PROPOSAL OF A CLASSIFICATION SCHEME FOR RATING THE CREDIBILITY OF FAULT SEISMIC PARAMETERS IN ACTIVE FAULTS DATABASES

Propuesta de un sistema de clasificación para ponderar la credibilidad de los parámetros sísmicos de falla en bases de datos de fallas activas

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***Abstract**: Rating the credibility of fault seismic parameters (maximum magnitude, average recurrence period) is an increasing demand from seismic hazard analysts and seismic engineers which make use of national-scope active fault databases for their projects. We proposed that the credibility of fault seismic parameters should be based on the reliability of the geological observations from which these are eventually derived. We present a classification scheme of the significance of the Quaternary activity evidence of a fault and of the explicitness of its slip rate calculation, as these are presented in literature. Based on this classification, three levels of increasing credibility of maximum magnitude and average recurrence period of a fault are proposed with the aim to become standard criteria in the forthcoming revision and updating of the Quaternary Active Faults Database of Iberia (QAFI).*

***Key words**: Active Fault Database, QAFI, Maximum magnitude, Recurrence period, Seismic hazard.*

Introduction

The creation of active faults databases is nowadays a common practice in many national geological services. The knowledge about the location and activity degree of faults is crucial for seismic hazard and risk assessment, as well as for anthropic activities that involve changing the natural stress-state in the crust: water reservoirs, gas underground storage, fracking, etc. The importance of active faults is a matter of concern in modern seismic code provisions, as for example in Eurocode-8, where a national active fault catalogue is referred to for an appropriate following of the provisions.

However, building an active fault database for widespread usage requires common and standard procedures. A main issue is the unresolved question of the definition of active fault, which varies widely from a geological to an engineering point of view. We can thus consider then two end members: for the geological approach fault activity concerns all faults optimally oriented to the current stress regime (that may involve a few million years back) while for the engineer view only those faults considered to be capable of producing earthquakes in the short-term life of structures are assumed active (which may mean only faults active in the last few thousand years). When we designed the QAFI database four years ago (García-Mayordomo et al., 2012), we decided to set a time cut-off at the Quaternary period (last 2.56 ma), as this would include most of the geologically active faults as well as all the potentially active faults that should concern seismic engineering.

Populating an active faults database is also a complex matter, particularly in countries with relatively low strain rates. It is not just because the available information on Quaternary activity varies broadly from fault to fault; it is also because the relevance of the observations, the accuracy of the measurements and, eventually, the determination of seismic parameters that may be later used by seismic hazard analysts are also very unbalanced from fault to fault. In the four years that QAFI has been available to the general public, we have experienced an increasing demand for classifying somehow the activity of the faults and the reliability of their associated seismic parameters.

To our current knowledge there is not yet a standard procedure for rating the “quality” of the information available about a fault based on published geological observations, whether these come from regional mapping interpretation or detailed field studies. Furthermore, there is not a standard procedure for rating the credibility of the seismic parameters that are derived from those geological observations. We shall share here with the rest of the Iberian community the outcome of the different discussions that we have come across in the last four years of use of the QAFI and, particularly, in the current year, when the works for updating QAFI to version 3 started and are still ongoing.

We present in this paper a tentative classification scheme for the records that build the QAFI database, and that we believe to be inspiring for other comparable fault-databases in the world. Our classification scheme is based, firstly, in rating the **significance** of the Quaternary activity evidence of the fault; we followed then with rating the **explicitness** of the calculation of the fault slip rate. Based on these two ratings, the **credibility** of the fault-seismic parameters are objectively appointed, namely maximum magnitude and average recurrence period.

Finally, it is convenient to highlight that the aim of our classification is far from rating the quality of other's people work. The quality of the work is taken for granted, as we assume that at least it reached the minimum standards of the peer-reviewed journal where the information was published. We pursue a classification scheme as much objective and straightforward as possible, especially when rating the seismic parameters of the fault.

Rating the significance of Quaternary activity evidence (QE)

The significance of Quaternary activity evidence (QE) is rated in three increasing levels of accumulated evidence: C_{QE}, B_{QE} and A_{QE}. Differentiation among levels is based, basically, on the scale of the observations and detail involved in obtaining the observations.

Level $\mathbf{C_{QE}}$ encompasses the less significant evidence. These are inferred from regional scale observations of the fault trace, from interpretation of general geological maps or broad range geophysical methods, to digital terrain models (DTM). At this level, there is usually a lack of field work focused on demonstrating these inferred evidences. Quaternary geochronology is usually only known in broad relative terms as generic Quaternary, or may be in the three stages of the Quaternary Period (Upper Pleistocene, etc.). Similarly, Quaternary landforms or deposits are mapped in broad units: terraces, alluvial fans, etc.). Numeric dating of certain deposits usually lacks or they are very scarce. An example of Level C_{QE} observations is summarized in Table 1.

Level $\mathbf{B_{QE}}$ assigns faults that, having Level C_{QE} evidences, they have additional observations from larger scale works, and may be some field work. Quaternary geochronology is better constrained, although numeric dating of relevant formations may be still lacking. The arrangement of Quaternary formations is known more precisely and there is a differentiation of phases or stages inside generic landforms (eg., differentiation of generations of alluvial fans, terraces,….) (Table 1).

Level $\mathbf{A_{QE}}$ faults are those that having Level B_{QE} (and C_{QE}) evidences, they also have observations obtained from field work. In general, Level A_{QE} evidences are gained after intensive work at the office (eg., photo-interpretation, DTM analysis,…) followed by field work focused on confirming the evidence (Table 1). Level A_{QE} observations evidence the activity of the fault as a major controlling agent of Quaternary landforms or sedimentation, as for example fault scarps offsetting Quaternary deposits. Numeric Quaternary geochronology may still be lacking, but the refinement reached on the definition of the geomorphic units permits a reliable approximation to their age based on relative spatial associations or inferred from other similar units in the area.

Finally, it is important to consider that the evidence of Quaternary activity of a fault commonly varies along its trace, and so it can be rated differently from section to section. The variation of the significance of the evidence sometimes simply reflects a lack of available published information. Otherwise, this variation could be due to natural erosion/sedimentation processes or even anthropogenic activities that blur the evidence at some parts. A common case is the differentiation of fault-segments based on contrasting activity; in that case QE rating should be applied differently to each segment. It is convenient then, that the QE rating considers also the representativeness of the evidence along the trace. To do so, the QE classification level is followed by a "+" or "-" sign. For example, a fault rated A^{-}_{QE} would mean that at least in one section along the fault-trace, level A_{QE} evidence has been documented. On the contrary, A^{+}_{QE} means that the fault shows documented QE consistently along all its trace or most of it. The same procedure can be followed for QE levels B or C.

LEVEL C; Observations just based on:
-Interpretations from regional-scale geological maps (1/100.000 or smaller) -Interpretations from geophysical methods at a regional scale -Topographic or DTM anomalies at a regional scale (lineaments, scarps,…) -Drainage network anomalies at a regional scale (deflections, captures,…)
LEVEL B; Additional observations based on:
-Interpretations from detailed-scale geological maps (1/50.000 or larger) -Interpretations from geophysical methods at detailed scale -Geomorphic indexes indicating recent activity -Drainage network anomalies (fault-aligned deflections, beheaded valleys, longitudinal profiles, differential dissection, captures,…) -Landforms anomalies (ridges along fault trace, faceted spurs,…)
LEVEL A; Additional observations from field work:
-Fault scarp controlling Quaternary geomorphic landforms -Fault offsetting or folding Quaternary deposits at surface or subsurface (from geophysical methods)

Table 1. Tentative classification of Quaternary activity evidence in three levels of increasing significance.

Rating the explicitness of slip rate calculation (SR)

We consider here the two basic parameters for a slip rate calculation: displacement and age. The accuracy of constraining the two parameters would lead to the classification of the slip rate estimation in three increasing levels of explicitness: C, B and A.

Level $\mathbf{C_{SR}}$ corresponds to a slip rate estimation based on the displacement of a marker measured from the interpretation of large scale cartography or DTMs;

while age control of the marker is assumed to correspond to the generic Quaternary Period or its stages (eg., 125 ka Upper Pleistocene). Level C_{SR} slip rates are broad approximations that usually lack direct observation of the slip vector and dip of the fault, and it may be assumed from generic considerations on the general kinematics of the fault (eg., a rake of -90º for a 60º dip normal fault). Hence, at Level C_{SR}, slip rates are usually quoted either as vertical or horizontal slip rates. The uncertainty of the estimation is very large depending generally on the broad controlling-age considered.

A level **B_{SR}** corresponds to an estimation where one of the basic parameters, displacement or age, are well constrained. Displacement of the marker may be measured from the interpretation of large scale cartography after some field work; and age may be controlled by numeric dating of the marker or by association to similar formations dated in the area. The slip vector of the fault and/or its dip are also better constrained than in Level C_{SR}; a net slip rate is usually estimated additionally to the vertical/horizontal components. Uncertainties can still be very large, but the range of maximum and minimum values is better constrained than in Level C_{SR} estimations. Typically, contrasting slip rate values are obtained when considering different hypothesis on the displacement and age of the marker.

Level **A_{SR}** describes slip rate estimations where both displacement and age-control are constrained by measurements at outcrop scale or inferred on field observations and age obtained from numeric dating methods or inferred from them. There is also a good knowledge on the true slip-vector and dip of the fault, and accordingly net slip rate values are obtained. Uncertainties in the estimation can be large, but these are mostly in relation to the accuracy of the dating results and its interpretation in relation to the true age of the marker. Uncertainties are usually quoted as standard deviations, or by similar statistical parameters (eg., mean error). Age and displacement are clearly stated in a way that an external reviewer could reach the same values as in the published information. Typically, there is a discussion on the variation of slip rate for different time periods.

Rating the credibility of fault-seismic parameters

Rating the credibility of seismic-fault parameters must come after QE and SR have been previously rated. This rating also accounts for three increasing levels of credibility: (D), C, B and A.

Maximum magnitude (MM): maximum magnitude is an important parameter in hazard calculations that accounts for the seismic potential of active faults. MM can be used to assess the upper bound of Gutenberg-Richter relations in seismogenic zones, to characterize the fault as an independent seismogenic source following a characteristic or maximum magnitude model (Schwartz and Coppersmith, 1984; Wesnousky, 1986), or in a Luco and Anderson (1983; Bungum, 2007) model to constrain the maximum seismic moment budget of the fault.

A credible MM value of a fault should be based primarily in the significance of its quaternary activity evidence (QE). In this sense, a higher or lower credible MM would come either from a Level A^{+}_{QE} or C_{QE}, respectively. Hence, we propose a straightforward determination of the credibility of MM based on the QE level of the fault. Furthermore, a MM value always comes from an estimation affected by uncertainty, and this should be always properly accounted for. This is a crucial matter in modern seismic hazard analysis, and so the credibility level of MM estimation should obligatory account for the sources of uncertainty.

A level A maximum magnitude estimation (**A_{MM}**) is assigned only when both the QE of the fault has been rated A^{+}_{QE} (i.e., the activity of the fault is well constrained and consistent along its trace, hence, the occurrence of earthquakes that ruptured all the fault/segment trace is very plausible) (Table 2) and the uncertainty in the MM estimation procedure has been analyzed from at least the following issues: 1) variation of displacement per event at outcrop scale, 2) variation of rupture parameters (length, width, depth) and, 3) variation of the value drawn from different empirical equations suitable to the type of faulting and tectonic environment. A level A_{MM} typically comes from published information that discuss possible segmentation of the fault based on slip rate variations, geometry variations or other related issues. Based on the data and discussion, the authors may prefer a particular MM value to other, but this is always clearly stated in a way that an external reviewer can reach the same value and its associated uncertainty, expressed either by a range of maximum and minimum values or by a statistical parameter as standard deviation.

A **B_{MM}** level comes from a fault whose QE is either A^{-} or B^{+} (Table 2) and uncertainties have been analyzed for both the variation of rupture parameters (length, width, depth) and the variation of the value drawn from different empirical equations suitable to the type of faulting and tectonic environment. Typically, an external reviewer is able to reach at least the same MM value proposed by the authors based on the data stated in the published information.

A **C_{MM}** level comes from a fault whose QE is either B^{-} or C (Table 2) and the MM estimation considers at least the uncertainties from the use of magnitude scale empirical equations.

An additional D_{MM} level could be considered in this scheme to rate MM values derived from fault information that lacks sufficient data to pursue the estimation procedure and/or any source of uncertainty is considered.

Average recurrence period (RP): recurrence period of maximum earthquakes is a crucial parameter for modeling the seismogenic potential of a fault in the characteristic or maximum magnitude models. Its estimation may be based on paleoseismic observations or may be derived from slip rate and maximum magnitude through the well-known equations of Aki (1966) and Hanks and Kanamori (1979).

We propose to base the credibility of RP directly from both the credibility of MM estimation and slip rate (SR) estimation. Similarly to MM, uncertainties are also crucial here and it is compulsory to account for them in order to reach a high credibility level.

A level **A_{RP}** is conceded only when both MM estimation has been rated A (i.e., the occurrence of earthquakes that ruptured all the fault/segment trace is very plausible) (Table 2) and the explicitness of its SR estimation is also rated the highest (A_{SR}). Additionally, uncertainty should be analyzed both from epistemic and aleatory sources. The former refers to account for, at least, the possibility that maximum events happened clustered in time, and for the consistency between the size of maximum events derived from single-event displacements in the field and the maximum rupture dimensions of the fault. The aleatory source refers to account for variations in the number of possible events in a time period, which has also an associated error in relation to the numeric dating results and their interpretation. Based on the data and discussion, the authors may prefer a particular RP value to other, but this is always clearly stated in the paper so an external reviewer can reach to the same value. The uncertainty of RP has to be quoted in a range (maximum to minimum possible values) or using a statistical parameter as standard deviation or mean average error.

Level **B_{RP}** comes from a fault with MM rated B and SR rated A or B (Table 2). At least the aleatory source of uncertainty should be analyzed (see above for an explanation), and quoted in a range (maximum to minimum possible values) or using a statistical parameter as standard deviation or mean average error.

Level **C_{RP}** comes from a fault with MM rated C and SR rated B or C (A_{SR} is not considered here as it would be unrealistic that a C_{MM} level, which comes from a B^{-}_{QE} or C_{QE} fault, could have that high level of SR explicitness) (Table 2). The RP estimation here is highly interpretative, but tentative bounds of the range of uncertainty in the preferred value/s should be shown in the information.

An additional D_{RP} level could be considered in this scheme to rate RP values derived from fault information that lacks sufficient data to pursue the estimation procedure and/or any source of uncertainty is considered.

Quaternary evidence significance (QE)	Slip Rate calculation explicitness (SR)	Max. Magnitude credibility (MM)	Average Recurrence P. credibility (RP)
A+	A	A	A
	B	B	B
A-	A / B		
B+	A / B		
B-	B / C	C	C
C	C		

Table 2. Resulting relations between possible levels of QE and SR, to credibility levels of MM and RP. The arrows on top show the connection among parameters.

Conclusions and prospects for future work

We have presented a tentative scheme for the classification of the significance of Quaternary activity evidence (QA) and the explicitness of slip rate estimation (SR) to be used in the QAFI v.3 database for rating subsequently, and accordingly, the credibility of fault-seismic parameters crucial in seismic hazard analyses (maximum magnitude and average recurrence period).

We propose that rating the credibility of fault-seismic parameters should be strongly based on the reliability of the geological information used to constrain them. Rating the credibility of fault-seismic parameters should be straightforward to the compiler of the data, assuring in this way the objectiveness in the assignment at the most.

Even though our main aim is to produce a practical approach to be used by the compiler as automatically as possible, we are aware that the best product will always come from a consensus among the community of Earth Science researchers. In this sense, we believe Iberfault-2014 is an excellent arena for discussion and agreement and, hopefully, will lead to an improvement of the scheme presented here, particularly at the classification of Quaternary evidence (Table 1).

We are also aware that few questions remain open in our scheme, namely, the consideration of instrumental and historical earthquakes and its likely relation to the fault; quoting the type of active-fault accordingly to the parameters specifically considered in seismic provisions of engineering structures (dams, bridges, pipe-lines, etc.).

And, finally, a very important question, at least for the QAFI v.3 database: should the value of fault-seismic parameters be directly taken from the source (publication) or should it be re-estimated by the compiler following a standard procedure?

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