16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

COMPARATIVE SEISMIC STUDY OF TYPICAL RC BUILDINGS ACCORDING TO A NEW RPA99 BASED APPROACH

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ABSTRACT

Building seismic codes commonly propose average design response spectra associated with mean site factors for the purpose of seismic structural design. These codes often distinguish between field effects referring to seismic energy. Unlike several of these contemporary codes, the Algerian Aseismic Rules (RPA99, ver 2003) provide response spectra, which do not integrate the site factor concept, even though it proposes different soil classes. The present work proposes a comparative study of the seismic behavior of typical RC buildings made according to RPA99 provisions and a new RPA99 based approach, which follows the Eurocode8 (EC8) provisions. It has been found that there are discrepancies in the results of the two approaches, mainly due to the frequency content reflecting the intrinsic signatures of the used seismic signals, on the one hand, and the integration of site factors via the new approach, on the other hand.

Keywords: Response spectrum; Site factor; RC building; EC8; RPA99.

1. INTRODUCTION

Local site conditions have a strong influence on shaking behavior of sites and plays a major role in the damage potential of earthquakes. Seismic waves near the soil surface usually suffer important fluctuations due to the difference in the geological contrast that can result in significant differences in structural damage within the same area. Indeed, because of the combined action of plate tectonics and erosion, the earth is much less consistent and more heterogeneous in surface than in depth. Surface soil arising from sedimentary rocks or alluvial deposits are less consolidated and less compact and therefore of lower impedance than the rock basement on which they rest. By crossing them, the seismic waves are amplified and even trapped. These changes, commonly called site effects, are governed by the transfer function (TF) of the medium, reflecting swings experienced by the rock motion. Local site effects, related to the local geology and topography in addition to earthquake source effects, and propagating path effects, correspond to the free field motion, representing the actual seismic excitation experienced by structures.

Despite some inconvenience from scientists and researchers in the field, knowledge of soil strata in terms of values of the shear waves (SW) velocity in the first thirty meters of the subsoil are a universally recognized means to inquire about the mechanical properties of the site soil and, therefore, its response to incident seismic waves. Almost all contemporary seismic codes (IBC 2006, EC8…) include site effects via seismic site categories associated with site factors and appropriate elastic response spectra. Site factors (Pitilakis, 2012; Beneldjouzi and Laouami, 2015; Beneldjouzi et al., 2017) represents the ground motion amplification with respect to outcrop conditions and reflect the change in the geological contrast between the bedrock and sedimentary material deposits. For practical design purposes, the current RPA99 propose acceleration values estimated at the bedrock and design elastic response spectra.

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However, these response spectra do not distinguish between seismic field types related to seismic intensity, and do not integrate clearly the concept of the site amplification factor. Indeed, all the elastic response spectra shapes show the same horizontal plateau level, although they represent different soil classes (Table 1 and Figure 1).

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 depth
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	$V_s \geq 200$ In the firsts 20 m

In this study, seismic behavior of typical RC buildings is analyzed and response's parameters are confronted according to the RPA99 approach and the approach proposed by Beneldjouzi and Laouami (2015). Following the second approach, linear and equivalent linear average TF performed over a wide sample of 1-D soil profiles have been proposed for each soil type, based on a stochastic simulation methodology. A probabilistic model using the random field theory (Fenton and Griffiths, 2000) allowed generating the bounded SW velocity values in each layer of any profile, according to RPA99 requirements (Equations. 1 and 2). The equivalent linear TF is used herein to emphasize seismic behavior of RC buildings.

$$\bar{V}_i^{\,j} = \bar{V}_{i\min}^{\,j} + \frac{1}{2}(\bar{V}_{i\max}^{\,j} - \bar{V}_{i\min}^{\,j})\left[1 + th\left(s\,\frac{\Delta\bar{v}_i^{\,j}}{2\pi}\right)\right] \tag{1}$$

where $\bar{V}_{i\min}^{\,j}$ and $\bar{V}_{i\max}^{\,j}$ are the minimal and maximal bounds of the average SW velocity in i^{th} layer of j^{th} soil profile, respectively; *th*, is the hyperbolic tangent; $\Delta\bar{v}_i^{\,j}$, is a local and standard random field having zero mean and unit variance and *s*, is a factor governing the mean SW velocity variability between its two bounds, and :

$$\Delta\bar{v}_i = \left(\frac{2}{N}\sum_j \cos(2\pi\phi_j)\right)^{\frac{1}{2}} \tag{2}$$

where, ϕ_j, is a random number and *N*, the number of elements in the summation. The average TF were also used to compute an average site factor and average elastic response spectrum for each site class, according to the methodology adopted in the current Eurocode8 (EC8). EC8 mainly proposes two kinds of response spectrum (type1 and type2) related to seismic intensity level in order to mark the difference between seismic excitations due to their frequency content.

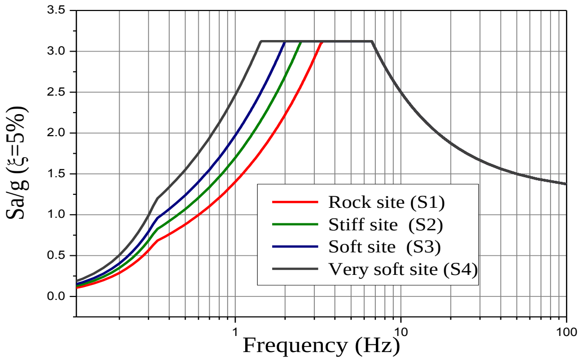


Figure 1. Normalized design response spectra (RPA99)

2. RPA99 REQUIREMENTS AND RECOMMENDATIONS

Recent seismic risk studies (Benouar, 1994; Bouhadad and Laouami, 2002) demonstrated that the northern part of Algeria is a moderate-to-strong seismic area. This was endorsed by some major seismic events (the last one being the Boumerdes earthquake that occurred in May 21, 2003, *M*w=6.8) which stroked the region causing important human and material losses. Many sites in this area have topographic, geological and geotechnical conditions that incite the appearance of local effects (Laouami and Slimani, 2013). In RPA99, the amplification phenomenon is indirectly considered through normalized response spectra corresponding to four soil categories (Table 1). Moreover, to avoid the resonance phenomenon, the code recommends that particular caution should be paid to the building site (RPA99 Sec. 2.1). The code encourages thus, specialists and engineers to carry out additional investigations according to the importance of the planned structure. For the purposes of structural design, it proposes the equivalent static method (pseudo dynamic method) for structures of a certain height and the modal spectral dynamic method for the case of all common structures, especially, those having more than two stories, which, in addition, must got bidirectional RC bracing walls.

3. BUILDING TYPES AND MODELLING

RC moment resisting frames systems offer a satisfactory ductility and enables an economic and safe structure, capable to resist, adequately, bearing and lateral loads. Most of the Algerian North real estate built before 2003 is made of bidirectional RC resisting frames. However, damages suffered by constructions of that system following the Boumerdes earthquake (2003, may 21) demonstrated its vulnerability to sever lateral seismic loads beyond a certain height. To ensure an adequate lateral load carrying capacity, resisting moment frames associated with bidirectional RC shear wall systems, are an ideal choice for multi-story RC buildings imposed within the revised RPA99 (2003 version). Currently, that is the most common construction system in Algeria, recognized economically viable and technically easy.

R+11 R+7 R+3

Figure 2. 3D models of the studied buildings

The studied buildings are within that construction system and are of substantially symmetrical geometry. These buildings are of mixed structural system (resisting moment frames associated with shear walls), with RC stairs and fillings of hollow brick masonry. They stay on RC raft foundation and have one basement floor, ground floor plus three floors (R+3), seven floors (R+7) and eleven floors (R+11), respectively. Floors and roof are of two-way solid RC flat slab. The basement floor's and floor's heighs are of 3m and 3.06 m, respectively. This choice reflects the wish to target specific natural frequency values characterizing buildings ranging from rigid to flexible (Figure 3). The dimensions of the structural elements in both directions are given in Table 2.

Table 2. Dimensions in Cm of building's structural elements

			R+3	**R+7**		**R+11**		
Element			Stories 1-4	Stories 1-4	Stories 5-8	Stories 1-4	Stories 5-8	Stories 9-12
Column	C1	$a_1 x b_1$	40x40		40x40			40x40
	C2	$a_1 x b_1$		50x50			50x50	
	C3	$a_1 x b_1$				60x60		
Beam	P	*bxh*	30x40	30x40	30x40	30x40	30x40	30x40
Slab	D	*e*	16	16		16		
Wall	W	*a*	20	20		20		
E(MPA)	32000							
ν	0.3							
ρ_c(t/m^3)	2.5							

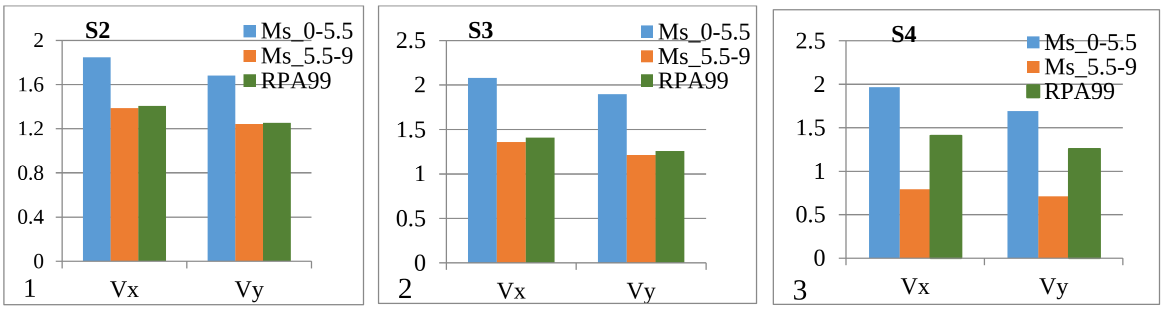
Comparative numerical study following the modal spectral method is conducted on finite element models established using CSI SAP2000 v15 software (Figure 3), considering a perfect embedding (rigid base). The study uses RPA99 5% damped response spectra and spectra suggested by Beneldjouzi and Laouami (2015) wherein site effects are reflected through the proposed site factors. Following the Beneldjouzi and Laouami approach, response spectra are performed considering two wave surface magnitudes, Ms, of records, according to the EC8 methodology. Type1 of EC8 response spectra refers to Ms > 5.5 whereas the type2 relates to Ms ≤ 5.5. Response spectra of type1 have more energy in low frequencies and correspond to far field records. Inversely, spectra of type2 have maximal amplitudes at high frequencies and refer to near field records.

4. RESULTS AND DISCUSSION

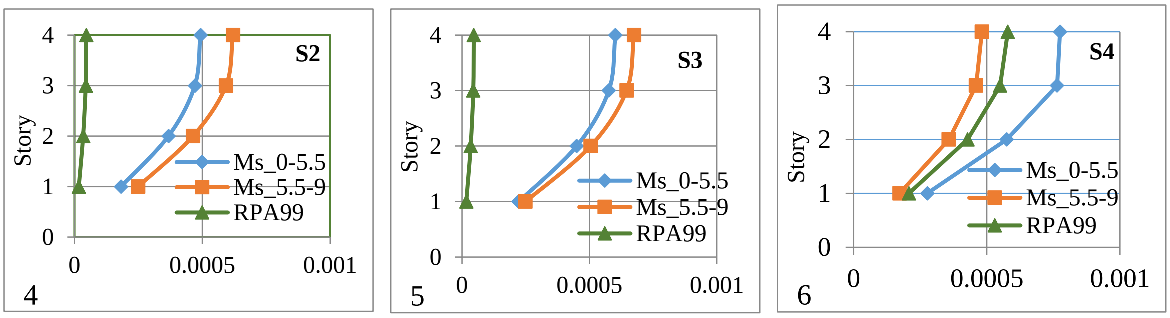
4.1 Building R+3

Figure 3 shows response's parameters considered in the analysis, where, discrepancies are highlighted ranging from weak to important. For the S2 site, the value of the overall base shear force (Figure 3.1) calculated with the type2 response spectra ((Ms ≤ 0-5.5) is important compared to those obtained via RPA99 and type1 (Ms > 5.5) spectra. This result makes sense for several considerations, the most important of which refers to the building's fundamental frequency exceeding 6 Hz (T_0 = 0.16 s). This frequency relates to maximum amplitudes that appear from 4 Hz in the calculated spectrum which is compatible with the characteristics of the near field (type2) and the nature of the stiff site (Figure A2.a). On the other hand, it is well known that the wedge frequency in the Fourier spectrum of an accelerogram is inversely proportional to the magnitude of the wave field. This supports the results obtained for the second level of seismic intensity (type1) for which, the value of the base shear force is lower, besides the fact that RPA99 spectrum underestimates the seismic force for this range of magnitudes. The same logic is maintained for the other two calculated parameters, i.e., the inter-story drift and story displacement since they are proportional to intensity of the seismic force (Figures 3.4 and 3.7).

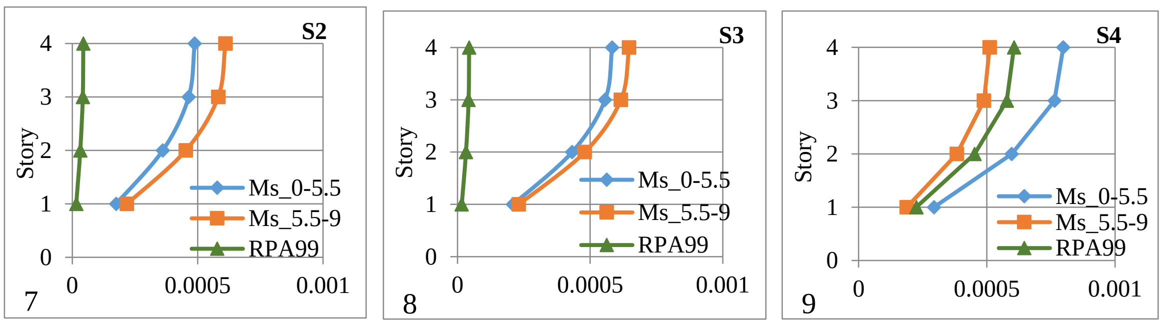
For the case of S3 site, the effect of the near field remains predominant and the fundamental frequency matches with a maximal spectral peak in the type2 response spectrum, and increased the seismic force relative to S2 site because of higher value of the S3 site factor (Table A1 and Figure A2b).
For the S4 site, the base shear force of the type1 spectrum (Figure 3.3) is significantly lower than that of type2 and RPA99. That is due to spectrum having maximum spectral amplitudes at low frequencies (0.6-1.5 Hz) which do not match the fundamental frequency of the building where, spectral amplitude is substantially small compared with spectra of type2 and RPA99 (Figure A2c). We note in this case that the regulatory spectrum overestimates the seismic force. The same trend is observed for the results for the other parameters considered in the analysis (Figures 3.6, 3.9, 3.12 and 3.15).



Global base shear (10^3 KN)



Story drift X-X (m)



Story drift Y-Y (m)

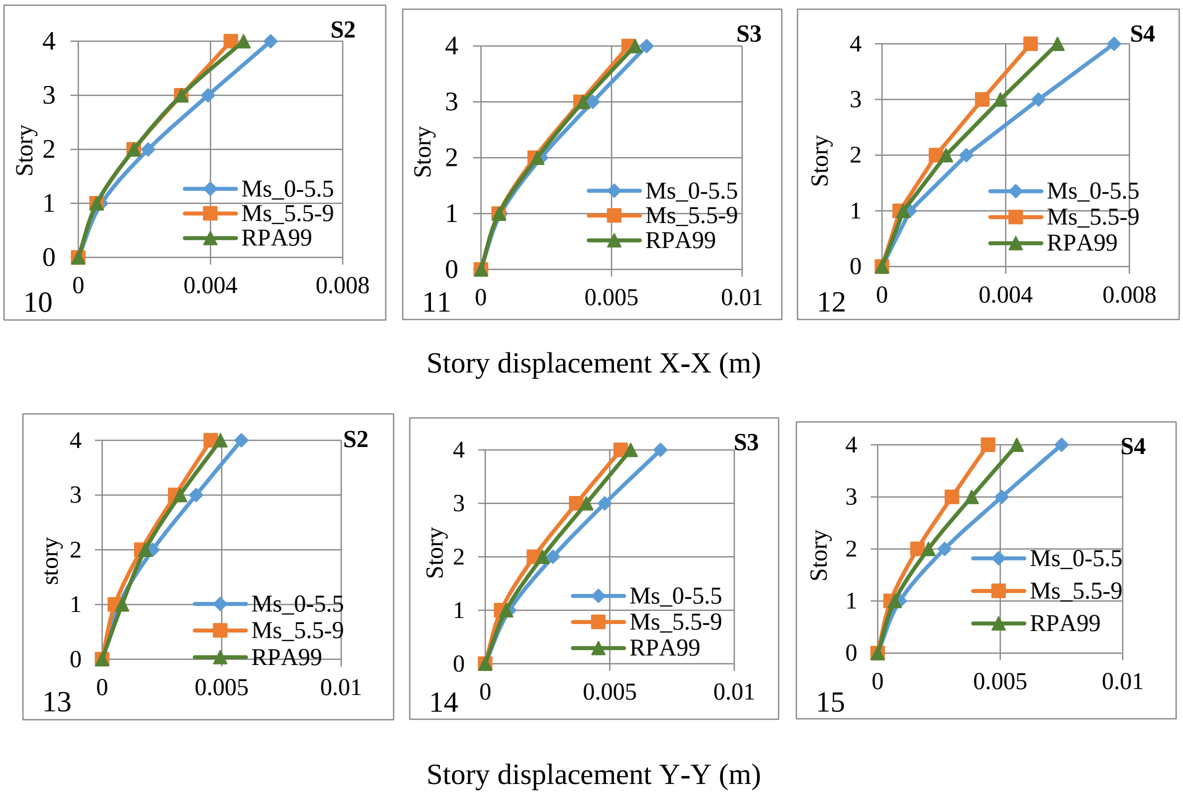
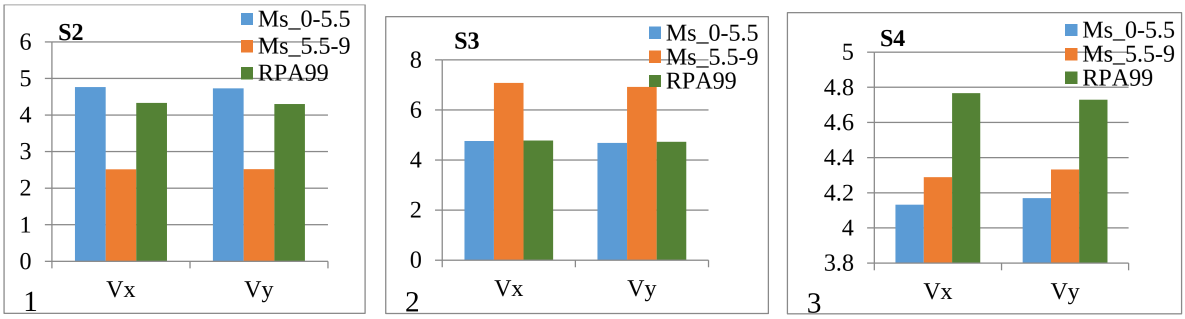


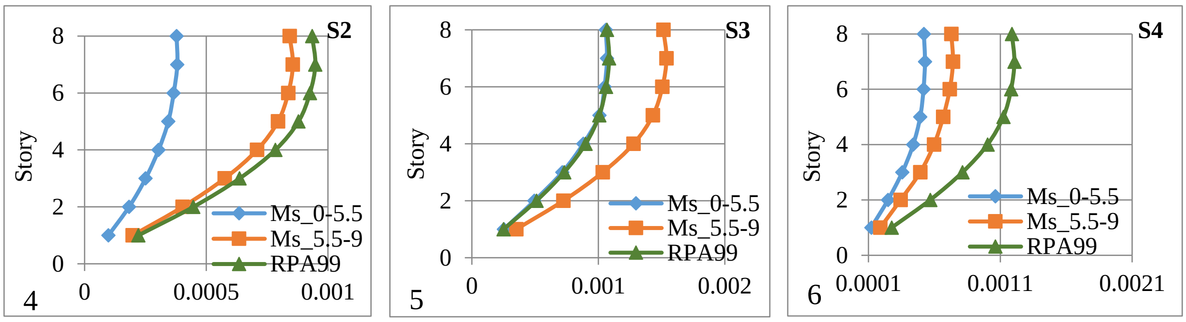
Figure 3. Representation of the response's parameters considered in the seismic analysis (base shear force, storey drifts and story displacements) for the building R+3.

4.2 Building R+7

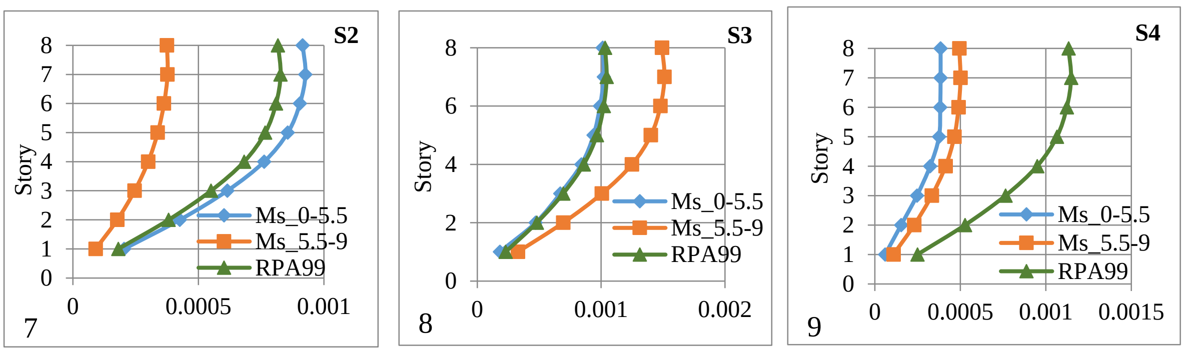
Figure 4 shows the response of the R+7 building represented as base shear force in addition to story drift and story displacement. For the site S2, the responses relating to type2 and RPA99 spectra are close and agree with a frequency content close to the natural frequency of the building (f_0 = 2.7 Hz) (Figures 4.1 and A.2a). These same values are much lower for the type1 spectrum because they have maximum spectral values remaining below those of the other two spectra for the whole frequency range of interest (Figure A3a). This demonstrates, once again, the dominance of the near field due to the relatively rigid nature of the building, although its natural frequency is higher than that of the R+3 building. For the S3 site, a large dominance of the far field effect is observed through the values of the base shear force (Figure 4.2), as well as the values of the other parameters relating to type1 spectrum because of spectral amplitude peaks, which occur within a frequency range containing the building's natural frequency (Figures 4.5, 4.8, 4.11 and 4.14). Moreover, for the type2 and RPA99 spectra, the responses considered are close because they relate to spectra having affluent frequency content near f_0 (Figure A.2b).
For the S4 site, the responses considered with respect to type1 spectrum and that of RPA99 are comparable regarding the spectral amplitudes of the two spectra. These values remain lower for the spectrum type2 and agree with the characteristics of the near field and the nature of the S4 site (Figures 4.3, 4.6, 4.12 and A.2c). Furthermore, it is well shown through results obtained for R+3 and R+7 buildings that RPA99 spectra do not distinguish between the field types. Indeed, the global base shear as well as story drift and story displacements tend appreciably to the same value for all site types except for the R+7 building on S4 site.



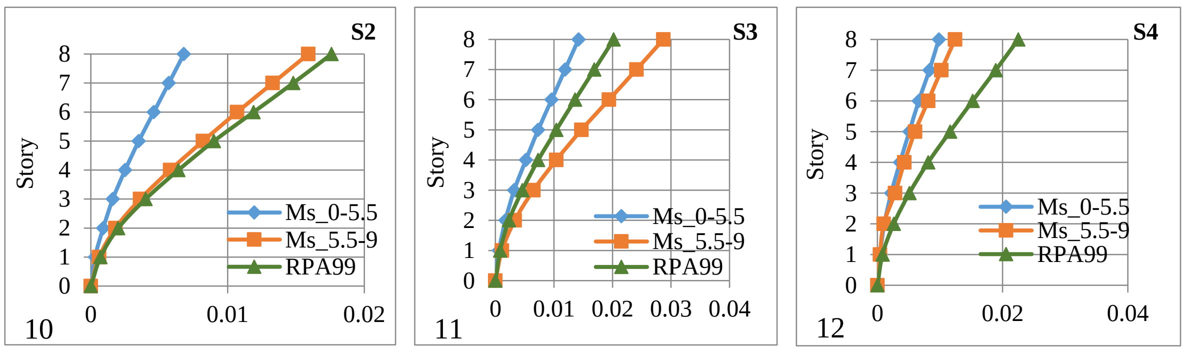
Global base shear (10^3 KN)



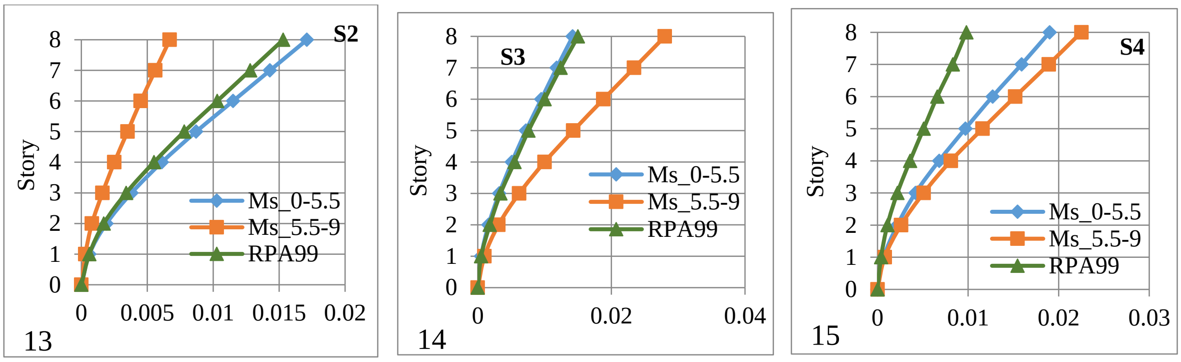
Story drift X-X (m)



Story drift Y-Y (m)



Story displacement X-X (m)

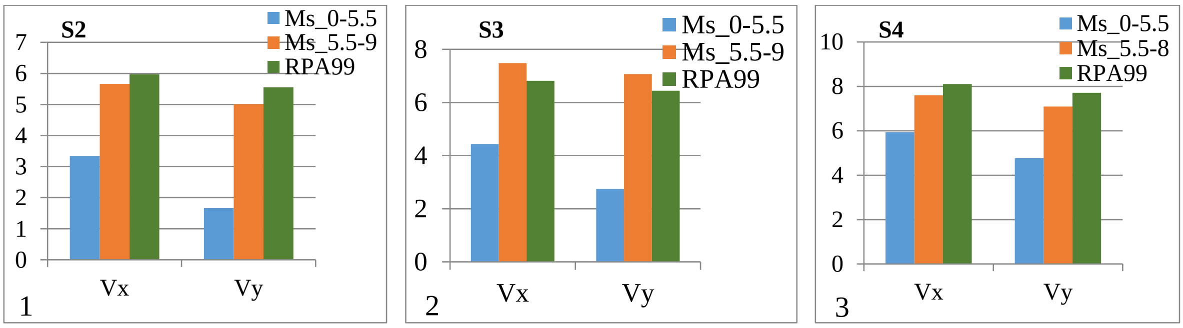


Story displacement Y-Y (m)

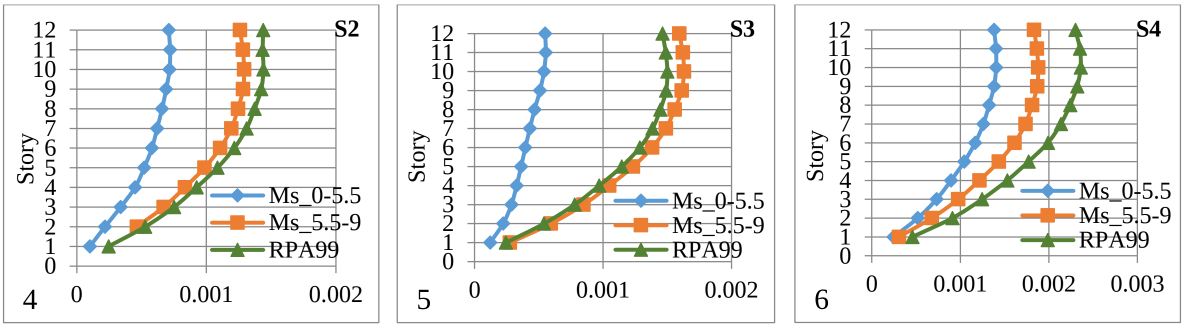
Figure 4. Representation of the response's parameters considered in the seismic analysis (base shear force, storey drifts and story displacements) for the building R+7.

4.3 Building R+11

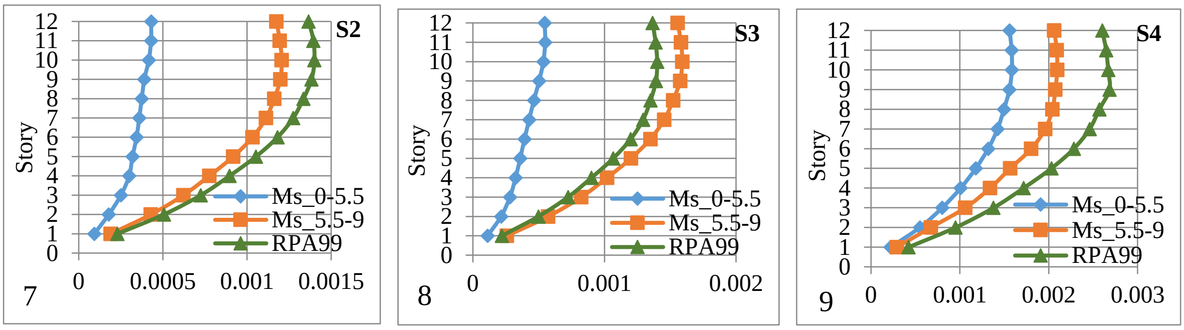
In contrast to the R+3 building, Figure 5.1 shows that the base shear force obtained through the type2 spectrum of the stiff site is lower than those of RPA99 and type1 and emphasizes influence of the far field. Indeed, within the type2 spectrum of S2 site (Figure A2.a), the structure's fundamental frequency reaching 1.52 Hz (T_0 = 0.66 s) lies outside of the maximum spectral amplitudes. However, the ascendant branch of the RPA99 spectrum starts to be influential at the fundamental frequency for the RPA99 spectrum and remains superior up to 3 Hz even to the type1 and type2 spectra.
For the S3 site, the building is more sensitive to high magnitudes that tend to excite low frequencies, giving a greater shear force even to that of the RPA99 (Figures 5.2 and A3b). This value of the shear force, higher than that of type2 and close to that of RPA99, denotes the dominance of the far field effect compatible with the nature of S3 site and the R+11 building having more flexibility.
For the S4 site, even though the RPA99 spectrum slightly overestimates the seismic force particularly with respect to type1 spectrum (except around *f*=1Hz), it can be considered that the two base shear are close (Figures 5.3 and A3c), because at the right of the fundamental frequency, spectral amplitudes of the two spectra are substantially close. The inversely proportional relationship between magnitude and frequency remains respected and stays valid for the other parameters considered in the analysis. It is clear that, overall, the regulatory spectrum overestimates the seismic force and consequently the other parameters related to it for S2 and S4 sites, whereas the others response's parameters obey the fluctuations noted for the case of base shear force for sites S2, S3 and S4.



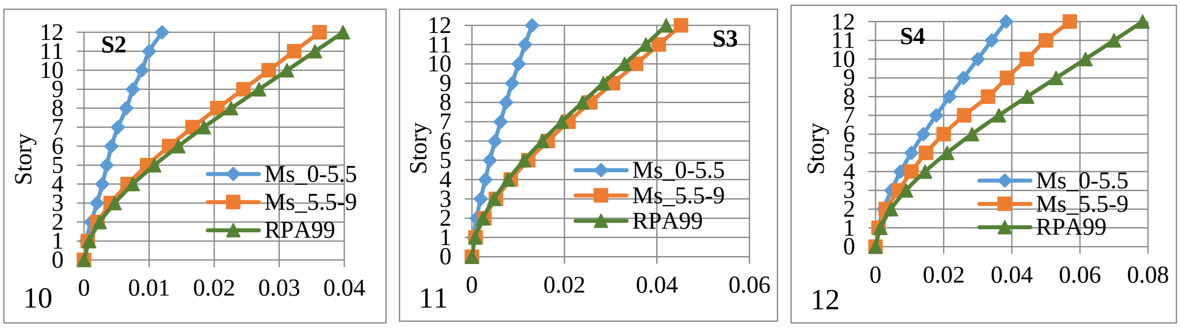
Global base shear (10^3 KN)



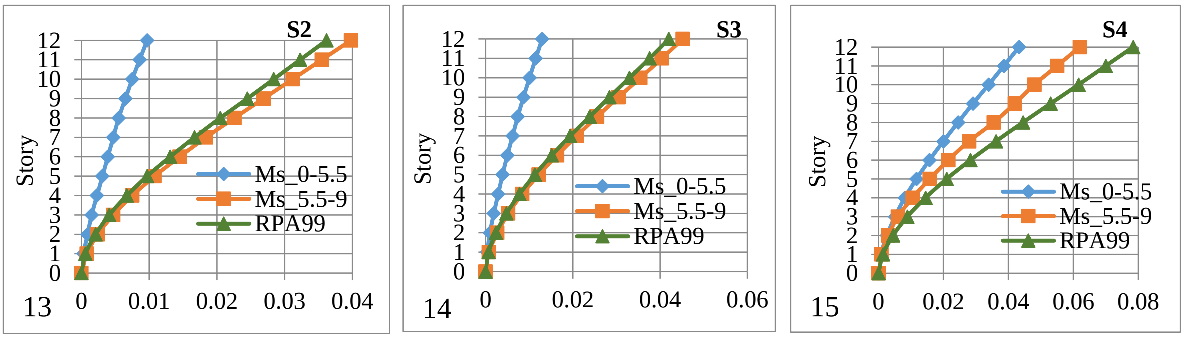
Story drift X-X (m)



Story drift Y-Y (m)



Story displacement X-X (m)



Story displacement Y-Y (m)

Figure 5. Representation of the response's parameters considered in the seismic analysis (base shear force, storey drifts and storey displacements) for the building R+11

5. CONCLUSIONS

This study provides linear seismic analysis through the response spectrum method, using regulatory and calculated spectra. The parameters influencing the response spectrum and, consequently, the structure's response are mainly soil conditions, magnitude of the seismic motion, epicentral distance as well as fundamental frequency of the structure. It can be concluded that for rigid buildings where the near field effect is dominant, the RPA99 spectrum is well correlated with type1 spectra but underestimates the seismic force compared to type2, except for the S4 site, where it overestimates the force compared to type2 and underestimates it with respect to type1 (R+3 building). For less rigid buildings, (case of the R+11 building for example), the regulatory spectrum is substantially coherent with that of the type1 but significantly overestimates the seismic force compared to the type2. Moreover, the observation of the levels of overall shear intensity for buildings R+3 and R+11 shows that the regulatory spectra are dominated by the far field effect. When the regulatory spectra underestimate or overestimate the seismic force compared to the calculated spectra, this is because that they does not distinguish between the type1 and the type2 records. Furthermore, observation of base shear forces from regulatory spectra obtained for buildings R+3 and R+7, and to a lesser degree for building R+11, are remarquably comparable for all the considered sites and denote absence of site factor concept within the RPA99 spectra.

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APPENDIX

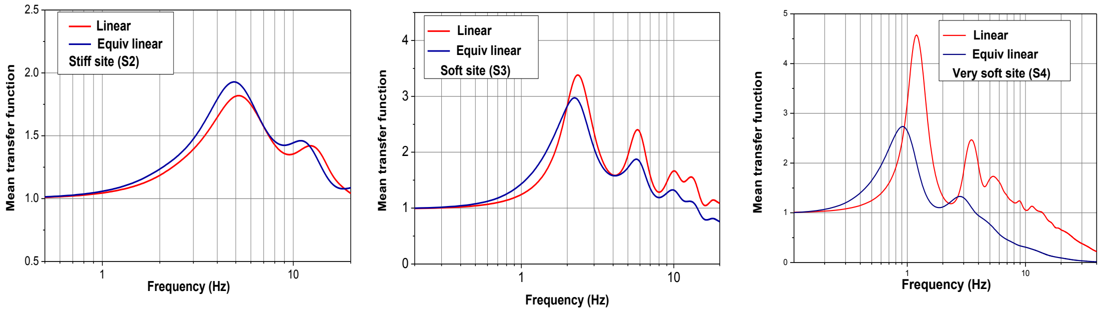

Figure A1. Mean equivalent linear transfer functions for RPA99 seismic site classes from Beneldjouzi and Laouami (2015).

Table A1. Calculated mean site factors and their standard deviations considering the two seismicity levels from Beneldjouzi and Laouami (2015). The site factors are compared with EC8 site factors and those found by Pitilakis et al. (2012), which are proposed for the next EC8 amendment from Beneldjouzi and Laouami (2015).

	Ms≤5.5 (type2)				Ms>5.5 (type1)			
	Linear case				Equiv linear case			
Site	Calculated mean SF	std	EC8	Pitilakis (2012)	Calculated mean SF	std	EC8	Pitilakis (2012)
S2-B	1.44	0.05	1.35	1.40	1.42	0.067	1.20	1.30
S3-C	1.70	0.131	1.50	2.10	1.65	0.144	1.15	1.70
S4-D	1.64	0.05	1.80	1.80	1.31	0.08	1.35	1.35

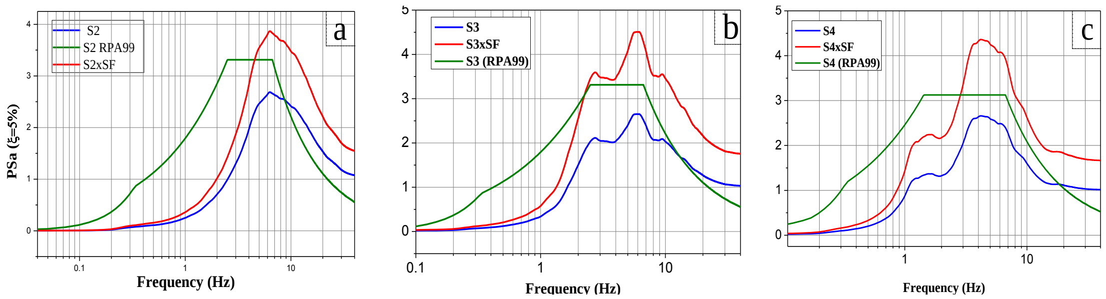

Figure A2. Type2 mean acceleration response spectra with 5% damping of the S2, S3 and S4 sites, compared with the corresponding RPA99 and type2 EC8 design response spectra from Beneldjouzi and Laouami (2015).

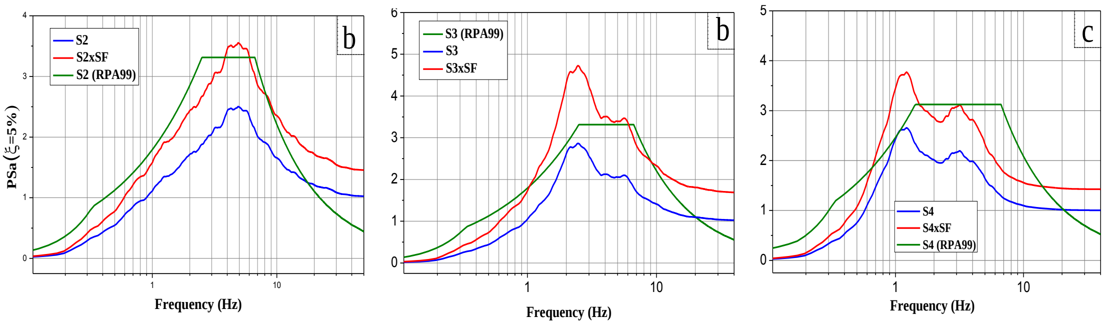

Figure A3. Type1 mean acceleration response spectra with 5% damping of the S2, S3 and S4 sites, compared with the corresponding RPA99 and type1 EC8 design response spectra from Beneldjouzi and Laouami (2015).