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ESI-07 ShakeMaps for Instrumental and historical events in the Betic Cordillera (SE Spain): a preliminary approach applied to seismic hazard based on geological data

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Abstract: *This work presents shake scenarios for two earthquakes occurred in the Betic Cordillera (SE Spain) such as the AD 2011 Lorca event (VIII ESI07; 5.2 Mw) and AD 1863 Huércal-Overa event (VIII ESI07; 4.9 Mw). The Lorca event presents instrumental measures, allowing comparison of the distribution and magnitude of the modelled PGA values, as well as a detailed field based characterization and mapping of the related geological effects. To explain the wide variety of slope movements and other geological effects recorded along the studied earthquakes, obtained PGA models must include a topographic amplification factor, normally not considered instandard Shake models. Additionally, V_s^{30}models derived from topography resulted in overestimations of the PGA values in flat terrains, such as, pediments or flat erosion surfaces, carved in resistant materials. This was corrected applying a factor related to the thickness of the Quaternary deposits. The incorporation of those basic amplification factors upgraded the resulting macroseismic scenarios, clearly identifying zones prone to record environmental damage.*

Key words: *ShakeMaps, ESI-07 Scale, PGA, Seismic Hazard, Betic Cordillera, Spain.*

INTRODUCTION

This work presents shake scenarios for two earthquakes occurred in the Betic Cordillera (SE Spain). The AD 2011 Lorca event (VIII ESI07; 5.2 Mw) and the AD 1863 Huercal-Overa event (VIII ESI07; 4.9 Mw). The Lorca event presents a significant range of instrumental measures, allowing the cross-cheking of the distribution and size of the obtained Peak Ground Acceleration (PGA)valuesand models. For both events there is a detailed field based characterization and mapping of the related earthquake environmental effects (EEEs) provided by the recently published Spanish EEE Catalogue (Silva et al., 2014a).

METHODOLOGY

From the methodological standpoint, the modelling of the spatial distribution of the PGA values (shakemaps) has required a workflow based on the integration of the diverse spatial models in a Geographic Information System (GIS) environment. Here, field EEE-data have been incorporated together with other levels of information (DTMs, slope models and ground-motion prediction models among others) for comparison purposes. In this environment, modelling results have been iterated many times to estimate how the different adjustments introduced in the workflow modified the results at different scales.

For the elaboration of earthquake models, 5 m and 25 m pixel Lidar DTMs, obtained from the IGN online database, wereused as the base-maps for the calculation of the different derived models and final ShakeMap scenarios. There is an important amount of Ground-motion prediction equations in the literature, (e.g. Ambraseys et al., 2005; Chiou& Young, 2008; Boore& Atkinson, 2008; etc.), but some of them are quite difficult to implement in a GIS environment. This complicated the election of only one fitting the requirements of this work. Among the different proposals, the selected one should be relatively simple in its application(due to the necessary iteration-related workflow), not much time consuming and yet reliable and well tested. Eventually, for the preliminary approaches presented here, the

Figure 1: Location of the two earthquakes analyzed in this work (stars) in the framework of the fault system of the Eastern Betic Shear Zone (EBSZ). Black circles are locations cited in the text.

method developed by Boore et al., (1997), widely used in the USGS Earthquake Hazards Program, fulfilled all those requirements.

A number of data and models are needed to design a proper PGA model of an earthquake from the Boore et al., (1997) ground-motion prediction equations. Those are: the location of the epicentre, fault type, dimensions and shape of the fault rupture, Mw, site condition map (V_s^{30}) and Joyner-Boore distance. In a first step we proceed to model the 2011 Lorca event in order to cross-check the results with the significant amount of instrumental (Morales et al., 2014) and field data (Alfaro et al., 2011; Silva et al., 2014b) existing for this event. In a second step, the obtained methodology was applied to a historical example from which sufficient ESI data areavailable, as is the case of the AD 1863 Huercal-Overa event (Silva et al., 2014c).

Shake map for the 2011 lorca event

For the 2011Lorca earthquake, the epicentre location, fault parameters and Mw were obtained from Morales et al., (2014). The fault plane geometrywas estimated as the envelope to the main set of deeper events of the aftershock seriesdescribed by these authors.Due to the absence of Vs_{30} measures in the study area, the site condition map is obtained applying the empirical approach used in the USGS ShakeMap program (Wald & Allen, 2007), in which the terrain slope is considered as proxy for seismic site conditions and amplification. Finally Joiner-Boore distance algorithm predicts the PGA spatial distribution and propagation from the modelled seismic source, otherwise easy to implement in the GIS environment from the theoretical fault geometry and kinematics (strike-slip, reverse, etc.).

Preliminary models obtained from the application of theBoore et al. (1997) equations fitted rather well with instrumental measures. However, some disagreement arose mainly related to the distribution and features of the mapped geological effects (Silva et al., 2014b). Those discrepancies are threefold:

1) There is a lack of correlation concerning the wide variety of slope movements recorded in the Lorca event and the calculated PGA values for those zones widely affected by EEEs. This typically occurs in places with steep slopes. Here, lithologies are usually hard and hence account for high V_s^{30} values. This implies that PGA values obtained from the preliminary model are systematically underestimated in steep areas. The conversion of inverted values of slope in progressively higher V_s^{30} values underestimate apparent topographic amplification occurred in these areas during the 2011 Lorca event (Rodríguez-Peces et al., 2011).
2) V_s^{30} models derived from terrain slope models resulted in overestimations of the PGA values in flat terrains, such as thin alluvial fan deposits, pediments, flat erosion surfaces or structural reliefs, carved in resistant Neogene materials. These models assume that flat terrains widely correspond to thick Quaternary fillings, but this is not the case for the aforementioned cases. Therefore a binary factor has been introduced in the terrain model in order to weight the complete or partial application of the slope as proxy of site conditions in relation to the occurrence / absence of thick Quaternary sequences at least 20-30 m thick.
3) The USGS ShakeMap program use the large scale 900 m/pixel DTMs from the global coverage SRTM30 data-base (Shuttle Radar Topography Mission), since some studies indicate that the use of more detailed terrain models do not significantly improve the results (Allen &Wald, 2009). However, in the cases explored here,maximum damage is restricted to areas around 100 km^2. Consequently, the use of SRTM30 base-maps result in limited coverage zones of about only 100 pixels, where mean slopes of these large-sized (900m) pixels diffuse the analysis. For these pixel scales the results are mainly controlled by the Joyner-Booreparameter (distance-dependent), blurring the slope component in the macroseismic areas. For the kind of moderate events studied here (c. 5.0 Mw) the small areas affected by EEEs are far for the resolution analysis offered by the SRTM30 terrain models. Higher-resolution DTMs (25 and 5 m/pixel) were used in order to identify areas affected by secondary earthquake effects of moderate-size, linked to intensities≥ VII ESI-07.

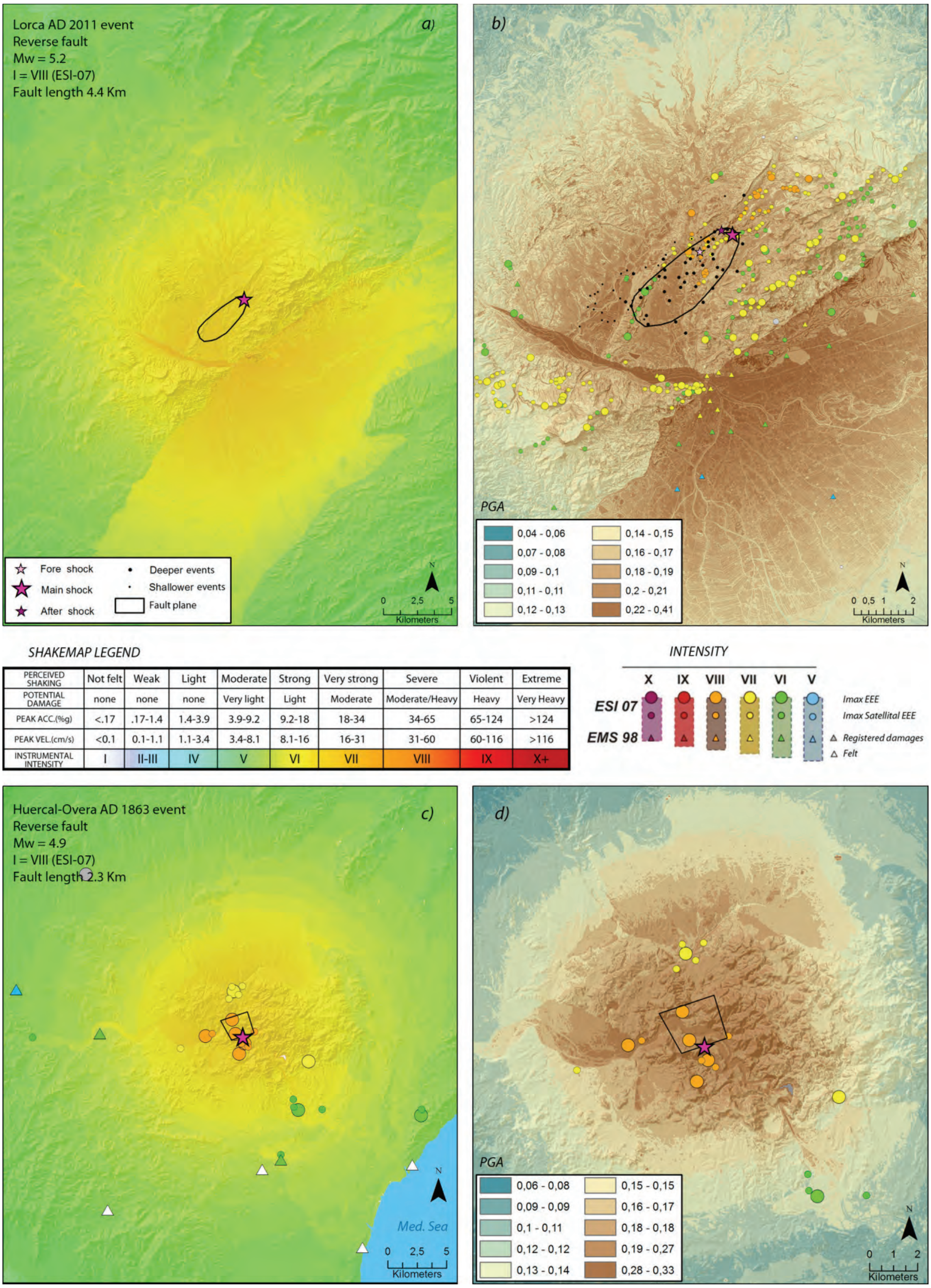
In order to correct the problems detected with the topographic amplification and the use of the terrain slope as an "inverse proxy" for site conditions (V_s^{30}), several improvements have been included in the calculation of the ESI07 ShakeMaps developed in this work:

(a) To explain the wide variety of slope movements and other geological effects recorded during the Lorca earthquake, PGA models must include a Topographic Amplification factor (T_S^0). Based on the works of Rodríguez (2006) and García Rodríguez &Malpica(2010), we scaled the slope-based topographic amplification intervals proposed these authors by means of the calculation of the best-fit 2nd Order Polynomial function, resulting in the following equation:

$$T_S^0 = -9\times10^{-5}s^2 + 0.0167s + 0.9864$$

where(s) is the terrain slope in degrees. This roughly means that for flat areas the amplification factor is 1 and for steeper areas (≥5º) is smoothly increasing up to 1.5 at slopes of 40^0 with maximum amplification of 1.8 for near-vertical locations (≥ 70º). This factor related to the slope amplification effect has not been considered in most available shake-models.However its use seems essential to fit instrumental PGA records, since the sole use of slope-derived V_s^{30} valuesdo not consider, and even minimize, the triggered topographic amplification.

(b) The significant impact of slope-derived V_s^{30} values in flat terrains without Quaternary cover has been corrected by applying a factor related to the known thickness of Quaternary deposits.Those places were the total thickness of Quaternary deposits is clearly less than 30 metres the applied correction factor is Q_T^{30} = ($Y_{Vs^{30}}$*0.8) in order to prevent overestimations in flat terrains without a significant Quaternary cover.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 2: (a)&(c) are the USGS-style ShakeMaps for the 2011 Lorca (a) and 1863 Huércal-Overa (b) earthquakes produced from 5 m/pixel (a) and 50 m/pixel (c) digital terrain models from ESI-07 (circles) andEMS-98 (triangles) data. The Lorca map (a) was produced by the implementation of existing instrumental data. The Huércal-Overa map (c) fault-parameters were estimated by empirical approaches and existing seismic data for the zone. (b) & (d) are detailed shake-models of the respective macroseismic areas for both earthquakes. Note different colour scales to enhance those zones where topographic amplification occurred.

The value of this correction parameter has been estimated from successive logic trial approaches to fit calculated PGA values to those instrumentally recorded for the entire affected area at 90% confidence level.
The Quaternary Thickness factor (Q_T^{30}), completes the function proposed here to calculate shakemap models in those zones where the thickness of Quaternary deposits is no significant:

$$PGA_{ESI} = Q_T^{30} \times T_S^0 \times Y_{Vs^{30}}$$

where$Y_{Vs^{30}}$is the obtained PGA from the Boore et al. (1997) ground motion prediction equations. In those zones, where the Quaternary thickness is significant (Guadalentin Depression and Guadalentin river valley) the Q_T^{30} correctionfactor was not applied since site conditions predicted by slope-derived V_s^{30}values are reliable, matching to the instrumental records with errors down to ± 10%.
In this way PGA values recorded in the city of Lorca (4 km away from the epicentre) was of 0.365g and those predicted by the Shake model are of 0.326g. For more distant localities, such as Alhama de Murcia (30 km away) recorded values were of 0.043g and those predicted by the model are of 0.050g. In the epicentral area, north of Lorca, maximum predicted PGA are in the range of 0.38 – 0.41g for a zone of about 10 km^2, matching with PGA ranges of intensity VIII MM of the USGS (0.34 -0.65g) and with ESI-intensity evaluations of the zone (Silva et al., 2014b).The comparison of instrumental data and calculated PGA models result in an uncertainty of c. ±10%,for the studied area. Faintly low calculated values result for the epicentral area (10 km radius) and faintly high ones for more distant areas when compared with the instrumental records. This fact indicates that the corrections introduced in this work for the production of PGA models are still conservatives for the epicentral zone where most EEEs were produced.
The obtained values fit better enough shake-models elaborated after the Lorca earthquake, which resulted in predicted PGA values for Lorca of about 0.250g (Benito et al., 2012). These authors used different ground motion prediction functions, but considering homogeneous ultraconservative hard rock-like Vs_{30} unreliable values (1100 m/s) for the entire Murcia region. Consequently all the models elaborated by these authors resulted in significant underestimations (c. 33%) of the computed values, otherwise similar to those resulting for the application of the existing Spanish Seismic Building Codes (NCSE-02) before the 2011 earthquake.
On the contrary, the shake model calculated in this work results in a good correlation between the modelled distribution of the PGA and the diverse geological data (251 data-points), the spatial distribution of the resulting ESI-07 intensities (Silva et al., 2014b) and the instrumental measures of the Lorca earthquake (10 data-points). Consequently, the incorporation of the basic correction factors considered here upgrades the resulting macroseismic scenario, clearly identifying those zones prone to record environmental damage.

SHAKEMAP FOR THE AD 1863 HUERCAL-OVERA EVENT: Historical Seismic Scenarios.

For thishistorical event, fault parameters and earthquake size were calculated from the set of available EMS and ESI data points (n = 40) and intensity distribution proposed by Silva et al. (2014c). This approach results in different seismic parameters (location and size) that those considered in the IGN Catalogue (Martínez Solares & Mezcua, 2002) or other recent re-evaluations (Mezcua et al., 2013).
The epicentre location is estimated from the spatial distribution of the ≥ VII ESI07 data-points, matching with the location of the Almanzora Tectonic Corridor blind-thrust zone and with the 3D distribution of recent seismicity recorded in the area (Pedrera et al. 2009). A focal depth of 5 km was assumed considering the geophysical models of blind thrusting and surface folding proposed for the area by the same authors. Mw was calculated by means of the intensity-derived functions used in Spain (Mezcua et al., 2013) resulting in a magnitude of 4.9 Mw. Fault dimension parameters has been estimated from standard empirical approaches (i.e. Wells and Coppersmith, 1994) adjusting the fault plane geometry to a simplified rectangular form resulting from the projection of the northwards blind-thrust at surface. The subsequent procedures have been the same ones that those checked for the calculation of the Lorca ShakeMap.
The resulting shake model clearly identifies the areas affected by environmental damage during the 1863 event within the Almanzora canyon-valley and the old depopulated areas of Los Oribes and the Ancient Obera. In all these zones VIII ESI07 intensities were recorded, by significant rock-falls, Apparition and relevant changes of flow-rate and position of springs, the river stopped to flow during several minutes and a small lake-basin completely disappeared by the occurrence of hectometric-length ground-cracks (Silva et al., 2014c). The model also match with the intensity ranges VI – VII assigned to different localities (EMS: Huercal-Overa, Cuevas, Vera, Albox, Arboleas, etc.) or natural locations (ESI: Alboraija lake, TresPacos, El Retablo, El Portillo, Almagrera mines, etc.).
The obtained shake model for the Huercál-Overa event provides a reliable seismic scenario for a historical event largely based on geological data derived from the application of the ESI07 Scale (Michetti et al., 2007). Other seismic scenarios, resulting for other parametric proposals of the event have been checked (Martínez Solares & Mezcua, 2002; Mezcua et al., 2013), but resulting in unreliable PGA distributions with respect to the existing ESI-07 and EMS-98 data-points.
The proposal of the IGN Catalogue (4.2 Mw event, close to Huercal-Overa; Martínez Solares & Mezcua, 2002) resulted in lower PGA values no matching with the intensity levels (≥ VI) in the affected area. Other proposal relating the earthquake with the Albox Fault, 7 km north of Huercal-overa (4.6 Mw; Mezcua et al., 2013), resulted in shake scenarios unable to explain the set of geological effects recorded in the Almanzora Canyon (Silva et al.,

2014c) and predict significant intensities (VI – VIII) for localities in which the 1863 earthquakewas only slightly felt (≤IV) or there are no intensity data.

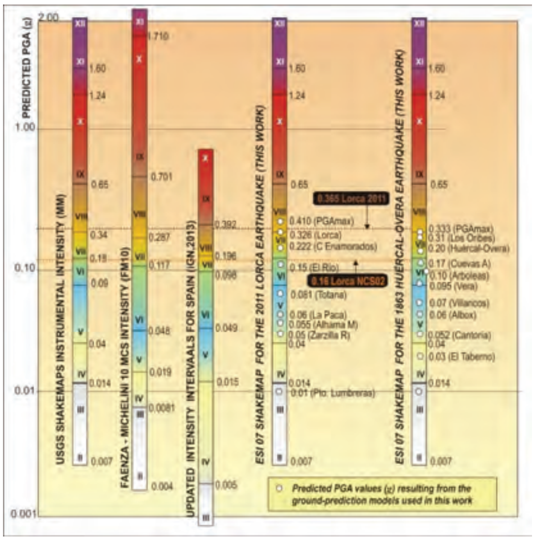


Figure 3: PGA values (g) obtained by the Shake-models elaborated in this work within the USGS MM intensity ranges (right) compared with PGA ranges for different intensity scales. Note the lower PGA EMS-intensity ranges of the updated values for Spain (IGN, 2013) when compared with MM and MCS intensity scales.

DISCUSSION

Shake models produced in this work are fully applicable to understand seismic hazard from instrumental and historical earthquakes. The two earthquakes explored here were no-surface faulting events, with moderate magnitudes of about 5.0 Mw, but produced a large number of earthquake environmental effects (EEEs). The use of these geological intensity data-points, by means the application of the ESI-07 scale improve the assessment of intensity distribution, providing upgraded frameworks to produce slope-derived Shake models similar to those developed by the USGS ShakeMap program (Fig. 2). However, the direct application of simple ground motion prediction models based on the slope as proxy for site conditions (i.e. Boore et al., 1997; Wald & Allen, 2007): (a) ignore the occurrence of topographic amplification; and (b) overestimate site conditions for flat terrains in rock-resistant materials.Correction factors introduced in this work upgrade the correlation of predicted and observed PGA values with an uncertainty of c. 10% improving previous proposed models (Benito et al., 2012).

Ground shaking prediction models presented here introduce correction factors to discriminate and solve these problems for detailed DTM scales down to 30 and 5m/pixel (Fig. 2). Larger scales used in the USGS program (900 m/pixel) are clearly applicable to stronger surface-faulting events with magnitudes above 6.5 -7.0 Mw which minimize these problems due to the larger affected areas. On the contrary, for regions in which moderate events (< 7.0 Mw) dominate the seismic records, seismic hazard can be clearly investigated from secondary EEEsthrough the application of the ESI-07 Scale. ShakeMaps developed in this work, have been generated with the aim to be simple to apply to historical or ancient events for which a representative number of EEE assessments might be merged with existing damage-based intensity dataas recommended in the ESI-07 Scale guidelines (Michetti et al., 2007).

Regarding to the state of the art in Spain, results from this work indicate that PGA assessments considered in the old and updated seismic hazard programs for the development of Seismic Building codes are clearly underestimated (Fig. 3). In detail, for the case of Lorca the obtained PGA values are close to those recorded instrumentally (IGN, 2012) being unnecessary appeal to suspect over-amplifications triggered by directivity effects along the fault trace as suggested by other authors (Benito et al., 2012). For the Huercál-Overa historicalcase, routines learned during the production of the 2011Lorca Shake Maps were applied. In this case we explored the different seismic sources and earthquake sizes cited in the literature, resulting in unreliable seismic scenarios, difficult to explain the variety and distribution of EEEs catalogued for this event (Silva et al., 2014).

PreliminaryShake models presented in this work are the first shake maps available for instrumental and historical earthquakes in Spain, but also the first ones world-wide produced from detailed digital terrain models. They represent a preliminary approach to the final products of the 1299 INQUA Project: EEE Metrics. Presently, we are checking and evaluating the application of second-generation ground prediction models (i.e. NGAE) in order to refine the resulting seismic scenarios and validate the use of geological data (EEEs) in the eventual production reliable tools for seismic hazard assessments.

In this first approach we choose the USGS MMI intensity-PGA conversion since the ones proposed for Spain (IGN, 2013) or other Mediterranean regions (Faenza & Michelini, 2010) don`t correlate well the observed intensity levels with the corresponding bracketed PGA values (Fig. 3).

Shake models presented in this work use the 2011 Lorca earthquake as the only "calibration event", since it is the only significant event (≥ 5.0 Mw) recorded during the instrumental period in Spain with representative instrumental and intensity data (ESI-07 plus EMS-98) to be compared. In spite of this limitation, its application to the historical case of Huercal-Overa is appropriate since, both events are located in close areas within the Eastern Betic Cordillera subject to similar seismotectonic features and fault slip rates (IGN, 2012). However future approaches will consider to calibrate the intensity levels using a sample of other representative and stronger earthquakes occurred in the Mediterranean region.

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