Database of Iberian Seismogenic Sources Parameterized for use in the SHARE European-scale Seismic Source Model

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SUMMARY:
In the context of the EC-funded project SHARE (Seismic Hazard Harmonization in Europe), an active fault database for Iberia and the nearby offshore region has been compiled and parameterized. The database synthesizes a broad range of geological and geophysical observations on active seismogenic sources. This Iberian database was designed for integration into the larger SHARE source model, for use in the production of seismic hazard maps for the Euro-Mediterranean region. As the success of project SHARE relied heavily on input from regional experts, the 2010 Working Group on Iberian Seismogenic Sources (WGISS) was established and includes researchers who have directly contributed data to the SHARE Iberian database. Other data sources include existing compilations, data from the literature, parameters estimated using empirical and analytical relationships, and, where necessary, expert judgment. The Quaternary Active Faults Database of Iberia (QAFI) provided additional data on faults in Spain for the SHARE database.

Keywords: seismic hazards, active fault database

1. INTRODUCTION

Active faulting on the Iberian Peninsula and in the surrounding offshore region is driven by distributed deformation at the Eurasia–Nubia (Africa) plate boundary. Along this boundary, the relative plate motion of 4 ± 0.2mm/yr is accommodated by ENE–WSW extension near the Azores triple junction, right-lateral strike-slip motion on the Gloria fault, and oblique WNW–ESE to NW–SE convergence to the east of the Gloria fault (DeMets et al., 2010). Whereas the highest rates of deformation and seismicity occur closer to the plate boundary, intraplate deformation also contributes to the seismic hazard of the Iberian region, particularly at longer return periods. Although historical and instrumental seismicity records are important in hazard analysis, they do not provide essential information about faults with longer return periods that can figure prominently into the hazard. For this reason, active fault databases with seismogenic parameters are essential input data for robust seismic hazard analysis for regions like Iberia.

The development of a fully parameterized active fault database for Iberia has been accomplished in the context of Project SHARE, an EC-funded initiative of the 7th Framework Program. SHARE is a regional program of the Global Earthquake Model (GEM) initiative, and represents a large collaborative effort to develop a methodologically consistent seismic source model to produce continuous seismic hazard maps for the Euro-Mediterranean region. One of the major tasks within project SHARE was the compilation of a European database of seismogenic sources. This ambitious goal required the integration of a vast amount of knowledge and data into a uniform European framework, and necessitated the adoption of common methodologies and uniform standards for the definition and characterization of active seismogenic sources. The Iberian active fault database compiled for SHARE incorporates geological and geophysical observations on active seismogenic sources from the literature and existing compilations as well as original data from contributing experts, parameters estimated using empirical and analytical relationships, and, where necessary, parameters derived using expert judgment by the compiler. The SHARE Iberian seismogenic source model represents the first source model for Iberia that includes fault data and follows an internationally standardized approach, based on the Italian Database of Individual Seismogenic Sources (DISS) (Basili et al., 2008, 2009). Previous seismic source characterizations for the Iberian region relied on earthquake data and source zones, and did not include fault sources. The SHARE Iberian fault source model is appropriate for use in national-, regional-, and European-scale seismic hazard assessments.

In January 2010, six months after the launch of Project SHARE, a workshop was held in Olhão, Portugal that brought together researchers on active faults and seismotectonics from throughout the Iberian region. The main objective of the workshop was to solicit community involvement in the development of the SHARE Iberian seismogenic source database, to ensure that sources in the Iberian region would be represented in and incorporated into the European source model. Researchers at the Olhão workshop formed the 2010 Working Group on Iberian Seismogenic Sources, and many regional experts from the working group contributed data for seismogenic sources on the Iberian Mainland and immediate offshore region. The QAFI (Quaternary Active Faults Database for Iberia) effort officially commenced after the SHARE Iberian regional meeting, and data from QAFI (García-Mayordomo et al., 2012) was subsequently incorporated into the SHARE database, marking a significant improvement in the SHARE database.

2. DATABASE SYSTEMATICS

The definition of an “active fault” can vary widely, and for practical purposes in PSHA applications, the appropriate definition of an active fault may be different for different tectonic regimes. Due to the slow slip rates over large portions of Iberia and the limited body of paleoseismic data, all faults in Iberia with a reasonable likelihood of being active and seismogenic within the current stress regime met the criteria for inclusion in the SHARE Iberian seismogenic source database. Following conventions in the DISS database (Basili et al., 2008; 2009), fault sources in the SHARE Iberian database are characterized as either: (1) individual seismogenic sources (ISS), which represent individual fault segments, (2) composite seismogenic sources (CSS), or (3) debated seismogenic sources (DSS). CSS are modelled with a complex geometry to capture geological and geophysical data from large-scale tectonic features and localized geomorphic, geological, and geophysical evidence for active deformation (Basili et al., 2008). The SHARE fault source model was restricted to include only CSS, so all ISS with a reasonable likelihood of being active and seismogenic were described in terms of the CSS model. All DSS were characterized but ultimately excluded from the source model.

The fault parameters in the database describe the geometry, kinematics, and activity rates of the faults. These parameters include: name, location (described as two or more pairs of geographic coordinates), segmentation data, style of faulting, minimum, maximum and preferred values for: length, width, minimum and maximum rupture depth, strike, dip, rake, slip rate, and maximum magnitude; preferred values for: recurrence interval, single event displacement, most recent earthquake, elapsed time since most recent and penultimate earthquakes. The compiler was responsible for performing a thorough quality check on all data contributed by experts and populating null values in the database where possible by developing and implementing appropriate assumptions and expert judgments.

2.1. Explanatory note on epistemic uncertainty

Many essential parameters for seismic hazard analysis are challenging to estimate with accuracy because of insufficient data. The specification of minimum, maximum and preferred values for many of these parameters ensures that the database contains the appropriate epistemic uncertainty ranges to encompass these critical parameters. In this context, "minimum" refers to the 5th percentile value, "preferred" corresponds with the 50th percentile value, and "maximum" refers to the 95th percentile value. In the logic tree framework, these values should be weighted 0.2, 0.6, and 0.2, respectively, to simulate 5th, 50th, and 95th percentile values in a lognormal distribution (Keefer and Bodily, 1983).

2.2. Specific parameters in the fault database

2.2.1. Fault length

Fault length is defined as the end-to-end length of an active fault (or the active portion of a longer fault), measured along its strike. If a contributing expert did not provide values for minimum and maximum fault length, the compiler estimated these on a case-by-case basis. In the absence of specific data, minimum and maximum fault length were estimated to be 5% less than and greater than the preferred lengths, respectively.

2.2.2. Minimum rupture depth

Minimum rupture depth is the depth to the top of the rupture, using sea level as a reference. If minimum, maximum and preferred values for minimum rupture depth were not provided by a contributing expert, for faults with evidence of surface rupture, the preferred minimum rupture depth was assumed to be zero with no uncertainty. For faults that can potentially rupture at or near the surface, the preferred minimum rupture depth was assumed to be 1 ±1 km; larger values were used as appropriate for blind faults. The range between minimum and maximum values for minimum rupture depth was constrained to be no greater than 4 km.

2.2.3. Maximum rupture depth

Maximum rupture depth refers to the base of the seismogenic zone, using sea level as a reference. If minimum, maximum and preferred values for maximum rupture depth were not provided by a contributing expert, the preferred values for maximum rupture depth were derived using estimates of seismogenic crustal thickness based on instrumental seismicity data (from the IGN online catalog) within each seismic source zone specified in the SHARE zonation model. To account for scattered deep seismicity, seismogenic thickness was estimated using the depth above which 95% of the earthquakes occur (d95) (Stein, 2008). To address focal depth uncertainty in the IGN seismicity catalog, the catalog was filtered according to the following parameters: $Mw>1$; $rms<0.5$; depth error<10 km. Using the d95 approach, a unique maximum rupture depth was determined for each seismic source zone in the zonation model. In the cases where individual seismic source zones contain <20 earthquakes that met the filtering criteria, those zones were lumped together with adjacent zones characterized by similar seismotectonic settings to produce larger zones with statistically significant numbers of earthquakes. In the absence of fault-specific values for maximum rupture depth, minimum and maximum values for maximum rupture depth were assumed to be equal to the preferred (d95) values for the zone containing the fault, with an uncertainty of ±4 km.

In cases where contributing experts provided values for maximum rupture depth and there is a discrepancy of <5km between the d95 value and the value provided by the expert, the d95 values were selected as the preferred values. Where there is a greater discrepancy (>5km) between the preferred value provided by a contributing expert and the d95 value, the d95 value was only selected as the preferred values if the contributed values were based on a contrasting estimate of regional seismogenic depth. If the contributed values were based on more local fault-specific data, those were selected as the preferred values. In that case, variable uncertainty bounds were imposed, as appropriate, to capture both the contributed value and the d95 value ±4 km. The minimum value for maximum rupture depth was constrained to be no less than 3 km; the range between minimum and maximum values for maximum rupture depth was constrained to be no greater than 8 km.

2.2.4. Fault dip

Fault dip describes the dip angle of the fault, measured between 0-π/2 from a horizontal plane. If an expert did not provide a dip value, the preferred values for dip were estimated based on the style of faulting and assumptions of classic Andersonian fault mechanics. Because dip can vary with depth and can be difficult to constrain, if no fault-specific data on dip uncertainty was provided by contributing experts, minimum and maximum values for dip were estimated to be 15° less than and greater than the preferred dip, respectively. The minimum value for dip was constrained to be no less than 5°; the range between the minimum and maximum dip was constrained to be no greater than 40°.

2.2.5. Fault Strike

Fault strike is the angle between the surface projection of a fault and North, as measured in map view. The value of strike is between 0-2π, measured clockwise from North, and is reported following the right-hand rule, which specifies that the fault dips down to the right of an observer standing on the fault and looking along the strike direction. Preferred values for strike were determined by measuring from the mapped fault traces. Though strike values can be quite variable along the length of a fault, they can generally be better constrained than dip values. Where only preferred values were given for strike, the minimum and maximum values were assumed to be equal to the preferred values ±5°.

2.2.6. Fault rake

Fault rake refers to the angle between 0-2π that indicates the direction of the sense of movement of the hanging-wall, measured within the plane of the fault counterclockwise from the strike direction. If rake values were not provided by a contributing expert but fault slip sense was indicated, preferred values for fault rake were assumed to be 0° for left-lateral faults, 45° for oblique (reverse-left-lateral) faults, 90° for pure reverse faults, 135° for oblique (reverse-right-lateral) faults, 180° for right-lateral faults, 225° for oblique (normal-right-lateral) faults, 270° for pure normal faults, and 315° for oblique (normal-left-lateral) faults. Because rake can be variable and challenging to constrain, minimum and maximum values of rake were estimated to be equal to the preferred values ±15°.

2.2.7. Fault width

Fault width is defined as the width of the source measured along its dip direction. Fault width uncertainty reflects the uncertainty in minimum and maximum rupture depth, which define seismogenic thickness, and fault dip. In the absence of a fault-specific value for minimum fault width, this parameter was calculated trigonometrically using the minimum seismogenic thickness and the maximum dip value (see black example, Figure 1). If no value was provided for maximum width, this value was calculated trigonometrically using the maximum seismogenic thickness and the minimum dip value (see red example, Figure 1). Preferred width was calculated in the same manner using the preferred dip value and the preferred seismogenic thickness (see green example, Figure 1).

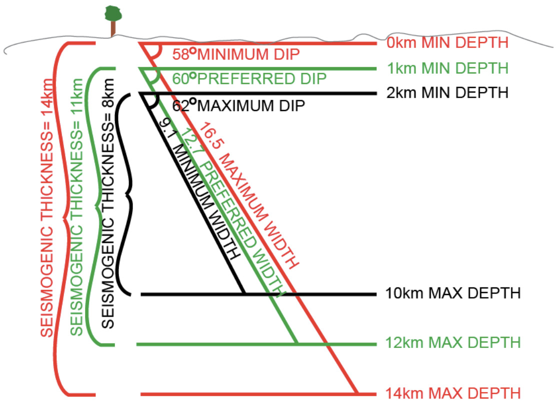

Figure 1. Schematic diagram illustrates how fault width uncertainty was determined based on the uncertainty in fault dip and minimum and maximum rupture depth.

2.2.8. Fault aspect ratio

Although not formally a seismogenic parameter, fault aspect ratios (defined as fault length/ fault width) were computed for each source during the quality checking process. Whereas most faults have aspect ratios >1.0 (e.g. Wells and Coppersmith, 1994), faults with aspect ratios in the range between 0.5-1.0 are considered permissible in cases where faults are laterally restricted (Nicol et al., 1996); aspect ratios below 0.5 are not considered realistic and were not permissible in the database. Where necessary, values for dip and maximum seismogenic depth were adjusted using expert judgment to arrive at permissible values for fault aspect ratio.

2.2.9. Maximum magnitude (Mmax)

Mmax is the maximum value of earthquake magnitude in the moment magnitude scale (Mw). Preferred Mmax values were calculated using published empirical relationships between surface rupture length and maximum magnitude [M(SRL)] and rupture area and maximum magnitude [M(RA)] for the specific style of faulting. Five published empirical relationships were considered: [M(SRL)] and [M(RA)] from Wells and Coppersmith (1994), [M(SRL)] and [M(RA)] from Stirling et al. (2002), and for strike-slip, reverse, and strike-slip/reverse oblique faults, [M(RA)] from Berryman et al. (2001). For each fault, five sets of minimum, maximum, and preferred Mmax values were calculated using each of these five empirical relationships, employing the minimum, maximum, and preferred values for length and width, as appropriate.

Next, for each fault a singular preferred Mmax value was calculated from the Wells and Coppersmith (1994) relationships that reflects a weighted average of the [M(SRL)] and [M(RA)] preferred values, weighted according to the inverse of the errors associated with the calculations. Similarly, a singular preferred Mmax value was calculated that represents a weighted average of the Stirling et al. (2002) [M(SRL)] and [M(RA)] relationships following the same methodology. For normal faults, the final preferred Mmax value was calculated using the weighted average from the Wells and Coppersmith (1994) relationships (weighted 70%) and the weighted average from the Stirling et al. (2002) relationships (weighted 30%). For strike-slip, reverse, and strike-slip/reverse oblique faults, the final preferred Mmax value was calculated using the weighted average from the Wells and Coppersmith (1994) relationships (weighted 60%), the weighted average from the Stirling et al. (2002) relationships (weighted 20%), and the value calculated using the [M(RA)] relationship from Berryman et al. (2001) (weighted 20%).

For normal faults, the final minimum and maximum Mmax values were determined using the least and greatest of the four values computed from the Wells and Coppersmith (1994) [M(SRL)] and [M(RA)] and Stirling et al. (2002) [M(SRL)] and [M(RA)] relationships. For strike-slip, reverse, and strike-slip/reverse oblique faults, the final minimum and maximum Mmax values were determined using the least and greatest of the five values computed from the five relationships considered. In cases where the calculated uncertainty range exceeds a 0.7 magnitude unit, expert judgment was used to characterize the uncertainty.

2.2.10. Slip Rate

Slip rate estimates the amount of slip along a fault (in mm) as a function of time (in years) over a specified time window. Slip rates are generally the most important fault parameters in hazard evaluation, but unfortunately most faults lack specific slip rate data. Furthermore many faults show substantial temporal and spatial variability in slip rates. If only a preferred value was provided for slip rate, in the absence of fault-specific data on appropriate uncertainty values, minimum and maximum slip rate were assumed to be equal to ±50% of the preferred slip rate. This wide range in uncertainty accounts for uncertainty arising from temporal changes in slip rate and temporal clustering behavior. Holocene slip rates are considered to have less uncertainty (± 30%). Where experts favored larger uncertainty bounds for related segments, the uncertainty range was increased accordingly. Where no slip rate was given, slip rates were estimated based on slip rates of neighboring fault segments; in these cases uncertainty ranges were assumed to be large, up to an order of magnitude.

3. RESULTS

There are 149 composite seismogenic sources (CSS), 298 individual seismogenic sources (ISS), and 40 debated seismogenic sources (DSS) in the SHARE seismogenic source database for Iberia (Figure 2). Of the CSS, 47%, are normal faults, 12% are reverse faults, 9% are left-lateral strike-slip, 9% are oblique (normal-right-lateral), 8% are oblique (reverse-left-lateral), 7% are oblique (normal-left-lateral), 5% are oblique (reverse-right-lateral), and 3% are right-lateral.

Figure 2. Composite seismogenic sources (CSS) (red lines) from the SHARE Iberia fault database were used in the SHARE source model for seismic hazard calculations. Debated seismogenic sources (DSS) (green lines) were considered to have a low likelihood of Quaternary activity and were excluded from the source model.

Slip rates across Iberia show substantial variability; however, because of the scarcity of paleoseismic data in this region, many of the slip rate uncertainties are high. The majority of the CSS in the database have low slip rates and are expected to contribute to the seismic hazard only at long return periods: 15% of the CSS have preferred slip rates between 0.0045-0.029 mmy/r; 32% of the CSS have preferred slip rates between 0.03-0.059 mm/yr; and 28% of the CSS have preferred slip rates between 0.06-0.19 mm/yr. 17% of the CSS have more moderate preferred slip rates between 0.2-0.49 mm/yr, 3% have higher preferred slip rates between 0.5-0.9 mm/yr; and 4% have the highest preferred slip rates in the database (>1.0 mm/yr) (Figure 3).

Figure 3. Map showing slip rates for composite seismogenic sources (CSS) in Iberia.

The highest slip rates in the database occur on offshore sources in the Gulf of Cadiz, although the Carboneras fault zone in Spain, with an onshore prolongation, also has a high preferred slip rate of 1.1 mm/yr (e.g. Gràcia et al., 2006; Moreno et al., 2008; Bell et al., 1997; Negredo et al., 2002) (Figure 3). The second highest slip rate among onshore faults in Spain is 0.54 mm/yr on the Carrascoy fault (e.g., Silva et al., 2003; Garcia-Mayordomo and Álvarez-Gómez, 2006; Sanz de Galdeano et al., 1998). The onshore fault in Portugal with the highest slip rate is the Manteigas-Vilariça-Bragança fault in northeastern Portugal, with a slip rate of 0.3mm/yr (Rockwell et al., 2009; Cabral, 1989; Vilanova and Fonseca, 2007). It is important to note that the Manteigas-Vilariça-Bragança is one of the few onshore faults in Portugal that has been trenched to-date. Despite a lack of paleoseismic data, the similarly oriented Penacova-Régua-Verín to the west is presumed by association to have a comparable slip rate, though with substantially greater uncertainty bounds.

15% of the CSS in the SHARE Iberia database have preferred Mmax values <6.2; 28% have preferred Mmax values between 6.2-6.59; 21% have preferred Mmax values between 6.6-6.89; 15% have preferred Mmax values between 6.9-7.19; 7% have preferred Mmax values between 7.2-7.49; 12% have preferred Mmax values between 7.5-7.79; and only 2% have preferred Mmax values >7.8 (Figure 4).

Figure 4. Map showing maximum magnitude (Mw) for composite seismogenic sources (CSS) in Iberia.

The highest Mmax values occur offshore in the Gulf of Cadiz (the Horseshoe and Cadiz Wedge faults); the Penacova-Régua-Verín fault in northern Portugal also has an extremely high Mmax (Figure 4). However, the segmentation characteristics and the likelihood of Quaternary activity along the Penacova-Régua-Verín fault are uncertain, and the fault has an estimated slip rate of 0.2 mm/yr. A discussion of the epistemic uncertainty about the likelihood of Quaternary activity follows in Section 4. Due to the scarcity of paleoseismic data in this region, uncertainties on Mmax are as high as +/- 0.6 magnitude points. In regions of relatively high seismic activity on the southern Iberian Peninsula, including the Betics in Spain and the Algarve region in Portugal, short mapped fault lengths give rise to small Mmax values.

4. FURTHER CONSIDERATIONS

For many faults that have not been mapped in detail or trenched, an evaluation of Quaternary movement is uncertain. Even faults with relatively youthful geomorphic expressions on aerial photography that appear to offset Quaternary deposits have equivocal interpretations of their activity until they have been investigated in the field. In some cases, despite detailed studies of suspected Quaternary faults, it can be difficult to demonstrate Quaternary activity where Quaternary deposits are not preserved over the fault traces. Furthermore, in contractional regimes, “blind” faults may be active despite the fact that they may not offset Holocene strata.

Whether a fault is active and seismogenic in the current stress regime is a seismic source parameter that has epistemic uncertainty. In cases where data on fault activity are incomplete, it is essential to capture this uncertainty, which can be parameterized as a probability of activity [P(a)]. P(a) describes the likelihood that a particular fault is 1) an independent seismogenic source; and 2) active within the modern stress field. Because of the slow slip rates in Iberia, there is a substantial amount of uncertainty regarding the Quaternary activity of many faults, and the implementation of a P(a) classification within the database would allow for the inclusion of fault sources for which there is no definitive data to indicate that they are active. The approach within the DISS and SHARE databases is to label controversial sources as "debated seismogenic sources". However, a shortcoming of that approach is that the debated seismogenic sources are ultimately subject to a binary decision about whether or not they should be included in the source model. In order to accommodate a more robust representation of the potentially active faults in Iberia, the P(a) scheme needs to be applied.

In practice, P(a) should be evaluated for each fault source based on an assessment of the following factors: age of youngest observed deformed or offset strata, rates of activity, spatial association with historical seismicity, geomorphic expression, amount of cumulative offset, orientation in the current stress regime, fault geometry, relation to other faults (particularly a direct structural relation and kinematic connection with another active Quaternary fault), and any evidence for a non-tectonic origin. Faults with definitive evidence for Quaternary activity, particularly where Holocene strata are clearly offset or deformed, should be assigned a P(a) of 1.0, whereas faults considered to be completely inactive should have a P(a) of 0.0. Faults for which there is evidence to suspect but not conclusively demonstrate Quaternary displacement should be assigned probabilities of activity ranging from 0.1 to 0.9 based on an evaluation of the available evidence of recent activity.

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