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COMPARISON OF THE RECORDED SEISMIC SIGNALS FOR THE 2012 EMILIA AND 2016 CENTRAL ITALY SEISMIC SEQUENCES WITH THE DESIGN EARTHQUAKES BASED ON THE PSHA APPROACH

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Abstract

The recent seismic sequences occurred in 2012 in the Emilia region and in 2016 in Central Italy have confirmed the high level of vulnerability typical of masonry historical buildings and historical centres. Among these, the historical centre of Amatrice was razed to the ground and most of the historical buildings of municipalities in the epicentral area suffered partial or total collapse. Ground motion recordings highlighted a remarkable difference with the design earthquakes provided by the national seismic hazard map, which is based on the PSHA (Probabilistic Seismic Hazard Assessment) approach. Specifically, the response spectra of the signals recorded at Finale Emilia and Mirandola (2012) and at Norcia and Amatrice (2016) have been compared to the design spectra prescribed by the national building code; from comparison, the strong underestimation of the design spectral accelerations is evident, especially for the historic centre of Amatrice, due to the additional effect of local amplification. All recent Italian earthquakes (L'Aquila 2009, Emilia 2012, Central Italy 2016) and many others around the world, have shown that the PSHA approach does not provide reliable results in case of severe events. On the contrary, the technical literature shows that the NDSHA (Neo-Deterministic Seismic Hazard) approach generally provides reliable results. The need to update the seismic regulations, therefore, is clear in view of a preventive policy against the collapse of historic centres and monuments, based on the correct definition of seismic hazard levels. In the present contribution the analysis of the above seismic events is presented, being part of a wider analysis on the effects produced on the built heritage by seismic sequences.

Keywords: Seismic sequences, Seismic signal analysis, Seismic hazard.

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1 INTRODUCTION

In recent years, the Italian earthquakes that struck the Emilia region in 2012 and Central Italy in 2016-17 were both characterized by a sequence of seismic events. Due to this, the observed damage gradually increased, leading to partial or even global collapse of several buildings or entire historical centres.

The seismic events of 2012 that hit the Emilia region in May and June, caused several victims, injuries and severe damage in historic centres as well as in rural and industrial areas. The sequence was characterized by two main shocks (Mw 5.9 and 5.8) on May 20 and 29, respectively, with 5 additional earthquakes having magnitude greater than 5, and thousands of minor events. The epicentre was located near Finale Emilia for the first shock and, for the second one, in the south-west direction, near San Felice sul Panaro [1]-[5]. The area affected by the 2012 seismic sequence is characterized by relatively moderate historical seismicity [5]-[7].

Between August 24 and October 30, 2016, a large area of the Central Apennines between the regions of Umbria, Marche, Lazio, and Abruzzo was hit by a seismic sequence characterized by four main events and several aftershocks that led to the collapse of numerous buildings and the death of many people [8]-[10]. The four main shocks occurred on: August 24 (Mw 6.0), with the epicentre near the municipalities of Accumuli and Amatrice; October 26 (Mw 5.4 and 5.9), with the epicentres near the municipality of Ussita, adjacent to the Sibillini mountains; October 30 (Mw 6.5), with the epicentre close to Norcia. In the following months, the seismic sequence continued, with several important tremors having magnitude even greater than 5 [11]-[18]. The Central Apennines belong to the Mediterranean regions characterized by medium-high seismicity; historical data show that the area of Amatrice and Norcia had already been affected by several destructive seismic events in the past [17],[18].

These two seismic sequences led to two different damage scenarios of the built heritage. In Emilia, residential buildings suffered minor to moderate damage, while churches, towers, bell towers, and castles were affected by severe damage and, in some cases, complete collapse (see [19]-[26]). On the other hand, in Central Italy, residential buildings of many historic centres were completely destroyed by the seismic sequence, while churches, towers and bell towers were progressively damaged, but did not completely collapse during the first mainshock (see [27]-[31]). The differences between the damage scenarios can be ascribed to the different accelerograms, the different site conditions, and the different construction techniques. The present contribution reports part of a wider analysis on the effects produced on the built heritage by the above seismic sequences [32]; in the following, the recorded seismic signals are analysed, and their peculiar features highlighted. Moreover, the relative response spectra are compared to those prescribed by the Italian building code and those proposed by the Neo-Deterministic approach as well.

2 ANALYSIS OF THE SEISMIC SIGNALS RECORDED DURING THE MAIN SHOCKS OF THE TWO SEISMIC SEQUENCES

2.1 2012 seismic sequence

The seismic signals recorded during the May 20 mainshock and the May 29 aftershock have been studied to assess the destructive potential of the seismic events. The strongest events of the sequence were recorded by more than 250 accelerometric stations belonging to the National Accelerometric Network (RAN) of the Civil Protection Department and to the National Seismic Network (RSN) of the National Institute for Geophysics and Vulcanology (INGV).

Hereafter, an analysis is done of the accelerograms recorded by the Mirandola station (MRN), for the May 20 and 29 seismic events, and by the Finale Emilia station (FIN0) for the May 29 seismic shock, the latter station being installed after the first shock to monitor the evolution of the seismic sequence. Both stations were located near the historic centres; from the Homogeneous Microzones in Seismic Perspective (MOPS) maps [33] it appears that the historical centres and the seismic stations lie on the same soil type; consequently, the recorded signals already take into account possible site amplification effects. The characteristic data of the stations are listed in Table 1. Both the stations are located on soil type C. Therefore, it is possible to compare the two seismic inputs, which differ in magnitude and recording distance from the epicentres, but correspond to similar stratigraphic and topographic conditions [4].

Station	Epicentral distance [km]		Subsoil category	M_W	
	20 May	29 May		20 May	29 May
MRN	16.1	4.1	C	5.9	5.8
FIN0	-	17.5	C		

Table 1: Characterization of Mirandola (MRN) and Finale Emilia (FIN0) accelerometric stations.

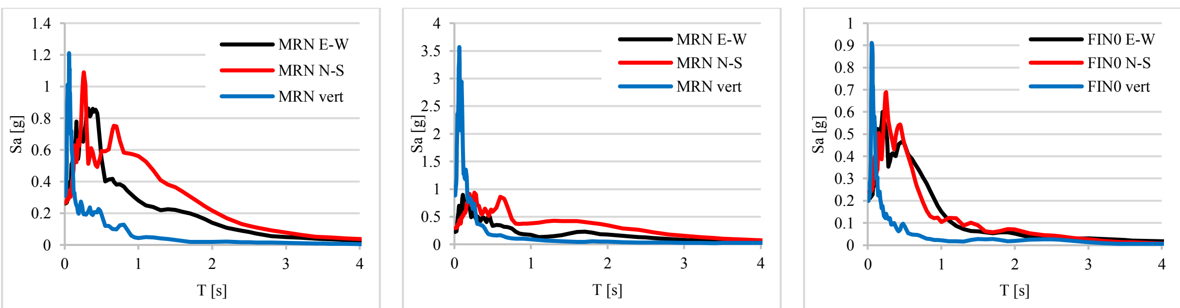
The acceleration elastic response spectra (5% damping ratio) of the horizontal and vertical components recorded in Mirandola and Finale Emilia are shown in Figure 1 (accelerograms are shown in [32]). The peak parameters (PGA, PGV and PGD), characterizing the seismic motion, are listed in Table 2 and Table 3.

Event		PGA [g]	PGV [cm/s]	PGD [cm]
20 May	MRN	0.26	46.3	10.4
29 May	MRN	0.29	57.5	14.4
	FIN0	0.24	17.6	3.0

Table 2: Peak parameters of the horizontal components for the 2012 seismic sequence.

Event		PGA [g]	PGV [cm/s]	PGD [cm]
20 May	MRN	0.30	5.9	1.9
29 May	MRN	0.86	26.4	5.6
	FIN0	0.19	3.0	0.9

Table 3: Peak parameters of the vertical component for the 2012 seismic sequence.



Mirandola, May 20 | Mirandola, May 29 | Finale Emilia, May 29

Figure 1: Acceleration response spectra of the recorded seismic events in the Emilia region.

The PGA values recorded during the two seismic shocks are well above of those reported in the national seismic hazard map, NTC2018 [34],[35]; in particular, very high PGA values were recorded for the vertical component at the Mirandola station. According to the national map, the peak ground accelerations for the Mirandola and Finale Emilia sites are 0.140g and 0.189g at Mirandola and 0.149g and 0.200g at Finale Emilia for return periods of 475 years (life safeguard limit state, SLV) and 975 years (collapse limit state, SLC), respectively. These values, being referred to a flat rigid soil, do not include local amplification effects.

The duration of the two seismic events was not short and several high amplitude peaks occurred; a meaningful interpretation of this can be obtained evaluating the Trifunac duration, which relates the seismic shaking duration to the energy content [36]. In the computations, the vertical component of the accelerometric records was also considered, because of the amplitude of the corresponding peaks. The results are summarized in Table 4 and in [32].

Event		Trifunac Duration [s]
20 May	MRN	6.32
29 May	MRN	7.01
	FIN0	9.42

Table 4: Trifunac Duration of the 2012 seismic sequence.

Examining the spectral accelerations, it appears that the vertical components exhibit a single peak for both the events and the stations. Looking at the spectral accelerations of the horizontal components, it is noticeable that maximum values were measured in the North-South direction for both the seismic events.

Looking at the spectral shapes, it is clear that vertical accelerations are characterized by a well-defined peak, associated with the same period for both the events and the stations, whereas the horizontal accelerations have peaks distributed over a wider range of periods.

Moreover, for both the Mirandola and Finale Emilia sites, the spectral accelerations corresponding to the main shocks have been compared to the elastic design spectra specified in the Italian building code (NTC2018 [34],[35]), see Figure 2. Return periods of 475 and 975 years were used, corresponding to the SLV (life safeguard) and SLC (collapse) limit states, respectively (10 % and 5 % probability of exceedance in 50 years); 5 % damping is assumed. Both class C and class D soils have been considered.

The horizontal spectral accelerations defined by the national code are clearly exceeded by those associated with the actual events. Code spectra corresponding to the highest return period and soil category D are comparable to ones associated with the signals recorded at Mirandola, whereas the signal recorded at Finale Emilia is compatible with the response spectrum associated with soil category C. The vertical spectral accelerations defined by the national code were largely exceeded: occurred earthquakes are not even comparable with the events corresponding to the highest return period. In this regard, it should be remarked that the spectrum specified in the building code for the vertical component does not account for the amplification effect caused by the subsoil category.

2.2 2016-2017 seismic sequence

The analysis of the accelerometric signals recorded during the mainshocks of August 24 and October 30 allows for the definition of some meaningful parameters for assessing the destructive potential of the seismic shocks. More than 200 accelerometric stations from the National Accelerometric Network (RAN) of the Civil Protection Department and the National Seismic Network (RSN) of INGV recorded the strongest shocks of the sequence. The signals corresponding to the two seismic events recorded at the accelerometric stations near the epicentres, namely Amatrice (AMT) and Norcia (NRC), are compared in the following. Table 5 summarizes the features of the stations under consideration. Both stations are located on soil type B. Therefore, it is possible to compare the two seismic inputs in terms of recording conditions (subsoil category and topography), even though they differ in magnitude and recording distance from the epicentres of the two seismic shocks.

The Norcia station is located near the historic centre; the Homogeneus Microzones in Seismic Perspective (MOPS) map [37] shows that the historical centre as well as the seismic station lie on the same soil typology; thus, it can be assumed that the recorded signals already consider possible site effects. Instead, the Amatrice station is located outside the historic centre, where the topographic and stratigraphic conditions are very different from those found in the old town, which is built on a soil composed of a 2-3m silty sand alluvial layer and a 20m layer of gravel and sand [38]. This configuration considerably amplified ground acceleration, as it was highlighted by the accelerometric records of some temporary stations installed by INGV after the first main shock of August 24 [30].

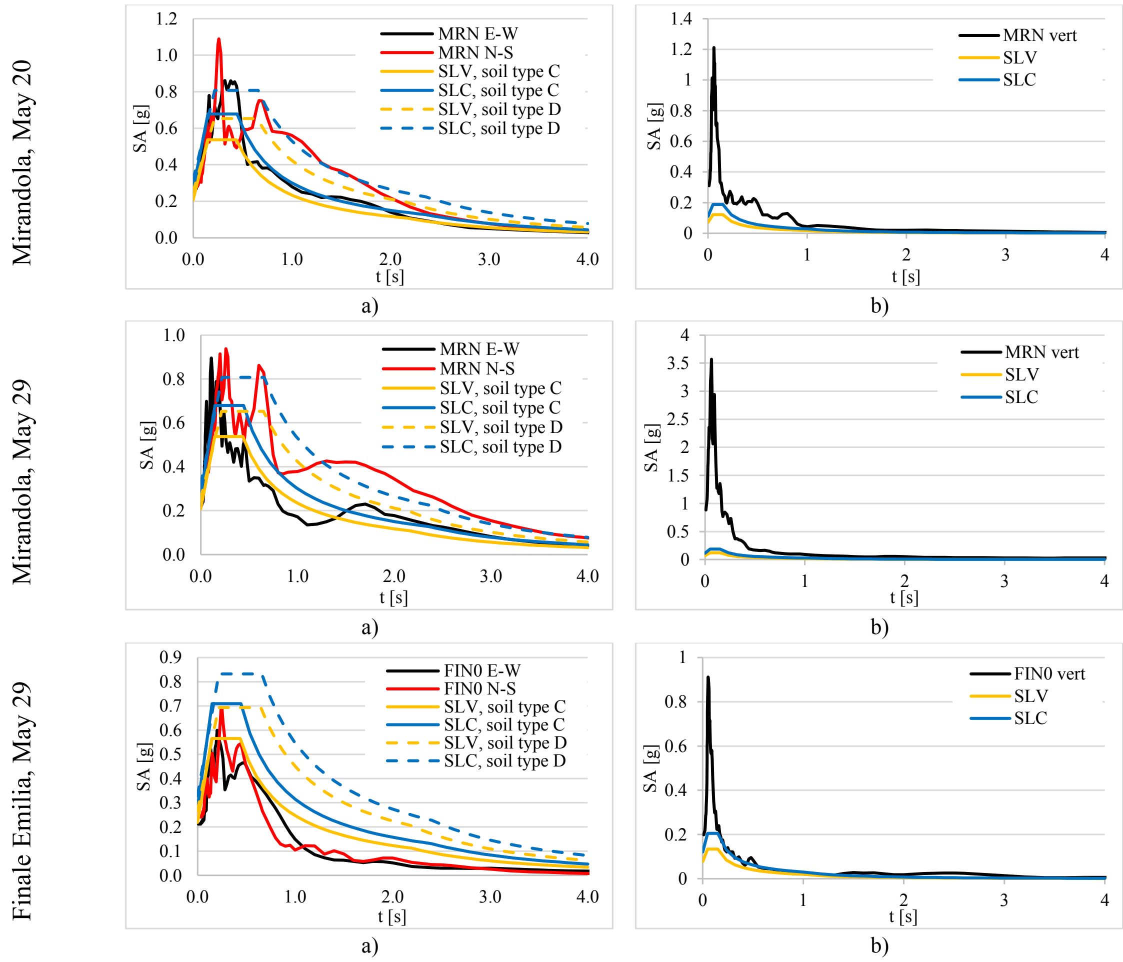


Figure 2: Comparison of the spectral shapes defined by regulation with the horizontal (a) and vertical (b) acceleration response spectra of the recorded signals in the Emilia region [32].

Station	Epicentral distance [km]		Subsoil category	M_W	
	24 August	30 October		24 August	30 October
AMT	8.5	26.4	B	6.0	6.5
NRC	15.3	4.6	B		

Table 5: Identifying parameters for the accelerometric stations at Amatrice and Norcia.

The acceleration response spectra of the horizontal and vertical components are shown in Figure 3 (accelerograms are reported in [32]). The response spectra of the amplified accelerograms, due to historic centre site conditions, have been superimposed to those of the accelerograms recorded at the permanent station, outside the town centre of Amatrice. Table 6 shows the peak parameters (PGA, PGV and PGD), which characterize the amplitude of the recorded seismic motion.

Event		PGA [g]	PGV [cm/s]	PGD [cm]
20 May	AMT	0.85	43.6	8.5
	NRC	0.37	29.8	6.6
29 May	AMT	0.52	37.9	7.5
	NRC	0.48	48.3	18.0

Table 6: Peak parameters of the 2016-2017 seismic sequence.

The recorded PGA values are much higher than the peak ground accelerations expected at the Amatrice and Norcia sites according to the national seismic hazard map (NTC2018 [34],[35]). Such values at Amatrice are 0.259g and 0.332g, whereas at Norcia are 0.255g and 0.327g, for return periods of 475 years (SLV) and 975 years (SLC), respectively.

Furthermore, as shown in [32], the PGA of the amplified signal is twice that of the signal recorded at the permanent Amatrice station.

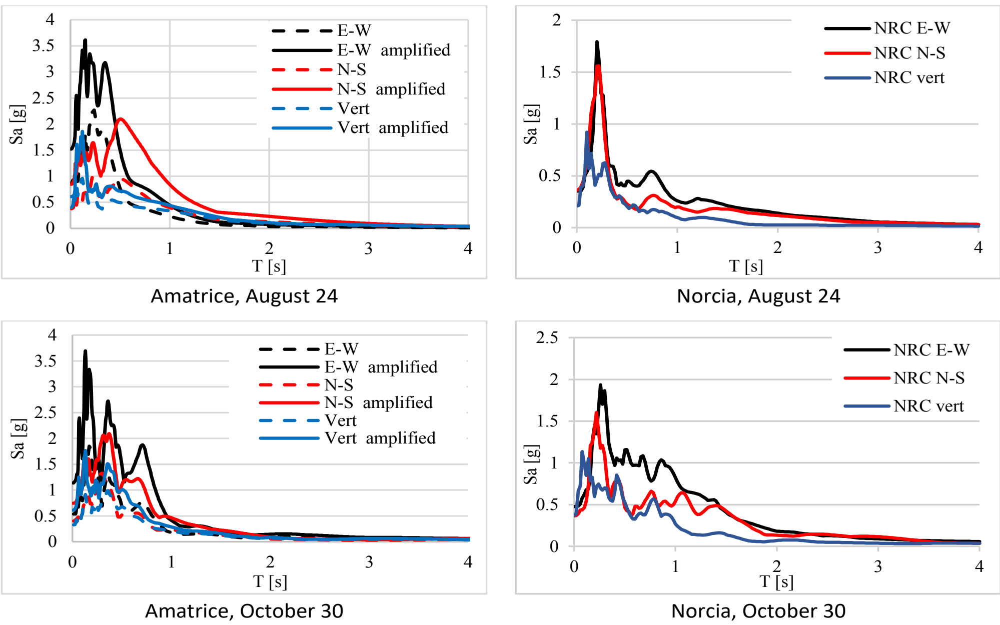


Figure 3: Acceleration response spectra of the recorded seismic event in Central Italy.

As shown in [32], the seismic event of August 24 is of the impulsive type, characterized by a short temporal window during which the peak accelerations occur, whereas the October 30 earthquake has a much wider time interval, during which significative accelerations occur. The Trifunac duration of the seismic events has been computed similarly to what done in paragraph 2.1.

The effective duration of the signals recorded on October 30 is greater than for those recorded on August 24, see Table 7 and [32].

Event		Trifunac duration [s]
20 May	AMT	3.64
	NRC	5.65
29 May	AMT	4.90
	NRC	9.88

Table 7: Trifunac Duration of the 2016 seismic events.

Examining the horizontal spectral accelerations for the Amatrice site (Figure 3), it can be seen that the maximum acceleration in the spectrum for the main shock of August 24 is extremely high: 2.32g in the case of the signal recorded at the permanent station outside the town centre, and 3.62g for the local amplified signal. The corresponding peak values in the October 30 event response spectra (Figure 3) are 1.77g and 3.69g. All of these values are from the east-west acceleration response spectra.

Analysing the elastic response spectra for the Norcia site, it can be noticed that the maximum spectral acceleration associated with the first seismic shock has a value of 1.80g (Figure 3). Instead, the peak value for the October 30 event is 1.93g (Figure 3). Also in the case of Norcia, the maximum values belong to the east-west components, implying that the two earthquakes were caused by the activation of the same family of faults.

Although associated with lower values, spectral accelerations in the north-south direction exhibit the same trend as those observed in the east-west direction. The amplitude difference is significant; for the August 24 event in Amatrice (recording station outside the town centre) the response spectrum has two peak values of 0.96g and 0.94g, which are far below the peak of 2.23g that characterizes the east-west direction. The amplified signal has two peaks equal to 1.64g and 2.10g, which, once again, are far below the peak of 3.62g associated with the east-west component.

A more precise comparison of the spectral shapes reveals that the peaks of the horizontal acceleration fall within in a narrow time interval (0.10-0.50s) for the event of magnitude 6, whereas they are distributed over a wider period range (0.26-0.88s) for the event of magnitude 6.5.

It is also worth noting that, despite the fact that the magnitude of the October 30 seismic event is greater, and the recording distance is shorter, the absolute peak acceleration associated with the Norcia response spectrum is lower than that associated with the Amatrice response spectrum of August 24, indicating a highly destructive seismic event.

Vertical component response spectra have lower acceleration values compared to those of the horizontal component response spectra. Maximum acceleration values exceed 1g in the spectrum of the signal recorded at Norcia during the Mw=6.5 event, and 1.5g in the spectra of both the Amatrice signals (amplified downtown motion).

Furthermore, at the Amatrice and Norcia sites, the horizontal spectral accelerations corresponding to the main seismic events have been compared to the elastic spectra defined in the Italian building code (NTC2018 [34],[35]) (Figure 4).

The spectral shapes referred to seismic events with return periods of 475 and 975 years, corresponding to the SLV and SLC limit states, are used in the comparison. In addition to the response spectra for soil type B, the spectra referred to soil type C are also shown.

The spectral acceleration values provided by national regulations were clearly exceeded: the occurred earthquakes are not even comparable with the event corresponding to the highest return period. In this case, the accelerograms from the permanent station outside the Amatrice town centre were only taken into account because they already far exceeded the values on the national seismic hazard map.

The occurrence of such kind of earthquakes in Central Italy and the overcoming of the life safeguard limit state (SLV) seem to indicate that the design seismic actions for the area are not adequate. However, statistical data for similar intensity events are not available, thus the corresponding return periods are unknown.

3 CONSIDERATIONS ON THE DIFFERENCE BETWEEN THE REAL EARTHQUAKE AND THE DESIGN EARTHQUAKE

The analysed seismic sequences have clearly demonstrated that PGA values greater than those provided by the national seismic hazard map are possible. This map is based on the Cornell's probabilistic method [39]; however, due to the number of uncertainties involved in the procedure, this approach may lead to an incorrect definition of the seismic hazard, underestimating PGA values in some cases [40],[41].

The Neo-Deterministic approach has been proposed as an alternative (see Panza [42]). The source rupture process is modelled and the ground shaking is described using synthetic seismograms in this method, which is based on the spatial distribution of strong magnitude earthquakes derived from historic seismicity, seismo-tectonic, geological and geophysical data.

The DGA values (Design ground Acceleration) provided by the Neo-Deterministic approach, which correspond to the anchoring point in the elastic response spectrum, have been compared to the PGA values for the Italian territory specified by the probabilistic method. It has been demonstrated [40] that, generally, the Neo-Deterministic approach provides lower acceleration values in low seismicity areas and higher acceleration values in high seismicity areas compared to the probabilistic method. When applied to the analysed seismic sequences, the Neo-Deterministic method provides ground acceleration values that are very similar to those recorded by INGV, and are almost always conservative [40]. As a matter of fact, for the 2012 seismic sequence, according to the Neo-Deterministic approach, the PGA value should be in the range 0.20g - 0.35g, well in line with real recordings (PGA > 0.25g), whereas the probabilistic approach provides a PGA value < 0.175g for a return period of 475 years. The same holds for the 2016-2017 seismic sequence: the probabilistic approach provides PGA values in the range 0.250g - 0.275g for a return period of 475 years, whereas the Neo-Deterministic method suggests a range of 0.3g - 0.6g [41]. As a result, in line with literature data, the Neo-Deterministic approach should also be considered for seismic risk assessments.

As shown in the technical literature, the progressive damage caused by the main events of these two seismic sequences on buildings and historic centres, led to different damage scenarios in Emilia and Central Italy (see [19]-[26], [27]-[31]). In order to explaining these differences, the main events can be compared in terms of magnitude, epicentral distance, depth, site conditions and PGA, see Table 8.

The type of focal mechanism that was activated in the two seismic sequences differs significantly; in Emilia, it was a revers fault mechanism (also known as an overthrust mechanism), whereas in Central Italy, it was a normal fault mechanism.

The magnitudes of the events that struck the Emilia region are comparable to the magnitude of the August 24 seismic event occurred in Central Italy; furthermore, the depth of the hypocentre is similar. The epicentral distances of the May 20, May 29 and August 24 seismic events recorded at the stations of MRN, FIN0 and NRC, respectively, are comparable. Given the similarity in magnitude, epicentral distance, depth, and soil category, the PGA values for the cited events at MRN and FIN0 are, as expected, very similar. Although the Norcia station is located on soil type B, a higher PGA value was recorded on equal terms of epicentral distance and depth. This could be because of the larger magnitude and the different focal mechanism.

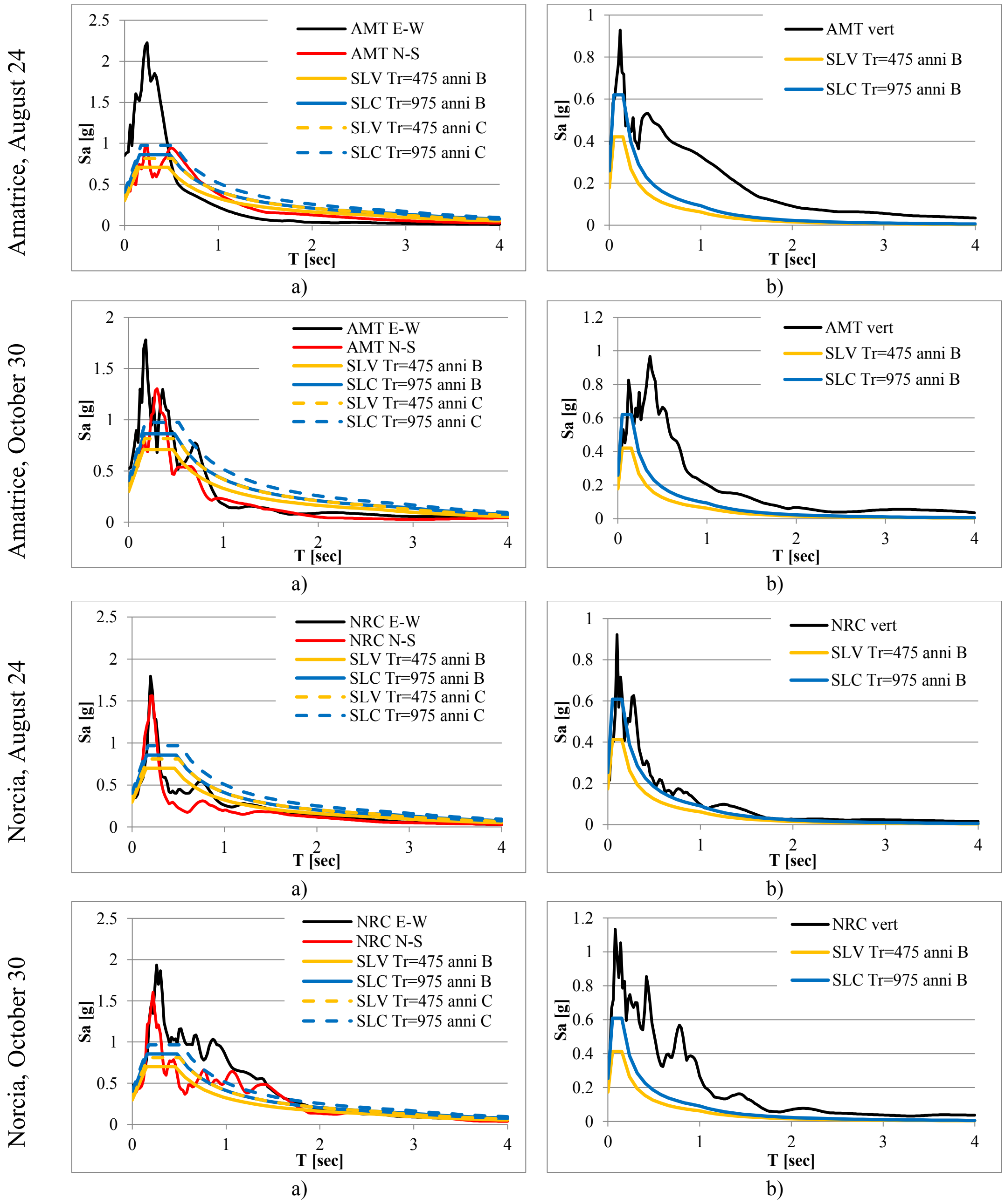


Figure 4: Comparison of spectral shapes defined by regulation with the acceleration horizontal (a) and vertical (b) response spectra of the recorded signals [32].

As expected, the lower the epicentral distance, the higher the recorded PGA; at the MRN station a higher PGA was recorded for the May 29 seismic event, characterized by an epicentral distance equal to 1/4 of the one of the May 20 seismic shock, while at the AMT station a higher PGA was recorded for the August 24 event, characterized by an epicentral distance of about 1/3 of the one of the October 30. Furthermore, as expected, towns located closer to the epicentre suffered more damage. Indeed, at Amatrice the main damage occurred with the August 24 event, while at Norcia with the October 30 event. At Finale Emilia, a more extended damage was observed with the May 20th shock, while at Mirandola with the May 29th earthquake.

Event		M_w	$d_{epicentral}$ [km]	Depth [km]	Soil category	PGA [g]
20/05/2012	MRN	5.9	16.1	9.5	C	0.26
29/05/2012	MRN	5.8	4.1	8.1	C	0.29
	FIN0		17.5		C	0.24
24/08/2016	AMT	6.0	8.5	8.1	B[1]	0.85
	NRC		15.3		B	0.37
30/10/2016	AMT	6.5	26.4	9.2	B[1]	0.52
	NRC		4.6		B	0.48

Table 8: Comparison of the main events of the two seismic sequences.

4 CONCLUSIONS

Based on what is widely debated in [32] and recalled here, the following conclusive remarks can be drawn.

This study examined two different series of seismic events that occurred in Italy, in the Emilia region in 2012 and central Italy in 2016-17, that caused severe damage to buildings and historical centres, leading to two different damage scenarios.

In order to understand the possible causes, the two series of events have been compared in terms of magnitude, PGA, response spectra, Trifunac duration, focal mechanism, epicentral distance, hypocentral depth and soil stratigraphy. As expected, severe damage scenarios have been observed for smaller epicentral distance and higher magnitude values; the stratigraphy of the site has also played a significant role, as in the case of the town centre of Amatrice.

Moreover, the analysis has clearly shown that the PGA reference values provided by the Italian seismic hazard map were largely exceeded at several locations. In order to avoid possible collapse of historical centres and buildings, as observed following the studied events, a preventive policy should be implemented based on a more correct definition of the seismic hazard; the Italian seismic hazard map needs therefore to be updated. To this purpose, the Neo-Deterministic approach, which has shown to provide a better estimation of maximum ground acceleration values, should also be considered.

In addition to all this, an extensive analysis of local amplification effects needs to be performed over the national territory, in order to identify critical locations where higher levels of the seismic hazard could be expected, as in the case of the Amatrice historical centre.

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