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EFFECTS OF STOCHASTIC SOIL LAYES ON GOUND-MOTION INCOHERENCE: A CASE STUDY IN NW ALGERIA

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Abstract

Seismic design of common engineering structures is based on the assumption that excitations at all support points are uniform or fully coherent. However, in lifeline structures with dimensions of the order of wavelengths of incident seismic waves, spatial variation of seismic ground motions caused by incoherence effects and stochasticity in the characteristics of the surface layers may introduce significant additional forces in their structural elements. The main objective of this paper is to provide estimates of coherency functions of spatially variable ground motion at the free surface of a layered stochastic soil sites in the epicentral region of the El-Asnam Earthquake in Algeria. Lagged coherency functions at bedrock have been estimated in [1] by simulating ground motion field (around Sogedia Factory) corresponding to the 1980 El-Asnam Earthquake. Considering randomness in the thickness of soil layers overlying the bedrock in the study area, an analytical approach proposed by Zerva and Harada [2] is used to evaluate lagged coherency functions at the surface. Soil proprieties are assumed to vary laterally with a Gaussian distribution. Contribution of various factors such as damping ratio of the soil, soil predominant frequency and its spatial variation, and wave propagation velocity on lagged coherency in the surface are investigated. Numerical results indicate that spatial coherence of surface motion is similar to that of bedrock motion, except at the predominant frequency of the site, where a sharp decrease in lagged coherency is observed. It is also observed that, even for firm soil conditions, later homogeneity of site can significantly affect lagged coherency of motion at ground surface.

Keywords: Coherency function; spatial variability; seismic ground motion; random soil

1. Introduction

Spatially varying ground motions (SVGMs), exhibiting spatial differences in their amplitude and phases, have a significant effect on the responses of spatially extended structures (e.g., [1]), such as Nuclear Power Plant (NPP) structures, where the nonlinear structural response history analysis necessitates the synthesis of SVGMs, as well as other lifeline structures. This phenomenon has been the motivation of numerous studies which have revealed four contributing mechanisms, namely, the wave passage effect, random loss of coherency due to source and path effects, the attenuation effect, and local site effects that cause incoherent ground surface motion.

Several generic models of coherency (random phase variability), which can be classified as empirical, semi-empirical, analytical, and theoretical models, have been proposed in the literature. Most of these models are derived or regressed from strong motion data recorded by dense arrays such as the El-Centro array in California, the SMART-1 strong motion array in Taiwan, and the Parkway Valley array in New Zealand (see, for example, [2]). It is well known that coherency models calibrated from data collected in one region may not be suitable for use in other areas (see, for example, [3]; [4]; [5]; [6]). Despite this, due to lack of local data, coherency models calibrated for one region are often used to simulate ground motion in other regions, sometimes with different tectonic and geological settings.

An alternative method, in lack of recorded data which is the case in the current study area (epicentral region of the 1980 El-Asnam Earthquake in northwest Algeria), is to numerically simulate spatially variable ground motion. In this context, stochastic simulation methods (see, for example, [7]) which require pre-specified coherency functions are not applicable, and one needs to resort to simulation based on the physics of seismic source and wave propagation. Recently, AfifChaouch et al. [8] presented an extension of the finite-source Empirical Green's Function (EGF) method of Irikura et al. [9] to synthesize SVGMs and thereby estimate lagged coherency functions at the bedrock of the study area. Based on simulated motion, a parametric model of lagged coherency at bedrock was also presented by AfifChaouch et al. [8]. This contribution extends the work presented in [8] by investigating the influence of local site conditions in lagged coherency functions, and thereby obtain lagged coherency functions at the ground surface, which can then be used to simulate spatially variable surface motion for engineering applications.

Influence of site conditions on surface ground motion characteristics has been widely investigated and extensively documented. Site influence on lagged coherency is generally strong as the surface layers underneath a site are usually the most heterogeneous portion of the propagation path between the source and the site. Complex wave propagation phenomena in laterally heterogeneous soil leads to alteration of ground motion phases and therefore contribute to incoherence of surface motion. (see, for example, [3]). Unfortunately, such effects cannot be deterministically quantified, and a stochastic approach needs to be adopted. Zerva and Harada [10] simplified horizontally stochastic soil layers at a site as an equivalent single-degree-of-freedom system with random characteristics and studied the effect of this stochasticity on lagged coherency function at the surface. Their results indicated that the effect of this stochasticity reduces the coherency function significantly at mean predominant site frequency. Their results are consistent with those of Cranswick [11] and Liao and Li [12].

In this contribution, we apply the method of Zerva and Harada [10] to investigate the effects of lateral soil hererogeneity in lagged coherency of strong ground motion in the epicentral region of the 1980 El-Asnam Earthquake in northwest Algeria. Due to the lack of sufficient information to describe lateral variability soil mechanical properties, only randomness in the thickness of the different layers are modelled.

2. Spatial coherency function

Spatial variability of ground motion is caused by a number of factors as is explained in [13]. Considering, motions $a_i(t)$ and $a_j(t)$ at two discrete locations i and j separated by a distance ξ, the complex coherency function in space and circular frequency (ω) is defined as:

$$\gamma_{ij}(\xi,\omega)=\frac{S_{ij}(\xi,\omega)}{\sqrt{S_{ii}(\omega)S_{jj}(\omega)}} \tag{1}$$

where $S_{ij}(\xi,\omega)$ is the smoothed cross spectral density function of $a_i(t)$ and $a_j(t)$; and $S_{ii}(\omega)$ and $S_{jj}(\omega)$ are their smoothed power spectral density functions. Separating $\gamma_{ij}(\xi,\omega)$ into its absolute value and phase, we obtain

$$\gamma_{ij}(\xi,\omega)=\left|\gamma_{ij}(\xi,\omega)\right|\exp\left[i\theta_{ij}(\xi,\omega)\right] \tag{2}$$

where $0\le\left|\gamma_{ij}(\xi,\omega)\right|\le 1$, is called the lagged coherency function and $\theta_{ij}(\xi,\omega)$ is the phase spectrum. Lagged coherency squared is termed as coherency.

3. Seismic ground motions in homogeneous stochastic layered media

3.1 Homogeneous stochastic horizontal ground

In conventional seismic ground response analysis, it is common to model the ground with layers of constant thickness and uniform mechanical properties. However, as schematically shown in Fig. 1, where X and Z represent the horizontal and vertical space coordinates, respectively, the soil thickness $H_j(x)$ of the j^{th} layer may vary randomly in the X-direction. Similarly, a representative soil property $q(x,z)$ may be a random function of x and z. As in the Zerva and Harada [10] study, it is assumed, as a first approximation, that the layer thickness $H_j(x)$ and soil property $q(x,z)$ are random functions only of the x coordinate.

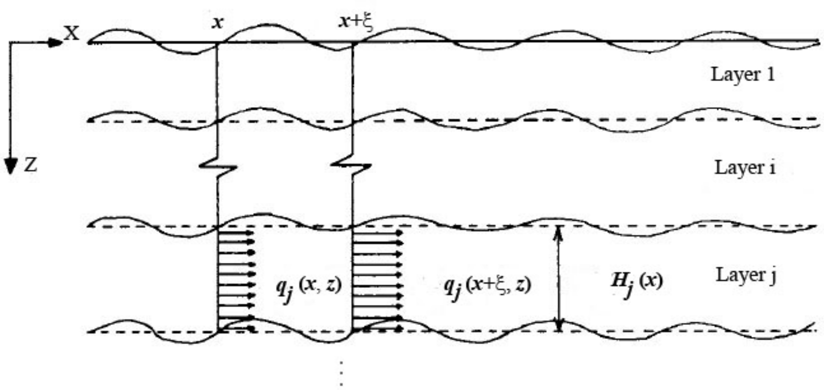


Fig. 1 - Horizontal soil layers showing layer depth $H_j(x)$ and soil property $q_j(x,z)$

$$H_j(x)=H_j\left[1+f_{H_j}(x)\right] \tag{3}$$

$$q(x,z)=q(z)\left[1+f_q(x)\right] \tag{4}$$

where H_j and $q(z)$ are the expected values of $H_j(x)$ and $q(x,z)$ with respect to x, and are deterministic functions of the z coordinate.

$$\mathrm{E}\left[H_j(x)\right]=H_j \tag{5}$$

$$\mathrm{E}\left[q(x,z)\right]=q(z) \tag{6}$$

The quantities $f_{H_j}(x)$ and $f_q(x)$ in Eqs. (3) and (4) represent stochastic fluctuations of $H_j(x)$ and $q(x,z)$ with respect to x and are both zero-mean random variables.

3.2 Propagation of ground-motion waves

Consider soil layers resting on rigid bedrock and subjected to earthquake ground motion as shown in Fig. 1. The total soil depth is assumed to be a constant H. The input earthquake ground motion at the bedrock is assumed to be a stationary random wave propagating with speed c in the X-direction and represented by $u_b(x,t)$. The displacement time history at any location (x,z) within the soil layers is the sum of $u_b(x,t)$ and the relative displacement between the bedrock and the location under consideration, denoted here as $u_r(x,z,t)$.

$$u(x,z,t) = u_b(x,t) + u_r(x,z,t) \tag{7}$$

The equation of motion at the surface $(z=0)$, expressed in terms of the generalized displacement $u^*(x,t)$, is given by (see, [10] for details):

$$\ddot{u}^*(x,t) + \left(2\zeta^*(x)\ \omega^*(x)\right)\ \dot{u}^*(x,t) + \left(\omega^*(x)\right)^2 u^*(x,t) \ = \ -\beta\ \ddot{u}_b(x,t) \tag{8}$$

where $\omega^*(x)$ is the predominant natural frequency of the ground, β is the participation factor, and $\zeta^*(x)$ is its equivalent damping ratio. The predominant ground frequency $\omega^*(x)$ and its equivalent damping ratio $\zeta^*(x)$ may also be written as:

$$\omega^*(x) = \omega_0\left[1+\omega(x)\right] \tag{9}$$

$$\zeta^*(x) = \zeta_0\left[1+\zeta(x)\right] \tag{10}$$

where ω_0 and ζ_0 are the mean values of $\omega^*(x)$ and $\zeta^*(x)$, respectively, and $\omega(x)$ and $\zeta(x)$ are homogeneous stochastic fields with zero mean and corresponding standard deviations $\sigma_{\omega\omega}$ and $\sigma_{\zeta\zeta}$. The cross-spectral density function of the surface displacement, can then be expressed as that of bedrock displacement as

$$S_{uu}(\xi,\omega) = \begin{pmatrix} (\omega_0^4 + (2\beta + 4\zeta_0^4 - 2)\omega_0^2\omega^2 + (\beta-1)^2\omega^4)\cdot\left|H(\omega_0,\zeta_0,\omega)\right|^2 \\ +4\beta^2\omega_0^4\omega^4 R_{\omega\omega}(\xi)\cdot\left|H(\omega_0,\zeta_0,\omega)\right|^4 \end{pmatrix} S_{u_b u_b}(\xi,\omega) \tag{11}$$

where, $R_{\omega\omega}(\xi)$ is the autocorrelation of the $\omega(x)$ and $H(\omega_0,\zeta_0,\omega)$ is the complex frequency response function given by the following equation.

$$H(\omega_0,\zeta_0,\omega) = \frac{1}{\omega_0^2 - \omega^2 + 2i\zeta_0\omega_0\omega} \tag{12}$$

The corresponding power spectral density is obtained from Eq. (11) by setting the separation distance equal to zero, $(\xi = 0)$, i.e.,

$$S_{uu}(\omega) = \begin{pmatrix} (\omega_0^4 + (2\beta + 4\zeta_0^4 - 2)\omega_0^2\omega^2 + (\beta-1)^2\omega^4)\cdot\left|H(\omega_0,\zeta_0,\omega)\right|^2 \\ +4\beta^2\omega_0^4\omega^4\sigma_{\omega\omega}^2\cdot\left|H(\omega_0,\zeta_0,\omega)\right|^4 \end{pmatrix} S_{u_b u_b}(\omega) \tag{13}$$

where $S_{u_b u_b}(\omega) = S_{u_b u_b}(\xi = 0, \omega)$ is the power spectrum of the bedrock motion.

3.3 Spatial variability of surface motion

The complex coherency function of surface motion is composed of terms corresponding to wave passage effects, bedrock motion coherency function, and site response contribution [13], expressed as (see, for example, [10])

$$\gamma_{SV}(\xi,\omega)=\frac{S_{uu}(\xi,\omega)}{S_{uu}(\omega)}=\gamma_{b,coh}(\xi,\omega)\cdot\gamma_{b,prop}(\xi,\omega)\cdot\gamma_{l,coh}(\xi,\omega) \tag{14}$$

where $\gamma_{b,coh}(\xi,\omega)$ is complex coherency function of bedrock motion. In this work, this function is parametrized by the Hindy and Novak model [14]

$$\gamma_{b,coh}(\xi,\omega)=\exp\left\{-(\alpha\omega\xi)^{\lambda}\right\} \tag{15}$$

where α and λ are model parameters, and its particular case with $\lambda=2$ is the Luco and Wong model [15]. These models have been extensively used by researchers in seismic response analysis of lifelines (e.g. [12]; [10]; [16]). The parameters of the model were calibrated from coherency functions estimated from ground motion simulated at the bedrock of the epicentral region of the 1980 El-Asnam Earthquake. In Eq. (14), $\gamma_{b,prop}(\xi,\omega)=\exp\left\{-\mathrm{i}\omega\xi/\omega\right\}$ is a term describing the wave passage effect, and $\gamma_{l,coh}(\xi,\omega)$ represents the contribution of the soil stochasticity, and is given by:

$$\gamma_{l,coh}=\frac{\left[H_1(\beta,\omega_0,\zeta_0,\omega)+R_{\omega\omega}(\xi)\cdot H_2(\beta,\omega_0,\zeta_0,\omega)\right]}{\left[H_1(\beta,\omega_0,\zeta_0,\omega)+\sigma^2_{\omega\omega}\cdot H_2(\beta,\omega_0,\zeta_0,\omega)\right]} \tag{16}$$

with

$$\begin{gathered}H_1(\beta,\omega_0,\zeta_0,\omega)=(\omega_0^4+(2\beta+4\zeta_0^4-2)\omega_0^2\omega^2+(\beta-1)^2\omega^4)\cdot\left|H(\omega_0,\zeta_0,\omega)\right|^2\\ H_2(\beta,\omega_0,\zeta_0,\omega)=4\beta^2\omega_0^4\omega^4\cdot\left|H(\omega_0,\zeta_0,\omega)\right|^4\end{gathered} \tag{17}$$

3.4 Stochastic characteristics of the ground

The parameters of the proposed model ζ_0, ω_0, $\sigma_{\omega\omega}$ and $R_{\omega\omega}(\xi)$ depend on soil type. In the present study, we consider the Sogedia site in El-Asnam city. The soil conditions at the site are shown in Figs. 2a and 2b and Table 1, over a length of 1200m. The thicknesses and material properties given in Fig. 2a and Table 1, respectively, represent mean values (expected values) estimated by Petrovski and Milutinovic [17]. Due to lack of data, it is assumed that stochasticity in soil characteristics is due to the variability in the depth of the layers. A Gaussian distribution [18] is assumed for layer thickness with a 20% coefficient of variation. The bedrock is assumed to be rigid. The ground is uniformly divided into sixty 20m sections. The predominant ground frequency of each of these sections, $\omega^*(x_n)$ (n= 1,2,...,60), may be computed by Eq. (18) (an extension of Okamoto's Equation [19]). The mean predominant frequency is $\omega_0=9.6\pi$ rad/s ($f_0=4.8$ hz) with a corresponding standard deviation of $\sigma_{\omega\omega}=0.06$.

$$\omega^*(x_n)=\frac{\pi}{2}\frac{1}{\sum_{j=1}^{M}H_j(x_n)/v_{S_j}(x_n)} \tag{18}$$

Damping in each layer was estimated by using equivalent linear one dimensional site response analysis (see, for example, [20]). The bedrock motion is used as input motion and an iterative procedure is used to estimate damping ratio of an equivalent linear system. The numerical values of damping ratio for each soil layer are given in Table 1 and they are in accord with those estimated by [17]. We note that this approach is different from the one commonly used in investigation of the effects of lateral ground heterogeneities in ground-motion coherence. For example, for a firm site, a damping ratio of 60% has been used by Zerva and Harada [10] based on observations that average power spectral density functions of recorded ground motion at firm sites match the so-called modified Kanai-Tajimi model with the parameter ζ_g equal to 0.6.

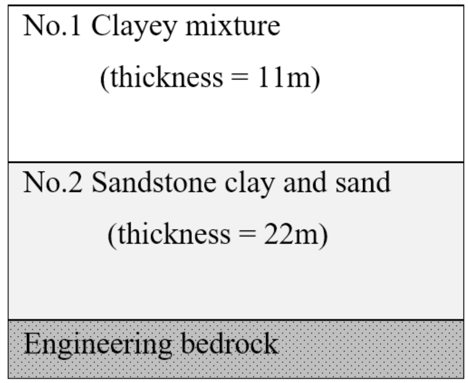
This parameter of the Kanai-Tajimi model can be interpreted to represent ground damping, but is not necessarily related to it. In particular, when power spectral density functions of ground motion recorded at different sites (all relatively firm but with slightly different predominant frequencies) are averaged, the averaging operation smoothens the peaks of the spectra of individual ground motion. The resulting average spectrum therefore has a broader peak whose width is not representative of the widths of the individual spectra. Estimating damping (which controls the width of the peak) from the average spectra may therefore not be reliable. In any case, damping values as high as 60% are not realistic for firm soils. It is interesting to note that damping ratios of soft and firm sites estimated from average Kanai-Tajimi spectra are not consistent with common geotechnical engineering practice. For example, in studies such as [10], soft soils are assumed to have much lower damping ratio than firm sites. It is well known that soft soils dissipate more energy during inelastic deformations and therefore exhibit higher damping than firm sites. The participation factor is taken as $\beta = 4/\pi$ (see, for example, Zerva and Harada [10]). The sample spatial correlation function $R_{\omega\omega}(\xi)$ of $\omega(x)$ is calculated by interpreting the sample $\omega^*(x_n)$ as a realization of the homogeneous stochastic process $\omega^*(x)$, using the following equation:

$$\tilde{R}_{\omega\omega}(\xi_k) = \frac{1}{N-k}\sum_{n=1}^{N-k}\left[\left(\frac{\omega^*(x_n+\xi_k)-\omega_0}{\omega_0}\right)\cdot\left(\frac{\omega^*(x_n)-\omega_0}{\omega_0}\right)\right] \tag{19}$$

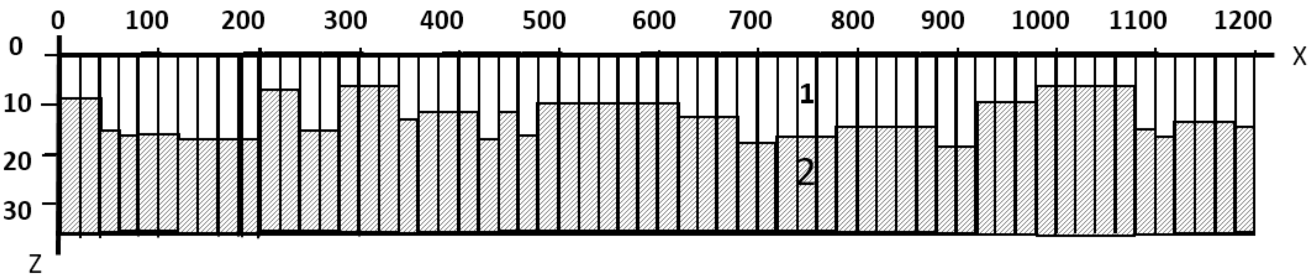
where N is the total number of soil sections (60). To avoid a small averaging number N-k in Eq. (19), $\xi_k = 600m$ is used as the longest separation distance.

Table 1- Material properties of the soil layers shown in Fig. 2.

Soil type	Mass density (gr/cm^3)	Poisson's ratio	Shear modulus (kgf/cm^2)	Shear wave velocity (m/s)	Damping ratio (%)
1- Clayey mixture	1.90	0.48	3040	400	5
2- Sandstone clay and sand	2.30	0.48	18630	900	3



(a)



(b)

Fig. 2 – (a) Site profile at Sogedia Factory in northwest Algeria with mean layer thicknesses as shown (from [17]), and (b) a realization of the soil profile (bedrock not shown) with stochastic layer thickness.

The resulting normalized spatial correlation function $\tilde{R}_{\omega\omega}(\xi_k)/\tilde{R}_{\omega\omega}(0)$ is shown in Fig. 3. The power spectral density of the surface motion and bedrock, their ratio, and the equivalent linear transfer function of the mean profile (Fig. 2a) are shown in Fig. 4. As expected, the power density near the site fundamental frequency is amplified.

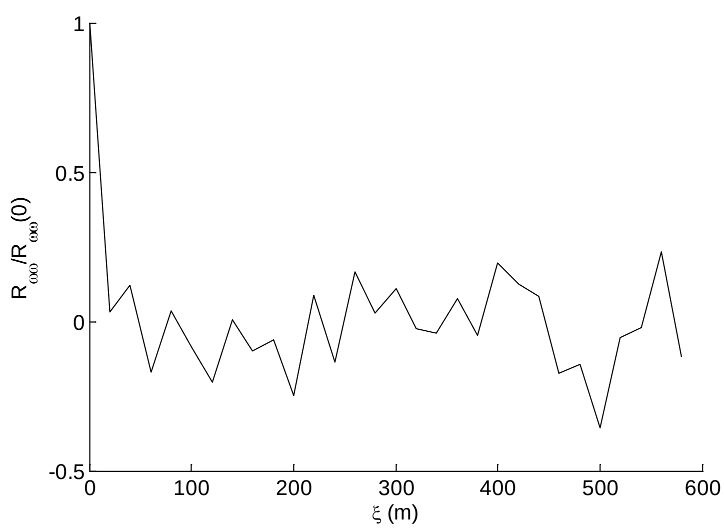


Fig. 3 – (a) Spatial auto-correlation function of natural frequency of the site profile shown in Fig. 2.

The contributions of the layer stochasticity to lagged coherency at the ground surface (see Eq. 16), at separation distances of 40, 100, 200, and 500 m are presented in Fig. 5. The effect of soil heterogeneity is to significantly decrease lagged coherency at frequencies close to the fundamental frequency of the site. The decrease is, as expected, proportional to the separation distance. Even at a short separation distance 40m, soil heterogeneity results in significantly incoherent motion. This observation is consistent with those reported by other researchers [10, 11, 12].

It is important to underline that the reduction of coherence is significant even for a relatively low covariance of 20% considered in this study. Zerva and Harada [10] adopted larger covariance (in the range of 30-90%), but observed less pronounced loss of coherence than that presented in Fig. 5. This is due to the high damping ratio adopted by Zerva and Harada [10] as discussed previously. The results indicate that the loss of coherence is very sensitive to damping in soil, and therefore, a proper estimation of soil damping ratio is very important to study soil effects in ground-motion incoherence. From Eq. (16) it is clear that soil damping ratio has a direct effect in the loss of coherence. On the other hand, the effect of covariance of layer thickness is indirect, and is through its effect on the autocorrelation function of predominant site frequency.

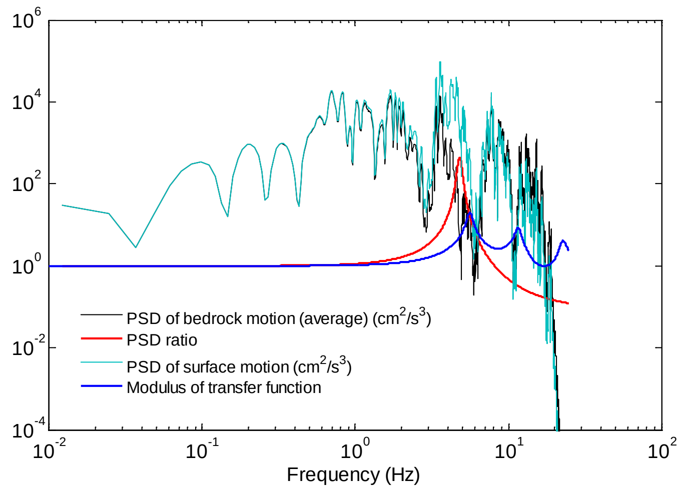


Fig. 4 – Power spectral density of ground acceleration at bedrock and the ground surface, their ratio, and equivalent linear transfer function of the site (see legend for units and descriptions).

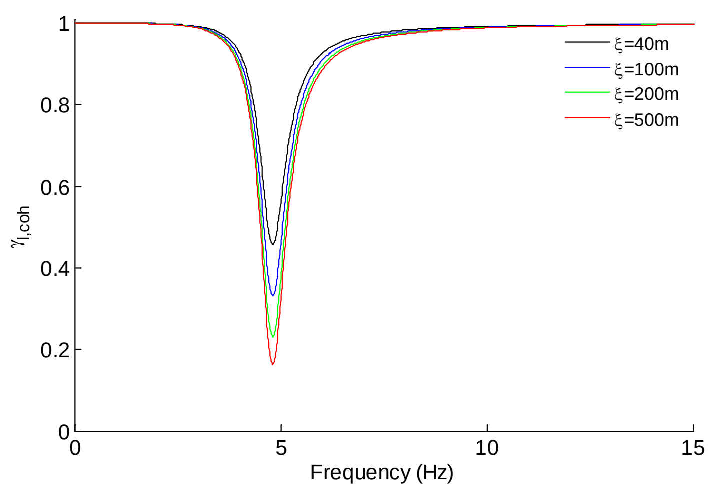


Fig. 5 – Contribution of layer stochasticity to the lagged coherency of surface motion (see Eq. 16).

Ignoring wave passage effects, the coherence of surface motion is the product of coherence of bedrock motion and the contribution of site (see Eq. 14):

$$\gamma_{coh}(\xi,\omega) = \gamma_{b,coh}(\xi,\omega) \cdot \gamma_{l,coh}(\xi,\omega) \tag{20}$$

The coherency function of bedrock motion is obtained from simulated ground motion and the details of simulation are explained in AfifChaouch et al. [8]. The lagged coherency functions at the bedrock for four separation distance are shown in Fig. 6. Parametric models of Hindy and Novak [14] and Luco and Wong [15] fitted to the estimated lagged coherency functions are also shown in the figure. The comparison in Fig. 6 shows that the two models are flexible and fit the simulated results well except at a separation distance of 500m where Hindy and Novak [14] model exhibits better fit to the simulated results, and is selected as the preferred model in this study. Using this model for bedrock, and the site contribution shown in Fig. 5, lagged coherency at the surface was estimated, and is presented in Fig. 7. The lagged coherency functions exhibit a sharp decrease near the fundamental frequency of the site. Even at a short separation distance of 40m, the effect of soil heterogeneities reduces the lagged coherency near the site fundamental frequency from ~0.95 at bedrock to ~0.4 at the surface.

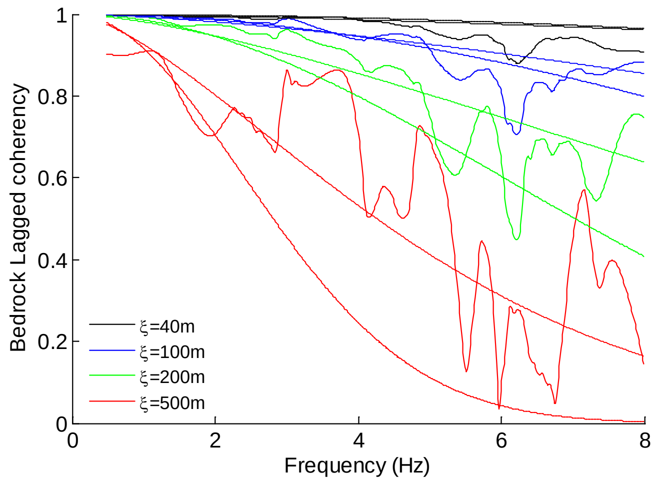


Fig. 6 – Lagged coherency function at the bedrock (solid lines) and the parametric models of Luco and Wong (dashed lines) and Hindy and Novak (dotted lines) fitted to the them.

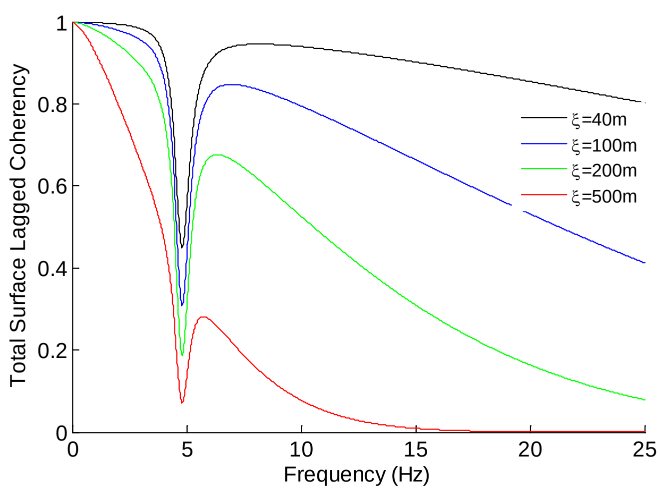


Fig. 7 – Lagged coherency function at the surface; obtained from bedrock coherency function (Hindy and Novak model as shown with dotted lines in Fig. 6) and the contribution of stochastic site as shown in Fig. 5.

4. Conclusions

Effects of lateral heterogeneities of surface soil layers in lagged coherency of ground motion has been presented for a typical site in the epicentral area of the 1980 El-Asnam Earthquake in northwest Algeria. The study is based on lagged coherency of bedrock ground motion estimated from ground motion field simulated by using the Empirical Green's Function method. Parametric models fitted to the lagged coherency functions of simulated motion are calibrated and used as suitable models of incoherence at bedrock. Lateral heterogeneities of surface layers is modelled by random variation of layer thickness. The results show that such heterogeneities alone (ignoring heterogeneities in mechanical properties of soil layers) can cause significant loss of coherence near the dominant frequency of the site. The loss in coherence is found to be proportional to the separation distance, and even a short separation distance of 40m, significant loss in coherency is observed. It was observed that damping ratio in the soil is a critical parameter affecting the degree of loss in coherency. The damping ratios adopted in this study are based on iterative equivalent nonlinear site response analysis of the soil layers when subjected to the bedrock motion, and are therefore considered to model hysteretic energy dissipation in the soil layers. Similar studies reported in the literature (for example, [10]) have adopted very large damping ratios inferred from the width of average power spectral density functions of ground motions recorded at different site conditions. This approach of estimating soil damping not only results in unreasonably high values, but also implies higher damping ratio in stiff soils than in soft ones, which is not expected in reality. One direct implication of larger damping ratios considered in the published literature is that the loss of coherency due to site effects is estimated to be much lower than what might be inferred from more realistic damping values.

Using bedrock coherency functions and the contributions of random site, parametric models of ground motion coherency at the surface of the study area have been presented. Such models are useful in random vibration analysis of lifeline structures under the action of earthquake excitation or in simulation of spatially variable ground-motion time histories to be used in nonlinear time history analysis of such structures.

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6. References

[1] Walling M, Abrahamson N (2007): Spatial coherency of ground motions for embedded structures. In. Proc. *4th International Conference on Earthquake Geotechnical Engineering*, Thessaloniki, Greece.

[2] Zerva A (2009): *Spatial Variation of Seismic Ground Motions*. Modeling and Engineering Applications. CRC Press, Boca Raton.

[3] Somerville PG, McLaren JP, Saikia CK (1988): Site-specific estimation of spatial incoherence of strong ground motion. In Proc. *Earth. Engin. Soil Dyn. II, Recent Advances in Ground-Motion Evaluation*, ASCE, Park City, Utah, 188-202

[4] Abrahamson N, Schneider JF, Stepp JC (1991): Spatial coherency of shear waves from the Lotung, Taiwan large-scale seismic test. *Structural Safety* 10: 145-162

[5] Santa-Cruz S, Heredia-Zavoni E, Harichandran RS (2000): Low-frequency behavior of coherency for strong ground motions in Mexico City and Japan. In Proc. *12th World Conference in Earthquake Engineering*, Auckland, New-Zealand, Paper No.76:1-8

[6] Ding H, Liu Q, Jin X, Yuan Y (2004): Coherency function model of ground motion at base-rock. In Proc. *14th World Conference Earthquake Engineering*, Paper No.2692 Vancouver, B.C., Canada

[7] Bi K and Hao H (2012): Modelling and simulation of spatially varying earthquake ground motions at sites with varying conditions. *Probabilistic Engineering Mechanics* 29:92-104

[8] AfifChaouch K, Tiliouine B, Hammoutene M, Rupakhety, Sigbjörnsson R. (2016): Estimating ground motion incoherence through finite source simulation: a case study of the 1980 El-Asnam Earthquake. *Bull. Earth. Eng.*10: 1193-1204.

[9] Irikura K, Kagawa T, Sekiguchi H (1997): Revision of the empirical Green's function method by Irikura (1986), Programme and Abstracts. *The Seismological Society of Japan* 2: B25

[10] Zerva A & Harada T. (1997): Effect of surface layer stochasticity on seismic ground motion coherence and strain estimates. *Soil Dynamics and Earthquake Engineering* 16: 445-457.

[11] Cranswick E. (1988): The information content of high-frequency seismograms and the near surface geologic structure of hard rock recording sites. *Pure and Applied Geophysics* 128: 333-363.

[12] Liao S, Li J (2002): A stochastic approach to site-response component in seismic ground motion coherency model, *Soil Dynamics and Earthquake Engineering*, 22: 813-820.

[13] Der Kiureghian A (1996): A coherency model for spatially varying ground motions. *Earth. Eng. Struc. Dyn*. 25: 99-111

[14] Hindy A, Novak M (1980): Pipeline response to random ground motion. *Journal of Engineering Mechanics*, ASCE, 106 (2): 339-360.

[15] Luco JE, Wong HL (1986): Response of a rigid foundation to a spatially random ground motion. *Earth. Eng. Struc. Dyn* 14: 891-908

[16] Ramadan O, Novak M (1993): Coherency functions for spatially correlated seismic ground motions, *Geotechnical Research Centre Report No. GEOT 9 93*, the University of Western Ontario, London, Canada, 1993.

[17] Petrovski J, Milutinovic Z (1981): Deconvolution analysis of surface accelerogram records in El-Asnam region. *Actes des journées scientifiques sur le séisme d'El-Asnam du 10.10.80*, Alger, 15-16 Juin:373-401

[18] Hori M (2006): *Introduction to computational earthquake engineering*. Imperial College Press, London WC2H 9HE..

[19] Okamoto S (1984): *Introduction to Earthquake Engineering*, Tokyo: University of Tokyo Press.

[20] Idriss IM, Sun JI (1992): SHAKE91: *A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits*, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, California.