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Numerical and random simulation procedure for preliminary local site characterization and site factor assessing

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Abstract. Seismic analysis of local site conditions is fundamental for a reliable site seismic hazard assessment. It plays a major role in mitigation of seismic damage potential through the prediction of surface ground motion in terms of amplitude, frequency content and duration. Such analysis requires the determination of the transfer function, which is a simple tool for characterizing a soil profile by estimating its vibration frequencies and its amplification potential. In this study, numerical simulations are carried out and are then combined with a statistical study to allow the characterization of design sites classified by the Algerian Building Seismic Code (RPA99, ver 2003), by average transfer functions. The mean transfer functions are thereafter used to compute RPA99 average site factors. In this regard, coming up seismic fields are simulated based on Power Spectral Density Functions (PSDF) defined at the rock basement. Results are also used to compute average site factor where, actual and synthetic time histories are introduced. In absence of measurement data, it is found that the proposed approach can be used for a better soil characterization.

Keywords: transfer function; simulation; RPA99; site factor; Power Spectral Density; random vibrations

1. Introduction

The energy released in the earth crust during a seismic rupture propagates up to the ground surface in form of seismic waves. Over the travel path, amplitudes and frequency content are modified due to the change in the characteristics of soil sub layers reflecting the presence of geological contrasts. These effects near the surface are commonly known as site effects. Seismologists and earthquake engineering researchers have put substantial efforts in the last several decades to understand and estimate more accurately site effects and take in account their consequences in structural seismic design (Lermo and Chávez-García 1994, Borcherdt 1994, Cadet *et al.* 2008). Indeed, the geological nature of the soil surface consisting of a stack of horizontal layers from less consolidated sedimentary deposits results in the filtering effect of frequencies and leads to amplification and amendment of the seismic waves. These changes are mainly controlled by the transfer function, which accurately enables the estimation of the free field motion particularly required in any soil structure interaction analysis.

Various methods of assessing site effects were developed by researchers and are successfully in use, based on measurements of background noise. The widely used method is the horizontal-to-vertical spectral ratio (HVSR) technique, firstly introduced by Nogoshi and Igarashi (1971) and enhanced later by Nakamura (1989). This method is based on the horizontal-to-vertical (H/V) ratio of Fourier spectrum performed from ambient noises. The method leads to accurate assessing of site's predominant frequency. (Nakamura 1989, Bard 1999), but does not provide a reliable estimation of the surface ground motion amplification needed in structural seismic analysis (Zhao *et al.* 2006). Wen *et al.* (2010) successfully used HVSR technique for classifying sites of strong motion stations after the Wenchuan earthquake (China). The use of this technique in seismic codes needs a regulatory framework, which is not often available. For that reason, these codes have trend to consider soil amplification through site factors.

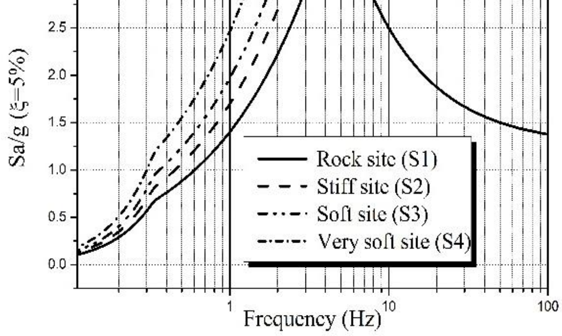

Fig. 1 Normalized elastic design response spectra-RPA99

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Table 1 RPA99 site categories

Site type	Geotechnical description	Mean value of V_s (m/s)
S1	Rock site: Rock or other similar geological formation	$V_s \geq 800$
S2	Stiff site: Deposits of dense sand, gravel and/or over consolidated clay with 10 to 20 m thickness	$V_s \geq 400$ From 10 m deep
S3	Soft site: Deep deposits of medium dense sand, gravel or medium raid clay	$V_s \geq 200$ From deep of 10 m
S4	Very soft site: Deposits of releases sand with/without presence of soft clay layers	$V_s < 200$ In firsts 20 m

Presently, RPA99 categorizes soils into four classes: rock site (S1), stiff site (S2), soft site (S3) and very soft site (S4) (Table 1). The soils are characterized by geotechnical subsoil description compatible with the geological nature of each site type, and average shear wave (S-W) velocity values in layers forming the first thirty meters of the subsoil. For structural design requirements, the RPA99 proposes 5% damped elastic response spectra. This study proposes an alternative characterization of design sites classified in the RPA99 by average transfer functions through numerical simulations combined with a statistic study. Unlike response spectra, the transfer function is an appropriate mean for site effects assessing. It allows a direct characterization of a soil profile by the determination of its vibration frequencies and, especially, its amplification potential. In addition, it leads to the appropriate response spectrum and helps to decide on the type of structure to build.

For each site class, representative S-W velocity profiles are statistically simulated from the reference profile representing indicative values of S-W velocity in each layer, according to RPA99 provisions. Deterministic average transfer functions are calculated for whole sample of the simulated profiles and the average transfer function is computed. Average transfer functions are then used to compute average site factors (SF) where, incident seismic fields formed of artificial signals are introduced. In absence of sufficient local strong motion time histories, a stochastic approach may be most suitable for generating synthetic accelerograms. The stationary filtered white noise model of Kanai (1957) and Tajimi (1960) has been the favorite model for many researchers and engineers to simulate synthetic ground motions. Non-stationary stochastic models of Amin and Ang (1968) were considered in this study. The generation of synthetic accelerograms allows stage the lack of data and provides civil engineers of particular time traces for dynamic approaches in structural seismic design. Also, it lets, in this study, to remain in the local seismic background throughout synthetic signals from real local seismic records.

3. Simulation methodology and average transfer functions calculation

The transfer function is a mathematical means governing the input/output relationship of a physical system in the frequency domain. It is defined as a ratio between the surface motion and the rock outcrop motion amplitudes

Table 2 Average S-W velocity profiles of RPA99 site classes. The mean V_s values (V_m) are proposed according to RPA99 requirements and are selected to obtain the maximum possible simulation number of Vs profiles

H (m)	S2 (V_m m/s)	S3 (V_m m/s)	S4 (V_m m/s)
0-10	380	150	100
10-20	580	300	100
20-30	650	450	200
Rock	800	800	800

$$V_s=V_m \pm \alpha\sigma \quad (\alpha=n.0.25,\ n=1,..,12) \qquad (1)$$

The transfer function makes possible an accurate quantification of the expected amplification levels of the seismic motion. This is able to answer the major concern in structural seismic design, which is the free field soil response.

In the following, one determines the deterministic mean transfer function for each RPA99 site class (except for site S1corresponding to a rock site and supposed as a reference site), taking into account the RPA99 requirements in terms of limitations imposed to values of the S-W velocity, V_s, in any layer of each site class (Table 1).

The approach considers for each site an average S-W velocity profile (reference profile, V_m), based on two proposed values of V_s: $V_{s,\min}$ and $V_{s,\max}$, corresponding, respectively, to two extreme mean values of V_s in any layer (Table 2). Moreover, for all sites, a coefficient of variation, C_v, of 10% is considered, regardless of the layer. C_v results in the variability of the S-W propagation velocity in each layer, as we interested in the average V_s within the layer. The standard deviation, σ, is then calculated around the mean S-W velocity. The average S-W velocity, V_m, is decreased and increased gradually by a uniform fraction of the standard deviation, regarding the coefficient of variation of mean V_s versus depth. This allows achieving a sample of 25 realizations of V_s profile all representing the considered RPA99 site class (Table 3). Also, it is found that for smaller values of σ, the results were the same:

SHAKE program (Shnable *et al.* 2012) allows

Table 3 Statistical sample of Vs profiles for a certain values of α where, H, is the layer thickness and, V_m, is S-W velocity value of the reference profile. Stiff soil (S2) is presented here as example

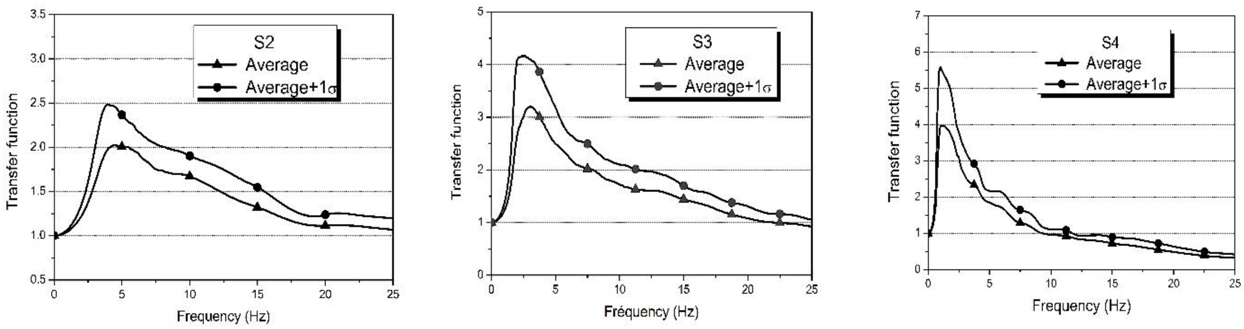
H(m)	V_m-3σ	V_m-.2.5σ	V_m-2σ	V_m-1.5σ	V_m-1σ	V_m-0.5σ	**V_m(m/s)**	V_m+0.5σ	V_{m+}1σ	V_{m+}1.5σ	V_m+2σ	V_{m+}+2.5σ	V_m+3σ
0-10	266	285	304	223	342	361	**380**	399	418	437	456	475	494
10-20	406	435	406	493	522	551	**580**	609	638	667	696	725	754
20-30	455	487.5	520	552.5	585	617.5	**650**	682.5	715	747.5	780	812.5	845
Rock	800	800	800	800	800	800	**800**	800	800	800	800	800	800

Table 4 Amplification and frequency values according to the dispersion compared to the reference profile of the stiff site (S2)

Profile	S2-3σ	S2-2.5σ	S2-2σ	S2-1.5σ	S2-1σ	S2-0.5σ	**S2**	S2+0.5σ	S2 +1σ	S2 +1.5σ	S2+2σ	S2+2.5σ	S2+3σ
Amplification	2.95	2.80	2.65	2.53	2.41	2.31	**2.21**	2.12	2.04	1.97	1.90	1.83	1.77
Frequency (Hz)	3.50	3.75	4.00	4.25	4.63	4.88	**5.13**	5.38	5.63	6.00	6.25	6.63	7.00

Table 5 Amplification and frequency values according to the dispersion compared to the reference profile of the soft site (S3)

Profile	S3-3σ	S3-2.5σ	S3-2σ	S3-1.5σ	S3-1σ	S3-0.5σ	**S3**	S3+0.5σ	S3 +1σ	S3 +1.5σ	S3+2σ	S3+2.5σ	S3+3σ
Amplification	5.97	5.74	5.43	5.24	5.04	4.87	4.70	4.58	4.44	4.31	4.19	4.08	3.96
Frequency (Hz)	1.88	2.00	2.13	2.25	2.38	2.50	2.63	2.75	3.00	3.13	3.25	3.38	3.50



(a) (b) (c)

Fig. 2 Mean transfer function and mean transfer function +1σ versus frequency for stiff site (S2), soft site (S3) and very soft site (S4)

calculating the deterministic transfer function versus frequency in the linear case for each profile between the half-space and the soil surface, within a frequency range of 0 to 25 Hz. Average transfer function curves with the corresponding standard deviation are obtained from the results.

3. Results and comments

3.1 Stiff site (S2)

The graphs of the Fig. 2 represent the mean transfer function curves versus frequency for the S2, S3 and S4 soil categories. The first peak in all curves indicates the fundamental mode which corresponds to the natural frequency of the soil category. This parameter varies with the change of V_s values. For lower values of V_s, the peak increases by sliding to lesser frequencies compared to the reference profile. For velocities greater than those of the reference profile, the peak decreases by shifting to higher frequencies in comparison with the reference profile (Table 4).

The mean transfer function curve indicates the maximum average value of amplification and the corresponding frequency. This amplification seems less with a value reaching 2.5, which appears at a frequency around 5 Hz. This is compatible with the firm nature of S2 site and denotes presence of good consistency, leading to a high value of amplification occurred at a higher frequency.

3.2 Soft site (S3)

As for the S2 site, the curve of the mean transfer function shows the fundamental mode and the corresponding frequency, with remarks being the same for fluctuations of the amplification peak relative to variations of S-W velocity values. Nevertheless, it is easy to see that amplification peaks pass to considerably higher values for both the reference profile and the other profiles, in

Table 6 Amplification and frequency values according to the dispersion compared to the reference profile of the very soft site (S4)

Profile	S4-3σ	S4-.2.5σ	S4-2σ	S4-1.5σ	S4-1σ	S4-0.5σ	**S4**	S4+0.5σ	S4 +1σ	S4 +1.5σ	S4+2σ	S4+2.5σ	S4+3σ
Amplification	7.33	6.44	7.32	5.92	6.98	6.11	6.54	6.20	6.14	6.10	5.73	5.90	5.41
Frequency (Hz)	0.75	0.88	0.88	1.00	1.00	1.00	1.13	1.13	1.25	1.25	1.38	1.38	1.38

comparison with the S2 site (Table 5). This justifies the passage of firm soil having improved mechanical properties to a soil less consistent. For the average transfer function curve, one observes that the peak amplification increases and shifts to a lower frequency compared to the S2 site.

3.3 Very soft site (S4)

The same considerations remain valid for this site type with, in addition, a remarkable shift of the mean amplification peak towards lower frequencies. Indeed, we are dealing with a very soft soil with poor mechanical properties, characterized by low values of S-W velocity, which outputs amplification higher than those of sites S2 and S3, appearing at a lower frequency (Table 6).

4. Site factors assessing

Despite some disagreements, analysis of the shear wave velocity at the top 30 meters of subsurface deposits remains an almost universally recognized way to learn about their geotechnical and mechanical properties and, consequently, its response to incident seismic waves. Moreover, the site factor is currently an adequate manner to consider site effects that would be consistent with the regulatory framework. Unlike several seismic building codes, the present RPA99 provides elastic response spectra which do not integrate the site factor concept, although it proposes different site classes (Fig. 1).

Site factor is an appropriate assessing of the amplitude's fluctuations of a seismic motion regardless frequency. It is considered in this study as the maximal acceleration amplitudes (PGA) ratio between the ground surface and the rock basement. Site factors of S2, S3 and S4 sites are estimated using a stochastic method based on the Power Spectral Density Function (PSDF) of a seismic motion, assuming linear elastic behaviour of material soil layers. Several incident seismic fields are simulated and used as seismic input acting on the different studied sites. Herein, incident seismic field indicates a coming up seismic wave field with certain characteristics (effect of distance, frequency content…) modelled by a PSDF. It is represented later by a set of accelerometric signals simulated from the PSDF.

The study was conducted in two stages: In the first stage, the incident seismic field is modelled by average PSDF calculated from PSDF of available actual accelerometric recordings characterized by a sampling frequency of 200 Hz, taking into account the effect of distance (Table 7). This allowed capturing certain seismic frequency contents capable to strike the soil site and, consequently, the existing buildings. Hence, a sample of twelve local actual accelerograms recorded at different locations from the main shock's source of the Boumerdes earthquake which occurred in May 21, 2003 with M_w=6.8 (Laouami *et al*. 2006), are used in this stage of the study (Table 7). This choice also meets the wish to consider the Algerian seismic context. Seismic field from actual recordings will designated below as actual incident seismic field.

In the case of actual PSDF, the center frequency and the bandwidth are the parameters controlling the effect of distance. In simulations' calculus, the incident seismic field is defined in terms of center frequencies and bandwidths (Fig. 3 and Table 8). The used PSDF is

$$S(\omega) = \frac{1}{\pi T_d} C_n^2(\omega) \qquad (2)$$

where, S, is the PSDF; ω, is the circular frequency, C_n, is the Fourier amplitude and T_d the movement's total duration.

Through their center frequencies, it is easy to see that incident seismic fields arising from the two sets of earthquake recordings have frequency contents that reflect an effect of distance compatible with firm-to-rock soils (Table 8). They would have no influence on soils with less consistency such as soft and very soft soils. Thus, seismic field should extend over a broad frequency range to cover the entire range that could request the studied soils, as it is asked to learn about the overall behavior of regulatory sites. For that reason, others seismic fields from the analytical Kanaï and Tajimi (K & T) model for the rest of frequency intervals complement the incident seismic fields, in the second stage. In this case, the PSDF is taken as a filtered white noise and the effect of the distance is controlled by the filter's frequency. The ground damping considered in the calculation is that proposed by Der Kiurighan and Neuenhofer (1992) and the change of the soil frequency is taken as the result of the filtering effect with distance (Table 8)

$$S_s(\omega) = |H(\omega)|_g^2 \, S_0 \qquad (3)$$

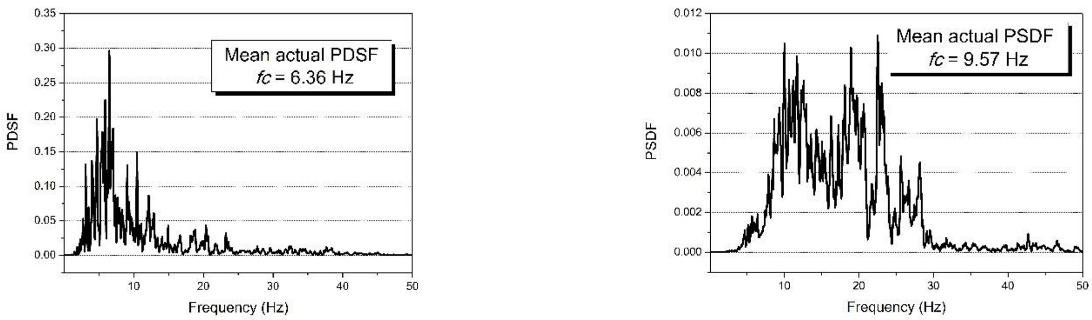
where, S_s, is the PSDF at the soil surface; S_0, is the white noise assumed at the bedrock, chosen in such manner to normalize accelerograms to 0.2 g; $H(\omega)$, is the transfer function of the soil profile and ω, the circular frequency

$$|H(\omega)|_g^2 = \frac{1+4\beta_g^2(\omega/\omega_g)^2}{\left[1-(\omega/\omega_g)^2\right]^2 + 4\beta_g^2(\omega/\omega_g)^2} \qquad (4)$$

where, ω_g, β_g and ω stand, respectively, for the predominant

Table 7 Accelerometric recordings used for modelling the actual incident seismic field

N°	Station	Component	Localization	Field type	Distance to the source (Km)
01	08292003_144751_ST2	E-W	Keddara	Near	21.9
02	08292003_144751_ST2	N-S	Keddara	Near	21.9
03	1002003_151147_ST2	E-W	Keddara	Near	21.9
04	1002003_151147_ST2	N-S	Keddara	Near	21.9
05	09082003_074410_STA2	E-W	Dar El Beida	Near	17.5
06	09082003_074410_STA2	N-S	Dar El Beida	Near	17.5
07	07022005_74249_AFR	E-W	El Afroun	Far	83.4
08	07022005_74249_AFR	N-S	El Afroun	Far	83.4
09	12012004_174225_HRA	E-W	Hamam Righa	Far	110
10	12012004_174225_HRA	N-S	Hamam Righa	Far	110
11	12012004_174225_KMA	E-W	Khemis Miliana	Far	127
12	12012004_174225_KMA	N-S	Khemis Miliana	Far	127



(a) (b)

Fig. 3 Mean PSDF modeling the incident seismic field in the case of actual recordings. Effect of distance is highlighted through the center frequency of the PSDF. The graph (a) represents the mean PSDF of the first six recordings of Table 7 (near field).The graph (b) designates the mean PSDF of the six last recordings of Table 7 (far field)

ground frequency, ground damping and circular frequency. ω_g relates to fundamental frequencies of the studied soils corresponding to amplification peak of average transfer functions. However, this filter leads to infinite values of the velocity and the displacement, due to the existing singularity when ω approaches 0. It is therefore necessary to pass the signal through a second filter so as to reduce the spectral values to the right low frequencies (Clough and Penzien 1975). This filter is expressed as

$$\left|H'(\omega)\right|^2 = \frac{\left(\omega/\omega_f\right)^4}{\left[1-\left(\omega/\omega_f\right)^2\right]^2 + 4\beta_f^2\left(\omega/\omega_f\right)^2} \quad (5)$$

where, ω_f and β_f are the characteristics of the filter patch. Because seismic ground motion exhibits a beginning and an ending, it cannot be really stationary, even thought, forpractical purposes, it is assumed stationary for the majority of its duration.

Non-stationary motion shows three stages (i) the motion increases rapidly from weak to strong
(ii) the motion maintains its average strength (iii) the motion gradually decreases. Hence, the input ground accelerations modeled as a uniformly modulated stationary process by a time deterministic envelope function. The model considering these features may be written as suggested by Amin and Ang (1968)

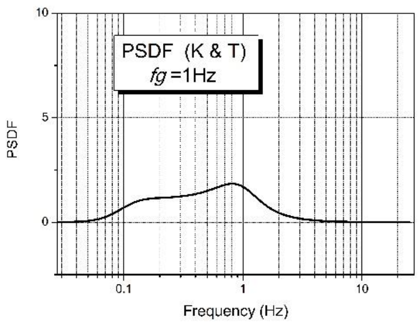
$$X_{nsta}(t) = a(t) \cdot X_{sta}(t) \quad (6)$$

where, Xsta, is a stationary process and is defined by

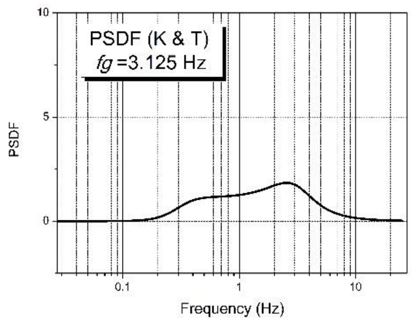
$$a(t) = \begin{cases} (t/3)^2 & 0 \le t \le 3\text{s} \quad \text{(early stage)} \\ 1 & 3 \le t \le 13\text{s} \quad \text{(strong stage)} \\ \exp[-0.26(t-13)] & t \ge 13\text{s} \quad \text{(finale stage)} \end{cases} \quad (7)$$

In all cases, the Monte Carlo method (Shinozuka *et al*. 1987) is used to simulate 1000 synthetic accelerograms from PSDF of incident fields resulting of the convolution via the average transfer functions previously calculated, according to the following series

$$\ddot{X}(t) = 2\sum_{1}^{N}\sqrt{S_s(\omega_i)\cdot\Delta\omega}\cdot Cos(\omega_i t + \phi_i) \quad (8)$$



(a)



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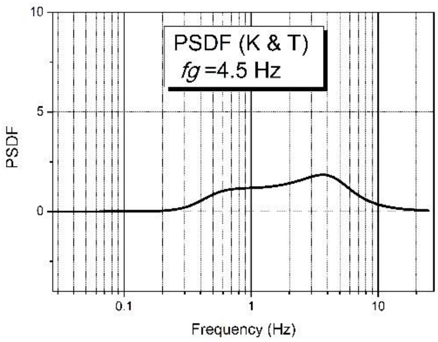
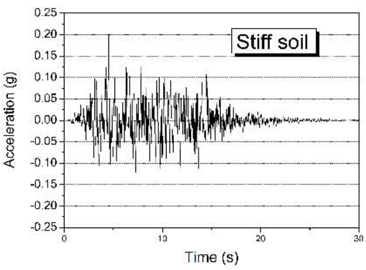


(c)

Fig. 4 PSDF modeling the incident seismic field corresponding to the analytical Kanaï and Tajimi model. The seismic field is defined by the filter's frequency, *fg*



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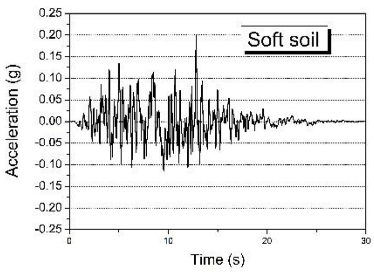

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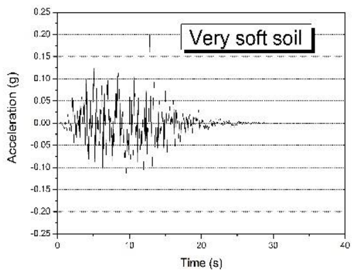

(c)

Fig. 5 Non-stationary synthetic ground motions simulated at bedrock (typical realizations: (a) stiff soil, (b) soft soil and (c) very soft soil)

Table 8 Parameters defining the PSDF modeling the incident seismic fields

PSDF	Real	Real	Kanaï &Tajimi	Kanaï &Tajimi	Kanaï &Tajimi
f_c or f_g (Hz)	f_c=9.57	f_c=6.36	f_g=4.5	f_g=3.125	f_g=1.0
Bandwidth	0.39	0.61			
Damping β_g			0.6	0.4	0.2

$$S_s(\omega) = |H(\omega)|^2 \, |H'(\omega)|^2 \, S_b(\omega) \qquad (9)$$

where, S_s and S_b, are the PSDF at the ground surface and at the base (bedrock) respectively, Dw is the frequency increment: $\omega_i = i\Delta\omega$, $N\Delta\omega$ is the maximum frequency considered, ϕ_i, are independent random phase angles uniformly distributed over $[0,2\pi]$. Note that the FFT technique is used for the digital generation of input motions. Also, beyond the number of 1000 realizations, results were found the same. 1000 seismic responses are calculated and 1000 site factors are then derived from the ratio PGA

Table 9 Site factors related to the different frequencies modeling the incident seismic fields used in the study. The table gives probabilistic site factors (SF prob) and statistical site factors (SF stat). Probabilistic site factors are given to allow comparison with statistical site factors

Soil type	Average site factor									
	f_c=9.57 Hz		f_c=6.36 Hz		f_g=4.5 Hz		f_g=3.125 Hz		f_g=1.0 Hz	
	SF prob	SF stat	SF prob	SF stat	SF prob	SF stat	SF prob	SF stat	SF prob	SF stat
S2	1.67	1.69	1.57	1.60	1.50	1.51	1.43	1.44	1.16	1.19
S3	1.98	2.02	2.40	2.43	2.34	2.33	2.40	2.37	1.73	1.76
S4	1.30	1.37	2.04	2.13	2.26	2.19	2.58	2.48	2.87	2.77

Table 10 Site factors versus incident seismic fields and mean site factors with the corresponding standard deviation

Soil type	Average site factor									
	f_c=9.57 Hz		f_c=6.36 Hz		f_g=4.5 Hz		f_g=3.125 Hz		f_g=1.0 Hz	
	SF prob	SF stat	SF prob	SF stat	SF prob	SF stat	SF prob	SF stat	SF prob	SF stat
S2	1.67	1.69	1.57	1.60	1.50	1.51	1.43	1.44	1.16	1.19
S3	1.98	2.02	2.40	2.43	2.34	2.33	2.40	2.37	1.73	1.76
S4	1.30	1.37	2.04	2.13	2.26	2.19	2.58	2.48	2.87	2.77

surface over PGA base. For each site, the average site factor is deduced for each incident field following the steps below (Table 9)

$$a_b(f) = FT(a_b(t)) \tag{10}$$

$$a_s(f) = H(f)(a_b(f)) \tag{11}$$

$$a_s(t) = FT^{-1}(a_s(f)) \tag{12}$$

$$SF = \frac{a_{s,max}(t)}{a_{b,max}(t)} \tag{13}$$

where, $a_b(t)$ and $a_s(t)$ are, respectively, the simulated acceleration signal at the base and that at the surface in the time domain; $a_b(f)$ and $a_s(f)$are the signals at the base and at the surface in the frequency domain, respectively. FT and FT^{-1} are, respectively, the Fourier and the inverse Fourier transforms.

To check the results authenticity, site factors calculated using the statistical analysis were compared, with those calculated by a probabilistic method based on random vibration theory. The average intensity of the incident seismic field or standard deviation, λ_0, is defined in the frequency domain by:

At the base

$$\lambda_0^b = \int_0^{\omega_n} S(\omega)\, d\omega \tag{14}$$

At the surface

$$\lambda_0^s = \int_0^{\omega_n} S(\omega)\left|H(\omega)\right|^2 d\omega \tag{15}$$

where, ω_n, is the Nyquiste frequency defined as the maximum frequency in the Fourier spectrum.

According to the random vibrations theory, the maximal response, $X_{\max}$, is given by:

At the base

$$X^b_{\max} = \lambda_0^b \cdot p^b \tag{16}$$

At the surface

$$X^s_{\max} = \lambda_0^s \cdot p^s \tag{17}$$

where, p, is the peak factor. Using this approach and considering p^b=p^s , the site factors can be calculated through the following formula

$$SF = \frac{X^s{}_{max}}{X^b{}_{max}} = \frac{\lambda_0^s}{\lambda_0^b} \tag{18}$$

The obtained results are presented in the table below.

5. Comments

Site factors were calculated for each RPA99 design site through the peak ground acceleration ratio between the base and the soil surface based on PSDF and random vibration theory methods. In both cases, the maximal amplitude at the surface is obtained by the convolution of that at the base with the transfer function of the considered site. The results show a good correlation between site factors calculated through the two considered methods. For each design site, the site factor values are in good agreement with the site nature in terms of steadiness reflected by the S-W velocity values of every site.

Furthermore, the obtained results show that site factors depend more on seismic field characteristics than on sites amplification's potential. It appears, at first sight, that very soft soils amplify more in lower frequencies than soft soils, and stiff soils show a relatively weak amplification over a wide frequency range. For frequencies greater than or equal to 4 Hz, the S3 site factor is more important compared to the other sites, particularly the S4 site. For frequencies less than 4 Hz, the S4 site factor is more important. Finally, up to 5 Hz, the S2 site factor is less important and exceeds that of S4 site for frequencies beyond 5 Hz. The calculation of average site factors reveals an important dispersion around the mean value. This dispersion increases from S2 site to reach a very significant value for S4 site (Table 10). If for S2 and S3 sites the magnitude of the standard deviation is reasonable, consider the resulted average site factor for S4 can lead to either an overestimation or underestimation of the seismic action owing the extent of the standard deviation and therefore, further investigations are recommended for the S4 site.

6. Conclusions

An alternative tool is proposed in this study for a preliminary characterization of RPA99 design sites (S2, S3, S4) through average transfer functions following numerical simulation approach combined with a statistical analysis.

The process consists first to simulate, for each site, a sample of soil profiles in compliance with regulatory requirements related to the limitations on S-W velocity profiles, then, make a deterministic calculation of the average transfer function and make statistics on the obtained results in order to determine the average values.

Second, a stochastic based method is used to estimate site factors. To this end, several incident seismic fields are used as seismic input.

They are defined first from available accelerometric recordings through their actual PSD representing certain frequency ranges, then, complemented for the other frequency ranges using the analytical Kanai and Tajimi model. Site factors are calculated for each RPA99 design site through the average peak ground acceleration ratio between the base and the soil surface, based on PSDF and random vibration theory methods. The results show a wide dispersion around the average site factor. This dispersion increases from the S2 site to reach a very important value for the S4 site, where the standard deviation exceeds 50%. It is clear that the amplification depends more on the frequency content of the incident seismic field than on the site's amplification potential. In the case of S4 site, consider the obtained average site factor can lead to either an overestimation or an underestimation of site amplification capacity, therefore, further investigations are recommended for the S4 site. This method is a complementary approach for the quantification of site effects in addition to experimental methods.

Additional investigations such as the enrichment of the incident seismic fields and their diversification, particularly by further experimental seismic inputs, are recommended to improve results found in this study. Simulation of soil profiles can also be amended by enhancing number and type of profiles, together with consideration of their nonlinear behavior. On the other hand, beyond all the results and due to the weak correlation between site class and amplification, a classification scheme including the depth of the bedrock should be developed as part of the improvement of the RPA99.

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