10th International Workshop on Seismic Microzoning and Risk Reduction

Analysis of site effects, building response and damage distribution observed due the 2011 Lorca destructive Earthquake.

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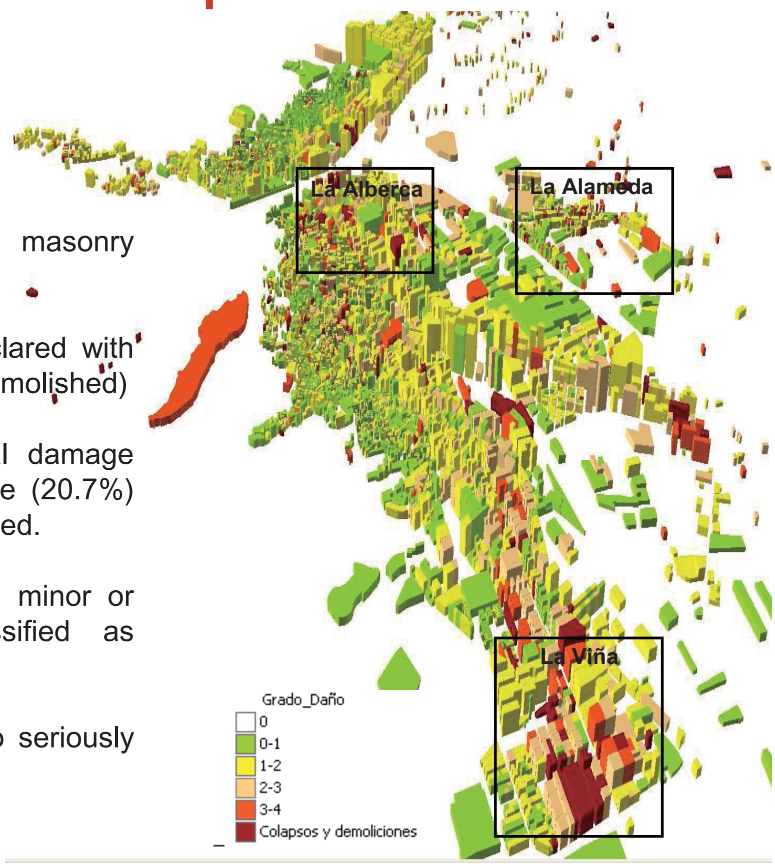
This relatively small event caused in Lorca an outwardly disproportionate impact:

- ✓ 9 Fatalities
- ✓ Near 300 injured
- ✓ One RC building and some masonry constructions collapsed
- ✓ 1052 buildings (15.8%) officially declared with structural damage (329 of them to be demolished)
- ✓ 1283 buildings with slight structural damage and/or moderate non-structural damage (20.7%) that need to be repaired before being used.
- ✓ 4047 buildings (62.9%) experienced minor or negligible damage and were classified as inhabitable.
- ✓ Cultural heritage buildings were also seriously damaged, especially religious ones.



RC Building collapsed

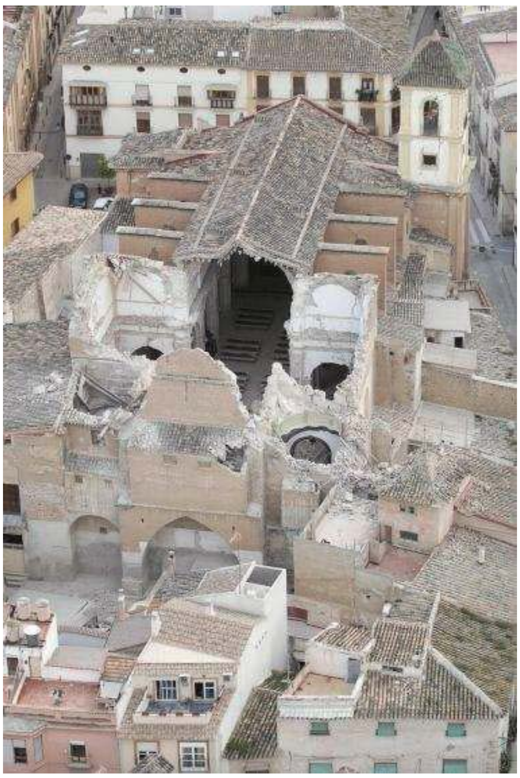
Damage at Masonry structures

Damage at nonstructural elements

The victims were due to detachments nonstructural elements (sills, parapets, etc.)

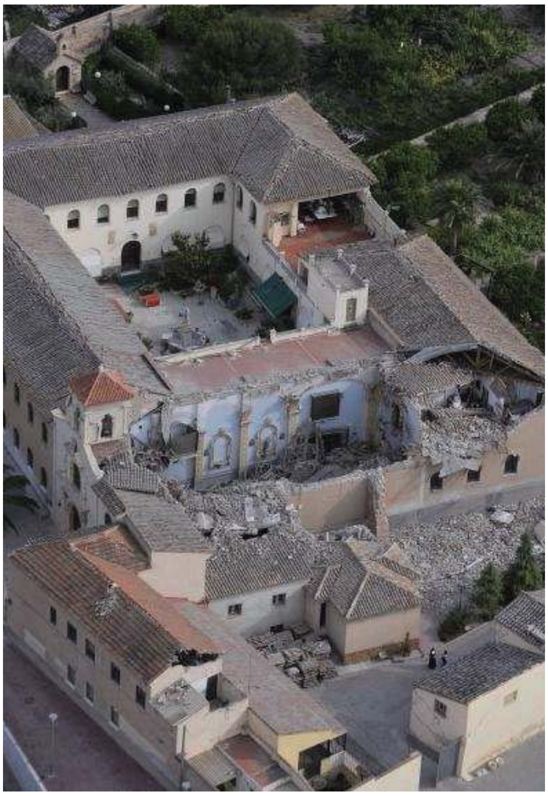
Damage to heritage

Church of Santiago (XVIII)



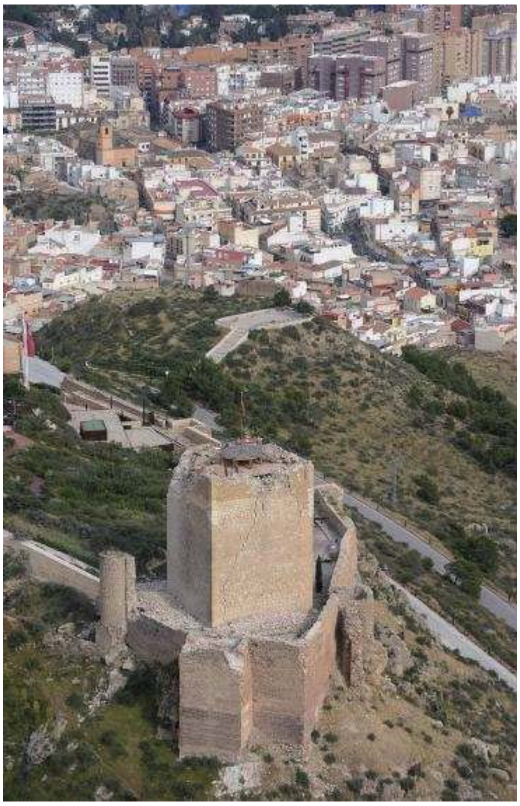
Damage to heritage

Convent of Las Clarisas (XVII)



Damage to heritage

Fortaleza del Sol (IX-XV)

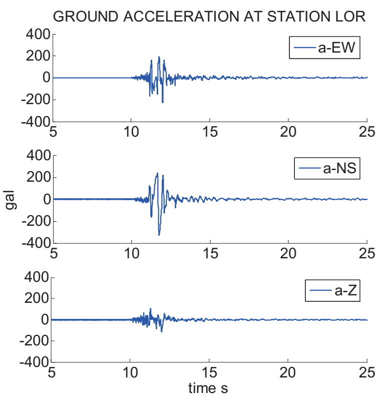


Effects on the ground. Landslides

The May 11th, 2011 Lorca destructive earthquake

The mainshock of Lorca seismic serie had Mw = 5.2. This event had a relevant foreshock with Mw = 4.6 and maximum intensity VI two hours before (15:05, UTC), as well as a Mw 3.9 aftershock four hours later (20:37 UTC). It was followed by more than one hundred aftershocks during the first month, 80% of them during the first week.

TIME (UTC)	LATITUDE	LONGITUDE	DEPTH km	MAGN. mLg	MAGN. Mw	MAX. INT. (EMS)	SEISMIC MOMENT (Nm)	EPIC. DIST. (km)
15:05	37.72 N	1.70 W	5.1	4.5	4.6	VI	9.6×10^{15}	5.3
16:47	37.73 N	1.69 W	4.6	5.1	5.2	VII	6.5×10^{16}	5.5



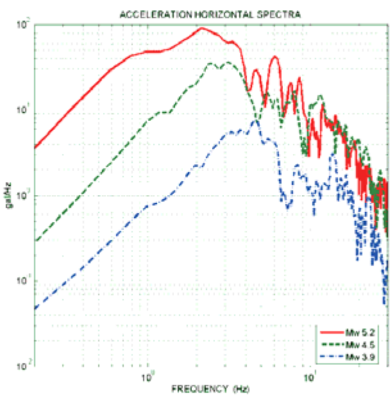
Mainshock accelerogram recorded at LOR station.

Foreshock (rock)

PGA = 0.29 g
PGV = 13.76 cm/s
PGD = 1.1cm

Mainshock (rock)

PGA = 0.37 g
PGV = 35.4 cm/s
PGD = 3.5 cm



It shows a maximum at 2–3Hz and another peak at 6Hz, in the decay zone of the spectrum.

Urban Geological cartography

The identification and classification of urban geology of Lorca town was a step to perform a ***geological mapping at scale 1:10,000*** and to interpret the spatial geometry of geological formations.

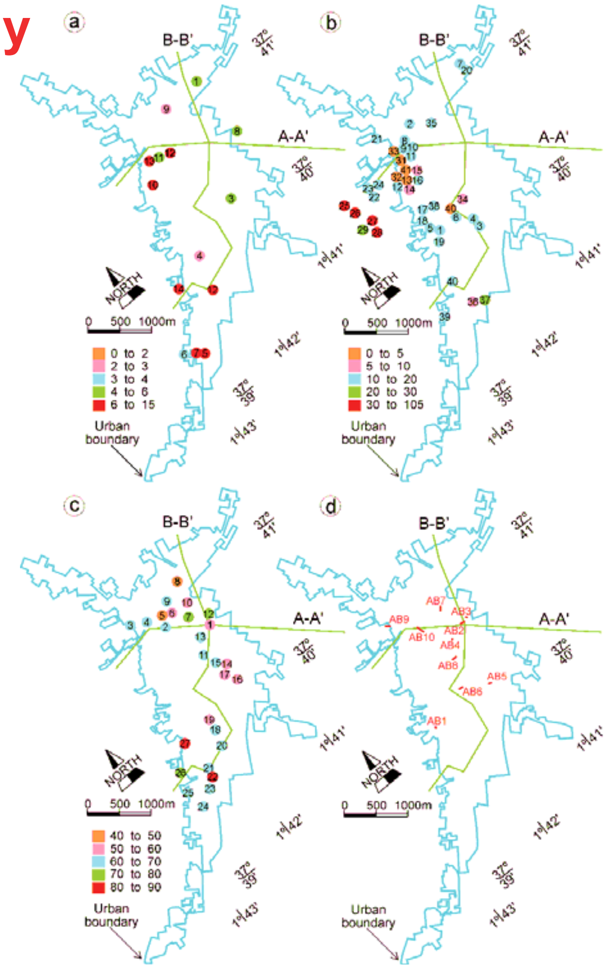
Field data:

(a) 14 field-ground testing data

(b) 40 mechanical drillings

(c) 27 electrical geophysical tests (IGME, 1992)

(d) 10 shallow refraction profiles (IGME, 1992)

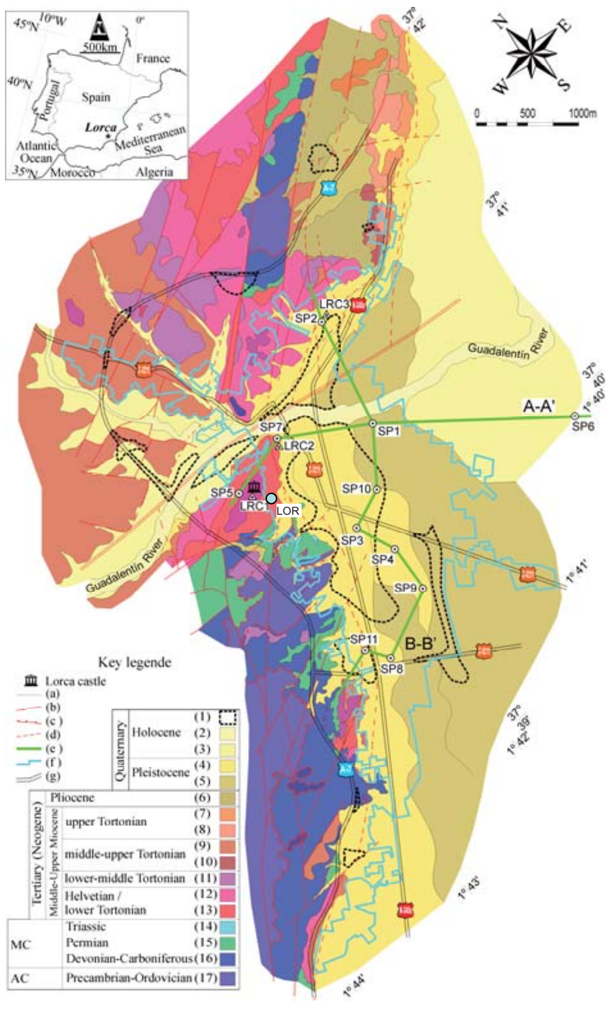


Geological map

Has been identified 17 geological formations:

1 Cropland and anthropogenic fillings, 2 Alluvial terraces, 3 Colluvials, 4 Glacis III, 5 Glacis II, 6 Glacis I, 7 Sandy marls and breccias, 8 Gypsum and marls, 9 Marls, 10 Breccias and marls, 11 Conglomerates, sandstone and marls, 12 Marls, gypsum and sandstone, 13 Polygenic conglomerates, 14 Dolomitic limestone, 15 Red clays, slates and quartzite, 16 Phyllite, schist and quartzite, ***17 Schist, phyllite, and quartzite.***

Array and **accelerometers locations** have been labelled from SP1 to SP11 and LOR (IGN station) and from LRC1 to LRC3 (UAL stations), respectively.



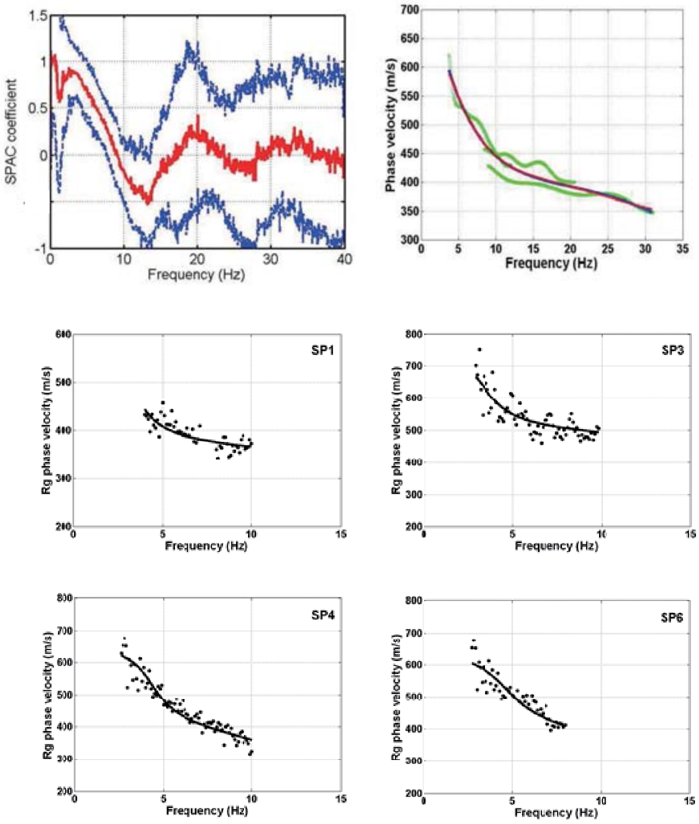
V_S^{30} velocity structure

The shallow geological structure of Lorca town has been studied using a **Spatial Autocorrelation method (SPAC).**

The measurements were carried out at **eleven open spaces**, obtaining Shear-wave velocity profiles from the Rg-wave dispersion curves by means of inversion procedure.

Vertical components of ground motion were recorded at the surface using **circular arrays**. Five sensors surrounding a sixth central sensor with same characteristics were used.

Different radii were used depending on the dimensions of the open areas.



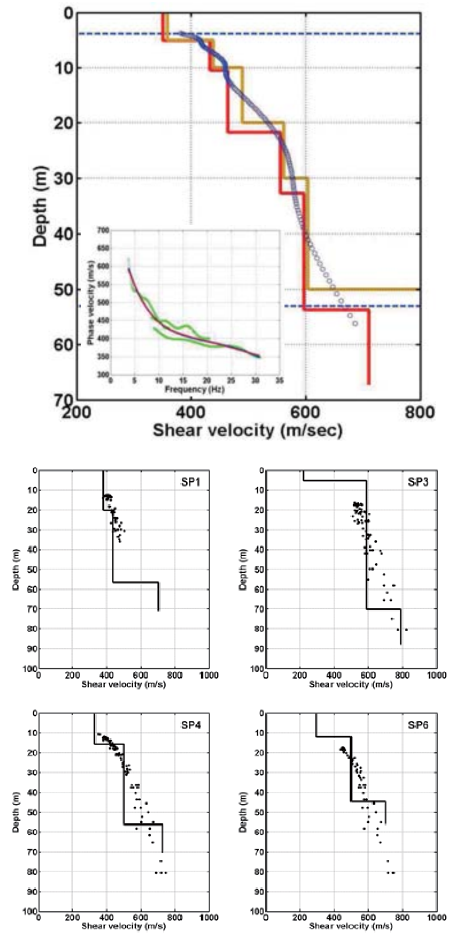
Examples of Rg-wave dispersion curves

Inversion of S-wave profiles

Shallow Shear-wave velocity structure has been obtained from Rg-wave phase velocities by using an iterative inversion method.

Finally, the average shear-wave velocity of the uppermost 30m (V_S^{30}) has been finally computed for each model.

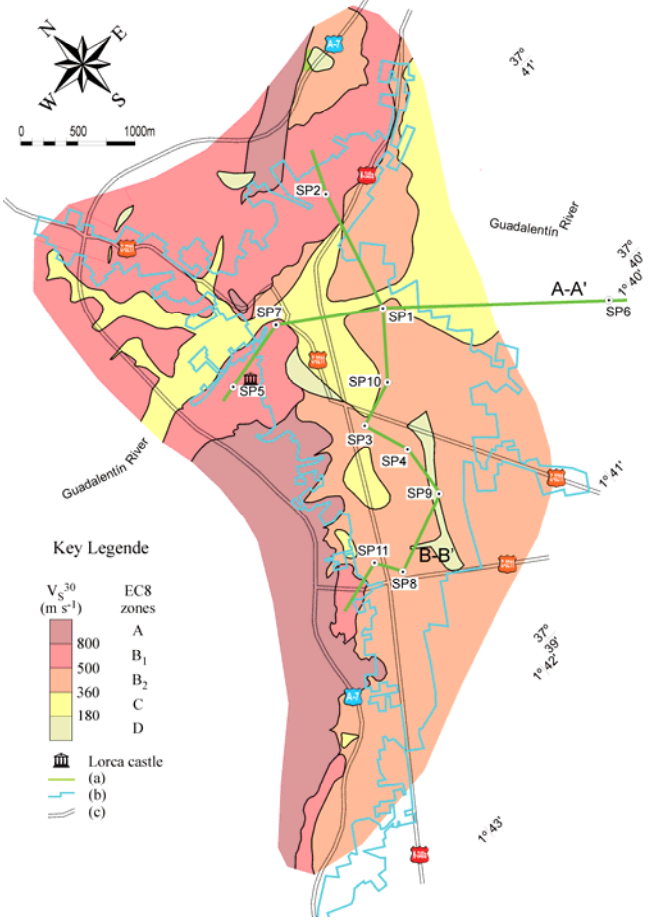
Spac	Δf (Hz)	Δc_R (m s^{-1})	ΔV_S (m s^{-1})	V_S^{30} (m s^{-1})
SP1	4.0 – 10.0	344 – 456	378 – 704	395
SP2	10.5 – 24.0	225 – 694	205 – **1223**	522
SP3	2.9 – 9.8	461 – **749**	222 – 790	452
SP4	**2.6** – 10.0	316 – 677	374 – 700	404
SP5	6.1 – 10.0	551 – 742	264 – 743	**552**
SP6	2.7 – 8.0	397 – 677	293 – 706	388
SP7	11.2 – 19.7	363 – 582	367– 800	536
SP8	3.3 – 15.5	325 – 552	343 – 662	411
SP9	4.5 – 10.0	269 – 454	237 – 579	333
SP10	4.1 – 19.0	**184** – 480	**176** – 568	**327**
SP11	3.7 – **30.9**	350 – 623	351 – 711	454



Soil classification map according to EC8 (1998)

The 17 geological formations identified in Lorca town have been clustered into 5 main geological/seismic formations:

Formation	Geological formations	EC8-ground class	V_S^{30} values range (ms^{-1})
1	**Cropland and anthropogenic fillings of variable thickness overlaying Pleistocene glacis.**	D	< 180
2	**Unconsolidated Holocene colluvials and alluvial terraces belong to the Guadalentin River valley.**	C	220-380
3	**The Pliocene and Pleistocene glacis**	B_2	340-580
4	**The lower-to-upper Tortonian post-orogenic medium-hard bedrock**	B_1	660-800
5	**Pre-orogenic Triassic carbonate hardest bedrock** **Pre-Triassic metamorphic hardest bedrock**	A	800-1000 >1000



3.- Computation of HVSR and predominant period

➢ Three-component ambient vibrations were recorded at 82 sites of a 400m x 400m grid.

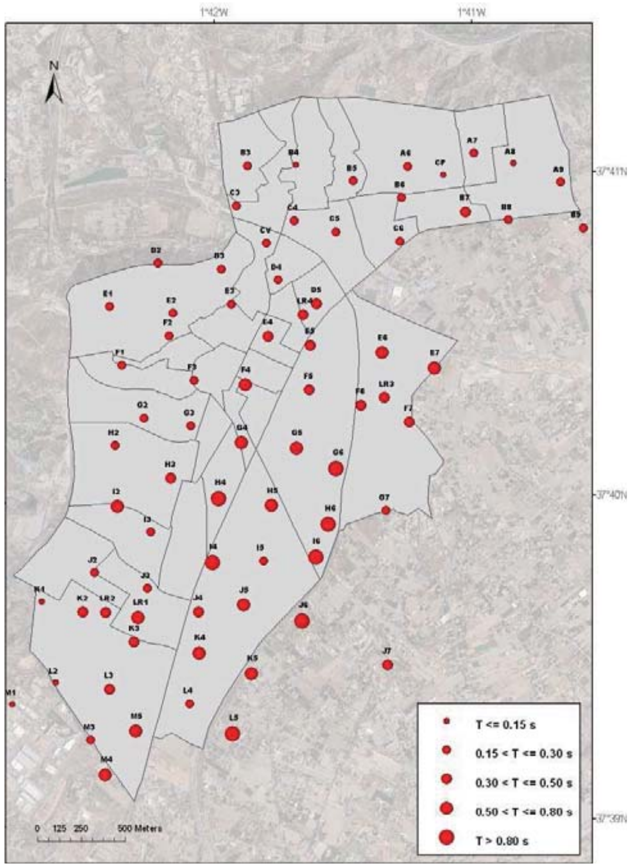
➢ Nakamura´s method (Horizontal-to-Vertical Spectral Ratio, HVSR; Nakamura, 1989) was applied to obtain the predominant period of each site.

➢ The shorter predominant periods are less than 0.15 s for the pre-Triassic hard-rock sites.

➢The Miocene medium-hard rock sites provides values between 0.15 and 0.3 s.

➢ The Pliocene and the older Pleistocene glacis formations show values in the 0.2-0.5 s range.

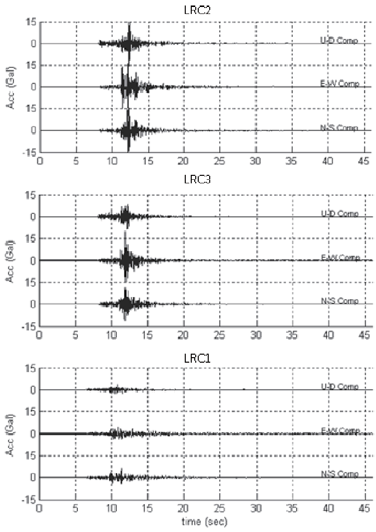
➢ The predominant periods are larger than 0.5 s for the latest Pleistocene glacis formations and the Holocene alluvial fan deposits from the Guadalentin River in the centre and eastern parts of the town.



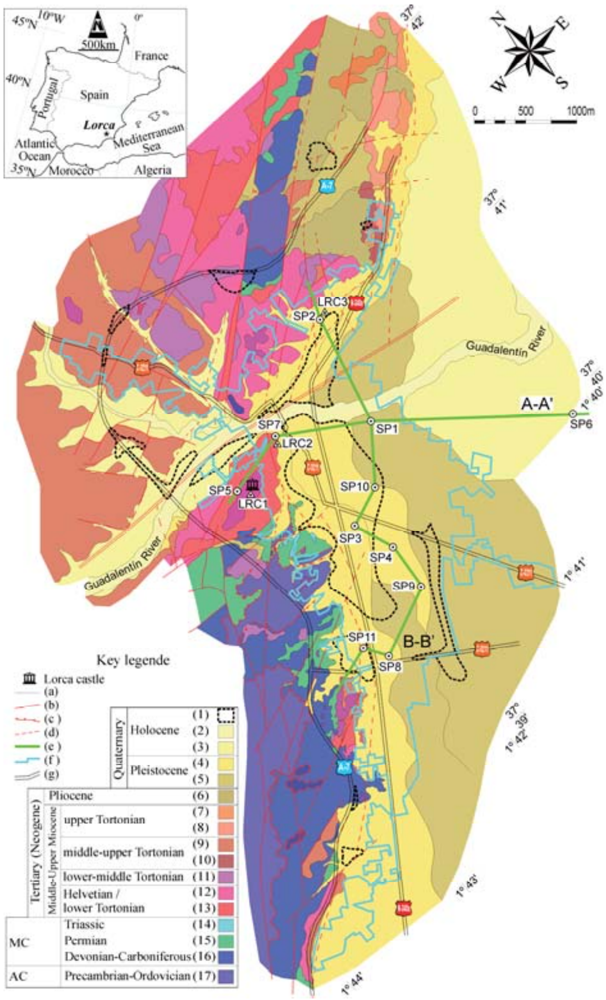
Site amplification

Classical spectral ratio

An elemental local array composed of 3 strong-motion stations (ETNA-KINEMETRICS) was deployed in different parts of Lorca town from March 2004 to October 2008.



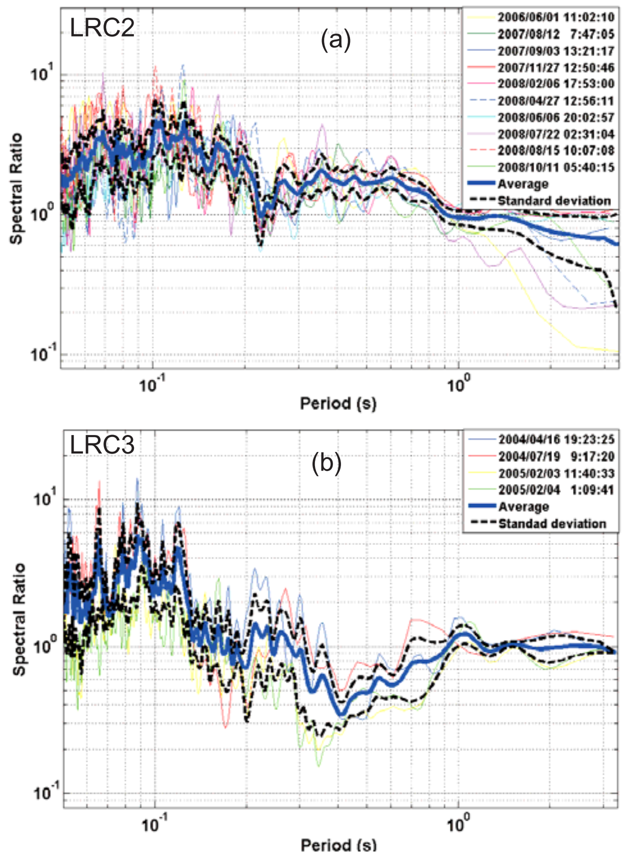
Example of simultaneous recorded acceleration time histories in Lorca town (mb=3.7 and epicentre distance 25.8 km)



Average spectral amplifications

Fourier spectra were calculated using a time window containing S and coda waves, and the classical spectral ratios between the stations over Pleistocene glacis and the reference station (Miocene medium-hard bedrock) were calculated.

The average amplification at LRC2 station is around three in the band from 0.1 to 0.2 s. The LRC3 station shows an average amplification of four for the periods less than 0.1 s.

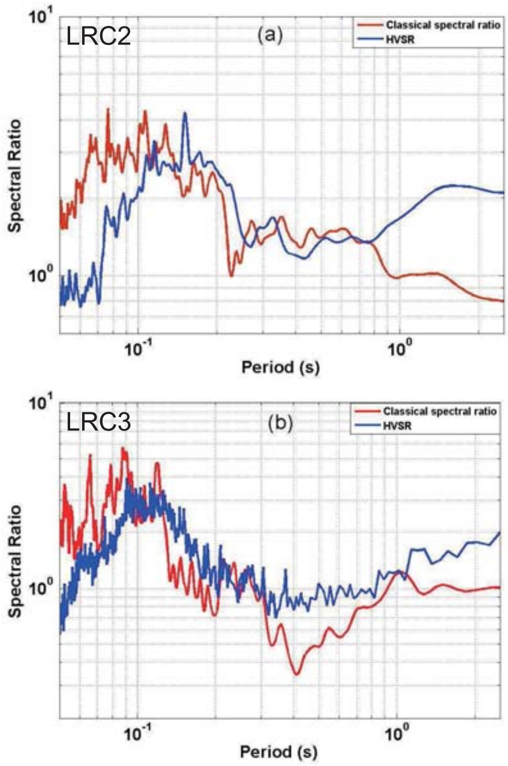


Average spectral amplifications obtained from classical spectral ratios (solid-bold blue lines) and standard deviation (solid-dotted black line). (a) LRC2 station; (b) LRC3 station.

Comparison between calculated transfer function by using classical spectral ratios and HVSR of ambient noise

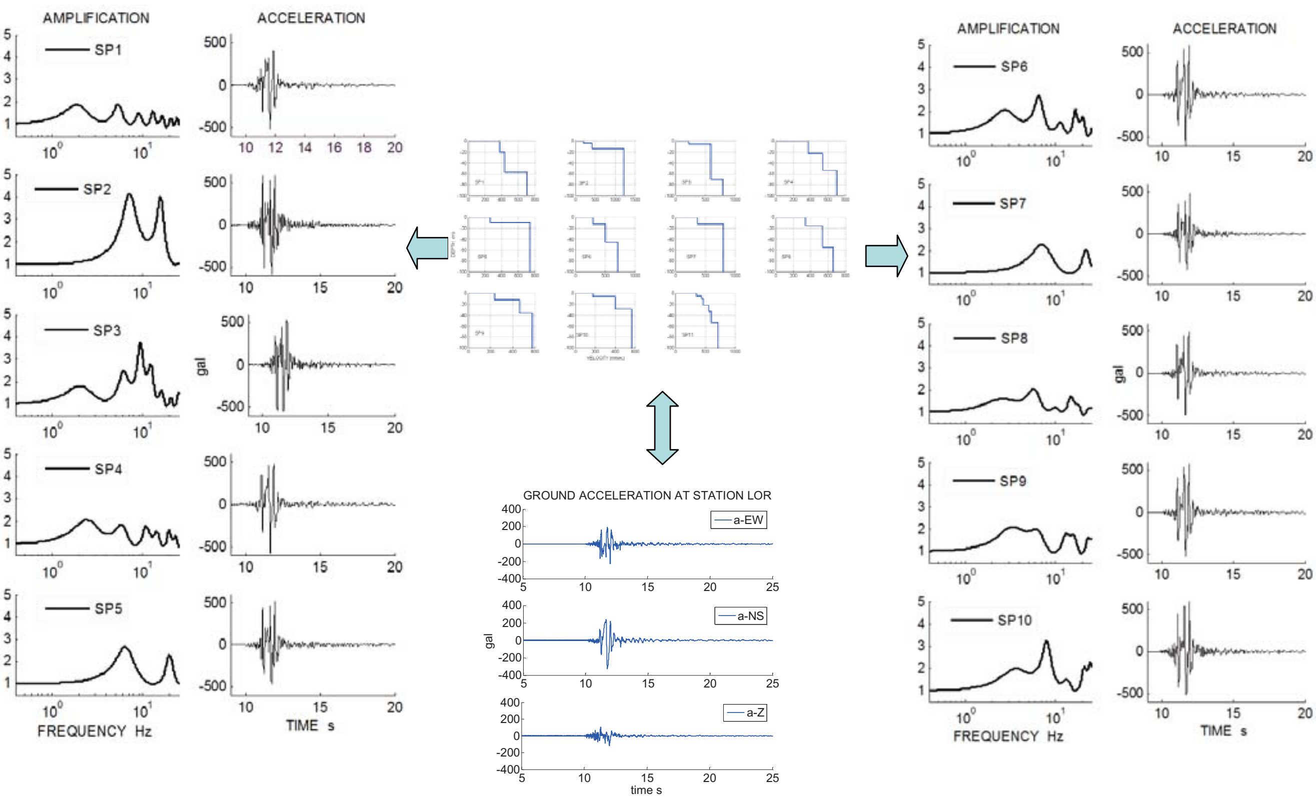
The spectral amplification bands obtained from classical spectral ratio and from HVSR of ambient noise are quite similar.

The different average amplifications obtained from these techniques at frequencies over about 1s evidence instability or larger statistical uncertainties in this band.

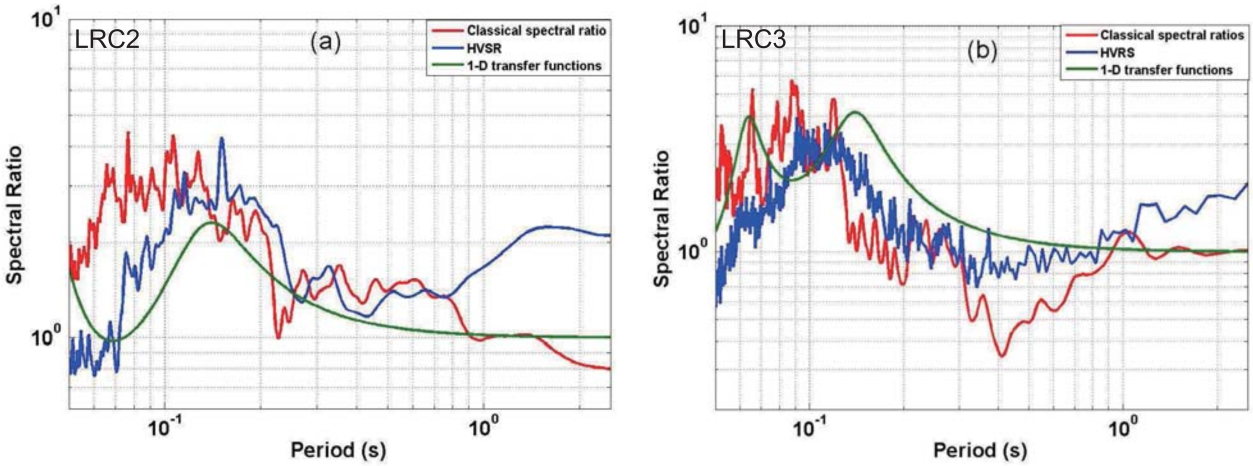


Comparison between calculated transfer function by using classical spectral ratios (red line) and HVSR of ambient noise (blue line). (a) LRC2 station; (b) LRC3 station.

Ground motion simulation at different sites.

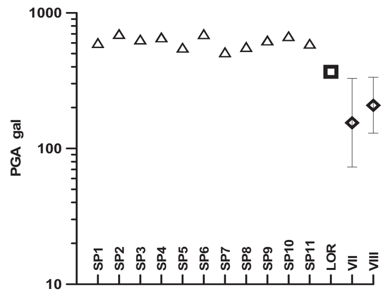


Comparison between calculated transfer function, HVSR and simulated 1-D transfer function.

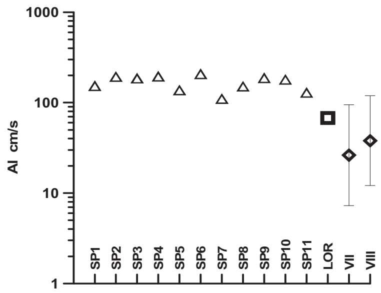


Strong ground motion parameters

For the record of the LOR station, and the simulated accelerograms at the SPAC points, a set of representative strong motion parameters were calculated to characterize quantitatively the shake severity at these points.



- ✓ The **PGA** and **PGV**

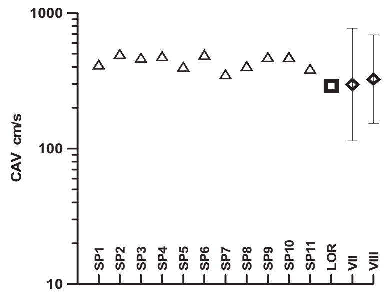


- ✓ The **Arias intensity** (Arias 1969)

$$AI = \frac{\pi}{2g}\int_{t0}^{tf} a(t)^2 dt$$

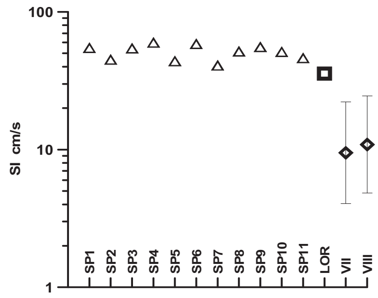
- ✓ The **Cumulative Absolute Velocity** (CAV)

$$CAV = \sum_{i=1}^{n}\int_{t_{i-1}}^{t_i} |a(t)| dt$$



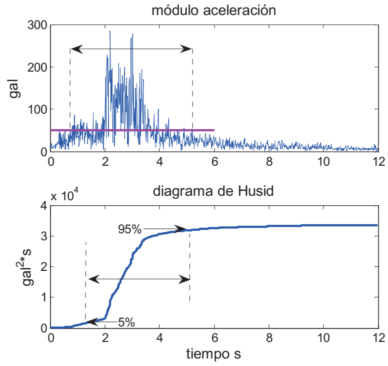
✓ The **Spectrum Intensity** (SI)

$$SI = \frac{1}{\Delta T}\int_{0.1}^{2.5} SV(T,\delta)dt$$



✓ The **Relative Significant Duration** (RSD)

$$H(t) = \int_{t_0}^{t_0+t} |a(\tau)|^2 d\tau$$



	PGA cm/s²	PGV cm/s	AI cm/s	RSD s	CAV cm/s	SI_{max} cm/s
SP1	585	55	147	**1,0**	406	53
SP2	**680**	46	186	**1,3**	**486**	44
SP3	620	56	179	1,1	456	53
SP4	643	**60**	187	1,1	468	**58**
SP5	540	45	132	1,1	391	43
SP6	679	59	**199**	1,1	480	57
SP7	**499**	**42**	**106**	1,2	**344**	**40**
SP8	547	53	145	1,1	396	50
SP9	610	55	180	1,1	461	54
SP10	656	51	173	1,1	462	50
SP11	578	44	124	1,1	378	45
LOR	***370***	***38***	***68***	***1,2***	***290***	***36***
VII *	156	8,9	27	7,6	299	10
VIII *	210	11	38	4,5	326	11

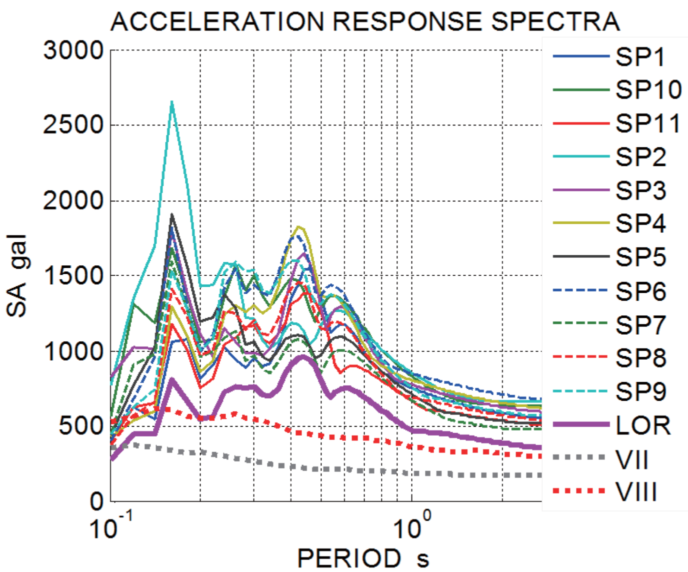
* *Parameter for the European record sets associated to local intensities of VII and VIII (EMS scale).*

The horizontal acceleration response spectra (SA)

The horizontal acceleration response spectra (SA) represents the peak acceleration that a single degree of freedom (SDOF) oscillator with free period T and damping δ reaches when it is excited with a given a(t).

The level of LOR record is above the reference of intensity VIII, and more clearly in the band 0.3–1.0 s.

Those corresponding to the SPAC site show significant amplifications for periods ~0.17 and ~0.4 s. For these peaks, the level exceeds 1.5 g at several SP points.



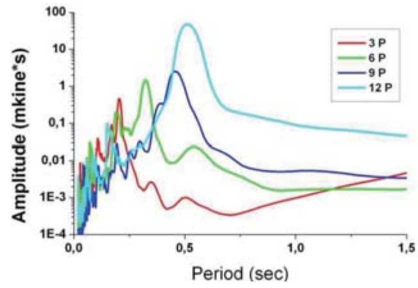
5. Dynamic Properties of Existing RC buildings

Changes in the fundamental translational period (T) and damping ratio (h) of a set of buildings in Lorca town (SE of Spain) have been examined, affected by the May 11th, 2011 earthquake.

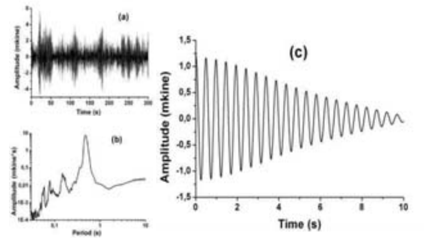
These building parameters have been calculated from ambient vibration measurements, recorded at top RC buildings pre- and post earthquake, using the Fast Fourier Transform and the Randomdec technique.

Before the earthquake sequence, the total number of measured buildings was 59, with a number of storeys range from 2 to 12.

34 buildings were measured again after the earthquake using the same methodology. 23 of them measured also before the earthquake.



Examples of amplitude spectra of the transverse component for buildings with 3, 6, 9 and 12 floors, respectively.



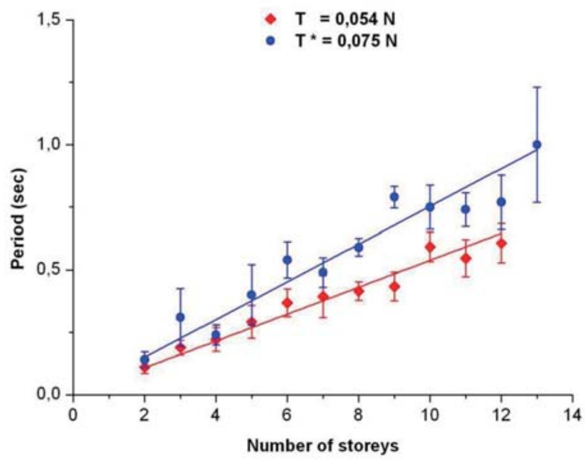
Example of damping evaluation by Random Decrement Technique. (a) Ambient noise record obtained at the top of LRC20 building. (b) Amplitude spectrum, (c) Damped response of the building.

Fundamental Translational Period

Average values of natural periods and damping factors corresponding to each number of storey, obtained pre- and post-earthquake for all building set.

NS	NB	T(s)	NB*	T * (s)
2	5	0.11±0.02	4	0.14 ± 0.03
3	6	0.19±0.03	2	0.31 ± 0.11
4	6	0.22±0.05	3	0.24 ± 0.04
5	8	0.29±0.07	9	0.40 ± 0.12
6	3	0.37±0.06	2	0.54 ± 0.07
7	4	0.39±0.08	2	0.49 ± 0.06
8	5	0.42±0.04	2	0.59 ± 0.04
9	3	0.43±0.06	1	0.79 ± 0.04
10	2	0.59±0.06	3	0.75 ± 0.09
11	3	0.55±0.07	2	0.74 ± 0.07
12	3	0.61±0.08	2	0.77 ± 0.11
13	-	-	2	1.00 ± 0.23

***NS** = number of storey; **NB** = number of buildings.*

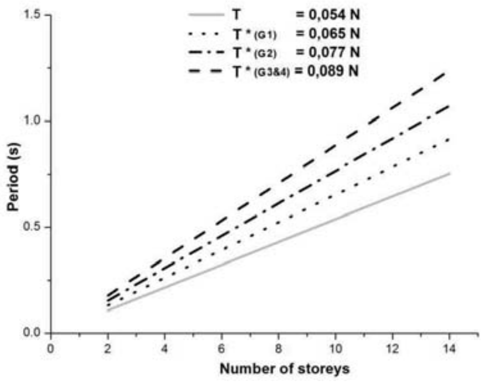


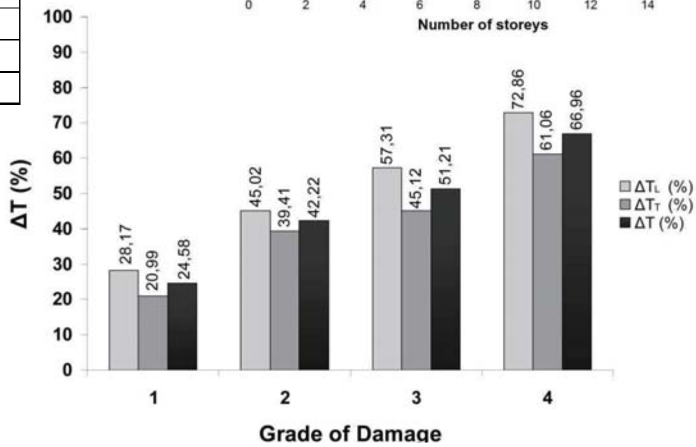
Relationships between the average natural period (T) and the number of storeys (N) for RC buildings obtained from ambient noise analysis for undamaged [T(N)] and damaged buildings [T(N)].*

T(N) relationships for different degree of damage

Average values of natural periods corresponding to each number of storey, obtained pre- and post-earthquake for 23 damaged buildings of Lorca.

NS	NB	T(s)	AD	T* (s)	ΔT (%)
2	2	0.12 ± 0.02	2.0	0.15 ± 0.05	26.72
3	2	0.21 ± 0.04	3.0	0.31 ± 0.11	49.60
4	3	0.19 ± 0.03	2.3	0.24 ± 0.04	24.40
5	5	0.27 ± 0.06	2.2	0.40 ± 0.16	47.59
6	2	0.34 ± 0.02	3.0	0.54 ± 0.07	58.60
7	2	0.37 ± 0.06	1.0	0.49 ± 0.06	32.26
8	1	0.44 ± 0.05	2.0	0.61 ± 0.04	39.43
10	2	0.59 ± 0.06	1.5	0.77 ± 0.05	30.05
11	2	0.57 ± 0.08	1.5	0.74 ± 0.07	40.22
12	2	0.62 ± 0.10	1.0	0.77 ± 0.11	23.55



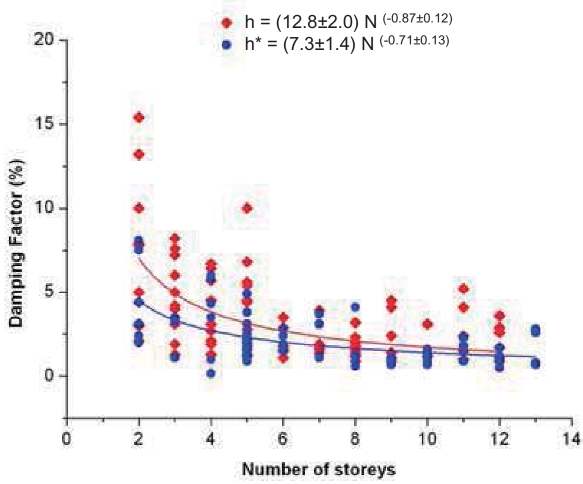


h(N) relationships for different degrees of damage

Average values of damping factors corresponding to each number of storey, obtained pre- and post-earthquake for all building set.

NS	NB	h (%)	NB*	h * (%)
2	5	7.19±4.53	4	4.58 ± 2.63
3	6	4.83±2.22	2	2.63 ± 1.33
4	6	3.51±1.96	3	3.46 ± 2.43
5	8	2.95±1.88	9	2.04 ± 1.05
6	3	2.07±0.93	2	2.15 ± 0.57
7	4	1.96±0.81	2	2.28 ± 1.32
8	5	1.66±0.69	2	1.75 ± 1.59
9	3	2.40±1.56	1	0.90 ± 0.28
10	2	1.68±0.95	3	1.13 ± 0.36
11	3	2.53±1.75	2	1.63 ± 0.59
12	3	2.13±1.07	2	1.08 ± 0.51
13	-	-	2	1.73 ± 1.13

NS	NB	h (%)	AD	h * (%)	Δh
2	2	10.40 ± 5.41	2.0	3.40 ± 1.41	-7.00
3	2	3.85 ± 2.08	3.0	2.63 ± 1.33	-1.22
4	3	4.56 ± 2.42	2.3	3.70 ± 2.09	-0.86
5	5	3.26 ± 2.28	2.2	2.05 ± 0.96	-1.21
6	2	1.95 ± 0.65	3.0	2.15 ± 0.57	0.20
7	2	2.33 ± 1.06	1.0	2.28 ± 1.32	-0.05
8	1	1.25 ± 0.07	2.0	0.90 ± 0.42	-0.35
10	2	1.68 ± 0.95	1.5	1.28 ± 0.34	-0.40
11	2	3.30 ± 1.66	1.5	1.63 ± 0.59	-2.28
12	2	1.83 ± 1.23	1.0	1.08 ± 0.51	-0.75



Relationship between the average damping factor (h) and the number of floors (N) for RC buildings of Lorca town obtained from ambient noise measurements.

Conclusions:

- ❖ The high acceleration values can be attributed to the proximity of the source fault, the near-field directivity effect (López-Comino et al. 2012) and the local site effect.

- ❖ Geological materials have been clustered into 5 geological/seismic formations according to the Eurocode 8. The most widespread EC8 soil class is B2 (360-500 ms^{-1}) followed by B1(500-800 ms^{-1}). Class C (180-360 ms^{-1}) also covers a significant part of the urban area.

- ❖ The general trend of ground predominant periods is grow as the thickness of Quaternary formations increases.

- ❖ The values obtained from strong ground motion parameters at the LOR station and at the simulation points correspond to intensity degree (EMS scale) of not less than VIII.

- ❖ The high values of HARS (SA >1.5 g) in the period ~0.17 s and in the band 0.3–0.5 s can explain the serious structural damage in buildings with fundamental period in this range.

- ❖ Damping factor does not show a significant variation with earthquake damage degree. This result suggest that damping factor parameter is not good indicator of damage in structures.

- ❖ Significant variations of T *(>20%)* indicate the occurrence of damage in buildings. Small variations of T (10–20%) indicate change in stiffness of buildings although damage evidences are not detected visually. This result shows that natural period parameter is a good indicator of damage in structures.

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