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

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A B S T R A C T

This work presents high-resolution ShakeMaps for three earthquakes occurred in the Betic Cordillera (SE Spain): the 2011 CE Lorca event (VIII ESI-07), the 1863 CE Huércal-Overa event (VIII ESI-07) and the 1829 CE Torrevieja event (X ESI-07). Detailed field characterizations and mapping of their coseismic environmental effects (EEEs) are catalogued and classified following the ESI-07 scale. The resulting macroseismic information reaches up to ten times the existing information based on conventional damage-based scales (e.g. EMS-98), providing a better constrain towards more realistic ground-motion scenarios. The 2011 Lorca earthquake has been used as a calibration event, since there is a relevant record of instrumental measures on source, and ground-motion parameters allowing a direct comparison with the modelled PGA values. From a methodological standpoint, the obtained ShakeMaps follow the basic guidelines and methodology proposed by the USGS ShakeMap Program. The two historical earthquakes analysed in this paper produced a wide variety of secondary EEEs but no surface faulting was reported. These effects need to be properly identified by high-resolution DTMs (5 m/pixel), far from the c. 900 m/pixel terrain models used by USGS program. Additionally, the proposed ESI-07 ShakeMaps incorporate correction factors to solve inconsistencies derived from the large scale terrain models considered in standard USGS program workflows: (1) empirical slope-derived $V_s^{30}$ models result in overestimations of the PGA values in flat terrains in absence of unconsolidated deposits; (2) the topographic amplification factor included here, explains the occurrence of rock-falls and landslides in steep areas, where ground motion is underestimated by the sole use of slope-derived $V_s^{30}$ models. Basic geological and geomorphological information need to be implemented in the modelling workflow in both cases. To prevent PGA overestimations in flat terrains a correction factor related to the spatial distribution and thickness of the Quaternary unconsolidated deposits has been incorporated (i.e. isopach maps). To correct PGA underestimations in steep terrains an amplification factor was modelled following standard guidelines of seismic topographic amplification.

The comparison via iteration of the spatial distribution of both ESI effects and EMS macroseismic data, with the obtained ground-motion spatial distribution, enables a better definition of the geological parameters for the studied historical earthquakes. A more accurate location and/or size of the suspect seismic sources are obtained for these historical earthquakes, providing scenarios more realistic than those resulting from old intensity maps. Quaternary Geology and Geomorphology are behind the implementation of the proposed ESI-07 ShakeMaps, being especially useful when exploring historic or ancient moderate earthquakes with scarce damage-based macroseismic data, but with sufficient paleoseismic or archaeoseismic records. In summary, the methodological workflow proposed here

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contemplates the implementation of a computational configuration seismologically relevant and able to test repeated seismic scenarios, with different parametric data, in a controlled GIS environment useful to reproduce historical events.



## 1. Introduction

ShakeMaps (USGS Earthquake Hazards Program) are typically used as a nearly real-time warning and management system to identify areas potentially affected by significant ground shaking or to define post-earthquake emergency plans in populated areas and/or seismic scenarios in strategic facilities. In the case of early warning and management systems, ShakeMaps are automatically generated and not initially supervised by humans, given the urgency to obtain rapid response seismic scenarios. Another potential use of the ShakeMaps is the production of scenarios for future or historical seismic events. However, existing ShakeMaps related to historical earthquakes are very scarce and they are usually straight applications of the existing geophysical/empirical ground motion equations. Examples of them are those produced for the 1975 Kalapana earthquake (Hawaii, Mw 7.7), the 2001 Mw 6.8 Nisqually earthquake (Frankel et al., 2009) or the 1811–1812 New Madrid earthquakes (Ramirez-Guzman et al., 2015), all of them available at the USGS web page: http://earthquake.usgs.gov/hazards/products/scenario/. Research on historical, ancient and pre-historic earthquakes can take advantage of this modelling tool by retrieving catalogued information on earthquake natural effects, paleoseismic and archaeoseismic data.

The use of the Environmental Seismic Intensity Scale (ESI-07, Michetti et al., 2007) is especially useful to recover, analyse and parameterize coseismic geological data from past earthquakes. This scale classifies and quantifies the earthquake environmental effects (EEEs) by primary (i.e. surface faulting) and secondary (ground cracks, slope movements, liquefaction processes, etc) EEEs related to moderate to strong seismic shaking. This scale can be regarded as an update, re-classification and quantification of the environmental effects included in the traditional macroseismic scales (MCS, MSK, MM) filling the gaps of some modern intensity scales, such as the European Macroseismic Scale (EMS-98; Grüntal, 1998; Musson et al., 2010), which basically excludes EEEs from intensity assessment (Serva et al., 2015; Silva et al., 2015a). Whatever the case, intensity is a multiparametric dynamic factor not only controlled by the size and epicentral distance from the causative event. Intensity combines the effects of seismic shaking with local topographic and geological conditions (topographic and/or site-effect amplifications) triggering temporal or permanent environmental effects in the landscape, widely retrievable from historical and/or paleoseismic research. Intensity is therefore a way to classify the interaction between the earthquake and the environment, including people, objects, buildings, lifelines, trees, soils, slopes, rivers, aquifers, coastlines (Silva et al., 2015a). In this sense the record of EEEs: (1) extend the set of information even far from urban areas, offering a better and more complete picture of the seismic scenarios; and (2) enlarge the macroseismic research to millennial time-windows, usually far from the analysis of the historical seismicity (Michetti et al., 2007). The study of EEEs alone (in unpopulated regions) or together with the macroseismic traditional scales, can offer a more comprehensive picture of the earthquake's scenario and impact, and a more consolidated characterization of intensity and seismic source parameters (Serva et al., 2007; Silva et al., 2015a), which is extremely useful in the investigation of historical and ancient events.

It is important to remark that only in the past few decades, the technological advance with an increasing density of seismic and accelerometric networks, provide the opportunity to compare earthquake damage levels with the instrumental records of horizontal ground acceleration, to classify and properly quantify the effects on buildings and environment, and consequently to refine intensity scales. By contrast, historical earthquakes can only be explored by macroseismic analyses, and intensity is the only parameter that allows an estimate of the earthquake size. Experience gained from the macroseismic analyses of instrumental events led to the development of empirical relationships in order to estimate the Moment Magnitude (Mw) of historical events from earthquake intensity distribution. However, instrumental records are, in the best case, only available from the first half of the 20th century. As a result, historical intensity analyses are worldwide behind most of the seismic hazard analyses, seismic-building codes and nuclear regulatory guides (Serva et al., 2007; Silva et al., 2011, 2015a) and some efforts has been done in the improvement of relationships between ESI-07 intensity mapping and seismic ground accelerations for instrumental (i.e. Papathanassiou and Pavlides, 2007; Papanikolaou, 2011) and historical earthquakes (i.e. Serva et al., 2007; Rodríguez-Peces et al., 2011a, 2011b; Ahmad et al., 2014). Consequently, the use and refinement of intensity scales and mapping in earthquake analysis will always remain imperative to the society.

This work is focused on the exploration of methodological workflows for the production of seismic scenarios (in terms of ground horizontal acceleration; PGA) for no-surface faulting historical events. These type of events (normally < 7.0 Mw) are beyond the traditional practices in paleoseismology (i.e. fault-trenching), but can produce considerable damage (Serva et al., 2015) as illustrated by recent events in Spain (Lorca 11/05/2011; 5.2 Mw) and Italy (Emilia-Romagna 20/05/2012; 6.0 Mw). The 2011 Lorca earthquake (Betic Cordillera) with a complete record of instrumental measures on PGA values, seismic size and location parameters (IGN, 2012; Morales et al., 2014) as well as many reported EEEs (Alfaro et al., 2012a; Silva et al., 2014a, 2015b), has been selected as the calibration event for the ESI-07 ShakeMaps. Once obtained a reliable workflow, this was applied to two historical events occurred in the same zone of the Eastern Betic Cordillera: the CE 10/06/1863 Huércal-Overa event (VIII ESI07; 4.9 Mw) and the CE 21/03/1829 Torrevieja event (X ESI07; 6.9 Mw). Likewise, the general geological framework is well studied for these two historical earthquakes and a large number of EEEs have been included in the "Catalogue of Geological effects of Earthquakes" recently published in Spain (Silva et al., 2014a).

The obtained ShakeMaps are among the first ever designed for historical earthquakes in Europe after the intensity-based ShakeMaps done in Germany by Schwarz et al. (2008) for historical events. As a final target, the resulting PGA values will be compared with those listed in the seismic hazard maps of Spain for different EMS-98 intensity levels updated after the 2011 CE Lorca earthquake (IGN, 2013). These updated PGA values come from a mixture (literally) of empirical relationships imported from EEUU (in MM Scale; Atkinson and Kaka, 2007) and Italy (in MSC scale; Faenza and