineering applications, the covariance function, intended as second-order statistics, between the accelerograms recorded at different stations are used to characterize the spatial variability of seismic ground motion. The frequency domain description of the second-order statistics is used because of its mathematical convenience in random vibration analysis. The coherency function $\delta_{ij}(\omega)$ between two accelerograms recorded at two stations i and j is defined as follows [9]:

$$\delta_{ij}(\omega) = \frac{S_{ij}(\omega)}{\sqrt{S_{ii}(\omega)\, S_{jj}(\omega)}} \tag{2}$$

Where $S_{ii}(\omega)$ and $S_{jj}(\omega)$ are auto-power spectral densities of point i and point j, respectively and $S_{ij}(\omega)$ is the cross power spectral density of the ground motion between two random points, the coherency function is a dimensionless complex-valued number that represents variation in Fourier phase between two signals. Lagged coherency is the absolute value of the coherency function, and it is often used to describe the SVGM [16,17]. The lagged coherency has been estimated after aligning the two-time histories by using the time lag that leads to the largest correlation.

$$\delta_{ij}(d,\omega) = \left|\delta_{ij}(d,\omega)\right| exp\left[i\theta_{ij}(d,\omega)\right] \tag{3}$$

Where the amplitude (lagged coherency) measures phase variations from random effects and the complex phase, $\theta_{ij}(d,\omega)$, represents deterministic effects (i.e. wave passage). Both determination of phase difference between two stations i and j are functions of separation distance, d , and frequency. As mentioned before, many researches have been done for spatial variability with the development of large seismic arrays and the collection of seismic records. The spatial variation of earthquake ground motion in an extended area has the following characteristics: The coherence of ground motion between two random points decreases as the distance between the points and the frequency of the ground motion increases.

3.2 Seismic Array Records

To estimate the lagged coherency, the researchers had to correlate the seismic ground motion collected from the seismic array. The correlation was made for the three directions EW, NS and VER components of the seismic ground motion. For clarification, the acceleration records of the second event occurred on December 23, 2014 at 08:59 for the EW direction are shown in Fig. 3.

The earthquake data window is placed to restrict the analysis to the frequency bands of interest for seismic signals analysis. The Hamming window [7], also called the ascending cosine window, is used in the data window. The window function is given by:

$$\omega(n) = \frac{1}{2}\left[1 - cos\left(\frac{2\pi n}{N-1}\right)\right] R_N(n) \tag{4}$$

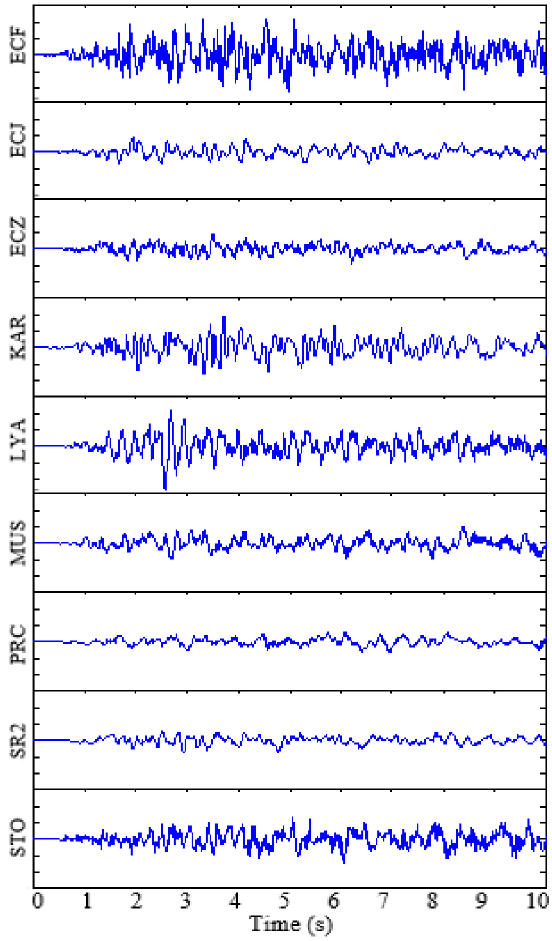


Fig. 3 Acceleration records of the array stations in the EW direction of the second event (one unit of the vertical axes represents 0.001 mm/s²: ±3 unit)

Its power spectrum is given by:

$$W(\omega) = \left\{0.5W_R(\omega) + 0.25\left[W_R\left(\omega - \frac{2\pi}{N-1}\right) - W_R\left(\omega + \frac{2\pi}{N-1}\right)\right]\right\} \tag{5}$$

$$W_R(\omega) = \frac{sin(\omega N/2)}{sin(\omega/2)} \tag{6}$$

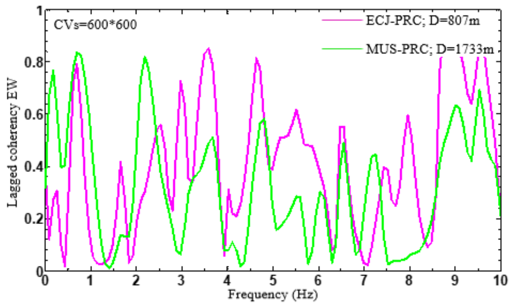
The coherency function generally depends on the frequency f and the separation distance d between the recording stations, the main goal of the paper at hand is to see the effect of V_{s30} on the SVGM, the nine (09) recording stations are placed on sites which have different V_{s30}. From a simple point of view, and to see the effect of f, d and V_{s30} on the SVGM, our analysis will be made for two lagged coherencies observed for a single event.

3.3 Effect of the Separation Distance *d*

Firstly, for two measuring points i and j having two V_{s30i} and V_{s30j} respectively, a coefficient of the shear wave velocity30 CV_{s30} is named and assumed equal to the multiplication of V_{s30i} and V_{s30j} , i.e. $CV_{s30} = V_{s30i} * V_{s30j}$. The researchers proposed a multiplication $(CV_{s30} = V_{s30i} * V_{s30j})$ and not a ratio $(CV_{s30} = V_{s30i}/V_{s30j})$, because they are aware that for the two recording stations i and j the lagged coherency are the same $(\delta_{ij} = \delta_{ji})$, so the ratio gives us two different CV_{s30} $\left((CV_{s30ij} = V_{s30i}/V_{s30j}) \neq (CV_{s30ji} = V_{s30j}/V_{s30i})\right)$ and therefore two different lagged coherency $(\delta_{ij} \neq \delta_{ji})$.

To see the effect of the separation distance d on the SVGM, two observed lagged coherences having the same CV_{s30} for each direction of the seismic ground motion have been compared. In this section, the sixth event occurred on March 17, 2015 will be analyzed.

Fig. 4 represents the variation of the observed lagged coherency during the sixth event for three components of seismic ground motion.



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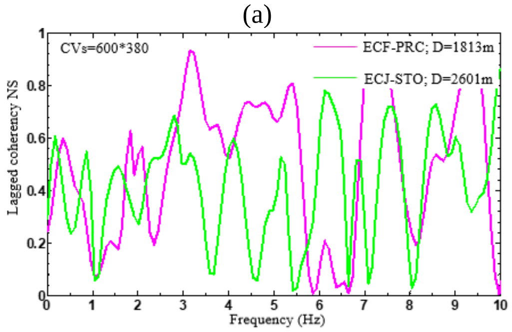

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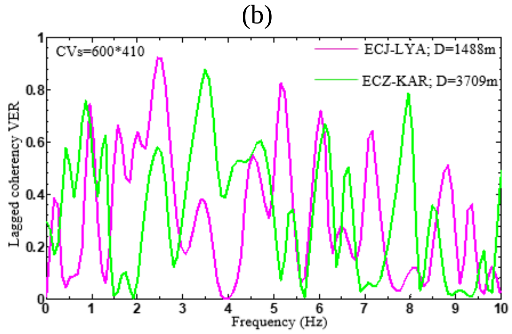


(c)

Fig. 4 Variation of the observed lagged coherency obtained from the sixth event: (a) EW component (b) NS component (c) VER component

Fig. 4-a shows that the CV_{s30} of ECJ and PRC is equal to that of MUS and PRC ($CV_{s30} = 600 * 600$), but the two distances along the seismic wave are different (for ECJ and PRC, d=807m, and for MUS and PRC, d=1733m), the analysis of the Fig. 4-a shows that the tendency of the observed lagged coherency of ECJ and PRC is large to that of MUS and PRC. Fig. 4-b shows that the CV_{s30} of ECF and PRC is equal to that of ECJ and STO ($CV_{s30} = 600 * 380$), but the two distances along the seismic wave are different (for ECF and PRC, d=1813m, and for ECJ and STO, d=2601m), the analysis of the Fig. 4-b shows that the tendency of the observed lagged coherency of ECF and PRC is large to that of ECJ and STO. Fig. 4-c shows that the CV_{s30} of ECJ and LYA is equal to that of ECZ and KAR ($CV_{s30} = 600 * 410$), but the two distances along the seismic wave are different (for ECJ and LYA, d=1488m, and for ECZ and KAR, d=3709m), the analysis of the Fig. 4-c shows that the tendency of the observed lagged coherency of ECJ and LYA is large to that of ECZ and KAR.

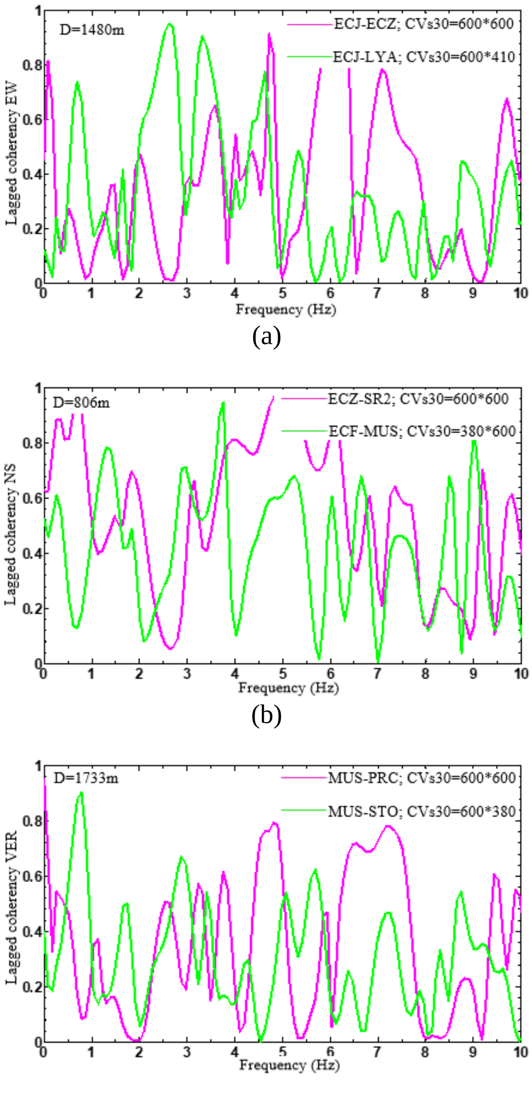
Therefore, for a particular value of CV_{s30}, tendency of the observed lagged coherency decreases with the increasing of the separation distances d between two recording stations, this decrease of the observed lagged coherency is noticed for the EW, NS and VER directions of seismic ground motion. Fig. 4 shows that the same conclusions can be drawn for another pair of recording stations.

3.4 Effect of V_{s30}

To investigate the effect of CV_{s30} on the lagged coherency, taking two lagged coherences having the same separation distance d are needed. This analysis is conducted for three directions of the seismic ground motion. Fig. 5 shows the variation of the lagged coherency observed during the sixth event for the same separation distance d considering the components: EW, NS and VER of the seismic ground motion.

Fig. 5-a shows that the separation distance d between ECJ and ECZ is equal to that between ECJ and LYA ($d = 1480m$), but the CV_{s30} of the two pairs of recording stations are different (for ECJ and ECZ, $CV_{s30} = 600 * 600$, and for ECJ and LYA, $CV_{s30} = 600 * 410$). The analysis of the Fig. 5-a shows that the tendency of the observed lagged coherency of ECJ and ECZ is large to that of ECJ and LYA. Fig. 5-b shows that the separation distance d between ECZ and SR2 is equal to that between ECF and MUS ($d = 806m$), but the CV_{s30} of the two pairs of recording stations are different (for ECZ and SR2, $CV_{s30} = 600 * 600$, and for ECF and MUS, $CV_{s30} = 380 * 600$), the analysis of the Fig. 5-b shows that the tendency of the

observed lagged coherency of ECZ and SR2 is large to that of ECF and MUS. Fig. 5-c shows that the separation distance d between MUS and PRC is equal to that between MUS and STO ($d = 1733m$), but the CV_{s30} of the two pairs of recording stations are different (for MUS and PRC, $CV_{s30} = 600 * 600$, and for MUS and STO, $CV_{s30} = 600 * 380$), the analysis of the Fig. 5-c shows that the tendency of the observed lagged coherency of MUS and PRC is larger than that of MUS and STO.



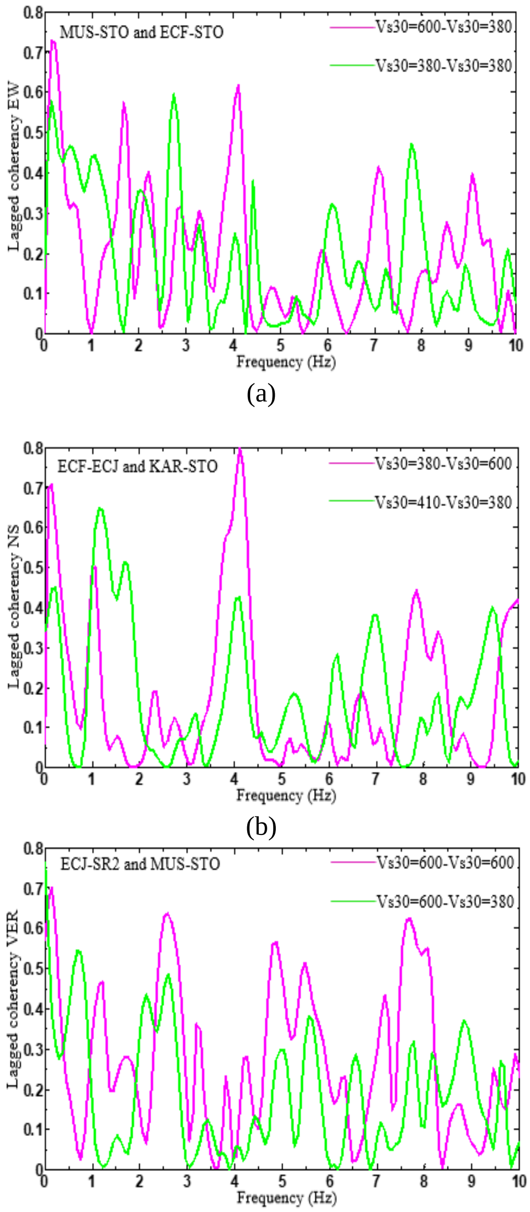
(a)

(b)

(c)

Fig. 5 Variation of the observed lagged coherency in terms of dependence of CV_{s30} for the sixth event: (a) EW component (b) NS component (c) VER component

Therefore, for a particular value of separation distance d, tendency of the observed lagged coherency increases with the increasing of CV_{s30}, this increase in observed lagged coherency is noticed for all components. Fig. 5 shows that the same conclusions can be drawn for another pair of recording stations. Now the researchers want to tackle an important observation concerning the effect of CV_{s30} in details, i.e. the effect of V_{s30} for each of the two sites to be studied on the variation of the observed lagged coherency. Therefore, the variation of the observed lagged coherency will be analyzed directly by using V_{s30i} and V_{s30j} of the two sites i and j respectively. In this part, the third event occurred on December 26, 2014 we will analyzed. We must emphasize that the low values of V_{s30}correspond to soft soil, while higher values of V_{s30} imply that the soil is rocky [10]. To see the effect of V_{s30} on the observed lagged coherency, it is necessary to consider two observed lagged coherences having almost the same separation distance d for each direction of the seismic ground motion.



(a)

(b)

(c)

Fig. 6 Effect of V_{s30} on the observed lagged coherency obtained from the third event: (a) EW component (b) NS component (c) VER component

Fig. 6-a shows that the separation distance d between MUS and STO is equal to that between ECF and STO ($d = 1738m$), and the V_{s30} of STO is the same for the two pairs of recording stations ($V_{s30} = 380$), but the V_{s30} of MUS for the first pair recording stations is different to that of ECF for the second pair recording stations (for MUS, $V_{s30} = 600$, and for ECF, $V_{s30} = 380$). So, the analysis of the Fig. 6-a shows that the tendency of the observed lagged coherency of MUS and STO is large to that of ECF and STO.

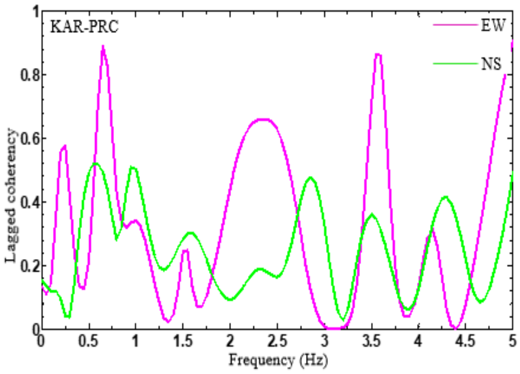
Fig. 6-b shows that the separation distance d between ECF and ECJ is equal to that between KAR and STO ($d = 1027m$), and the V_{s30} of ECF and STO is the same for the two pairs of recording stations ($V_{s30} = 380$), but the V_{s30} of ECJ for the first pair recording stations is different to that of KAR for the second pair recording stations (for ECJ, $V_{s30} = 600$, and for KAR, $V_{s30} = 410$). So, the analysis of the Fig. 6-b shows that the tendency of the observed lagged coherency of ECF and ECJ is large to that of KAR and STO.

Fig. 6-c shows that the separation distance d between ECJ and SR2 is equal to that between MUS and STO ($d = 1779m$), and the V_{s30} of ECJ and MUS is the same for the two pairs of recording stations ($V_{s30} = 600$), but the V_{s30} of SR2 for the first pair recording stations is different to that of STO for the second pair recording stations (for SR2, $V_{s30} = 600$, and for STO, $V_{s30} = 380$). So, the analysis of the Fig. 6-c shows that the tendency of the observed lagged coherency of ECJ and SR2 is large to that of MUS and STO.

Therefore, for a particular value of separation distance d, interesting results have been obtained (Fig. 6). If it is assumed that two sites i and j have two average shear wave velocities V_{s30i} and V_{s30i} respectively, and if V_{s30i} is known, then, tendency of the observed lagged coherency increases with the increasing of the V_{s30j} (that's mean the point j located on rock soil) and decreases with the decreasing of the V_{s30j} (that means that the point j is located on soft soil). This result in the variation of the observed lagged coherency is noticed for all components.

3.5 Comparison Between the Observed Lagged Coherency of Vertical and Horizontal Ground Motion

The observed lagged coherency for the three directions of seismic ground motion is obtained on the basis of seismic records in terms of acceleration for the three components. In order for the three components EW, NS and VER of the observed lagged coherency to be compared, they must be observed during the same event and for the same pair of recording stations (i.e. the same separation distance d between the recording stations for the three components). For this purpose, the eighth event occurred on April 26, 2015 will be chosen. Within the same event, the two recording stations KAR and PRC with a separation distance of $d = 3096m$ will be selected. This analysis is presented in Fig. 7. The observed lagged coherency is not isotropic for either horizontal or vertical ground motion. This result has been found by other authors [11]. The relationship between the results of lagged coherency of EW, NS and VER components of the seismic ground motion data is studied for the coefficient of the shear wave velocity30 $CV_{s30} = 410 * 600$.



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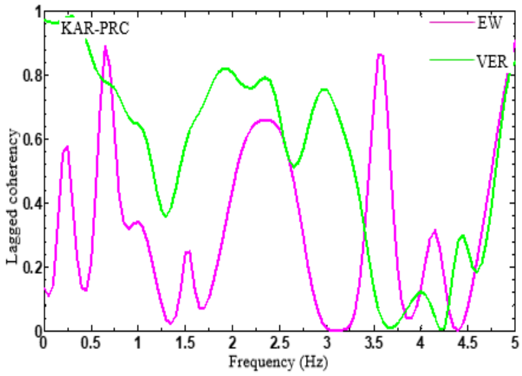

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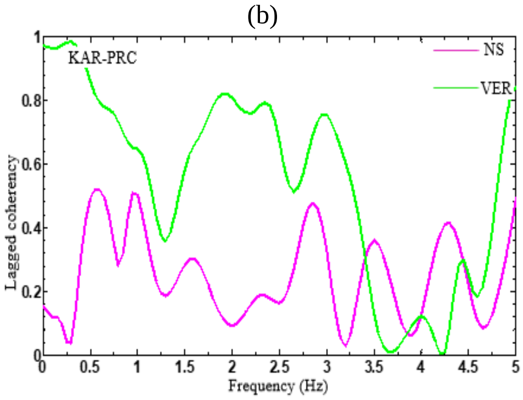

(c)

Fig. 7 Comparison of the three components of the lagged coherency observed during the eighth event

For a particular value of CV_{s30}, trend of the lagged coherency for the VER component is larger than the EW and NS components, and trend of the lagged coherency for the EW component is larger than the NS component. Since the separation distance is long ($d = 3096m$), the comparison was made only for low frequencies [2] so that the figures can be analyzed well.

4. CONCLUSION

The current study aimed at analyzing the influence of the site effect on the SVGM. Fifteen local and regional events were recorded by nine seismological stations installed in Chlef city, which is considered among the Algerian cities most exposed to seismic risk. In the first part, the site effect has been estimated, i.e. determining the average shear wave velocity over the upper 30m of depth $\boldsymbol{V_{s30}}$ for each site where a recording station was placed. The acceleration records have been correlated with one another and for the three directions of seismic ground motion in the second part to have the observed lagged coherency. Through a parametric analysis of the observed lagged coherency, the following conclusions were perceived:

(1) Tendency of the observed lagged coherency decreases with the increase of the separation distance d between two recording stations, this result is noticed for the three directions seismic ground motion.

(2) For two measuring points i and j having the average shear wave velocity over the upper 30m of depth V_{s30i} and V_{s30j} respectively, tendency of the observed lagged coherency increases with increasing of the V_{s30i} and/or V_{s30j}, to put it differently, tendency of the observed lagged coherency increases with the increasing of the coefficient of the shear wave velocity30, CV_{s30}, defined as $CV_{s30} = V_{s30i} * V_{s30j}$.

(3) The observed lagged coherency of the horizontal seismic ground motion, as well as the observed lagged coherency of the vertical seismic ground motion, is not isotropic. Tendency of the observed lagged coherency of the VER component of seismic ground motions is larger than that of EW and NS components of seismic ground motion, and tendency of the observed lagged coherency of the EW component of seismic ground motion is larger than that of the NS component of seismic ground motion.

This article proposes an analysis of the observed lagged coherency based on the site effect estimated by the average shear wave velocity over the upper 30m of depth $\boldsymbol{V_{s30}}$. This study can provide a basic information about modelling coherency of seismic ground motion in terms of soil heterogeneity for the engineers who study the effects of the SVGM on the dynamic response of extended structures, such as bridges, pipelines and tunnels, notably built on sites with non-uniform soil profiles.

5. ACKNOWLEDGMENTS

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