Design site characterization via stochastic transfer functions

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SUMMARY:
This paper provides an alternative and efficient means for characterisation of design sites classified in the Algerian Resistant Seismic Rules (RPA 99, 2003 version) by average transfer functions, through a stochastic approach, combined with a statistical study. For each soil type, the deterministic calculation of average transfer function is performed over a wide sample of 1-D soil profiles, for which, the average shear wave velocity, *Vs*, in soil layers is simulated using the random field theory. Thus, for any layer of each design site, *Vs* is defined between two bounds, so, to describe its variability neither the normal or lognormal distributions are appropriate. For that purpose, a probabilistic model that allows transforming the normal unbounded distribution to a bounded one has been used considering equivalent linear analysis method to approximate the nonlinear soil deposits response. These information help to decide on the aspect of structure type to build.

Keywords: Random fields; transfer functions; soil classification; RPA99; statistics

1. INTRODUCTION

It is well known that local site conditions have a strong influence on shaking behaviour of the site and, therefore, plays a major role in the damage potential of earthquakes. Hence, the local site analysis is a fundamental component of earthquake engineering when related to the geotechnical aspect of the problem. It makes possible the prediction of surface ground motion in terms of amplitude, frequency content and duration. Seismologists and earthquake engineers have put substantial efforts in the last several decades to understand and estimate, more accurately, the site effects on ground motion characterization, and take in account the associated effects in structure design.

Overall, estimating site effects, namely potential amplification, pass mainly by classifying them with respect to a previously defined soil site classes, adopted in many earthquake resisting rules, which have tendency to categorize sites into different classes wherein the commonly used parameters for site classification are the average shear wave velocity over 30 meters of the subsurface geological materials, V_{s30}, and the dominant period, habitually associated again with normalized elastic response spectra. Furthermore, some others information such as surface geological and geotechnical description are also introduced. On the other hand, for including influences of site conditions on the earthquake resistant design of structures in the seismic codes and design guidelines, number of site classification techniques was developed by several researchers. Among those, the most elementary is the borehole data assessing and geologic maps and/or geomorphology data interpretation. However, with the increase in the number of strong ground motion stations as well as extension of the use of more simple and less onerous techniques around the world, many efficient other methods were successfully used. Almost of these methods are based on site predominant period determination's, in order to assigning site class by reference to site class provisions, without providing reliable amplification levels, needed in structural dynamics analysis. In this study, we propose an alternative tool for characterizing design sites classified in the RPA99 by average transfer functions, through stochastic approach, combined with a statistical study. For many reasons, the transfer function is a useful means, unlike to response spectra, since it allows characterizing directly and fully the soil profile with previously known local conditions, by determining its vibration frequencies and, especially, its amplification potential. Thus, for each soil type, the deterministic calculation of the average transfer function is carried out on a large sample of one dimensional soil profiles, for which, the average shear wave velocity, V_s, in any layer is simulated based on random field theory. V_s is known as an unbounded-positive parameter, so, it supposed be log-normally distributed. However, for each layer of any design site classified in the RPA99, V_s is bounded both above and below, so, to describe its variability neither the normal nor the lognormal distributions are appropriate. For that purpose, a probabilistic model which allows transforming the normal unbounded distribution to a bounded one has been used. The obtained results show that followed approach provides a better and accurate site identification tool since it gives a reliable measure of it amplification capacity and the corresponding frequency ranges. These informations which are not integrated in the actual RPA99 characterization help to decide on the aspect of structure types to build.

One of the early and widely known methods is the standard Spectral Ratio (SSR), initially put in practice by Borcherdt and Gibbs (1970). It is based on comparison of white noises or earthquake signals recorded over unknown site conditions and those obtained at a nearby reference rock site; its major drawback is then the need of a reference rock station (Lermo., Chavez Garcia et al., 1994, Seo et al., 1996). Alternative empirical techniques could be used when there is a lack of information for recording sites. The receiver functions technique was proposed at first by (Langston.,1970), based on the assumption that the vertical component of motion is a little affected or not affected by local amplification, therefore, the reference station response can be substituted by the vertical component measured at the same station. Hence, unlike to the SSR method, it does not require the presence of reference rock station. On the other hand, it should be mentioned that the receiver functions method gives only particular information on the site effect, such as the fundamental frequency (Riepl et al., 1998).

In previous studies on site characterization, the more successfully and extensively used method is the horizontal-to-vertical spectral ratio (HVSR) technique, firstly introduced by Nogoshi (1971) and improved later by Nakamura (1989) (also called Nakamura method), using the H/V ratio of Fourier spectrum, performed from earthquake records or ambient seismic noises. Ruizhi et al (2010) have successfully used that method for classifying sites of strong motion stations after the Wenchuan earthquake in China. Both the receiver functions and the SSR methods were used, in fact, to determine the fundamental frequency of studied sites, which can be considered as a primary parameter for site classification, according to a site categorization schemes.

Several kinds of site classification were shown by Ruizhi et al (2010), among those, the Nakamura method was selected to calculate predominant period, in order to classify 77 strong motion sites after the Wenchuan earthquake. Although the H/V Nakamura method relies on some assumptions and reliable explanation to this method is not available yet, it makes possible to get too accuracy predominant frequency than those of other microtremor analysis methods. It is again recognized that above techniques are not capable to capture reliable information of site amplification, and there is no effectiveness in assessing potential site amplification involved in structure design using these methods. Recently, the HVSR using strong motion records was widely used for classifying strong motion stations around the world (Lee et al., 2001, Zhao et al., 2006, Ghasemi et al., 2009, Ruizhi et al., 2010).

Lee et al (2001) has used the response spectral shape (RSS) method for purpose to perform classification for 708 free-field strong motion stations in Taiwan, originally proposed by Seed et al (1976), based on the 5% damped acceleration response spectral shapes for four site classes. They also made a comparison with HVSR method for checking.

In Zhao et al (2006), it was suggested an empirical method, similar to the receiver functions approach, based on the HVSR of earthquake records, where ratios of 5% damped velocity response spectra were used instead to Fourier spectral ratios, commonly used in the receiver functions method. Essentially based on the amplitudes and the shapes of the HVSR with respect to periods, the technique was developed for assigning site classes to the K-net strong motion stations, in order to confer a reliable modelling of site effects to the Japanese attenuation models. For site classification, he designed the site classification index, SI, computed for each site class, using geometric mean H/V ratios both for the site of interest and site class averaged over all sites of the K-net strong motion database, through a cumulative distribution function. It should be noted that site classes were already determined for studied strong motion stations, based on the predominant period.

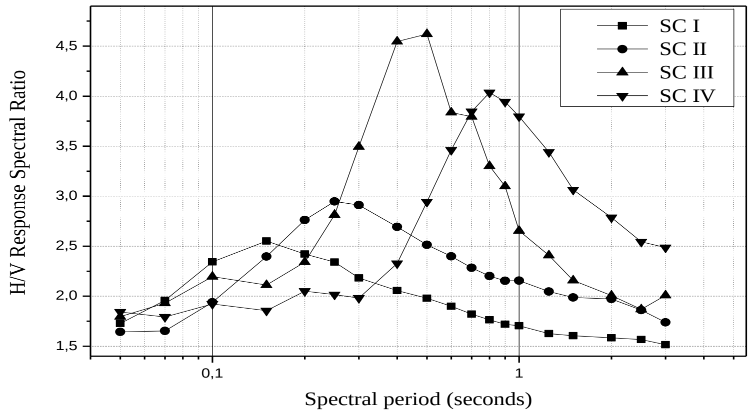


Table 1. Site class definitions (JRA 1980, 1990)

Site classes	Site natural periods (sec)	average shear-wave velocity
SC I: (Rock/stiff soil)	T_G < 0.2 sec	V_{30} > 600m/s
SC II: (Hard soil)	0.2 sec < T_G < 0.4 sec	300 m/s < V_{30} =600 m/s
SC III: (Medium soil)	0.4 sec < T_G < 0.6 sec	200 m/s < V_{30} =300 m/s
SC IV: (Soft soil)	T_G = 0.6 sec	V_{30} = 200 m/s

In order to show reliability of empirical site classification techniques, Ghasemi et al (2009) tried to classify 107 strong motion stations of the Iranian Strong Motion Network, following three different empirical schemes. First, the stations with site classes previously determined by local geological conditions and V_{s30} measurement are reclassified using recorded strong motion at each station. In this regard, the average H/V spectral ratio of records at each station is determined, and then, the first predominant peak is taken as the natural period of the site. To classify strong motion stations, the natural period at each station is compared with site-dependent period ranges recommended by JRA (1980). In the second method, they used the SI (site classification index) introduced by Zhao et al (2006), for classifying and comparing obtained site classes with the previous ones. In the third method, another site classification index based on the Spearman's rank correlation coefficient was used. It allows the measure of correlation between average HVRS curves for the site of interest and mean HVSR ones for different site classes. The obtained site classification results were found presenting, overall, slightly higher accuracy. The same conclusions that those concluded by Zhao et al (2006) are to be retained in that study, in particular, the no capacity of these empirical classification techniques to account for special features of site effects.

The HVSR method was improved and its usefulness was confirmed trough the all further site classification studies. In this regard, a new site classification approach based on neural networks was suggested by Saman et al (2011) along with a selected set of representative horizontal to vertical spectral ratio curves for four site classes. It was used to classify 87 strong motion stations with local conditions previously known using the Chi Chi Taiwan strong motion records, according to the mean HVSR curves proposed by Zhao et al and the earlier site classification based on the local conditions.

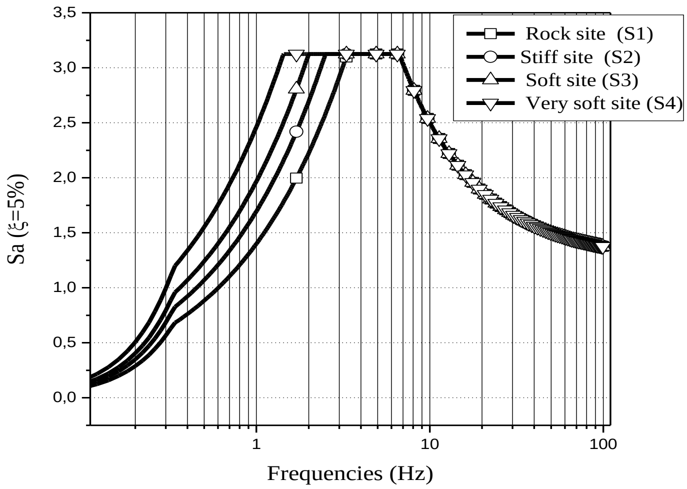
2. Brief review of accounting for site effects by the RPA99 (2003 version)

A big part of Algeria is seismic and many sites show topographic, geological and geotechnical conditions which are able to favour the appearance of local effects. Because of its importance, some of these effects are partially integrated into seismic building codes via response spectra. However, it should be useful to accurately take in account of that into the town planning and seismic resisting rules. This involves a good knowledge of physics phenomena, and the development of reliable methods for their quantification. In the RPA99 (2003 version), the amplification phenomenon is indirectly considered through normalized response spectra corresponding to four defined soil categories. In addition, to consider the local effects, the RPA99 recommend that particular caution has to be made against a choice of building implementation sites, because of no favourable conditions which could exist there, particularly, for non compacted embankment or alluvium soils, mainly in reason of their high amplification capacity, and in order to avoid the resonance phenomenon, it also requires preferring the rock soils than the soft soils. Four site categories are also proposed according to mechanical properties of their soil deposits, principally rock site (S1), stiff site (S2), soft site (S3) and very soft site (S4) (table 2). They are characterized by amplification factors for the equivalent static method and normalized response spectra for the modal spectral method. However, the response spectra do not clearly include the site coefficient concept which varies toward the amplification potential of the site.

Table 2. RPA99 site categories

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

Figure 1. Normalized acceleration design response spectra - RPA99 (2003 version)



3. Methodology for transfer function calculation

The state of the art on the above site classification works demonstrates that having reliable site classification schemes is vital for seismic hazard studies. They also may serve as fundamental information for site effects analyses. However, in engineering structures design, the major concern for engineers is quantifying forces and/or displacements to which engineering structures might be exposed. In this regard, assessing site class according to a certain design code to a particular engineering site, even if the classification is valuable cannot be sufficient alone. In order to answer to that apprehension, we propose as a simple tool allowing appropriate site classification and reliable amplification potential assessing, the mean transfer function, for classifying engineering soil sites. The transfer function is, in fact, a mathematical means governing the input/output relationship of a physical system in frequency domain. Thus, site classification via mean transfer function has many advantages which are not all related to that new classification manner different to reviewed classical methods (shear wave profile, mean HVSR schemes, predominant period....), but due to the fact that it makes possible quantifying simply and accurately both the amplification levels expected at the output and the mean site coefficient or frequency dependent site coefficient. On the other hand, it allows truly estimating the ground surface responses representing effective excitations aimed to be introduced in the basis of engineering structures, what allows to protect from deficiencies linked to bad estimation of local effects, which are, overall, neglected, underestimated or overestimated. Response spectra computed via mean transfer function are compatible with local site conditions and account correctly for the amplification capacity of the site of interest, because it is based on the maximal spectral response at soil surface, therefore, taking in account modifications brought at this response in terms of amplitude and frequency content. Thus, for a particular studied site, the natural frequency can easily be computed by one of the H/V spectral ratio (e.g. Nakamura method), and then, the corresponding site class is derived by getting the computed frequency on the appropriate mean transfer function curve. For the strong motion stations, the natural frequency is derived from mean HVSR of strong motion records and the site class is assigned by the same manner above.

Our purpose is to suggest an average transfer function, for each design site classified in the RPA99 (2003 version), except rock site (S1) which is assumed as not affected by amplification effect. The deterministic calculation of mean transfer function has then to be made over a very large sample of V_s profiles, all representing the design site of interest in terms of V_s values and thicknesses for each layer, according to those specified in the RPA99 (table 2). However, in most cases with not enough data on V_s on the subsurface geological settings, gives the data on V_s back unreachable and because of this reason, resorting to probabilistic model for V_s profiles simulation becomes necessary.
As a major task, one dimensional soil profiles have been performed through average shear wave velocity profiles simulation for all of design sites, except the rock site (S1). V_s is known as an unbounded positive parameter; its variability follows then a lognormal distribution. However, for any layer of each design site classified in the RPA99, *Vs* is included between two bounded values. Therefore, it becomes a bounded positive parameter. Hence, a probabilistic model allowing bringing the unbounded distribution of V_s to a bounded one was then used (Gordon Fenton., D.V.Griffiths., 2000). It arises from a simple transformation of an average local and standard random field having zero mean and unit variance. Thus, for each soil layer present at any site, we simulate, with respect to recommended requirements of the RPA99, a sample of one thousand (1000) shear wave velocity profiles by first, simulating stochastically a normally distributed random fields having zero mean and unit variance, and then, using them to perform mean shear wave velocity profiles according to the followed relationship:

$$\bar{V}_i^j = \bar{V}_{imin}^j + \frac{1}{2}\left(\bar{V}_{imax}^j - \bar{V}_{imin}^j\right)\left[1 + th\left(s\,\frac{\Delta\bar{v}_i^j}{2\pi}\right)\right] \qquad (3.1)$$

Where $\bar{V}_{imin}^j$ and $\bar{V}_{imax}^j$ are the minimal and maximal bounds mean shear wave velocity in ith layer of jth soil profile respectively (table 2), $\Delta\bar{v}_i^j$ is the local and standard random field having zero mean and unit variance and *s* is a factor governing the mean shear wave velocity variability between its two bounds:

$$\Delta\bar{v}_i = \left(\frac{2}{N}\sum_i \cos(2\pi\emptyset_i)\right)^{\frac{1}{2}} \qquad (3.2)$$

where $\emptyset_i$ is a random number, and N is the number of elements in the sum. Average transfer function for linear viscous-elastic model in frequency domain is obtained by calculating the arithmetic mean of transfer function values over a 1-25 Hz frequency band:

$$A_m(f_j) = \sum_{i=1}^{n} \frac{A_i(f_j)}{n} \tag{3.3}$$

where A_m is the mean amplification for jth frequency, A_i the ith amplification for jth frequency and n the total number of profiles. The standard deviation is also performed for any mean amplification value corresponding to a given frequency. Note that beyond a number of 1000 profiles, we remarked that there was no change of average transfer function.

3.1. Nonlinearity effects

It is widely recognized that soil deposits near the surface behave nonlinearly over strong motions. In this study, we deem the dissipative character due to the decrease of elastic shear modulus values, *G*, and the increase of damping values, *β*, under strong motion, to approximate their nonlinear response of soil deposits. However, with non available G and *β* reduction curves data, we made resort to reduction curves existing in the literature. These reduction curves are chosen according to the dissipation level which varies following the soil mechanical properties. Time-histories collected from several international databases (K-net and Kik-net databases, PEER database, European database) are used as input motions through analyses conducted by developed program to compute ground response, and then, equivalent linear transfer function for any simulated soil profile.

Figure 2. Mean transfer function (S2)

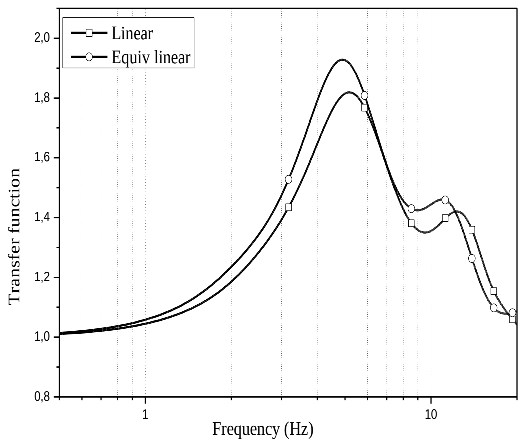


Figure 3. Mean transfer function (S3)

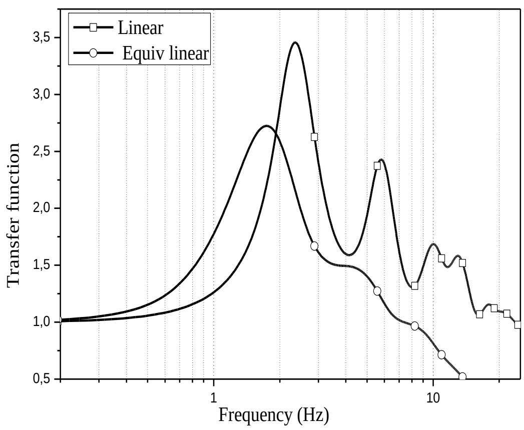


Figure 4. Mean transfer function (S4)

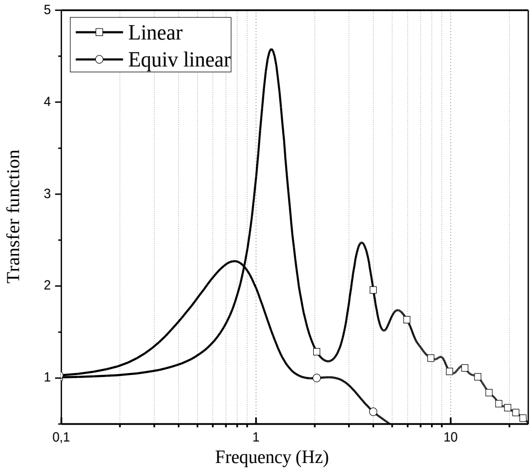


Figure 5. Mean transfer functions-Linear case

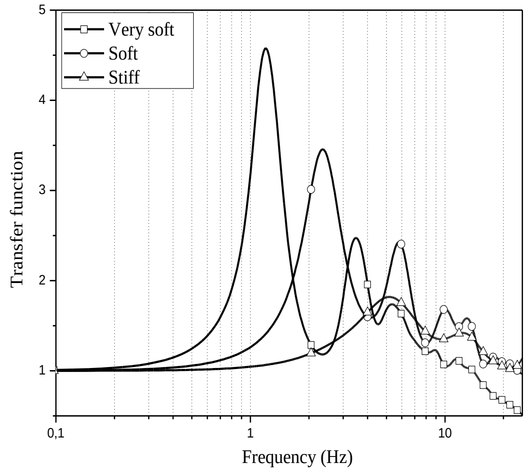
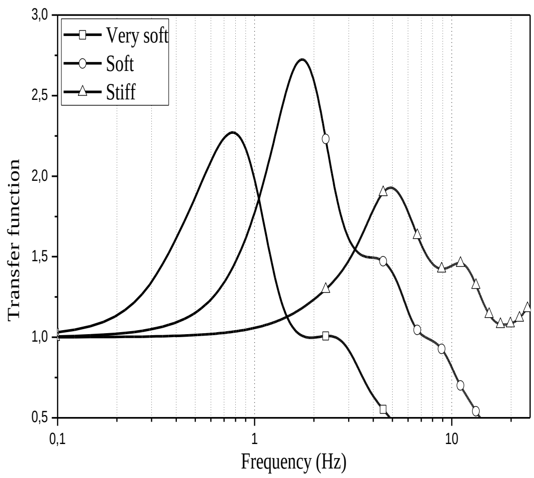


Figure 6. Mean transfer function
Equivalent linear case



4. Discussion results

Figures 2 to 4 show mean transfer function curves and their variability towards the frequency range, considering both the linear and equivalent linear cases. They account for the amplification peak and the corresponding frequency for any analysed site. The peak highlights the fundamental mode of the site and also brings out the corresponding fundamental frequency (table 2). These two parameters vary with shear wave velocity changing.

Transfer function curve of stiff site (S2) illustrates clear peak amplification at 5.17 Hz. For the soft and very soft sites (S3, S4), the corresponding peak appear at 2.34 and 1.19 Hz respectively.
Observing overall shape of transfer function curves, it is easy to remark that peak amplification levels vary disproportionally according to frequency vibration. It again means that peak amplification increases significantly where getting ahead of high frequencies (S2) to low frequencies (S4). In addition, it is possible to conclude that shear wave velocity tends to vary according to mechanical properties changing for any deemed site, which are steady for stiff soils and meddling for soft and very soft soils.

Table 3. Amplification values and corresponding frequencies

Site	Frequency (Hz)		Amplification	
	Linear	Equivalent linear	Linear	Equivalent linear
S2	5.17	4.9	1.8	1.9
S3	2.34	1.73	3.45	2.72
S4	1.19	0.78	4.57	2.27

Frequency bands used for characterizing site categories were determined based on probabilistic concept, according to which the Power Spectral Density (PSD) is calculated as a white noise filtered by the mean transfer function of the concerned site category. The bandwidth determined for PSD allows, when centered on the fundamental frequency of site category (pick frequency in the mean transfer function), determining the frequency band for each design site (table 4).

Table 4. Frequency and period bands for RPA99 site categories

Site	Frequency (Hz)	Period (s)
S1 (Rock site)	$f > 6.7$	$T < 0.15$
S2 (Stiff site)	$3.16 < f \leq 6.7$	$0.15 \leq T \leq 0.3$
S3 (Soft site)	$1.52 \leq f \leq 3.16$	$0.3 < T \leq 0.65$
S4 (Very soft site)	$f < 1.52$	$T > 0.65$

5. Conclusion

This study allowed proposing a simple wealth for RPA99 design sites characterization, through determining average transfer functions by the way of a probabilistic simulation approach combined with statistical study. The process consists first to simulate, for any site type defined by the RPA99, many soil profile realizations with respect to RPA99 requirements in terms of limitations imposed towards the shear wave velocity profiles, and then, make a deterministic calculation of mean transfer functions. The obtained results are of a great interest whereas they give an innovative vision to geophysical prospection's results. The mean transfer function is a practical tool permitting to characterize fully and directly the sites objects of study and will, henceforth, be able to allow classifying the studied soils by comparing their in-situ measured data with transfer functions concerning the RPA99 design sites, S1, S2, S3 and S4.

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