Historical Earthquakes, Paleoseismology,
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New Insights and Suggested Procedures

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Best practice of macroseismic intensity assessment applied to the earthquake catalogue of southwestern Germany

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Abstract

The earthquake catalogue of southwestern Germany for the last millennium now contains about 30,000 digital macroseismic intensity data points (IDPs). Intensity assessments are based mainly on primary sources using the European Macroseismic Scale 1998 (EMS). The article describes a guideline for best practice of conventional macroseismic evaluation in application to historical and modern-time earthquakes in SW-Germany. Suitability of various diagnostics for intensity assessment is discussed. Assumptions to estimate damage grades and vulnerability classes of buildings are presented. Data restrictions and treatment of special cases are outlined. Further topics are quantification of uncertainties and IDP quality as well as substitutes for intensity. An essential task is to bridge the gap between information from historical sources and seismological needs for use in the earthquake catalogue, thus all issues have a focus on historical earthquakes. Questions of completeness, subjectivity, transparency, and interdisciplinary work are addressed also. Special emphasis is given to a well balanced use of the EMS scale throughout all time periods leading to consistent assessments in the catalogue.

1. Introduction

1.1. Earthquake catalogue

The parametric *earthquake catalogue* of southwestern Germany (SW-Germany) was compiled by the Seismological Service Baden-Württemberg (the "Landeserdbebendienst", abbreviated: LED) in a five-years project from 2013 until 2017 at Freiburg, Germany (Brüstle et al., 2021). The name of the project was "Seismological and historical compilation of the earthquake catalogue for Baden-Württemberg, SW-Germany, from 1000 AD until today and acquisition of earthquake information in a database" (referred to as "the/this project"). The "LED catalogue" (or simply "the catalogue", if not specified otherwise) covers the region that is today the German Federal State of Baden-Württemberg including surroundings, as far as seismicity there is seen relevant for the catalogue, hence particularly including the border regions in France and Switzerland alongside the river Rhine.

In this article, the term "historical" is used generally for the time period of the last millennium before the turn of the 19th to the 20th century. All year dates mentioned are years AD. The period of the 20th century and thereafter is called "modern time" or "instrumental time" with reference to the seismographical records. The project was oriented towards a conventional assessment of macroseismic "intensity data points" (abbreviated: IDPs in plural, and IDP in singular form, see section 2.1.1. below) from the most relevant sources. "Conventional" stands for a non-formalized manual evaluation of the sources by expert judgement. The term "sources" is used denoting any kind of information on that the evaluation can be based on. Macroseismic intensities (or "intensities" for short) were assessed using the *European Macroseismic Scale 1998* (published by Grünthal, 1998; hereafter abbreviated and shortly quoted as "EMS" or "EMS scale") and a special guideline (see section 1.2.). Intensity is notated in Arabic numerals. The terms "damage" and "vulnerability" refer to buildings in the sense of the EMS, if not specified otherwise. Internet macroseismic data acquisition and automated determination of intensities are not considered in this article.

The present article focuses on methodological issues of macroseismic evaluations. Examples from the catalogue serve for illustrative purposes only. – In the remainder of this section just a short overview over the catalogue is given. Detailed information about the catalogue and the project, including sources and IDP data, will be published elsewhere (Brüstle et al., 2021).

For the first time in SW-Germany, a systematic and comprehensive search for information about *historical earthquakes* was carried out in the project using *primary sources* as far as possible. "Primary sources" are understood as contemporary witness testimonies, on-site records, field survey reports, first-hand information accounts of various kinds, etc. (occasionally also referred to as "direct sources" or "original sources"). The search for primary sources was considered an essential prerequisite for the compilation of a reliable earthquake catalogue (see also IDP quality in section 2.8.4.). More than 30 archives and libraries were visited on-site and many others online. Altogether about 1,100 relevant documentary sources from the 15th to the 19th century could be found, of which 700 had been unknown to seismology before. For earthquakes in the Middle Ages, on the other hand, almost no new primary sources were found. – Earthquake information was retrieved from various source types, comprising both official and private documents, either handwritten, printed or pictured, for example from annals, chronicles, protocols, repair bills, church registers, sermons, diaries, memoirs, letters, leaflets, notices, gazettes, newspapers, questionnaires, bulletins, catalogues, journals, and visual material. – The historical sources were evaluated in a *historical-critical* way by properly taking into account their context with regard to geographical, political, social, cultural, and mental, as well as to linguistic, historiographical, and archival aspects (see EMS, pages 50-53; Gutdeutsch et al., 1987; Guidoboni, 2000; Gisler, 2003; Grünthal, 2004; Albini et al., 2004; Mayer-Rosa & Schwarz-Zanetti, 2004; Hammerl, 2017; and many others). Great care was taken to ascertain historical detail and to document the sources as well as the evaluation process. Special emphasis was given to a well-balanced use of the EMS scale throughout historical and modern times.

The project work was strongly focussed on historical IDP assessment. For the *historical time period* only few IDPs had been available before. Now, for the first time, historical seismicity of SW-Germany is fully present in IDP format. About 3,000 digital IDPs, with intensities based on the EMS scale, from more than 400 historical earthquakes were determined in the project, in majority of the 15th to the 19th century. This constitutes a completely new data set.

In the *modern time period*, instrumental seismology started in SW-Germany at the beginning of the 20th century. Routine seismographic epicentre localisation and calculation of local magnitudes on the Richter-Scale, however, were established just in the 1960ies. *Traditional macroseismic questionnaire surveys* have been continuously carried out already since the end of the 19th century. At first, the questionnaires had been replied primarily by selected correspondents ("makroseismische Beobachter", i.e. macroseismic observers) with focus on their individual observations. Later on, the system has been changed towards responses from the municipality or town administration offices using a collective form (with questions to the burgomaster office in the style of, "what happened in your commune?"). Hence, in general, an IDP has been based on one collective questionnaire. To a minor part, spontaneous responses, usually in the form of letters and postcards, came in as well. Questionnaires have been distributed and returned by postal mail, lately also by fax and email; the originals are kept in the LED archive. – The bulk of these questionnaires was completely re-evaluated in the project on the basis of the EMS scale. Dealing with various questionnaire styles and handwritings, appropriate working procedures had to be established. Thereby, a high level of consistency of intensity assessments from questionnaires could be achieved, which had not been given before due to changing questions, forms, practices, scales, and evaluators in the course of the 20th century.

For the *modern time*, about 140 of the strongest 20th-century earthquakes in SW-Germany (from about intensity 5 EMS upwards), plus a few after 2000, were re-assessed in the project yielding an amount of about 26,000 digital IDPs. About 80% of these IDPs were derived from the questionnaires, about 20% from direct surveys, letters, postcards, newspaper reports, as well as from secondary transcriptions. This data set is also novel inasmuch as the IDPs are now all digital and consistently based on the EMS scale.

The most recent macroseismic data come from questionnaires using forms made available via the internet (hereinafter termed *internet macroseismic questionnaires*, abbreviated: IMQ); this kind of data is processed automatically, usually within postal code areas (e.g. Wald et al., 1999 and 2011). IMQ data have been collected by the LED since 2012 but are not dealt with in this article.

In a few cases, some IDP data were adopted from other seismological agencies, catalogues, or compilations keeping the original choice of the intensity scale; hence, no transformation of intensities from other scales into the EMS scale (e.g. by using a formula) was carried out. To some part, these "imported IDPs" complement own ones. If own IDPs had been present from earlier work and were replaced by re-assessed ones in the project, the "replaced IDPs" were kept in the database as well, for comparison, with original intensities and scales. A review of intensity scales has been published by Musson et al. (2010).

A *relational database* hosts the entire catalogue, including earthquake and IDP data, all relevant source information, and links relating with the respective text documents. The database structure, with its tables and attributes, is particularly adapted to the needs of historical IDPs and sources. – *Information regarding IDP data* is stored in a table with the following IDP attributes: responsible agency, geographical coordinates, administrative region, seismo-geographical region, location (place name) and additional location information, lower and upper bound intensity, most probable intensity, intensity scale, quality, felt-flag, damage-flag, sound-flag, lights-flag, ground-flag, earliest reporting date, earthquake evidence, and comments. Each IDP is linked to the related earthquake, including date and time, and to the related source(s) using author/reference key(s) and associated importance weight(s). – *Information regarding source documents* is stored in a table with the following source attributes: author(s) or reference, year of publication/origin, place of publication/origin, original archive, complete quotation, comments, type, duration period (time span covered by the source), appraisal, local archive for the source, and local archive for the transliteration (explanations further below). Bibliographical data can thus be queried for IDPs or earthquakes alike. One IDP may be based on many sources (and one source may be related to many IDPs). Within the project, the number of sources supporting an IDP ranged from one to about a dozen.

For the first time, *seismic histories* (chronological sequences of IDP intensities) for places in SW-Germany can be plotted, even though partly incomplete. For the time being, no attempts have been made to draw *isoseismal lines* onto the IDP maps as scatter is generally quite large. Also, earthquake *magnitude and depth* estimates from IDP data have not yet been determined.

At the end of the project, the catalogue contained a total number of about 10,000 *earthquakes with epicentres in SW-Germany* and surroundings, the majority of which were not-felt earthquakes, i.e. instrumentally recorded only, within the last decades. The number of IDPs per earthquake in the catalogue ranged from zero to well over a thousand, some extending to far outside of SW-Germany. For a historical earthquake, the number of IDPs can be considered "a sort of measure of the quality and quantity of information a preinstrumental earthquake relies upon" (quoted from Rovida et al., 2020). *Maximum intensities* of the earthquakes in the catalogue covered the range from 1 to 9 EMS, located mainly in the regions of the Upper Rhine Graben, the Swabian Jura, and northern Switzerland. Earthquake epicentres derived from IDP data (*macroseismic epicentres*) and intensities at the epicentres (*epicentral intensities*) were determined in general on an empirical basis. For completeness, additional earthquake event data was implemented into the catalogue also, adopted from existing regional and national catalogues of Germany, Switzerland, and France, from seismological bulletins and data collections as well as from unpublished documents.

1.2. Guideline

One of the major tasks in the earthquake catalogue project was the evaluation of sources and the IDP intensity assessment. For reasons of standardisation and guidance within a multidisciplinary team working in the fields of historical science, seismology, as well as information technology, a *guideline* has been required to serve as a methodological and coordinative reference and a link of common understanding within the project (see also e.g. Moroni et al., 1996; Guidoboni & Ebel, 2009). Among other topics, the guideline documents best practice procedures of intensity assessment based on EMS principles under historical, seismological, and engineering aspects. It is in general conformity with the EMS scale and has insofar also supported the proper implementation of EMS rules and the consistency of EMS intensity assessments in the project. In part, however, it had to go beyond the EMS. Particularly for assessment of intensity from historical accounts, the guideline also served as a detailing supplement and extension. It has been specially designed for use in the evaluation of earthquakes in SW-Germany, but may be helpful for macroseismic work in other regions as well.

The present article draws from the guideline (see Brüstle et al., 2021) and deals mainly with intensity and IDP assessment related issues in the following sections:

(2.1.) basic concepts (intensity data points, quantities, distribution of effects);
(2.2.) diagnostics (suitable, weak, and unsuitable diagnostics, frightening earthquakes);
(2.3.) damage grades;
(2.4.) vulnerability classes (vulnerability in different time periods, assumptions);
(2.5.) data restrictions (poor data, missing and extrapolating information, negative reports, fake and lost earthquakes);
(2.6.) special cases (earthquake series, earthquakes at night, during mass, ringing of church bells, falling of roof tiles, damage to chimneys, freestanding walls, tall buildings, secondary damage);
(2.7.) substitutes for intensity;
(2.8.) uncertainties (probabilities, uncertainty notation, intermediate intensity, IDP quality, quality and precision); and
(2.9.) other issues (completeness, consistency, subjectivity, transparency, interdisciplinarity).

References are made to the EMS scale (Grünthal, 1998) throughout this article.

2. Intensity assessment

2.1. Basic concepts

2.1.1. Intensity data points

Macroseismic intensity is considered a classification of the severity of ground shaking of an earthquake on the basis of observed effects in a limited area; intensity is derived from "sensors", which can be people, objects, buildings, and nature (EMS, page 21). The core of the intensity assessment procedure is tied to the conception of the *intensity data point* (abbreviated: IDP). The IDP concept aims at just one single intensity value ("IDP intensity") that best characterizes the severity of shaking during a particular earthquake expressed by all its macroseismic effects in a village or town as a whole. This locality is called "IDP place". An IDP is identified as a data triplet of intensity, place, and date (plus time). Our *IDP intensities* were conventionally assessed by expert judgement using the EMS scale. Some authors prefer to use the term *macroseismic data point* (abbreviated: MDP), including also cases where macroseismic information is available but insufficient to assign an intensity value. In this article we use the term IDP only, with IDP being equivalent to MDP without this distinction. The information to assess IDP intensity may come from a variety of sources. In this project, we mainly dealt with paper sources ranging from classical historical documents to postal questionnaires (see e.g. Cecić & Musson, 2004); internet based sources (IMQ, etc.) were not considered.

We assigned *IDP places* to rural municipalities (or sub-municipalities) and urban towns (or town districts in cases of large towns) and evaluated macroseismic effects for assessment of IDP intensity within respective areas (i.e. within respective administrative boundaries). We did not use postal code areas (as it is common for IMQ) because our data were related to towns, villages, and parishes. Our IDPs are thus more related to localities than to population. The place list contained about 3,600 IDP places inside of Baden-Württemberg. This corresponded to an average area of about 10 square kilometres and an average number of about 3,000 people per IDP (in historical time much less people, of course). Only rarely we had to "split an IDP" because of a too large area of the IDP place, for example in case of a large rural municipality, or in order to separate parts of the IDP place area with grossly different underground settings, to obtain suitably smaller areas for intensity assessment in accordance with EMS rules (EMS, pages 26-27). As geo-referencing and geographical coordinates (latitude and longitude in the WGS84 system) of IDPs inside of Baden-Württemberg were concerned, mainly central points of the IDP place areas were used, as derived from data of the land surveying office of Baden-Württemberg.

We based *IDP place names* on a modern gazetteer derived from official lists of commune and town names and took care to use identical place names for historical and modern times. In principal, the most recent name was chosen. We also were attentive to discriminate between different places of the same or a similar name in order to avoid "name confusions". To take an example, 19 different places named "Hausen", some with name extensions, had to be distinguished inside of Baden-Württemberg. Differing names, as for example former names, name extensions, name suffixes and affixes, different language versions, different styles of writing, of the same place were noted in a comment to the IDPs. We also took note of extinctions or movements of places in the course of history as well as of changes in administrative structures. Additional database information was added to the place names, with regard to community, district, region, country, etc., for clarification and to ensure unambiguity. Both place names and coordinates ensured the identity of IDP places.

For historical documents, it was also important to be sure that an IDP place of macroseismic observation was not confused with the locality where the respective source document had been written or published (to avoid "place confusions"; see also Musson, 1998b). Information about earthquake observations that could not be associated with a place in IDP format was entered as a comment to the corresponding event in the database, if possible, or had to be laid aside. Examples for that were occasional fragments of information that had been mentioned in passing, as for instance, "An earthquake was felt in the duchy of Württemberg in the year ….".

We made a particular effort to provide a *common time base* for all periods in the catalogue. We determined the date (day, month, year) and the day of the week associated with historical IDP observations to the best of historical knowledge (see Grotefend, 2007). As for the type of calendar, we transformed Julian calendar dates into that of the *Gregorian calendar*, where applicable (10 days had to be added in the first period of calendar transformation starting 1582). Attention was paid to avoiding the frequent "calendar date errors" and subsequent duplications of earthquakes. Ambiguities of date also arose from an occasional uncertainty in some historical sources whether an earthquake at night time had occurred before or after midnight ("midnight error").

If the hour of the day, or even the minute, had been mentioned in historical reports, we transformed the time into today's *Universal Time* system (Coordinated Universal Time, abbreviated: UTC) to the best of our knowledge. UTC time was generally set as 1 hour earlier than the corresponding local time, if not required otherwise. Different measuring scales of time and hour styles had to be minded. Substitutes for time of day in the historical past had been, for example, "at cock-crow", "at sunrise", "at vespers time", "at dawn", "at midnight", etc. Some of these expressions of time we could translate into an approximate hour of the day, some others remained unspecified. From about mid of the 19th century reported times have become more precise but have also become subject to further corrections (e.g. different local time zones in Germany according to geographical longitude, later also differences due to the alternation of wintertime and summertime, and even double summertime, etc.).

Calendar date and time of day of historical earthquakes were derived from that of related IDPs; reversely, date and time, as well as respective uncertainties, were crucial information for correctly associating IDPs to respective earthquakes. Correct dating/timing helped therefore to untangle IDPs and earthquakes within clusters. This frequently meant to separate erroneously merged or to combine erroneously separated IDPs and earthquakes, respectively, thereby avoiding lost, duplicated, or time-shifted earthquakes in the catalogue due to errors of date and/or time.

In strict accordance with the EMS scale rules, we deliberately did not take the amplifying or attenuating effect of geological underground and soil conditions on seismic waves and ground shaking into account for intensity assessment (EMS, pages 29-30). Any *geological effect* on intensity, whether known or conjectured, was not corrected for but has been kept implicit in the intensity value. Hence, earthquake hazard can be derived directly from IDP data, if so desired. Should a "geological correction" of intensities, nonetheless, be required for some specific application, this will have to be done in the course of a separate processing at a later stage. – The same applies to *topographical effects* on intensity.

Our IDP intensities are *observed values* as they were derived from reported observations. We did not calculate IDP intensities for places with no observations, neither by inter- or extrapolation from other IDP data nor by conversion from instrumental data. We also did not derive any IDP intensities from existing macroseismic maps but we rather re-evaluated the sources. An atlas of traditional macroseismic maps of the 19th- and 20th-century earthquakes in the region has been published by Brüstle et al. (2015), though, for historical documentation.

Maximum intensity for a particular earthquake was, by definition, set to equal the highest IDP intensity observed anywhere in the macroseismic field, if it had a reasonably good IDP quality, and provided that it appeared likely that the maximum could be captured thereby. – By contrast, if *epicentral intensity* could not be based on an IDP observation at the epicentre, simply if there was none, it was generally derived from IDPs nearby in an empirical way (no fractional intensity was calculated, though; epicentral intensities followed the same format as IDP intensities). Epicentres and epicentral intensities outside of SW-Germany were mainly taken over from earthquake catalogues of neighbouring regions.

2.1.2. Quantities

The core concept of the EMS scale is based on the *quantifiers* "few", "many", and "most" (EMS, pages 25-26). In principle, any macroseismic effect should be used for IDP intensity assessment together with its quantity, i.e. together with the frequency of occurrence at the respective IDP place. The definitions of contiguous ranges of respective percentages, as read from the graph in EMS on page 17, are: "few" from 0% to about 15%, "many" from about 15% to about 55%, "most" from about 55% to 100%, with an overlapping range of about 10% in both transitions. In practice, though, we interpreted "few" starting from about 1%. We assumed that "a few", as used in the EMS scale text, can be understood synonymously with "few". "Only very few", however, we interpreted in the sense of less than few, similar to "only at isolated instances …" (which should be less than 1%, according to EMS, page 17). If a source text had used the term "all", we, in general, did not take this literally but translated it into "most" of the EMS-quantification. We were aware of the frequent comprehension of "many" in an absolute sense (meaning "a large number"), which is not the relative sense of the EMS-quantifier percentages. For historical earthquakes, determination of quantities was particularly difficult. In practice, we often had to guess EMS-quantities just from the context. Absolute numbers of buildings and people living at the IDP places could, to some extent, approximately be estimated from town pictures and population statistics.

2.1.3. Distribution of effects

Macroseismic effects are not expected to be uniform within the IDP place. Conventional IDP-intensity assessment is, in general, based on the strongest effects observed at the respective IDP place for the particular earthquake, i.e. on so-called *maximal effects*, and not on effects of average strength. Maximal effects of an IDP usually occur just in few cases ("few" in the sense of EMS-quantifiers) within the IDP place, whereas *average effects* usually occur more frequently, except e.g. for "pile-up" or saturation effects near the upper end of the scale or scale segment (compare EMS, Figure 4-1 on page 60). Finding maximal effects was facilitated by the circumstance that major effects were quite likely much better reported than minor ones. In particular, also spontaneously communicated singular observations tended to be rather on the side of the stronger effects, as this might have been the reason for writing in the first place. Therefore, a sample of known effects was not random but probably skewed towards the stronger ones. We were aware, however, that IMQ data are being evaluated differently (see e.g. Tosi et al., 2015).

Maximal effects should be coherent with other effects at the same IDP place. This is why effects of smaller strength or size should be examined as well, if it is possible. On the other hand, one has to be aware of *singular extreme effects* that may have been caused by constructional defects of buildings ("an earthquake finds out deficiencies"), geotechnical problems or locally-limited anomalous soil conditions at the respective building sites; or may have affected tall (except for 2 EMS; see section 2.6.8.), monumental, or exceptional buildings only (see section 2.2.2.); or may have been extraordinary for some other reason. Singular extremes could also have been due to exaggeration or incorrectness in reporting. The right way for us was to look for maximal effects that were not isolated extremes standing far out from all other effects at the same place. We disregarded any singular large building-damage for intensity assessment at a place where shaking obviously was moderate (see also EMS, pages 27-28). A scenario where, for example, "no other damage occurred except that the church spire broke", even though the shaking was moderate, was reason to assign a lower intensity, if applicable, accompanied by a comment describing the singularity. Notably for historical earthquakes, however, it often remained a discretionary decision whether the report of an individual case of large damage could be included or should be downgraded or disregarded for intensity assessment (see also e.g. Hough, 2013).

It has been postulated that, in an ideal case, the *occurrence-probability distribution of building damage* is, for a given IDP place, intensity, and vulnerability class, an almost normally (Gaussian like) shaped curve about the mean damage grade, except for the "pile-up" effect near the lower and upper bound of damage (with reference to EMS, Figure 4-1 on page 60, and pages 58-60). Intensity is derived from the highest, as well as possibly from the second-highest, damage grade observed for a particular vulnerability class with regard to EMS-quantities (EMS, pages 17-20), and excluding singular extremes (as above).

Similarly, it can be conjectured that, to some extent and for limited parts of the intensity scale, also the strength of macroseismic effects on ordinary objects and on people may follow a quasi-normal occurrence-probability distribution, ranging from minimal to median to maximal effects that are observed for a particular IDP (except near both ends of the scale or scale segment because of "pile-up" or saturation, accordingly); an idealized example distribution of the expected *occurrence frequency of the strength of macroseismic effects* for an IDP, with regard to EMS-quantities, is schematically sketched in Figure 1.

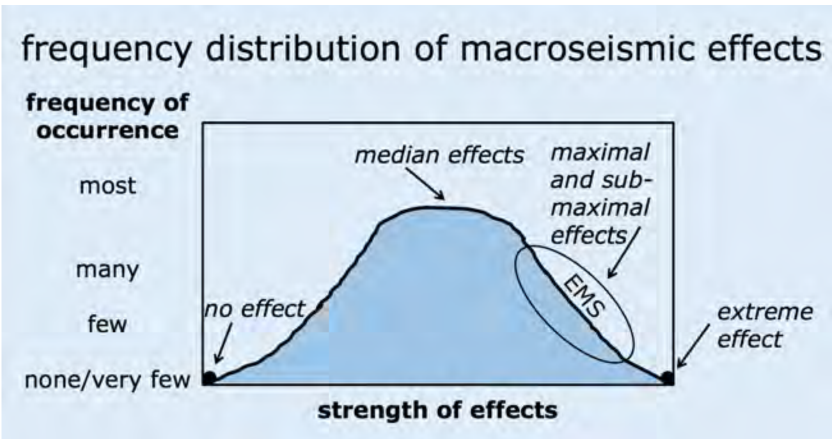

Figure 1. Sketched example of expected occurrence-frequency distribution of the strength of macroseismic effects for an IDP (within the IDP place for the particular earthquake). IDP intensity (EMS) is assessed from effects at the upper tail of the distribution curve. Further explanation is given in the text.

Again, IDP intensity is assessed from the maximal, as well as possibly from the sub-maximal, effects at the upper tail of the distribution curve, taking respective quantities into account. Obviously, given this distribution, an IDP intensity assessment based on the effects that occur with the highest frequency (sometimes referred to as being the "representative" ones) would quite likely be too low, and an assessment based on effects at a randomly selected single site within the area of the IDP place would hardly be relevant. In practice, a detailed distribution can be obtained in cases of high-quality IDP data sets only.

2.2. Diagnostics

2.2.1. Suitable diagnostics

What are suitable *sensors* and *diagnostics* for assessment of intensity (EMS, pages 21-22)? All features that by and large linearly scale with intensity are suitable to be used as indicators ("diagnostics"), at least in parts of the scale. Up to intensity 6 EMS, one of the best type of diagnostics simply is the percentage of people (the "sensors") that have felt the earthquake. Situations where observers are indoors, outdoors, or sleeping are differentiated by the EMS scale (see, however, Sbarra et al., 2014). For intensities of 6 EMS and higher, buildings are generally the best sensors, and building damage is the best diagnostic if taken as the quantities of buildings of a particular vulnerability class that suffered particular damage grades at the respective IDP place. Observations and diagnostics are never complete, though. Hence, the best way of intensity assessment is that of a *pattern matching* between the observations (i.e. "the data") and the scale (i.e. "the model") and thus determine the best fit in each case (EMS, pages 27-28; Musson, 1998a; and others).

2.2.2. Weak diagnostics

Any building damage that is not directly caused by seismic ground shaking should according to the EMS scale not be considered for intensity assessment (EMS, page 24). Nevertheless, in cases of sparse information we did consider some other earthquake-related effects, described in the following, offering *weak diagnostics*.

Weak diagnostics, in the aforementioned sense, may have been derived from building damage that was not due to ground shaking but due to dislocation of building foundation because of non-reversible, i.e. permanent, *earthquake related ground movement* (e.g. ground dislocation, subsidence, spreading, tilting, sliding, etc.). We noted earthquake-induced permanent changes on the ground surface in any case, at least in form of a "ground-flag" to the IDP. Likewise, weak diagnostics could have come from *geotechnical damage* resulting from such permanent ground movement (e.g. base failure, breaking of subsurface pipes, cracks in embankments and pavements, etc.).

Furthermore, we regarded some *effects in the natural environment* related to the earthquake as potentially representing weak diagnostics. Such effects in nature were, for example, hydrological anomalies (changes of springs, wells, ground water, etc.), anomalous waves in lakes or basins (seiches, etc.), cracks and fissures in the ground, liquefaction, slope instabilities (landslides, rock falls, etc.), shaking of trees and bushes, etc. (see EMS, pages 95-98; Vogt et al., 1994; and others). Effects in the natural environment, however, are more favourably measured on the *Environmental Seismic Intensity Scale* (abbreviated: ESI; e.g. Michetti et al., 2007) and were, for the intensity range below 9 EMS and in presence of "ordinary diagnostics", not regarded essential for assessment of intensity in this project.

With care and restrictions, we did also use some reports of *damage to exceptional buildings* (towers, freestanding walls, fortifications, bridges, dams, etc.) and to *monumental buildings* (palaces, castles, large churches such as cathedrals, halls, etc.) as constituting weak diagnostics, even though these are not buildings listed for standard EMS intensity assessment (EMS, pages 29 and 53, etc.). We were particularly aware of the danger to overestimate intensity from this sort of damage (see e.g. Graziani et al., 2015). Damage to monumental buildings, on the other hand, was the sort of damage preferably reported in historical times. In view of the generally sparse information from historical earthquakes, we could not completely exclude it from the assessments; we made exceptions if it was accompanied by comparatively coherent other observations. If it was the only information for an IDP, however, a favourite choice was to merely assign a "damage-flag". A particular feature that had to be paid attention to is that damage to monumental buildings to a greater extent results from a lower frequency band of ground motion (see e.g. Camelbeeck et al., 2014). If churches and halls were just of small size, we generally did not classify them as monumental buildings. Caution was demanded, though, if damage at several places in the region had exclusively been reported from church towers, for example.

The *twisting and rotation of objects* (for example gravestones, monuments, etc.) was considered typical for earthquake damage scenarios on the one hand, but proved less suitable for intensity assessment on the other (e.g. Lombardi et al., 2016). The same held for *falling of roof tiles*. – *Falling of elements of parapets, claddings, architectural decorations* (pillars, statues, figures, etc.) from the façade or from the top of buildings was even more difficult to evaluate than that of roof tiles, as the building settings were more divers. A civil engineering study on this topic has been published e.g. by Rudisch et al. (2016). A notable example in the catalogue is the incident in the November 16, 1911, earthquake with epicentre at Albstadt, SW-Germany, where the large stone monument of the imperial eagle was thrown down from the top of the main post office at Konstanz, SW-Germany, in about 60 km epicentral distance (IDP intensity at Konstanz was assessed as 7 EMS from the total of observations there).

Some of the aforementioned diagnostics are discussed as "special cases" in section 2.6. We tried, with caution, to make use of weak diagnostics in complementing other observations or, at least, for assigning a lower limit of intensity. A last resort to parameterize weak information was just using a "flag" substituting intensity (see section 2.7.).

2.2.3. Frightening earthquakes

The personal judgement of a witness or author whether an earthquake had been experienced as *slight, moderate, or strong shaking* turned out to be a weak diagnostic as well, even though it directly points to the meaning of intensity. The reason was that, in our opinion, such rating was per se rather subjective and, in general, inconsistently used. It sometimes also seemed to have been intrinsically linked to the individual sensation of fright.

In the same way, we found the extent to which earthquakes had *frightened people* in historical times to be rather subjective, and hence rather unreliable for assessing intensity (accompanying reports of how many people had been running outdoors were seen to be more objective, though).

When earthquakes in SW-Germany were mentioned in older historical sources, the incidents often seemed to have been termed "frightening" out of habit. A common way of speaking about earthquakes was that of "ein schröckliches Erdbeben", meaning "a terrible earthquake". Earthquakes apparently scared people in general, not necessarily because shaking was strong but merely because even a moderate one was a rare and disquieting experience in SW-Germany. Various historical theories "from Aristotele to Kant" (Oeser, 1992) about the origin of earthquakes, searching for natural causes inside the earth instead of a religious explanation as an "act of God", could not relieve the general fear. Particularly before the Age of Enlightenment, an earthquake was frequently seen as a supernatural event, a *miraculous sign* (prodigium, "Wunderzeichen"), as God's warning ("Menetekel"), anger, or punishment, and eventually as a forerunner of something worse (see e.g. Gisler, 2003; Schwarz-Zanetti & Fäh, 2011; Hammerl, 2017; and many others). The contemporaneous writer himself may have had a mindset, belief, or even intention that favoured the report of "fear and fright". The frightening effect actually related to intensity was hard to assess for us, as frightening, historically, seemed to have been more dependent on mental, cultural, social, and religious factors than on earthquake intensity; hence, we used it, if at all, as a weak diagnostic only.

Similarly, we could hardly interpret the reported *duration of earthquake shaking* in terms of earthquake parameters, since shaking durations in historical times often seemed to have been exaggerated. Reports ranged from the "duration of a Lord's prayer" to "several minutes". Eventually, an earthquake was even said to have "lasted for hours", hence probably was confused with the following aftershocks.

We also found that the *behaviour of animals* during earthquake shaking could not easily be related to intensity. Frequently, domestic animals were reported to have shown frightened reactions at lower intensities than is suggested by the EMS scale. Hence, we disregarded the EMS-rating of animal reactions.

2.2.4. *Unsuitable diagnostics*

A vast number of *meteorological and astronomical observations* during earthquakes have been reported in historical documents, such as wind, precipitation, air pressure, temperature, phases of the moon, fall of meteorites, and several other. We disregarded all these for intensity assessment as there were no proven physical relations to earthquakes and intensity. Yet, we usually noted the observations in a comment, as well as concurrent events of other kind.

Observations of *earthquake sounds* and *earthquake lights* we did not use for intensity assessment either (the latter are poorly understood anyway) but rather described these acoustical and visual effects in a comment to the respective IDP and attributed a "sound-flag" and a "lights-flag", if applicable.

In historical sources we found reports of observations of *visibly swinging walls or towers*; observations of this kind could, for the earthquakes evaluated in this project, not justify high intensities on its own. We rather suspected that such observations could have been caused by an effect of motion of the observers eyes, if they were not just pure imaginations triggered by excitement. In a similar way, we decided in cases of reports of e.g. "waves seen on firm ground".

The number of *human fatalities* and *injured people* in an earthquake was, albeit correlated in general, regarded not to be related to intensity in a way to allow assessment of intensity without further constraints (see e.g. Coburn et al., 1992). An example taken from the region is the 1356 Basel, Switzerland, earthquake (e.g. Fäh et al., 2009).

Finally, we excluded all "secondary damage" effects (subsequent damage following the primary one, see section 2.6.9.) from intensity assessment.

2.3. Damage grades

For intensity assessment in the damage part of the EMS scale (i.e. from 5 EMS upwards) earthquake damage to buildings is considered according to *damage grades* (see EMS, pages 24-25). The EMS-classification of damage grades ranges from grade 1 (lowest damage grade) to 5 (highest damage grade). In simplified terms, damage grade 1 is for negligible to slight damage, grade 2 for moderate damage, grade 3 for substantial to heavy damage, grade 4 for very heavy damage, and grade 5 for destruction; a distinction is made between structural and non-structural damage (EMS, pages 15-16). For the relevant provisions of damage grades we refer to EMS.

In principal, the damage grade may change from one house to the next at the same IDP place, even with unchanged vulnerability class; thus, damage to one randomly selected house is not decisive for IDP intensity (see section 2.1.3.).

We were aware of the problem of *pre-damaged or weakened buildings*. Damage from previous earthquakes had to be excluded as far as possible (see section 2.6.1. about earthquake series). We also attempted to distinguish between shaking as the relevant cause for building damage on the one hand and shaking that constitutes a kind of "triggering effect" for building damage, whereby deficits in construction, material, or maintenance were likely to actually be the relevant causes, on the other hand. These problems are addressed also in the context of building vulnerability.

Determination of *damage grades from historical sources* was particularly difficult, as damage descriptions were rarely detailed to the needs of the EMS scale and almost no pictures were available. Therefore, the assessment of damage depended on text and wording. The vocabulary had been different, though; hence, the meaning of terms as "damaged", "destroyed", "ruined", "collapsed", etc., as well as "much", "large", "great", "terrible", etc., or even respective superlatives, in historical documents was not necessarily the same as in modern times or in the EMS scale text. For assessment of damage grades from historical accounts, historical criticism had to be applied and inferences had to be made from the general context (see e.g. Musson, 1998b). We took care to avoid any overestimation of intensity due to reports of singular damage, suspected exaggerations or generalisations. A reliable intensity value could be assigned only if historical sources included sufficiently detailed information about the damage.

In general, an error in building damage being wrong by one grade may result in an error of intensity of one degree of the EMS scale. We nonetheless felt that, in comparison of sources, IDPs, and earthquakes over several centuries, our assessed intensities were not grossly over- or underestimated due to systematic errors in damage grades.

2.4. Vulnerability classes

2.4.1. General remarks

For intensity assessment in the damage part of the EMS scale (i.e. from 5 EMS upwards) earthquake vulnerability of buildings is considered according to *vulnerability classes* (see EMS, pages 31-49). The EMS-classification of building vulnerability comprises four main groups: masonry, reinforced concrete (abbreviated: RC; possibly with some level of earthquake-resistant design, abbreviated: ERD), steel, and wood; the structures (buildings) are differentiated into six vulnerability classes ranging alphabetically from class A (highest vulnerability) to class F (lowest vulnerability). According to EMS, in simplified terms, class A is the most likely vulnerability class for adobe (earth brick), rubble stone, and fieldstone masonry; class B for simple stone masonry and unreinforced masonry with manufactured stone units; class C for massive stone masonry, unreinforced masonry with RC floors, and RC frame / RC walls without ERD; class D for reinforced or confined masonry, RC frame / RC walls with moderate level of ERD, and timber structures; and class E for RC frame / RC walls with high level of ERD and steel structures (with reference to EMS, page 14). Strengths and weaknesses of a building may change its vulnerability class within specific ranges (EMS, pages 14 and 47-48). The lower the vulnerability the higher is the *earthquake resistance* of the buildings (EMS, pages 33-34). Class F is for structures of the highest earthquake resistance due to the incorporated design principles (EMS, page 32). For the relevant provisions of vulnerability classes we refer to EMS.

Because of lack of information we mostly could accomplish the determination of vulnerability classes, particularly for historical earthquakes, in a general and presumptive way only. We distinguished different time periods.

2.4.2. Vulnerability in different time periods

Tyagunov et al. (2006) have given an overview over vulnerability classes of the recent residential building stock in Germany. Based on this publication, we estimated *for the second half of the 20th century* that vulnerabilities of residential buildings in SW-Germany were essentially represented by the vulnerability classes A to D and were, generalized, predominantly of class B and C, with a smaller fraction in class D, and a very small one in class A. Notably, in communities up to 3,000 inhabitants most buildings were classed as B, whereas in towns starting from 30,000 inhabitants most were classed as C (Tyagunov et al., 2006). As these findings provide just a general vulnerability composition, they could only be applied in a generalised way. Beginning with this most recent time period, we developed a tentative picture of building vulnerabilities in earlier times.

For the first half of the 20th century, we estimated that the general distribution of vulnerability classes from the second half of the century, as described above, was shifted a little bit towards higher vulnerabilities, such as that there were fewer C- and D-class buildings and in turn more of class B. The reason for this was seen, among others, in fewer RC buildings on the whole and, particularly also, fewer RC floors in masonry buildings and more wooden floors accordingly.

For the period from the end of the 19th century backwards in time to about the 16th century, we found very little information about historical building techniques and architectural history in SW-Germany from that earthquake resistance could be derived. Moreover, the EMS vulnerability classification is not specially adapted for historical buildings (see, however, EMS, page 51). On the whole, we regarded the main part of the residential building stock in SW-Germany for this time period to have been of masonry type and half-timbered structures, respectively, to a smaller part also timber structures; we tentatively estimated that the general distribution of vulnerability classes was again shifted to higher vulnerabilities as compared to the first half of the 20th century, but again not very much so. If going back in history, we assumed that the portion of A-class buildings was, on the whole, increasingly larger, partly because of lower structural engineering standards and poorer economic conditions. At times, high vulnerability could also have been related to wars and crises, for example. In general, however, the *sustainable material* that had commonly been used for buildings in SW-Germany and the *good workmanship* at large still spoke in favour of a majority being of vulnerability lower than class A. Houses had been built to resist wind and snow, particularly also in the countryside and in the low mountain ranges, which implied a basic resistance against earthquakes as well. A robust design, high-quality building materials available nearby (mainly brick, stone, and wood), and a good state of maintenance and repair had been sought, as the quality of the houses reflected the reputation of the people and the houses ought to be used by subsequent generations as well. The number of storeys had generally been low, the openings small, and the ground plans and structures fairly regular. – Compound constructions using wooden framework (*half-timbered structures*, "Fachwerk"), with infill panels of stone, brick, wattle and daub, or other, had widely been in use. A collection of almost 700 painted "town views" in the duchy of Württemberg was prepared by Kieser in the years 1681 to 1686 (Kieser, 1681-1686). The "Kieser atlas" pictures showed that half-timbered masonry constructions had at that time dominated for residential houses in towns and villages of the region. The atlas also showed the size of each settlement. We assumed a favourable performance of half-timbered buildings in earthquakes, which, however, extended primarily to the bearing wooden structure and therefore rather applied to high damage grades (heavy structural damage or collapse) but not to low damage grades (related to cracks in masonry infill, cladding, plaster, etc.). See also EMS, pages 48-49, as well as pages 40-42.

The considerations above led us to assume that, for the purpose of this project, the majority of residential buildings in SW-Germany in the time period from about the 16th to the end of the 19th century can be estimated to be of vulnerability class B, with minor parts in class A and class C, and some minor portion even in class D. A differentiation between urban and rural areas was considered in individual cases if possible. In conclusion, we were aware that our picture of historical building vulnerability is generalized and hypothetical. Much more research is necessary to better determine building vulnerability in the historical time period.

For the medieval time period (the Middle Ages), building vulnerabilities have, in a general way, not been evaluated in this project.

2.4.3. Vulnerability assumptions

In practice, building damage should be linked to the actual vulnerability of the buildings in question. If the vulnerability of the damaged buildings was known, we could properly take it into account. If it was not known, as usually was the case in the historical time period, and if no better estimate could be made, we assumed a *notional vulnerability* class B for intensity assessment of residential buildings in SW-Germany for all time periods after the Middle Ages (see also EMS, pages 48-51). If there were some indications to one or the other side, we rather considered notional "intermediate classes" B-C in the 20th century and A-B in the historical time range on a case-by-case basis. For the medieval time, in particular, we decided on vulnerability classes individually. Non-residential buildings had to be treated separately and also case-by-case.

If buildings are pre-damaged or weakened, for instance due to preceding strong earthquakes, or due to acts of war, bad state of maintenance and repair, or simply age and dilapidation, it can be seen as a *conditional increase of building vulnerability* with regard to the original vulnerability. We tried to handle these cases individually (see also sections 2.3. and 2.6.1.).

We were aware that damaging earthquakes affect the higher-vulnerability buildings in a stronger way than the lower ones (see also EMS, pages 47-48 and 51). Thus, for IDP cases of a small number of damaged houses at a particular place and without knowledge of their actual vulnerabilities, it could be suspected that the damaged houses were just those with the *highest vulnerability locally* (hence e.g. rather class A than B or better). As, on the other hand, a few ordinary houses of vulnerability class A, respectively also houses in poor condition, had quite likely not been in the focus of historical reports, we did not take this consideration as a reason to a priori change the general rule. For the modern time period, on the other hand, vulnerabilities of damaged buildings were much better known, though.

In general, an error in building vulnerability being wrong by one class may result in an error of intensity of one degree of the EMS scale. The dependence of intensity on vulnerability class is of the same order as on damage grade. Since, in general, it was easier to determine damage grades and quantities than vulnerability classes, vulnerability was seen as the least known and hence most delicate parameter in the assessments. We nonetheless felt that, applying the assumptions above, our assessed intensities were best estimates, for the time being, also in regard to uncertainties of vulnerability class.

2.5. Data restrictions

2.5.1. Poor data

Documentary sources reporting about historical earthquakes tended to be brief and fragmentary, and, with respect to the seismological information contained, frequently even sparse, vague, ambiguous, and contradictory. Obviously, reports about earthquakes were in historical times rarely written for seismological purposes but rather for social ones; hence, the seismologically useful information content may have been small even in a lengthy treatise. The choice of what was important to be written down in case of earthquakes changed during the centuries. A different mentality was reason for a different kind of awareness and also a different *style of writing* (e.g. Guidoboni, 2000). The purpose of writing may even have been anything else but reporting facts. The "Zeitgeist" has changed then in the 19th century when many reports began to consider seismological aspects out of their own interest.

Particularly for historical accounts, quantities, damage grades, and vulnerability classes, as specified in the EMS, had mostly to be inferred from the context or conjectured by way of comparison. We were very cautious in dealing with IDP intensity assessments based on *singular observations*, for example, if we only knew a single person's perception or a single building's damage description (see also EMS, page 28). For historical earthquakes, we could, nevertheless, not completely omit all *poor-data* IDP cases. We made exceptions if circumstances suggested that a singular observation reported can be understood as an example standing for similar perceptions or comparable damage at the same place as well. Particularly, the damage to the village church could have been mentioned exemplifying damage in the village as a whole. Whether this had probably been the case or not, we had to judge from the context. Ultimately, we tried to assess IDP intensities from poor information also, but rated them as being uncertain (see section 2.8.4. about IDP quality).

Such exceptions were justified, however, just to a certain limit. In cases of *very poor information*, we generally did not assign an intensity value but a "felt-flag" or a "damage-flag", if possible (see section 2.7. about substitutes for intensity). We avoided any inappropriate parameterisation of vague historical information but stored such information in textual form.

If, moreover, an earthquake was documented by one single and poor-data IDP only, the situation was even more precarious for the question of certainty of event type ("has it actually been an earthquake?"), let alone for the question of epicentral location and intensity. All such "one-IDP-events" in historical times are encumbered with uncertainty (e.g. Musson, 1998b).

2.5.2. Missing information

For the lower part of the scale (below 6 EMS), intensity is assessed mainly from the severity of earthquake shaking as perceived by people; for the upper part, intensity is to be based on damage. We generally assigned IDP intensity 6 EMS or higher only if building damage had occurred; this applied for modern-time earthquakes in any case. A small exception to this rule were some historical IDPs assessed as 6 EMS where shaking believably had been very strong but *damage was not mentioned* ("no evidence"). In historical context it seemed possible, though, that strong shaking as such and its various effects on people and objects were seen to be more relevant for reporting than a few detached roof tiles or cracks in ordinary houses, for example. The latter may have been unknown to the writer also.

We generally tried to avoid concluding from any *missing information* that something, we would like to know but was not mentioned in the sources, actually had not happened (see also EMS, pages 28 and 52; Musson, 1998b; and others). Especially in the historical past, there may have been many reasons for omitted information, missing reports, or just gaps in knowledge. In some cases, however, no mention of damage from authoritative sources could be used to, at least, disprove a high IDP intensity.

2.5.3. *Negative reports*

Negative earthquake reports ("Fehlanzeigen", "état néant", "nil returns", etc.) usually stood for the message "nothing to be reported". Negative reports were frequent in 20th-century questionnaires collectively reporting for an entire village or town, since the return of the questionnaire form was asked for even at the edge of perceptibility. We interpreted such negative reports in collective community-questionnaires cautiously in the sense of "the local authority / the reporter is not aware of the earthquake being felt at this place". We generally did not translate negative reports of this kind into intensity 1 EMS (which is for "Not felt, even under the most favourable circumstances"; EMS on page 17) without careful review, even if the report literately read "the earthquake has not been felt here" (which often more likely meant "has not been felt here to our knowledge"). In many such cases, particularly near the presumed edge of the area of perceptibility, an IDP that came with a negative report in the first place turned out later to be probably of intensity 2 or 3 EMS, occasionally it could have even been 4 EMS.

Estimating the outer *edge of perceptibility* was difficult as intensities 1 and 2 EMS can hardly be discriminated by conventional questionnaire surveys, let alone by historical research. Intensity 2 EMS is, by definition, scarcely felt, i.e. felt by less than 1% of the people under special circumstances (EMS, page 17), and many of them will have ignored or quickly forgotten about the tiny sensation. Even news media today are unlikely to report about an intensity as low as 2 EMS. The situation might change with IMQ (see e.g. Boatwright & Phillips, 2017), though, or with reports focussed on high rise buildings, for instance. For good reasons, the traditionally determined "perceptibility radius" is better defined referring to 3 EMS rather than to 2 EMS.

Overall, we were very careful in evaluating any "negative evidence" for the perception of shaking. Negative reports in the sense that the earthquake has been felt but building damage did not occur we regarded to be more credible and significant, though.

2.5.4. *Extrapolating information*

In general, we also avoided to "extrapolate" a diagnostic that is specified in the EMS scale for one intensity degree only to a higher or lower degree, if this was not supported by empirical evidence. For example, "In a few cases window panes break" is a diagnostic for 5 EMS (EMS, page 18). "Many window panes break" is not explicitly mentioned in the EMS scale text but could point to an intensity higher than 5 EMS. Which intensity was appropriate therefor, had to be decided case-by-case. – Some diagnostics, moreover, show a *saturation effect*. If, for example, a report read "felt indoors by all", we did not take it, on its own, as an evidence that the intensity was higher than 5 EMS.

2.5.5. *Fake earthquakes*

Particularly in historical sources, we encountered a number of reports describing "earthquakes" that finally had to be classified as events that are not tectonic earthquakes in the seismological sense. This, first of all, resulted from the habit of some historical authors to use the term "earthquake" for any sudden shock or vibration. In many such cases, we had to deal with observations during a storm, particularly a *thunderstorm*, that had been associated with an earthquake or even named as such. IDPs of this kind ranged from virtually 3 to 5 EMS. Only careful interpretation of the sources led us to recognise such an event as a *fake earthquake*. Decision about the type of event came from the kind of effects reported (e.g. "rattle", "tremble", "bang", etc. in case of a storm) and, more convincing, from evaluation of several IDPs of the same event. In particular, a "flag" for "earthquake evidence" was routinely assigned to IDPs indicating whether the reported effects for themselves, at this place, suggested that the event was a tectonic earthquake or not. – Similarly, also several occurrences of *landslides*, and even *meteorite falls*, had erroneously been classified as earthquakes in some earlier publications, which we could correct in this project. Most prominently, we found the event in 1588 at Singen (Hohentwiel), SW-Germany, to be definitely not a damaging earthquake, as it had been claimed before, but a large landslide.

Many fakes simply arose from dating errors, erroneous locations, transcription errors, confusions, misinterpretations, and hoaxes. We documented fake earthquakes, and included them into the database (flagged as "false/fake"), to prevent their reappearance in future earthquake catalogues as "zombies" (e.g. Musson, 2005).

2.5.6. Lost earthquakes

We have to assume that in the historical past many earthquakes had been documented of which the information is no longer available today or, at least, has not been found yet. These "forgotten earthquakes" are missing in the catalogue, unless they are recovered by future research. The research done in this project yielded 134 "new" earthquakes, i.e. earthquakes that had been unknown to modern catalogues before. These earthquakes, almost entirely, occurred from the 16th to the 19th century; none of them had an intensity of more than 6 EMS.

Earthquake historiography is strongly affected by other contemporaneous events. If earthquakes occurred during natural disasters of larger size, during times of war (e.g. The Thirty Years' War 1618 to 1648), famine, epidemic plagues, etc., nothing at all may have been written down about them. In historical times, smaller earthquakes were probably often not recognized by chroniclers or, if so, were regarded not to be relevant for any writing. A particular consequence of *lost earthquake information* is the increasing incompleteness of IDPs and earthquakes as we go back in historical time (see section 2.9.1. about completeness).

2.6. Special cases

2.6.1. Observations during earthquake series

Assessing intensity, special caution is warranted in cases of *earthquake series* (seismological terminology distinguishes foreshocks, mainshocks, aftershocks, multiple shocks, etc., and sequence, cluster, swarm, etc.), when earthquakes follow each other rather closely in time and space. This regards to both building damage as well as perception of shaking.

If the time interval between successive strong earthquakes had been short and damage could not be assigned to a particular earthquake in the series (see e.g. Camassi et al., 2008), an individual assessment of intensity was not possible. Building vulnerability, moreover, may have been increased for buildings affected by preceding damaging earthquakes even though structural damage may not have been obvious (see also EMS, pages 25 and 41, etc.); in such cases of *pre-damaged or weakened structures*, intensities in subsequent earthquakes could have been overestimated. Even if *damage progression* had been surveyed, the problem of *vulnerability increase* in subsequent events remained. Often only a kind of "cumulative assessment" of damage and intensity was possible, but not an individual one (compare e.g. Graziani et al., 2019). The sequence pattern of damaging earthquakes in a series can also be very complex (e.g. Guidoboni & Valensise, 2015; Rossi et al., 2019; Azzaro et al., 2020; and others). – An example taken from the SW-Germany catalogue is a series of damaging earthquakes in 1943 with epicentres in Albstadt, SW-Germany; a strong foreshock and the mainshock occurred within one month, on the 2nd and on the 28th of May 1943, respectively, reaching IDP intensities up to 7 and 8 EMS. In this case, we tried to assess intensities of the two earthquakes individually.

On the other hand, also people's perceptions and corresponding reports are strongly influenced during a series of felt earthquakes; *individual and public awareness* is generally intensified. Within long lasting series in SW-Germany we encountered amplified perception by *sensitisation*, depending on the sequence of events and intensities, earlier seismic history, perceived seismic risk, opinion-forming, individual attitudes, etc. (see also e.g. Cucci & Tertulliani, 2007). – In rare cases, there was also a tendency towards diminished perception because of *habituation*. An example for the latter is the earthquake series 1822/23 with epicentres near Freudenstadt, SW-Germany, comprising almost 100 felt events within about one year and maximum intensities of up to 6 EMS. A report from the Freudenstadt series read, "We had an earthquake as usual", without many details. Newspaper reporting had ceased to some extent as there had been "no news" about "the earthquakes" any more.

There inevitably are historical earthquakes in the catalogue that are *intrinsically cumulative* consisting of closely successive events that could not be distinguished on the basis of the available reports. Any suspicion, coming from the sources, that an earthquake had in fact been a double, triple, or multiple event was noted in a comment.

We did not apply a rule of thumb to solve the problems of assessing intensity within earthquake series. We took, however, all constraints into account, mostly case-by-case. If in doubt, we just assigned a "felt-flag" or a "damage-flag", respectively. We tried, in any case, to acquire earthquake series data as completely as possible.

2.6.2. Earthquakes at night

On a long term average, about half of all earthquakes should occur at night. We nonetheless regarded an earthquake during night time as a case that demanded attention. Being *woken up by an earthquake* is a simple and objective characteristic for intensity. Hence, the information on how many sleeping people were woken up by the shaking is a particularly good type of diagnostics in the lower intensity range. In this respect, we consistently evaluated the 20th-century macroseismic questionnaires of earthquakes at night. Unfortunately, the quantity of people that had been woken up was rarely specified. With some assumptions, however, this quantity could be derived from the overall quantity of people that were reported to have felt the earthquake (indoors). As a result of this study, we assumed that if the earthquake had been "felt by many" (in the sense of EMS-quantifiers) during main sleeping-hours (i.e. between about 1 and 5 o'clock at night), this pointed to 5 EMS, instead of 4 EMS outside this time window.

2.6.3. Earthquakes during mass

Historical earthquakes that had occurred *during church service* were seen as being special cases in that the perception of shaking seemed to have been intensified. Occasionally, also panic reactions had occurred due to the special circumstances. We interpreted these scenarios in a historical context.

2.6.4. Ringing of church bells

Also special cases in the historical past were those when bells in church towers started to ring caused by earthquake shaking. *Ringing of church bells* was included in some earlier intensity scales, but had, to our knowledge, just occasionally been reported in the sources. Historically, it surely was a remarkable effect and should hardly have failed to be heard and noticed. We regarded church bells to be bad sensors for assessing intensity inasmuch as spontaneous church-bell ringing in case of earthquakes depended heavily on several other factors, as for example on dominating frequencies of seismic waves and resonance of the church tower, design of the bell system, and unknown technical details of ringing mechanism and practices (locked, hammered, or "pre-set" bells, etc.). An engineering study about the topic has been published by Blakeborough (2001). We assumed that ringing of church bells, if it had occurred, could be seen as an indication for a lower limit IDP intensity 5-6 EMS (see e.g. Hough et al., 2000, for a few observations). Notably, there were several cases in history when strong distant earthquakes caused church bells ringing over a large area in SW-Germany.

2.6.5. Falling of roof tiles

Detachment of roof tiles is an earthquake effect listed for damage grade 3 in the EMS scale (EMS, page 15). We did not follow this classification as we thought that, for SW-Germany earthquakes, roof tiles started to slip and fall in situations that were closer to damage grade 2 or even grade 1 of masonry buildings (let alone that tiles used to fall during storms also). Falling tiles have, on the other hand, little to do with building vulnerability as a whole or damage to the main part of the building, as was confirmed by pictures of heavily damaged buildings with almost unaffected roof tiles on top (for example from several European earthquakes of the last decade). We estimated roof tiles not to be particularly good sensors of intensity anyway, since *detachment and fall of roof tiles* in case of earthquakes strongly depended also on several other factors, as for instance the dynamic response of the building top, the steepness of the roof, the type of tiles, how firm the tiles lay on the roof battens and were attached to each other, the state of repair in general, whether there was a snow grid, etc. According to Brendler et al. (2006) horizontal acceleration alone will hardly lead to detachment and fall of roof tiles, vertical acceleration was seen to be relevant. We usually considered roof-tile damage as an indication for an IDP intensity of at least 5-6 EMS if some tiles had detached respectively fallen from the roofs of several houses at the place.

2.6.6. Damage to chimneys

Earthquake damage to chimneys in SW-Germany has widely been reported, particularly as it has been (and still is) enquired by questionnaires. Chimneys had even been used as special sensors of intensity in older studies (e.g. von Schmidt & Mack, 1912), and chimney damage has since been regarded to be a favourite diagnostic. We found empirically that IDP intensities 6 and 7 EMS could be derived, or at least consistently been supported, from surveys that had focussed on quantities and grades of chimney damage. We disregarded damage to factory chimneys, however, for assessing intensity. – In the following, only residential masonry chimneys are considered. Fragility of these chimneys depended, for example, on design, height (i.e. height above the roof), material, age, state of repair, and further on the way the chimneys were integrated into the structure of the buildings (see e.g. Maison & McDonald, 2018). We, nevertheless, took damage to 20th-century un-reinforced brick-built rooftop-chimneys of ordinary height to be an indication for damage grade 2 or 3 of masonry buildings (EMS, page 15), depending on how badly chimneys were damaged. We attributed a damage grade 2 for reports of "cracked", "partly collapsed", "partly broken", "damaged", etc. chimneys and a (minimum) damage grade 3 to cases where chimneys had been reported to have "fractured at the roof-line", "fallen off the roof", "collapsed", "been broken", "been destroyed", etc. As there was little dependence of chimney damage on the overall building vulnerability, damage to chimneys could be considered separately. If assessing intensity solely from chimney damage, we generally assumed a fictitious building vulnerability of class B (with results proven empirically).

2.6.7. Damage to freestanding walls

In case of historical earthquakes, there were a number of reports of *damage to freestanding walls*, as for example town walls, graveyard walls, garden walls, etc. *Non-freestanding walls*, as retaining walls, embankment walls, fortification walls, etc., were occasionally also mentioned in the sources. All these kind of walls are not buildings, or parts of buildings, in the sense of the EMS vulnerability classification. In looking to archeo-seismological studies, however, we nevertheless could come to some cautious estimates regarding lower limits of intensity (generally about 6-7 EMS).

2.6.8. Perceptions in and damage to tall buildings

Intensity assessments from *observations in tall buildings or on higher floors*, respectively, have been discussed by many authors, some also with regard to earthquake magnitude and distance (e.g. Sbarra et al., 2012 and 2015). In SW-Germany, this discussion goes back to Lais (1914). We followed the EMS recommendation to discount all perception reports "from observers higher than the fifth floor" for assessing intensity (which we interpreted as the fifth floor above the ground floor at street level; EMS, page 29). As an exception to this "floor rule", we may have assigned 2 EMS from perceptions on higher floors at IDP places where no other observations were available because shaking was very weak (see EMS, page 29). As far as observations from watch or church towers were concerned, we treated these on a case-by-case basis according to the height of the tower. – As for *damage to tall buildings*, we took such damage into consideration only as a weak diagnostic, if at all. In many such cases, just a lower limit of intensity could be derived thereof.

2.6.9. Secondary damage effects

Intensity assessment should be made from building damage that is caused by the reaction of buildings to earthquake ground-shaking motion. If damage had resulted from ground movement that was not shaking but was of permanent-displacing type, we considered this in form of weak diagnostics only (see section 2.2.2.).

We excluded building damage from intensity assessment, however, that had not been caused by the aforementioned seismic actions in a direct way ("primary damage") but constituted an indirect or *secondary damage effect* ("secondary damage") mostly being caused by the primary one (for example, damage caused by building parts falling off the building, by fire or inundation after the earthquake, etc.; see e.g. EMS, page 72). Only primary damage was considered relevant for intensity. Albeit, falling building parts, parapets, chimneys, roof tiles, etc., causing damage on other parts of the building or in its neighbourhood, have been frequent earthquake scenarios in SW-Germany also (and a danger of life for people). In case of the June 27, 1935, earthquake with epicentre at Bad Saulgau, SW-Germany, a prominent secondary damage occurred as parts of the church tower at nearby Buchau fell onto the roof of the nave and thus destroyed the main part of the church.

2.7. Substitutes for intensity

In cases of very poor, contradictory, or insufficient information, serious doubts in credibility, or large uncertainties out of any reason we generally did not assign an IDP intensity but assigned an annotation, called a "flag". Well known are the *felt-flags* and the *damage-flags* (see e.g. EMS, page 58). An IDP with a flag, instead of an intensity value, may be called a macroseismic data point (MDP), if one wants to make this distinction (in this article we do not).

On the whole, we used the following felt-flags and damage-flags for macroseismic information of IDPs:

- "felt unknown" (even after enquiry, it is not known whether the earthquake has been felt at that place),
- "not felt" (should be intensity 1 EMS),
- "felt" (means higher than 1 EMS),
- "strongly felt" (probably higher than 4 EMS),
- "damage unknown" (even after enquiry),
- "no damage" (probably lower than 6 EMS, a few buildings of damage grade 1 may have gone unnoticed),
- "damage" (probably higher than 5 EMS), and
- "heavy damage" (probably higher than 7 EMS).

The flags "felt unknown" and "damage unknown" underline that respective enquiries about "felt?" or "damage?" remained unknown, even after searching for information. For historical earthquakes this is an important detail to be noted. A negative report (section 2.5.3.) was coded as "felt unknown" if there were doubts as to whether really nobody felt the earthquake at the place concerned. The damage-flags refer to damage to buildings; the felt-flags do not a priori exclude damage; the flag "felt" includes "heard only"-cases also.

In general, the flags were not assigned in parallel to intensity but as a substitute. Exceptions to this rule were flags not replacing intensity but giving additional information, for example an IDP intensity assignment of 6 EMS together with a flag "damage unknown" (could be unreported damage), or of 5 EMS with a flag "damage" (damage reported not qualifying for a higher intensity), or of 4 EMS with a flag "damage" (damage reported but disregarded for intensity), etc. If neither intensity nor flag were assigned, the case is pending.

2.8. Uncertainties

2.8.1. Probabilities

Dealing with uncertainties of macroseismic evaluations, particularly for historical earthquakes, implicit or explicit assumptions of probability play an important role. Historical earthquake evaluations are subject to many uncertainties; hardly anything is proven beyond doubt; occasionally even the existence of the earthquake itself is not certain. Hence, dealing with uncertainties of various types and sizes makes it necessary to introduce probability. Within this project, it was essential to have a common understanding of the verbal representations of probability, as several terms had been understood quite differently by the project team members.

For communicating probability in questions regarding macroseismic evaluations, we established the following simplified *scale of probabilities* for use within the project:

- "certain" for more than about 95% probability,
- "probable" for considerably more than 50% probability,
- "questionable" for roughly about 50% probability ("fifty-fifty case"), and

- “improbable” for considerably less than 50% probability with a lower cut off at about 10%, below which probability was assumed to be “negligibly small” for the macroseismic issue at hand (see also e.g. Renooij & Witteman, 1999).

The advantage over earlier procedures dealing with uncertainties was that, in this way, uncertainties were consistently quantified and included in the assessments.

2.8.2. A notation of uncertainty

In the process of assessing IDP intensity (see section 2.2.1.), we used two intensity values to denote the *range of uncertainty*: A lowermost (1) and an uppermost estimate (2) of intensity that are, on the basis of the available data, still assumed to be reasonably possible (even if “questionable” or “improbable”, according to the “scale of probabilities” above). Thereby, a reasonable range of uncertainty of IDP intensity was specified (see also Fäh et al., 2011); statistical error measures (e.g. standard deviations) were not regarded to be appropriate. The uncertainty of intensity assessment was to a large part related to *epistemic uncertainties* due to imperfect knowledge of what really happened. If data allowed, a “least conservative” and a “most conservative” scenario could be constructed, for example from combinations of the triplet “vulnerability class, damage grade, quantity” that were considered reasonably possible (see e.g. Monachesi & Moroni, 1995). These two scenarios, in turn, could have yielded the aforementioned range of uncertainty from estimate (1) to (2). – Having done this, we assigned a best-estimate intensity (3), which we supposed to be the most probable value within the range of uncertainty and was the final intensity assignment for entry into the catalogue as the IDP intensity.

We assigned historical IDP intensities jointly together within the project team. At times, the range of individual judgements of the team members also reflected part of the uncertainty. The reasons why a given uncertainty range may have been small or large are discussed below. A full evaluation of IDP uncertainties led to the overall IDP quality code (see section 2.8.4.).

2.8.3. Intermediate intensity

If the aforementioned best-estimate intensity remained undecidable between two consecutive intensity degrees on the scale, i.e. if the data fitted equally well with the lower and the higher value hence there was about the same probability for both of them, we expressed this ambivalence by assigning a so-called “*intermediate intensity*”. If, for example, the best estimate was 6 EMS or 7 EMS with approximately equal probability, the final assignment was denoted as 6-7 EMS, which means the intensity was “either 6 or 7 EMS”. This was not expression of an “intermediary degree” of 6½ between 6 and 7 in the scale (see also EMS, page 62), but was just saying that the question whether intensity was 6 or 7 EMS could not be decided. Nevertheless, in this case, we entered the number 6.5 as an *intermediate value for the IDP intensity* into the catalogue database; this number may be processed for numerical calculation purposes in later applications. – If in another case, for example, data somehow “exceeded” the description for 6 EMS, but were much less compatible with the description for 7 EMS than with that for 6 EMS, we assigned 6 EMS as best estimate being most probable. – If, in still another case, uncertainty was even higher, and intensity assignment could, for example, have been 6-8 EMS, meaning “6 or 7 or 8 EMS” with about equal probability, we mostly preferred to assign a “damage-flag” instead of an intensity value (of e.g. 7 EMS, in this example). – The examples in this section were taken from EMS (compare EMS, page 57; Musson, 1998a).

During the 20th century in SW-Germany, there even had been the habit of assigning “quarter-degree” intensities, for example “6+” standing for about 6¼, or “7-” standing for about 6¾, etc., referring to some older scale. Whenever possible, we re-evaluated the sources and assigned intensities according to the EMS scale, instead.

2.8.4. IDP quality

IDP quality, on the whole, has to be estimated starting with the sources. We rated the sources according to their *reliability* in general and to their *credibility* and *independence* for the individual case. The evaluation of sources implied various kinds of uncertainties, particularly if sources were sparse in information, “filtered” due to intention or format, or doubtful out of any other reason.

If the historical sources at hand were not *primary sources* but contained information that had been copied, cited, retold, paraphrased, or reworked from (several) earlier ones, the likelihood for alteration, distortion, or loss of original information in these *secondary sources* (occasionally also termed "indirect sources") tended to be quite large. Frequently, the distorting effect had stepwise increased in the course of time. Eventually, the original facts may, to some extent, have got lost during the passing on of information through the centuries. The larger the delay between the date of writing and the date of the earthquake had been, the more unreliable the source had possibly become (with some exceptions, though, for publications that had reviewed the event with the benefit of hindsight after a reasonably short delay, for example). We used a database attribute (the "earliest reporting date") to denote this time delay for historical IDPs, notably to serve as an indication for potential unreliability. – Similar held for the distance of the place of writing from the earthquake.

The further going back in historical time, the more the *absence or loss of primary sources* was something we had to live with. For earthquakes in the time before about the 15th century primary sources were rare, and secondary sources had to be used. When using secondary sources, we did this with a special focus on veracity.

An important bias that we encountered for IDPs from historical sources about medieval earthquakes was that reporting had been concentrated towards cultural centres and large towns. This implied that in ancient documents, urban areas had, according to circumstances of the time, been given a greater reporting attention than sparsely populated rural areas, where earthquake information had possibly even been disregarded by the chroniclers. The further back in time, the more pronounced this *attraction of earthquake information towards urban centres* had been.

We also were attentive to a possible *reporting bias* that may have come with selection and emphasis of information. Well known examples were the dramatizing presentations in historical news-pamphlets. When, for example, a rather small earthquake was reported on the front page of newspapers, this implied a special importance factor. Sometimes, the significance was further enlarged just by reworking and reprinting of local news by papers in greater distance. A possible "media bias" was described by Hough & Pande (2007) and Hough (2013) for 19th-century newspapers. – Possibly generalized singular effects and overemphasized or exaggerated reports had to be paid attention to in any case. We were particularly aware of possible biases in historical sources and, despite the critical approach we used, we had to assume that there still remained a considerable amount of uncertainty due to reporting biases inherent in the sources. We did, however, not see reasons to apply a general "correction factor" to the historical intensities assessed in this project (compare e.g. Hough, 2014). A favourite situation was, particularly for an historical case, if there were two or more independent sources for an IDP thus giving a "second opinion".

Apart from the rating of the sources, IDP quality mainly depends on the *quality of data* in the sense of the available amount of reliable and useful information for assessing IDP intensity (as outlined in this article). Additionally, we also considered uncertainties regarding IDP place and time (see also Musson, 1998a) as being part of (and potentially reducing) IDP quality. We finally condensed all appraisals regarding source(s) and information into a rating scale called the *quality code of the IDP*. This code ranged alphabetically from A (very good) down to E (very bad). It can be viewed as an overall measure of quality of the IDP. We were attentive to ensure that the IDP quality code was consistent over time, in particular over the transition from prevailing classical historical documents before about the 19th century to those thereafter, which were, to a large part, newspapers and questionnaires. IDP quality codes can be used also for weighting the IDPs in algorithms to determine earthquake epicentre and magnitude or to estimate seismic hazard from IDP data.

To illustrate the *assignment of IDP quality codes*, a few examples are given. IDP quality code A was rarely assigned, since for code A we required quantitative information about perception of shaking or building damage, including building vulnerabilities, on a sufficiently dense grid of individual sites within the area of the respective IDP place. In this way, the IDP could be "fully covered" in its areal "distribution of effects" (see section 2.1.3.) and the intensity-relevant EMS-quantities could be calculated. A rating with code A could be achieved by a detailed macroseismic field survey (see e.g. Cecić & Musson, 2004), for example. Intensity assessment from a number of individual reports or from a respective summarizing report may have lead up to IDP quality code B depending how well relevant quantities and parameters could be estimated. The 20th-century collective community-questionnaires, filled in by one person as a report for the entire IDP place, in average yielded IDP quality code C. An IDP from one individually-answered questionnaire or letter, reporting one person's perception or reporting damage to one building, could be rated with code D if the singular observation sounded reasonable and could be seen exemplary. Historical IDP quality codes generally ranged from rare B's to frequent D's. There were even IDPs with quality code E in cases of very poor data, serious doubts, or large uncertainties inherent in the source(s), which may have also included uncertainties about the respective IDP place and time. In cases of code-E intensities, however, we may have substituted intensity by a "flag" instead (see also section 2.5.1.).

Quality rating of IDPs was regarded highly important, particularly for historical data. IDP quality needed to be quantified; a simple "flag for uncertainty" (e.g. a question mark) was seen to be inadequate. It also turned out to be very advantageous for the entire catalogue, as low-quality IDP data that otherwise would probably have been disqualified could hence be kept in the catalogue with appropriate distinction. If, however, historical information could not be parameterized at all, we had room for keeping it in form of notes and comments.

2.8.5. Quality and precision

Occasionally, we noticed a kind of trade-off between *quality of data* available for IDP intensity assessment (in the sense stated above) on the one hand and *precision of IDP intensity* (in the sense of certainty of assignment of a particular intensity degree) on the other hand (see also EMS, page 58; Musson, 1998a). Unfortunately, and to our surprise, increasing quality of data did in some cases not lead to a smaller range of uncertainty of intensity, in particular did not necessarily allow us to resolve an "intermediate intensity" (see section 2.8.3.) to be finalized to a single integer value. An example is the September 3, 1978 Albstadt, SW-Germany, earthquake at the maximum-intensity IDP Albstadt-NE, where we assigned 7-8 EMS; i.e. we could not decide whether intensity was 7 or 8 EMS even though unprecedentedly dense and high-quality data (IDP quality code A) were available for this IDP (see e.g. Schwarz et al., 2005). – Sparse data, on the other hand, could have been such that, from the information available, only one single intensity degree could possibly be considered. This formally constituted a precise assignment on one hand, but a doubtful value on the other because of poor or very poor data quality (IDP quality code being D or E, for example). – Finally, if an IDP was both of low-quality data and uncertain intensity, the case may also have been solved with a "flag".

Occasionally, earthquake effects appeared to be more complex and irregular than is suggested by the EMS scale (and by the usual scheme of "distribution of effects", see section 2.1.3.). Reasons for that could be sought, for example, in anomalies of seismic waves, subsoil effects, building factors, demographic structures, etc. Precision of intensity was not improvable in some IDP cases, data quality was considered to be highly essential in any case.

2.9. Other issues

2.9.1. Completeness

Low seismicity in certain time periods may be due to lack of earthquakes or lack of sources. Hence, there is the fundamental question of *completeness*, particularly for the historical part of the earthquake catalogue. Completeness of archives is essential for completeness of IDP acquisition and, in turn, also for completeness of the earthquakes in the catalogue with respect to particular intensity thresholds. There were a number of limiting factors, among them were the completeness of documentation in writing as such, the continuity of archiving the sources, the likelihood that respective documents still exist in repositories (despite loss of sources due to destruction, disposal, disorder, dislocation, etc.), and the chances to actually identify and find the relevant sources today (see e.g. Guidoboni, 2000; Castelli, 2003; Stucchi et al., 2004; Bragato, 2018; and others). Even if number and quality of historical sources available for a particular time period were excellent, the question remained as to what extent the sources "speak of earthquakes" or "are silent".

For a regularly appearing 19th-century SW-Germany newspaper, for example, completeness of reporting earthquakes that were felt in the geographical distribution area of the newspaper could be assumed for intensities down to 5 EMS. This was not as favourably the case for many other historical source types that, for some reason or other, reported earthquakes irregularly, or only in cases of heavy damage, or refrained from mentioning earthquakes altogether. Damage to private residential buildings was often assumed to just be a private matter and was therefore not registered in official documents, in contrast to damage to public, administrative, or clerical buildings. Official sources first and foremost recorded what was relevant for official matters and frequently were silent with respect to other issues.

Overall, we felt that, through historical research done in this project, a fairly high level of potential completeness for IDPs in SW-Germany could be achieved. For a discussion of completeness of IDPs and earthquakes in the catalogue see Brüstle et al. (2021).

2.9.2. Consistency

A major achievement of this project is that IDP intensities of historical and modern-time earthquakes in the catalogue are now based on primary sources as far as possible, and are based on one and the same scale (EMS). A particular EMS intensity value, moreover, should have the same meaning regardless of the date and the place of the IDP. To some extent, systematically evaluating an extensive amount of IDP data within a tight project has been a favourable basis for the achievement of temporal and spatial homogeneity of results. As we knew that there is a possibility that intensities derived for historical earthquakes might be biased towards higher values (for reasons some of which are discussed in this article), we particularly have focussed on *consistency* in this respect. We made an effort to achieve consistency of IDP intensities and quality rating, as well as consistency of IDP coordinates, name places, calendar dates, and times of day, during all centuries to thus produce a homogeneous earthquake catalogue. A major guarantor of consistency was the consequent implementation of the guideline. In a way, the guideline also helped to minimize any personal bias or subjectivity in the team assessment process (see below).

The transition from historical to modern time, around the turn from the 19th to the 20th century, can be seen as a turning point with respect to macroseismic investigations in SW-Germany. Hence, it was of special concern for us to secure consistency of assessments for IDPs before with those after this transition. Extensive macroseismic surveys started at that time and yielded very dense IDP data sets, which never had existed before. Particularly the earthquake on November 16, 1911, with epicentre at Albstadt, SW-Germany (maximum intensity 7-8 EMS and perceptibility radius about 500 km), served as a benchmark and calibration event, as it was the first earthquake with an extensive macroseismic questionnaire survey in all of SW-Germany and beyond. The 20th-century data constitute the *main reference* on that intensity is calibrated; therefore, historical IDP intensities had to be measured in comparison with that of modern time. The EMS scale as well, through its precursor scales, is mainly based on macroseismic evaluations of 20th-century earthquakes. Apart from the enormous amount of macroseismic data, there were in modern time also many ways of cross-checking with instrumental data.

From the experience that we gathered with the re-evaluation of the 20th-century IDP data in SW-Germany we were able to approach historical-earthquake evaluations in the centuries before with best possible consistency. A helpful exam was to imagine how a modern-time earthquake scenario would look like if it had occurred in historical time considering the sources available, and vice versa (see e.g. Hough, 2013).

2.9.3. Subjectivity

Apart from any subjectivity in observation and reporting (as discussed in this article), there is also *subjectivity in evaluation*. Frequently, in particular for intensity assessments from historical accounts, macroseismic evaluations are not straightforward and not unequivocal, and, even on the basis of the same data, the same scale, the same scientific background, etc., differing intensity assignments by experienced evaluators may have to be regarded as valid results because of an ambiguity factor. Moreover, any IDP intensity assessment is dependent on a certain amount of personal subjectivity inherent in an evaluator's comprehension, opinion, preferences, or even mood in interpreting the data.

There is, generally speaking, quite often some arbitrariness in evaluation because of a lack of standards in procedure. In cases of sparse data, even nuances of wording and details of context may have an influence on the judgement. The intrinsic subjectivity in macroseismic evaluations is widely known and has been accepted to some extent as being inevitable. Automated algorithms have been proposed to reduce subjectivity in historical assessments by a formalized decision process (e.g. Ferrari et al., 1995), but have not yet become established to our knowledge. According to the results of an intensity assessment exercise, Moroni et al. (1996) concluded that "the lack of procedures" is even more important than the incompleteness of the data. With regard to this conclusion, we attached great importance to project management, implementation, and process (e.g. workflow, team work, decision making, quality control, documentation, reproducibility, etc., see also section 2.9.4.).

In this project, we tried to minimize the subjective component of expert decisions by consistently applying the rules of the guideline, but subjectivity could never be zero, though. In practice, differing judgements by the project team members resulted in differences in IDP intensity assessments, which, at times, were as large as one full degree of the EMS scale, however not often so. Yet, such cases of disagreement usually went in parallel with a low IDP quality. Discrepancies had then to be reconciled in the project team after re-examinations and re-assessments. Overall, we felt that the *team results* were more significant and robust than those of a single evaluator.

2.9.4. Transparency

In particular for assessment of historical IDPs, we followed a predetermined workflow from (a) acquisition, transcription, translation and interpretation of sources; to (b) individual intensity assessments by up to four members of the project team; to (c) reconcilement to achieve a common final result, if necessary; to (d) documentation of sources and arguments on that the final IDP assessment was based on; to (e) protocol denoting evaluators and date of the assessment; to, finally, (f) database entry and quality control. All sources that were seen relevant for IDP assessment were archived (originals or copies of relevant pages, and/or bibliographical links) and connected to the IDP(s) by a link in the database, comprising also "silent sources" in some cases. A ranking of sources for individual IDPs was denoted also. Additional descriptive information, characteristics, and peculiarities of the IDPs were recorded in accompanying comments, where appropriate, including e.g. a short abstract of the most relevant macroseismic information, effects in the natural environment, remarkable details that could not be parameterized, etc.; further including e.g. a reference to preceding, simultaneous, or subsequent earthquakes and other events, hints to the historical context, reasoning for the assessment, problems in evaluation, inconsistencies, lack of knowledge, stage of review, relevant scientific studies and cross-references, where applicable. A revision history is kept in the database as well. In this way, a high level of *transparency of work process and results* could be achieved, which may serve as a basis for any continuation or revision of this project.

2.9.5. Interdisciplinarity

Since the establishment of historical seismology as a science field some decades ago, it has been recognized by the scientific community that historical seismology is by definition an *interdisciplinary field* where historians and seismologists, and possibly also civil engineers and architects, should work closely together (see e.g. Eisinger et al., 1992, among many others). Historical seismology has proven to be an independent branch of science in connection with paleo-, archeo-, and instrumental seismological records (e.g. Valensise et al., 2020).

For this project, it turned out that professional historical work was indispensable for the evaluation of sources before about mid of the 19th century. This insight was one of the most important "lessons learned". *For the historical work*, this meant investigative historical research tracing back information to the primary sources whenever possible (a complete "genealogical tree" was followed, however, just if necessary); searching for the relevant documents; deciphering (handwriting, script), transcribing, and translating the significant text passages with respect to language (Latin, Old-German, partly also French), style of writing, and wording. It further meant critically interpreting the text in its historical and social context regarding author, addressee, purpose, locality and time of writing; determining date and time of the earthquake; applying historical thinking to investigate circumstances, clarify ambiguities, separate facts from fiction, and to appraise sources and texts from an historian's point of view. Finally, results had to be secured and source information had to be edited for use in the following assessments within the seismological framework.

On the side of seismology, the task was first and foremost to understand the historical information within its context and limitations as far as possible in order to be able to assess intensity. Due to the aim of this project, historical work had to follow seismological needs. Seismological requirement was to search for primary information and to aim at completeness of the earthquake catalogue, both in space and time. Future seismological utilisation of the catalogue data had to be kept in mind; catalogue work, however, was done irrespective of any particular application. Special questions had to be asked from the seismological side that helped to parameterise historical information in a proper way, as far as the sources allowed parameterisation. Evaluating the historical information, seismological constraints were applied in respect of geophysical plausibility (identifying unlikely effects and relations, probable outlier IDPs, for example) and consistency (as above). Historical earthquake scenarios were mirrored in recent ones; thereby, consistency could be established in comparison with sources and earthquake scenarios of the modern time period. Particularly advantageous was an iterative working scheme that "fed back" preliminary seismological results into the historical work to improve the research.

Overall, the main task was to make best use of historical sources for the earthquake catalogue. The guideline helped to bridge the gap between historical information and seismological needs.

3. Conclusions

The earthquake catalogue of SW-Germany contains about 30,000 newly determined digital IDPs of historical and modern times. To date, this data set is unique in Germany. The usage of primary sources and the quantification of uncertainties have been considered essential. Macroseismic intensities were assessed conventionally using the EMS scale. The EMS has proven to be a suitable instrument, where data came from all kinds of sources ranging from historical documents to 20th-century macroseismic questionnaires. For project work within a multidisciplinary team, a guideline has been required. The guideline had to go beyond the EMS defining best practice of macroseismic evaluations in greater detail, in particular for historical earthquakes. This has allowed earthquake information to be best used for the purpose of a consistent catalogue. The guideline may be helpful for other projects as well.

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