Chapter 12

Intensity and Intensity Scales

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12.1 Intensity and the history of intensity scales

Intensity can be defined as a classification of the strength of shaking at any place during an earthquake, in terms of its observed effects. The fact that it is essentially a classification, akin to the Beaufort Scale of wind speed, rather than a physical parameter, leads to some special conditions on its use. Principal among these is its being an integer quantity when assigned from observed data. Traditionally, Roman numerals have been used to represent intensity values to emphasise this point (it is hard to write "VII½"). Nowadays the use of Roman numerals is largely a matter of taste, and most seismologists find Arabic numerals easier to process by computer.

The word “macroseismic” is used to denote those effects of an earthquake that can be determined without the use of instruments. This includes intensity data but is not restricted to it. A list of places with associated intensity values is macroseismic data; so is the information that an earthquake was felt at a place, or caused damage there. The phrase “intensity data point” (IDP) refers to a datum specifying latitude, longitude and intensity (and usually location name). One also encounters “macroseismic data point” (MDP) in which the numerical intensity may be replaced by some code to indicate “felt”, “damage”, “heavy damage”, etc. The study of the felt effects of an earthquake is termed *macroseismology*. A contour line enclosing places where the intensity was predominantly equal to or higher than a certain value is called an *isoseismal*.

The use of intensity scales is historically important because no instrumentation is necessary, and useful measurements of an earthquake can be made by an unequipped observer. The earliest recognisable use of intensity was by Egen in 1828, although simple quantifications of damage had been made in the previous century by Schiantarelli in 1783 (Sarconi 1784), and some earlier Italian examples are said to exist. However, it was only in the last quarter of the 19th century that the use of intensity became widespread; the first scale to be used internationally was the ten-degree Rossi-Forel Scale of 1883. The early history of intensity scales can be found in Davison (1900, 1921, 1933), a later study can be found in Medvedev (1962), and see also the discussion on the evolution of scales in Musson et al (2010).

The scale of Sieberg (1912,1923) became the foundation of all modern twelve-degree scales. A later version of it became known as the Mercalli-Cancani-Sieberg Scale, or MCS Scale (Sieberg 1932), still in use in Southern Europe. The 1923 version was translated into English by Wood and Neumann (1931), becoming the inappropriately named Modified Mercalli Scale (MM Scale). This was completely overhauled in 1956 by Richter (1958) who refrained from adding his name to the new version in case of further confusion with "Richter Scale" magnitudes. Richter's version became instead the "Modified Mercalli Scale of 1956" (MM56) despite the fact that the link to Mercalli was now extremely remote. Local modifications of Richter's MM56 scale have been used in Australia and New Zealand. Later attempts to radically modernise the MM scale, such as that of Brazee (1978), did not catch on. Stover and Coffman’s (1993) version of the scale consists of modifications to Wood and Neumann’s (1931) version, bypassing Richter (1958). This version is now the most widely used, thanks to it being the basis of the popular “Did You Feel It?” system maintained by the USGS.

In 1964 the first version of the MSK Scale was published by Medvedev, Sponheuer and Karník (Sponheuer and Karník 1964). This new scale was based on MCS, MM56 and previous work by Medvedev in Russia, and greatly developed the quantitative aspect to make the scale more powerful. This scale became widely used in Europe, and received minor modifications in the mid 1970s and in 1981 (Ad-hoc Panel 1981). In 1988 the European

Seismological Commission agreed to initiate a thorough revision of the MSK Scale. The result of this work (undertaken by a large international Working Group under the chairmanship of Gottfried Grünthal, Potsdam) was published in draft form in 1993, with the final version released (after a period of testing and revision) in 1998 (Grünthal 1998). Although this new scale is more or less compatible with the old MSK Scale, the organisation of it is so different that it was renamed the European Macroseismic Scale (EMS). Since its publication it has been widely adopted inside and also outside Europe.

The one important intensity scale that does *not* have twelve degrees (now that the Rossi-Forel Scale is no longer much in use) is the seven-degree Japanese Meteorological Agency Scale (JMA Scale). This is based on the work of Omori, and is the scale generally used in Japan (but nowhere else). A recent modification to the JMA scale subdivides degrees 5 and 6 into upper and lower, and explicitly describes a degree 0, resulting in a ten-degree scale (JMA 1996, 2009). Also, the scale used in Taiwan up to 2000 ran from degree 0 to degree 6, but now includes a degree 7, making eight degrees in total (Wu et al, 2003).

A point to be stressed is that intensity in the modern understanding of the word is a measure of the strength of shaking of an earthquake, not just a list of things that may accompany an earthquake. Thus, for instance, tsunami observations bear no relation to intensity. It may be that in places where the intensity is high, there is also a strong tsunami – but one can also observe strong tsunami effects at great distances where the earthquake is not even felt, and an earthquake that does not displace the seabed will not produce a tsunami no matter how strong the shaking. The same stricture applies to secondary effects due to surface faulting.

To some extent the middle years of the 20th century saw a decline in interest in macroseismic investigation, with the improvements in instrumental monitoring. However, since the middle 1970s there has been a revival of interest in the subject since macroseismic data are essential for the revision of historical seismicity and of great importance in seismic hazard assessments. Macroseismic studies of modern earthquakes are vital for (i) calibrating studies of historical earthquakes; (ii) studying local attenuation, and (iii) investigations of vulnerability, seismic hazard and seismic risk.

The use of the internet as a medium for gathering data has proved an extremely powerful tool, and in developed countries a vast amount of data can be gathered and processed very rapidly, giving immediate information on the impact of an earthquake; information that formerly would not be available after the processing of many paper questionnaires, a work that could occupy months. The possibility of showing, via the internet, the distribution of effects of an earthquake within a matter of minutes or hours, is an excellent opportunity for communicating science to the public, and has attracted a lot of interest. The wealth of macroseismic data now readily available has renewed interest in intensity as an analogue for physical ground motion parameters, especially velocity (e.g. Ebel and Wald 2003, Kaka and Atkinson 2004, Boatwright et al 2006, Atkinson and Wald 2007).

12.2 Modern intensity scales

The three most important intensity scales in current use are the European Macroseismic Scale (EMS-98), the Modified Mercalli Scale (MM or MMI) and the JMA scale, although the latter is not widely used in practice any longer to assign intensities. Each is given in turn here.

12.2.1 European Macroseismic Scale (EMS)

The complete EMS-98 scale is too long to reproduce in its entirety, being a small book in length. This is because, while historically intensity scales have been presented simply as a list of classes and diagnostics for the user to make of what he will, the EMS-98 scale comes with extensive support material, including guidelines, illustrations and worked examples. Even the traditional "core" part of the scale contains tabular and graphical material explaining the classification of buildings and quantities used.

Some intensity scales in the past, such as the Modified Mercalli scale (in its 1956 incarnation, Richter 1958) have attempted to distinguish between the effects of earthquake shaking on buildings of different construction types, using type as an analogue of strength. An essential feature of the EMS is that it employs a series of six vulnerability classes which represent strength directly, and involve construction type, but also other factors such as workmanship and condition. These vulnerability classes allow a flexible and robust approach to assessing intensity from damage. The system is also adaptable to new or different building types, and includes consideration of engineered structures with earthquake resistant design. Damage is handled in a way that discriminates between structural and non-structural damage, and the different forms damage takes in buildings of different types. A system of five damage grades is used: negligible to slight; moderate; substantial to heavy; very heavy, and destruction. These are not only defined but also illustrated pictorially (Figure 12.1).

The probabilistic nature of intensity is stressed by the use of numerically-defined expressions of quantity. For any intensity degree, it is expected that for buildings of equivalent strength there will be a modal level of damage that will be most frequently encountered, and decreasing proportions of the building stock of equivalent strength will show lesser or greater degrees of damage. This relates closely to real experience from damage surveys.

Although natural phenomena such as landslips, rockfalls, cracks in ground, etc., have been used in intensity scales for a long time, more recent experience has shown that the occurrence of these is very strongly influenced by other factors than the severity of earthquake shaking - especially pre-existing hydrological conditions. In the EMS, although these effects are not deleted entirely, they are relegated to an Annexe rather than being included in the core scale; they are treated in a graphical table which shows the ranges of intensities over which such phenomena are commonly (and exceptionally) encountered.

The full scale is published as Grünthal (1998). It can also be obtained in full at the following WWW address: http://tinyurl.com/cp7dc2

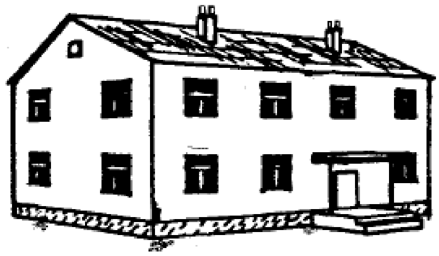
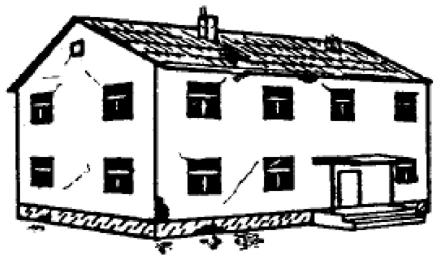
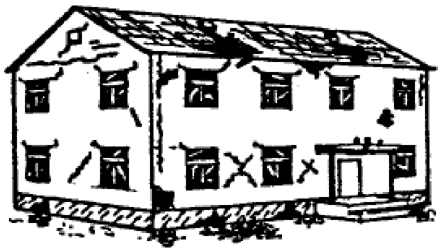
Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage** **(slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage,** **heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage** **(heavy structural damage,** **very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction** **(very heavy structural damage)** Total or near total collapse.

Fig. 12.1 An example of the use of pictures in classifying damage grades in the European Macroseismic Scale

Despite the name of the scale (which reflects the fact that it was developed at the instigation of the European Seismological Commission), the scale is equally suitable for use outside of Europe, and has been used successfully for assessing modern earthquakes in many parts of the world. It is possible that the scale will be officially renamed in the near future to reflect this.

Here the short form (section 8 of the published scale) is reproduced. *This is not suitable for, and not intended for, use in assigning intensities*. It gives the character of each degree in a very simplified and generalised form for educational purposes.

EMS Scale of 1998 (abstracted)

I	**Not felt**	Not felt.
II	**Scarcely felt**	Felt only by very few individual people at rest in houses.
III	**Weak**	Felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	**Largely observed**	Felt indoors by many people, outdoors by very few. A few people are awakened. Windows, doors and dishes rattle.
V	**Strong**	Felt indoors by most, outdoors by few. Many sleeping people awake. A few are frightened. Buildings tremble throughout. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.
VI	**Slightly damaging**	Many people are frightened and run outdoors. Some objects fall. Some houses suffer slight non-structural damage like hair-line cracks and fall of small pieces of plaster.
VII	**Damaging**	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many well built ordinary buildings suffer moderate damage: small cracks in walls, fall of plaster, parts of chimneys fall down; older buildings may show large cracks in walls and failure of fill-in walls.
VIII	**Heavily damaging**	Many people find it difficult to stand. Many houses have large cracks in walls. A few well built ordinary buildings show serious failure of walls, while weak older structures may collapse.
IX	**Destructive**	General panic. Many weak constructions collapse. Even well built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure.
X	**Very destructive**	Many ordinary well built buildings collapse.
XI	**Devastating**	Most ordinary well built buildings collapse, even some with good earthquake resistant design are destroyed.
XII	**Completely devastating**	Almost all buildings are destroyed.

12.2.2 Modified Mercalli (MM) Scale

As stated, the situation regarding the MMI scale is confused. Most of the versions in circulation (e.g. on internet pages) are either the short form of the 1931 version, or some arrangement of the 1956 version. While papers frequently cite Stover and Coffman (1993) as the currently preferred version, one searches in vain for a copy of the scale according to Stover and Coffman (1993), since even Stover and Coffman do not present it in a unified form. Instead, they give Wood and Neumann's longer version, and a separate section in which they describe the modifications they apply in practice. Since this is the version of the scale that underlies the "Did You Feel It?" system (Wald et al 1999) and most of the recent studies on intensity and physical ground motion measures, the Stover and Coffman version is important, and it is strange that, hitherto, it seems to exist nowhere in print as an integrated scale.

Presented below is an attempt to give Stover and Coffman's 1993 version of MMI in one piece. This is not straightforward as it is not always clear precisely what Stover and Coffman's meaning is for some diagnostics, so a certain amount of editing has been necessary. Notable changes introduced by Stover and Coffman are that effects on people (other than loss of balance) are entirely removed from the scale above intensity 4. A number of other diagnostics are removed, and some are downgraded. The general result is that intensities assessed with this version are likely to be lower than before, especially in the range 4 to 7.

MMI Scale of 1993 (Stover and Coffman, after Wood and Neumann, edited Musson)

I Not felt - or, rarely under especially favourable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway - doors may swing very slowly.

II Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water may sway; doors may swing very slowly; sometimes birds, animals reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV Felt by many to all. Trees and bushes shaken slightly. Buildings shook moderately to strongly. Walls creaked loudly. Observer described the shaking as "strong." Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V Buildings trembled throughout. Broke dishes, glassware, to some extent. Cracked windows - in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging pictures fall. Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started or ran fast, or slow. Moved small objects, furnishings, the latter to slight extent. Trees, bushes, shaken moderately to strongly. People have difficulty standing or walking. Felt moderately by people in moving vehicles.

VI Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks in chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Moved furnishings of moderately heavy kind. Small bells rang - church, chapel, school, etc. The intensity can only be assessed as VI if damage to buildings is observed, unless many small objects fall from shelves or many glasses or dishes are broken.

VII Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roofline (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones.

VIII Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture. Trees shaken strongly - branches, trunks, broken off, especially palm trees.

IX Damage considerable in (masonry) structures built especially to withstand earthquakes: threw out of plumb some wood-frame houses built especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames.

X Damage serious to dams, dykes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations.

XI Damage severe to wood-frame structures, especially near shock centres. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less.

XII Damage total - practically all works of construction damaged greatly or destroyed.

Notes: It is ambiguous in the text of Stover and Coffman (1993) whether the section of diagnostics for intensity 4 beginning "Awakened few …" and ending "Rocked standing motor cars noticeably" is intended to be included in the scale or not. USGS practice is to include them (Dewey 2009 *pers. comm.*). According to some sources, e.g. Boatwright and Bundon (2005), the revisions of Stover and Coffman (1993) include treating the fall of few chimneys as intensity 6 and the fall of half of all chimneys or more as 7. This is not actually found anywhere in Stover and Coffman (1993).

12.2.3 Japan Meteorological Agency (JMA) Scale

The JMA scale has evolved over the years from the seven-degree scale of Omori (1900). The revision of 1996 added two new degrees, but to try and maintain consistency with older data sets, the new scale divided degree 5 into "5 Lower" and "5 Upper", and similarly for degree 6. The latest revision in 2009 maintains this system, but the scale is reworded and revised throughout, and is generally greatly improved in clarity and cohesiveness.

However, routine practice in Japan seems to be largely to rely on estimates of intensity made by customised strong-motion instruments. The scale is therefore a guide to what might be expected to happen in a place where the local intensity instrument registers a given value; it is not a means of recording what actually was observed. Thus the scale notes that at intensities above 4, railway services may be suspended for safety checks. No-one would use that information to assign intensity, but it is useful information for people affected by an earthquake.

JMA Scale of 2009 (re-arranged)

0	*Effects on*
*People***:**	Imperceptible to people.
1	*Effects on*
People:	Felt slightly by some people keeping quiet in buildings.
2	*Effects on*
People:	Felt by many people keeping quiet in buildings. Some people may be awoken.
Indoors:	Hanging objects such as lamps swing slightly.
3	*Effects on*
People:	Felt by most people in buildings. Felt by some people walking. Many people are awoken.
Indoors:	Dishes in cupboards may rattle.
Outdoors:	Electric power lines swing slightly.
4	*Effects on*
People:	Most people are startled. Felt by most people walking. Most people are awoken.
Indoors:	Hanging objects such as lamps swing significantly, dishes in cupboards rattle. Unstable ornaments may fall.

Outdoors: Electric wires swing significantly. Those driving vehicles may notice the tremor.

5 Lower *Effects on*

People: Many people are frightened and feel need to hold onto something stable.

Indoors: Hanging objects such as lamps swing violently. Dishes in cupboards and items on bookshelves may fall. Many unstable ornaments fall. Unsecured furniture may move, and unstable furniture may topple over.

Outdoors: In some cases, windows may break and fall. People notice electricity poles moving. Roads may sustain damage.

Wooden houses (low earthquake resistance): Slight cracks may form in walls.

Ground and slopes: Small cracks in ground may form and liquefaction may occur. Liquefaction may be seen in areas with a high groundwater level and loose sand deposits. Damage observed as a result of liquefaction includes spouts of muddy water from the ground, outbreaks of subsidence in riverbanks and quays, elevation of sewage pipes and manholes, and leaning or destruction of building foundations. Rock falls and landslips may occur.

Utilities and infrastructure: In the event of shaking with a seismic intensity of about 5 Lower or more, gas meter with safety devices are tripped, stopping the supply of gas. In the event of stronger shaking, the gas supply may stop for entire local blocks. Suspension of water supply and electrical blackouts may occur in regions experiencing shaking with a seismic intensity of about 5 Lower or more. In the event of shaking with a seismic intensity of about 5 Lower or more, elevators with earthquake control devices will stop automatically for safety reasons.

5 Upper *Effects on*

People: Many people find it hard to move; walking is difficult without holding onto something stable.

Indoors: Dishes in cupboards and items on bookshelves are more likely to fall. TVs may fall from their stands, and unsecured furniture may topple over.

Outdoors: Windows may break and fall, unreinforced concrete-block walls may collapse, poorly installed vending machines may topple over, automobiles may stop due to the difficulty of continued movement.

Wooden houses (low earthquake resistance): Cracks may form in walls.

Reinforced concrete buildings (low earthquake resistance): Cracks may form in walls, crossbeams and pillars.

Ground and slopes: As 5 Lower.

6 Lower *Effects on*

People: It is difficult to remain standing.

Indoors: Many unsecured furniture moves and may topple over. Doors may become wedged shut.

Outdoors: Wall tiles and windows may sustain damage and fall.

Wooden houses (low earthquake resistance): Cracks are more likely to form in walls. Large cracks may form in walls. Tiles may fall, and buildings may lean or collapse.

Wooden houses (high earthquake resistance): Slight cracks may form in walls.

Reinforced concrete buildings (low earthquake resistance): Cracks are more likely to form in walls, crossbeams and pillars.

Reinforced concrete buildings (high earthquake resistance): Cracks may form in walls, crossbeams and pillars.
Ground and slopes: Cracks in ground may form. Landslips and landslides may occur.

6 Upper *Effects on*
People: It is impossible to remain standing or move without crawling. People may be thrown through the air.
*Indoors:*Most unsecured furniture moves, and is more likely to topple over.
Outdoors: Wall tiles and windows are more likely to break and fall. Most unreinforced concrete-block walls collapse.
Wooden houses (low earthquake resistance): Large cracks are more likely to form in walls. Buildings are more likely to lean or collapse.
Wooden houses (high earthquake resistance): Cracks may form in walls.
Reinforced concrete buildings (low earthquake resistance): Slippage and X-shaped cracks may be seen in walls, crossbeams and pillars. Pillars at ground level or on intermediate floors may disintegrate, and buildings may collapse.
Reinforced concrete buildings (high earthquake resistance): Cracks are more likely to form in walls, crossbeams and pillars.
Ground and slopes: Large cracks in ground may form. Landslips are more likely to occur; large landslides and massif collapses may be seen. When large landslides and massif collapses occur, dams may form depending on geographical features, and debris flow may occur due to the large quantities of sediment produced.
Utilities and infrastructure: In the event of shaking with a seismic intensity of 6 Upper or more, gas, water and electric supplies may stop over wide areas.

7 *Effects on*
People: It is impossible to remain standing or move without crawling. People may be thrown through the air.
Indoors: Most unsecured furniture moves and topples over, or may even be thrown through the air.
Outdoors: Wall tiles and windows are even more likely to break and fall. Reinforced concrete-block walls may collapse.
Wooden houses (low earthquake resistance): Buildings are even more likely to lean or collapse.
Wooden houses (high earthquake resistance): Cracks are more likely to form in walls. Buildings may lean in some cases.
Reinforced concrete buildings (low earthquake resistance): Slippage and X-shaped cracks are more likely to be seen in walls, crossbeams and pillars. Pillars at ground level or on intermediate floors are more likely to disintegrate, and buildings are more likely to collapse.
Reinforced concrete buildings (high earthquake resistance): Cracks are even more likely to form in walls, crossbeams and pillars. Ground level or intermediate floors may sustain significant damage. Buildings may lean in some cases.
Basic infrastructure: Electrical, gas, and water supplies are interrupted over a large area.
Ground and slopes: As 6 Upper.

Notes:
Wooden houses and RC buildings are classified into two categories according to their earthquake resistance, which tends to be higher for newer structures. Earthquake resistance tends to be low for structures built up to 1981, and high for those built since 1982. However,

to maintain a certain range of earthquake resistance according to differences in structure and wall arrangement, resistance is not necessarily determined only by building age. The earthquake resistance of existing buildings can be ascertained through quakeproofing diagnosis.

The walls of wooden houses are assumed to be made of mud and/or mortar. Mortar in a wall with a weak base can easily break off and fall, even under conditions of low deformation. Damage to wooden houses depends on the period and duration of seismic waves. In some cases (such as the Iwate-Miyagi Nairiku Earthquake of 2008), few buildings sustain damage in relation to the level of seismic intensity observed.

12.3 Collection of macroseismic data

Collection of macroseismic data from current earthquakes is derived principally from two sources - questionnaire surveys and field investigations, either or both of which may be required for a particular earthquake. As a general rule, questionnaire surveys are used for assessing intensities in the range of 2 to 6, while for 7 and above field investigations are necessary. Questionnaires used to be distributed predominantly as paper documents, to be filled in and returned to the investigator. Since about 2000, this has been progressively replaced by internet collection of data.

One thing in common with both questionnaire surveys and field investigations is the desirability of rapid response - evidence of earthquake damage is patched up within days or even hours, and human memory of details (and interest in the subject) also wanes rapidly. There is a third source - documentary material, for instance, newspaper accounts - which is the principal source of macroseismic data for historical earthquakes. The treatment of this is a separate subject involving the techniques of the professional historian as well as the seismologist, and is not dealt with here.

A general point common to both paper and internet questionnaires is the problem of geo-location. One cannot ask people to give their location in terms of latitude and longitude, and interpreting addresses from a large number of questionnaires would be too onerous. So the usual practice is to rely on postcodes (zip codes). The problem here is that different countries use different systems with different resolutions, so in one country the postcode may be convertible to a co-ordinate location with accuracy of tens of metres, while in another, the accuracy may not be better than tens of kilometres.

In either case, someone who fills in a questionnaire for an earthquake he felt other than at home, may not know the postcode of the location where he was – and may simply put in his home postcode, a potential source of error in the data.

12.3.1 Macroseismic questionnaires, pre-internet

When dealing with traditional macroseismology, when surveys of earthquake effects had to be conducted using paper forms and the postal service, one could distinguish two basic types of macroseismic questionnaire, dependant on the intended recipient. The first is the questionnaire to be answered by an individual citizen recounting his personal experiences of the earthquake. The second is the questionnaire designed to be answered by someone with knowledge of the experiences of the entire community. Which of these two approaches is used will shape the macroseismic investigation as a whole; the choice may well be forced on the investigator by circumstances. For example, in some countries there will be found an official in each town or rural community whose job includes completing such requests for data, and who can be relied on to fill in any questionnaire submitted. In some other countries such officials are not to be found, and this means of investigation is therefore not possible. Some institutes may have the resources to post out thousands of questionnaires as mailing shots; others may not be able to afford such a technique.

One may discern four basic types of person who may fill in a macroseismic questionnaire, two in each of the classes outlined above.

(i) *The unselected individual* - questionnaires may be distributed haphazardly and in great bulk by publication in newspapers, dissemination at libraries, etc. This guarantees a large response, but probably biases the results in favour of positive responses.

(ii) *The randomly selected individual* - there exists a methodology, highly developed in the social sciences, for disseminating questionnaires in such a way as to maximise the statistical validity of the results, using random selection procedures based on electoral rolls and direct mailing, often with some incentive to return the questionnaire (such as a prize draw). This is the best method in terms of the reliability of the results, since a random sample enables one to make statistically valid estimations of the characteristics of the whole population. The drawbacks are that such a response may be difficult to organise rapidly after an earthquake, and is likely to be relatively expensive. It should not be forgotten, that the art of questionnaire design and methodology has been studied in detail by social scientists for many years, and the expertise accumulated should not be ignored by seismologists whose background usually lies in the physical sciences.

(iii) *The public official* - it is very convenient to be able to send a single questionnaire to the local burgomaster/postal officer/police superintendent's office and have it filled in with the details of the effects of the earthquake in the whole of the community under the official's jurisdiction. What the seismologist cannot be certain of is how conscientiously the questionnaire is filled in. Does the official make detailed enquiries, or does he jot down the first thing that comes into his head?

(iv) *The volunteer* - some seismological institutes arranged networks of local volunteers with some standing in the community (schoolteachers, clergymen) and enthusiasm for the task of supplying useful data. Such volunteers can be given a stack of blank questionnaires in advance and can be relied upon to fill one in after an earthquake occurs with dependable data on the effects in the locality. Such a system is very effective, but can be laborious to set up and maintain. An advantage of such a system is that one stands a good chance of getting reliable negative information.

A further division of questionnaire design is that between the free-form questionnaire and the multiple choice style. The first style gives open-ended questions to which the respondent can answer in his own words ("What sort of shaking did you experience?") while the second gives a series of boxes to tick ("The shaking was A - weak; B - moderate; C - strong"). The second style is easier to process, but runs the risk of losing information that doesn't easily fit the predefined categories. A combination of both styles is also possible.

Length of questionnaire is also important. Too long or difficult a questionnaire will discourage people from filling it in, as will asking questions that are too hard for most people to answer - for example, how many people can accurately describe their local geology? One should guard against asking questions that are not strictly necessary (such as personal details). From the above discussion it will be seen that questionnaire design is somewhat of an art, and that what will work for one country won't work for another.

A sample of a typical paper questionnaire for distribution after an earthquake is given in section 12.3.3 below.

12.3.2 Macroseismic questionnaires, post-internet

The use of the internet as a tool for collecting macroseismic data has transformed the subject over the first decade of the 21st century, at least in developed countries where the use of the internet in ordinary homes is widespread. Not only can data be collected in very large volumes very rapidly, it can also be processed in real time and the results displayed immediately. The adoption of such a system answers definitively the question discussed in the previous section as to who is expected to provide the response – internet questionnaires will be completed by ordinary persons, who visit the institute’s web site and choose to record their experience. The internet questionnaire will therefore be designed to capture this type of individual experience, from persons lacking technical expertise. It does mean that the sample is always self-selecting, and therefore will tend to be biased in favour of positive responses. Automatic processing routines favour the collection of data where answers are predefined between several options, so a check-box approach will usually be most appropriate, though space should be provided to allow for extra comments to be written in; these will need to be read individually by the investigator.

It was difficult in the past to produce a standard macroseismic questionnaire that could be used internationally, because of the different types of respondent in different countries. However, since all internet questionnaires are directed at ordinary individuals, there is a real possibility that a single standard questionnaire could be developed. Indeed, both the USGS and EMSC have collected data for earthquakes in many different countries, according to standard questionnaire formats.

The main obstacle to a single unified questionnaire is that internet questionnaires are to some extent shaped by the intensity scale in use and the system that will be used to process the data. This is likely to vary from country to country still, due to a desire to maintain compatibility with past data sets. The establishment of a global standard questionnaire, from which national institutes can select subsets of questions as desired, is still a realisable goal. Currently, a draft standard internet questionnaire has been drawn up by the ESC Working Group on Internet Macroseismology.

Examples of online questionnaires can be seen on the USGS (http://earthquake.usgs.gov/earthquakes/dyfi/) and EMSC (http://www.emsc-csem.org/Earthquake/felt.php) websites, among others.

12.3.3 Sample questionnaire

EARTHQUAKE QUESTIONNAIRE

The following questionnaire is part of a study of the effects of the _______ (name) earthquake, which occurred on ________ (date) at _______ (time). You are invited to use it to record what you experienced.

If you did NOT feel the earthquake, or notice it at all, please tick here [ ]
and complete questions 1, 2 and 5, below. This information will still be useful for our study.
Please send completed questionnaires to this address:
……………………………………….
……………………………………….
……………………………………….

SECTION A – WHERE YOU WERE

1. At the time of the earthquake, where were you?
   Address (including post code)……………………………………………………………………
   ………………………………………………………………………………………………
   Outdoors [ ] Ground floor [ ] Upper floor [ ] ; If so, which floor? ____
   Stationary vehicle [ ] Moving vehicle [ ] Other ____________________
   If indoors, please describe the type of building:
   Function (house, school, church, etc) ………………………………………………………
   Height (number of stories) ……………………………………………………………….
   Construction (brick, stone, wood, etc) ……………………………………………………...

2. What were you doing?
   Walking [ ] Standing [ ] Sitting [ ] Kneeling [ ]
   Lying down [ ] Sleeping [ ]

SECTION B – EARTHQUAKE SHAKING AND SOUND

3. What best describes the shaking you felt?
   No shaking [ ] Trembling [ ] Swaying [ ] Jerky motion [ ]
   Impact [ ] Rolling motion [ ] Other [ ] …………………………………………
   It was … Weak [ ] Moderate [ ] Severe [ ]

4. What best describes any sound you heard?
   No sound [ ] Rumbling [ ] Roaring [ ] Explosion [ ]
   Other [ ] ……………………………
   It was … Faint [ ] Moderate [ ] Loud [ ]

SECTION C – EFFECTS ON PEOPLE AND ANIMALS

5. Which best describes what happened where you were (your house, neighbours)?

Nobody noticed it [ ] Only one or two people noticed it [ ]
Some people noticed it, but not many [ ] Many people noticed it [ ]
Most people noticed it [ ] Everyone noticed it [ ]
People indoors noticed it, but not those outside [ ]
People upstairs noticed it, but not those on the ground floor [ ]
I don't know whether other people noticed it or not [ ]

6. (Only for earthquakes that happened at night) Did the earthquake wake you?
   No [ ] Yes [ ] I wasn't asleep [ ]
   Were other people where you were woken up?
   No [ ] Yes, a few [ ] Yes, many [ ] Yes, most/all [ ] Don't know [ ]

7. Were you frightened?
   No [ ] Yes [ ]
   Where you were, did anybody run outdoors in fright?
   No [ ] Yes, a few [ ] Yes, many [ ] Yes, most/all [ ] Don't know [ ]

8. Was it hard to stand or walk?
   No [ ] Yes, a bit [ ] Yes, very [ ]

SECTION D – EFFECTS ON OBJECTS, BUILDINGS, ETC

9. Did any of the following things happen?

	Yes	No	Don't know
Windows/doors rattled	[ ]	[ ]	[ ]
Crockery, etc rattled	[ ]	[ ]	[ ]
Hanging objects swung	[ ]	[ ]	[ ]
Pictures moved askew or fell	[ ]	[ ]	[ ]
Small objects shifted or fell	[ ]	[ ]	[ ]
Books or similar shifted or fell	[ ]	[ ]	[ ]
Furniture shook visibly	[ ]	[ ]	[ ]
Furniture shifted out of place	[ ]	[ ]	[ ]
Furniture toppled over	[ ]	[ ]	[ ]
Liquids splashed or spilled	[ ]	[ ]	[ ]

   Please give details, or note any other things that you noticed:…………………………..
   ……………………………………………………………………………………...............

10. Was there any damage to buildings where you were?
    No [ ] Yes [ ] Don't know [ ]
    If yes, please describe the damage …………………………………………………....
    ………………………………………………………………………………………

11. Were there any effects on natural surroundings where you were, for example, landslips, cracks in ground, effects on ponds or streams, etc?
    No [ ] Yes [ ] Don't know [ ]
    If yes, please describe the effects …………………………………………………........
    ………………………………………………………………………………….....
    ………………………………………………………………………………………
    ………………………………………………………………………………………

12. Have you any other comments about the effects of the earthquake that might be useful?

12.3.4 Field investigations

Earthquakes can't be predicted; but one can know, in any region, the events that are likely to occur at some time or other, and one can at least partially prepare in advance. As always in macroseismology, there is no fixed rule how to do things, because how one proceeds will heavily depend on the size of the earthquake, its location and the importance of the data for the overall knowledge of the seismicity of the area. For example, an earthquake of intensity 6 will not surprise anyone in Italy or Greece, and will probably be surveyed only briefly, but such event in Finland or Denmark might be one of the strongest felt in a very long period, and therefore would be studied very much in detail.

There are quite a few distinctions in procedure in dealing with an event with only minor (non-structural) damage and a more severely damaging one.

Field work in macroseismology in general can be divided in three main phases: preparation, the field activities themselves, and finally later activities. The following issues need to be discussed: arranging teams of investigators, providing equipment, arranging travel and accommodation, methods of investigation, and ensuring safe working practices.

12.3.4.1 Preparation – before the earthquake occurs

Some preparation should be done on a contingency basis, before any earthquake has occurred; this minimises the amount of time needed arranging things between the occurrence of the earthquake and the setting out of the field investigation team.

The first issue is building a roster of potential participants in field investigations. These may be observatory staff (seismologists) but may also include other seismologists, either from other institutes in the same country or from abroad (especially neighbouring countries; cross-border earthquakes may need to be considered). In case of an earthquake strong enough to cause structural damage, it is essential to be able to call on the help of one or more civil engineers with experience in earthquake engineering. The help of a geotechnical engineer or engineering geologist will also be needed in cases of high-intensity earthquakes. In cases that it is expected that international team members will be called in who do not speak the local language, suitable translators should be available. Names and phone numbers of potential team members should be compiled in advance.

In some cases it may be useful to include team members with less experience, for training purposes, though this is not recommended for earthquakes that are humanitarian disasters.

Equipment (discussed in detail below) needs to be collected in advance and stored for use when needed, and checked at regular intervals to make sure that things like batteries are in a state of readiness.

Procedures for arranging travel can also be made in advance, for fast issuing of tickets, travel insurance and other travel documents. If the observatory does not have its own vehicles, arrangements should be in place for quick availability of rented vehicles (and in extreme cases of very strong earthquakes, a helicopter will probably be needed).

Additional items to consider: a list of passport/identity cards/driving licenses expiry dates of all team members, to be checked regularly so that the documents can be updated in time; a list of passwords for remote connections, for laptops, and pin numbers of mobile phones.

12.3.4.2 Preparation – after the earthquake occurs

Immediately after the earthquake has occurred, the actual field investigation can be prepared, in the light of the severity of the event and its actual location. In the case of earthquakes causing only minor damage, a quick arrival into the field is essential, as damage will swiftly be made good and debris swept away. In the case of major earthquakes causing severe damage and many casualties, rapid response is less essential (ruined buildings will not be cleared so quickly) and may even be a bad idea, as priority must be given to rescue work. Scientific investigation should not be allowed to hinder or compromise humanitarian relief.

For an earthquake of intensity up to 6 it is usually enough that two people spend a few days in the field. If the earthquake was felt in a large town, an additional day spent collecting data in schools can be useful. Of course, it depends how important the earthquake is for the knowledge of the seismicity of the region. In countries with low seismicity such earthquake would definitely justify more work than elsewhere. For a severe earthquake, one should expect that around six people (two groups of three) should work for four or five days, though this can vary according to the situation and resources.

Travel arrangements vary very much depending on the size of the event, the level of destruction and the distance from the epicentral area to the starting point of the team. In the majority of cases, a car or several cars will be enough. In case of a major earthquake, one might consider aerial survey (plane, helicopter) to get an idea of the situation in the most damaged area. Public transport might be not available in the affected area, so one cannot rely on it. If the nearby airfields are closed, the teams might need to use humanitarian or rescue flights; for this, it would be advisable to establish contacts in advance and keep the contact data updated.

Regarding accommodation, a centrally placed hotel is ideal when dealing with relatively minor earthquakes, but in cases of major events with strong aftershock sequences, one should choose a hotel well away from the epicentral area. In extreme cases, for instance if the damaged area is difficult to access by road, or the area of destruction is very large, it may be necessary to camp in tents.

When dealing with a strongly damaging earthquake it will be essential to liaise with the civil authorities in advance of arriving in the damage zone, to arrange authorisation and access. After the 2010 Haiti earthquake, remote sensing data was made available rapidly, from which it was possible to identify the worst damaged areas, and locations of landslides and other major ground failures. This sort of data is likely to continue to be available in the future, at least for major disasters, and may be extremely useful in planning locations to visit.

Lastly, point of contact arrangements should be made with observatory staff back at base, with the team making contact regularly (usually once a day, in the evening) to report that all are safe.

12.3.4.3 Equipment

The equipment that will be needed can be divided into two: items that are always needed, and items needed when investigating areas with structural damage.
The basic items are the following:

- Maps, road navigation devices/GPS, cameras, extra sets of batteries, laptop, notebooks, portable voice recorder, tape measure, copy of the intensity scale.
- Optionally, one may wish to carry printed questionnaires (especially if one intends to visit some schools) when dealing with earthquakes with limited damage. Also educational material (especially guidelines to earthquake safety) could be carried, and again, this is particularly useful in case of visits to schools.
- Clothes and shoes should be chosen depending on the weather conditions and the type of terrain. If the investigation will last several days, and conditions are likely to be difficult (e.g. weather is bad) then special care should be taken in choosing clothing. Clothes should be comfortable to wear and not complicated to take care of. Sturdy shoes, materials, that behave well in rain (jeans can be impractical when wet), jackets, hats and mittens, and multilayered clothing is recommended. Basics like sunglasses, insect repellent, sunscreen should not be forgotten.
- When in a damaged area, safety clothing is essential. This means a helmet, high-visibility jacket, and steel-tipped boots. The jacket should preferably be marked clearly with the name of the institute or field investigation team. It can be very difficult to access the epicentral area without very visible identification (Figure 12.2).

Fig. 12.2 Italian seismologists making a macroseismic field investigation after the 2009 L'Aquila earthquake: note the safety helmets and high-visibility jackets clearly marked with the institute name.

- In general, clothes with the institute logo are useful, and IDs with photographs should be carried at all times. Residents are sometimes suspicious of people going round photographing houses.
- In case of a high intensity earthquake it might be necessary for a team to use a tent; so camping equipment needs to be available, and regularly checked/renewed as well: tents, sleeping bags, cooking equipment, etc. Lamps, flashlights, batteries and first aid kits should be ready, as well as dry food and water for a few days. Disaster zones can be insanitary, so water purification, surgical masks, and gloves may be needed.

12.3.4.4 In the field

In dealing with a relatively low-intensity event, a visit to epicentral area should include a short stay in each (or at least in a representative number) of the damaged localities. Each locality should be surveyed on foot (if small) or by car, to get the overview of the situation and to note the extreme cases of damage. Contact with local authorities is recommended; information about damage can be found from the emergency services, insurance agencies and just talking to people. Schools are a good source of information – if there are enough team members, one can spend a few hours visiting the local school, especially if it is in a rural setting, where children are being brought from a wider area. In villages it is often enough to stop in the shop or in the pub, these being the points where many people come and talk to each other. One can consider leaving some printed questionnaires with some person willing to conduct a small survey and send back the answers, or at a local library or post office.

The team will usually split up into pairs or trios, one pair per car. While one drives, the other one can deal with the collected information, study maps, take phone calls etc. In the ideal case the pairing should consist of one seismologist and one civil engineer. In case of geotechnical issues (liquefaction, etc), an engineering geologist or geotechnical engineer should accompany them. In practice, a team member can be anyone working in seismology, with working knowledge of the scale and some basic training in recognising the building type and grade of damage. For low intensity earthquakes, it is not expected that there would be language barriers between the team and the inhabitants of the epicentral area, as the investigation would be made only by members of local institutes; in case of language differences, it is recommendable to have an interpreter along as well. For large earthquakes, the size of the team can vary during the time of the survey, as more participants can arrive later, if necessary, and the team members may be changed according to circumstances.

As a rule, if all the damage is non-structural, a team consisting only of seismologists is sufficient. Once structural damage needs to be registered, the assistance of a civil engineer becomes essential.

In the field, it is necessary to combine both detailed and general surveys of structural behaviour. Structures need to be surveyed in terms of: the distribution of different types; the overall vulnerability (resistance or lack of resistance to earthquake shaking) of typical structures while noting deviations in terms of good or bad examples; and the distribution of different grades of damage within each building type. Care should be taken over making accurate records of the location of all structures studied or photographed. Data should be gathered as written notes and photographs.

For engineered structures, a detailed study should be carried out to identify both good and bad performance in a sample of both damaged and undamaged structures. Both external and internal damage should be recorded if safe to do so (bearing in mind that entering damaged buildings may be too dangerous), identifying typical modes of failure. In order to be able to relate the damage to the intensity scale, information on the strength of the building is required: strengths and weaknesses in the construction techniques, special points of vulnerability, or high resistance, irregularity or symmetry in the building design, the quality of the materials used, and so on. It is a good idea to collect information on what earthquake-resistant design regulations were in force before the earthquake, and also, where possible, to investigate to what extent these regulations were followed in the buildings examined.

The case is similar for non-engineered structures; these are likely to be less individual, so the task becomes one of identifying the main characteristic structural forms, their age and condition. Again, the extent and types of damage, both interior and exterior, need to be recorded.

Detailed photographic surveys can be made of individual streets or districts to record the percentages of various types of buildings that were damaged to a lesser or greater degree. These surveys should be supplemented with internal records from at least a sample of the buildings examined.

The overall spatial distribution of damage can be recorded over a large area by the use of general surveys employing proper sampling techniques to generate statistically consistent data. Distinctions between different construction types, usage, height and age and quality of construction should always be made wherever possible.

Geotechnical aspects should also be investigated. Any relationship between local geology and damage distribution should be investigated. (This does not entail "correcting" intensities for local conditions, but does explain local variations in observed intensity). Data should be gathered on groundwater and hydrological conditions before the earthquake. The following topics also need to be considered: types of foundation and their performance; effects on embankments, cuttings and river banks; liquefaction and other ground effects like cracking; landslides and rockfalls. Negative data as well as positive data should be collected.

Special studies may be needed of individual industrial or civil facilities. Effects on factories can include damage to pipework and ducting, pumps and valves, cabling systems, tanks, machinery, electrical controls, computers and cranes. The effects on dams, bridges, port facilities, tunnels and irrigation systems should be recorded. The effects on lifelines (services, transport) also merit attention: underground provision of water, gas, electricity and telecommunications; railways, roads etc. These sorts of data are not generally suitable for intensity assessment per se, but are important to record, particularly when making an assessment of the economic impact of the earthquake, or looking at lessons to be learnt from an engineering perspective.

One should not forget that for intensity evaluation the data be statistically representative, and in larger settlements this is difficult to achieve. Therefore, the teams should not lose too much time on a single building, but try to optimize the time. Teams of engineers will study building by building, and their data can be used to check some cases, if necessary.

When dealing with a small settlement (village or a fraction of the village) it is more or less simple to go around and see all the buildings. When dealing with a larger settlement, it is reasonable to divide it into parts and assign several teams to do the job block by block. All the collected data should be geo-referenced in situ, if possible; backup copies of photographs, videos and files produced during the field work should be made at least once a day. To be safe, it is good to have the ability to email or ftp the data regularly to another location, to prevent losses.

While entering areas with high intensity effects, team members must wear safety gear and be aware of the danger. In many cases a special permit should be obtained from the civil authorities, who then assign specialists (firemen, policemen, soldiers etc) to accompany teams and take care of safety issues. One should not underestimate the danger of aftershocks and additional collapses they might cause. The safety of the team members comes above the data.
In case of two or more field investigation teams working in the same area, one should as much as possible liaise with these, with a view to avoiding duplication of effort and sharing experience.

As a general rule, one should also be careful to maintain good relations with the local community in the area being investigated. In areas that have suffered a major earthquake, residents may still be traumatised or shocked, and one needs to deal with them with tact and care. Even in cases of low-intensity earthquakes, one should take care to respect local cultural conventions (e.g. with respect to appropriate clothing).

12.3.4.5 Later (post-earthquake) activities

On return to base team members should take care to label carefully and archive all the collected data; all photographs, videos and other material should have in titles or captions clear data about the place where they were taken, names of the streets, buildings etc. All the data should be copied several times and stored in different archives, to prevent losses. It may be appropriate to continue liaison with other groups involved with the earthquake with a view to pooling and sharing data and experience.

12.4 Processing of macroseismic data

The way in which intensity is assessed varies enormously according to whether one is proceeding from traditional paper questionnaires, in which case the process is essentially a subjective matching of the data to descriptions in the scale, or whether one is using an automatic algorithm to process data from the internet. These will be discussed separately. Field observation data can be considered “traditional” in this respect.

12.4.1 Traditional intensity assessment

Although the conversion of descriptive information to numerical intensity data by use of an intensity scale is fundamental to macroseismic studies, the process was in general rather poorly documented in the past. This led to considerable variations in practice from worker to worker, resulting in serious inconsistencies in results. It is widely recognised that assessing intensity in the traditional way is to some extent a subjective exercise, and that some variations between workers will always occur, but it is better if these are minimised through common methodology as much as possible.

The following points apply to most common intensity scales:

- Data should be grouped by place prior to assessing intensity. By "place" is meant a village or town or part of a city. Places should not be too big (like a county) or too small (like a single house). When assessing intensity for a place, all the data relating to that place should be considered together. If there are fifteen reports from one village, a single intensity should be assigned to those fifteen jointly, rather than making fifteen assessments and combining them. It is common for intensity scales to use phrases like “in many cases”, or “in few cases”, and this cannot be assessed on the basis of one questionnaire, hence the need to combine them.

- Make sure there are sufficient data for a reasonable assessment. If there are too few reports, or the reports are too lacking in detail, it is better to record merely that the earthquake was felt rather than forcing an intensity value on inadequate data. In some cases it will be possible to make a range assessment, e.g. 4-5, >6, (4 or 5, more than 6) etc. A single report may be very unrepresentative of the general experience.

- For each place, compare the picture of earthquake effects provided by the data with the idealised pictures provided by each description of an intensity degree in the intensity scale, in order to look for the best overall fit. The match will seldom be perfect, so it is necessary to look for the most coherent, general comparison. It should be remembered that given the very variable nature of intensity, in any place individual effects may be observed that are higher or lower than those to be expected from the general (modal) intensity level. It is important not to give these too much attention. For example, if most of the data for a place are suggesting intensity 4, but there is a single exceptional report that a chimney fell, this chimney does not invalidate an assessment of intensity 4 for the place.

- When using a quantitative intensity scale (MSK, EMS) then the comparison of the data with the scale will usually be a question of making a best fit of the percentages of a particular observation that were recorded and the percentage ranges expected for each degree of the scale. For EMS-98, the procedures for assessing intensity are discussed in detail in the scale support material (Grünthal 1998).

- The absence of reports of a particular phenomenon may or may not be evidence that it did not occur, depending on the nature and quality of the data. It cannot automatically be inferred that, for instance, an absence of reports of damage indicates no damage occurred, although this will often be the case. A positive statement along the lines of "there was no damage" is more reliable.

- To make inferences from a particular source of data requires an understanding of the nature and limitations of that data source. For instance, newspapers often pluralise things for effect, so a newspaper report that says "pictures fell from walls" may mean one picture fell from one wall. Where the sources are historical documents the advice of a professional historian in understanding the nature of the documents should be taken.

- Effects on nature (landslides, ground water changes, etc) should only be used with caution, since their frequency is strongly influenced by local hydrological conditions and other factors not related to intensity. It is therefore very difficult to arrive at reliable intensity values for remote, largely uninhabited, rural areas. (This point has been found unpalatable by some, but unfortunately is realistic).

12.4.2 Automatic intensity assessment

The collection of macroseismic data rapidly from internet questionnaires lends itself to automatic data processing. If intensity can be assigned algorithmically, the results of the macroseismic survey can be continually updated and displayed in real time, a huge advantage. This also does away with any subjectivity in assessment, since the results are defined in terms of the algorithm, and are totally objective. The downside is that the correspondence between the algorithm and the actual intensity scale that it is intended to mimic is uncertain.

There are several systems in current use, but all can be divided into one of two approaches: those based on regression, and those based on an expert-systems approach.

The regression approach is typified by the "DYFI?" system, the basis of which is fully described in Wald et al (1999). In this system, each questionnaire is assessed as it is received, and scores are given based on answers to key questions. For each location from which responses are received, the scores from each question are tallied. The final score for the location is the weighted sum of the average scores for each question.

When the system was set up, a training set was compiled of scores for a set of locations, together with human-assigned intensities for those locations. From that training set, a regression equation was developed between location score and intensity (Figure 12.3). For a current earthquake, this equation gives the intensity for any location by simply converting the final score value, or "community weighted sum" (CWS). Intensity is calculated from the CWS according to the equation

$$I = 3.4 \ln CWS - 4.38 \tag{12.1}$$

This allows decimal intensities, in that, for instance, a CWS of 15 gives an intensity of 4.8 MM – but this should be tempered by the standard error of equation (12.1), which is unfortunately not given by Wald et al. (1999), but appears by eye to be between ± 0.5 and ± 1.0 degrees. The lower the CWS the greater the scatter in the regression, though this is probably mainly due to poorly constrained values in the training data set. The inherent uncertainty in computed values is uncertain, but likely to be higher for locations with few questionnaires.

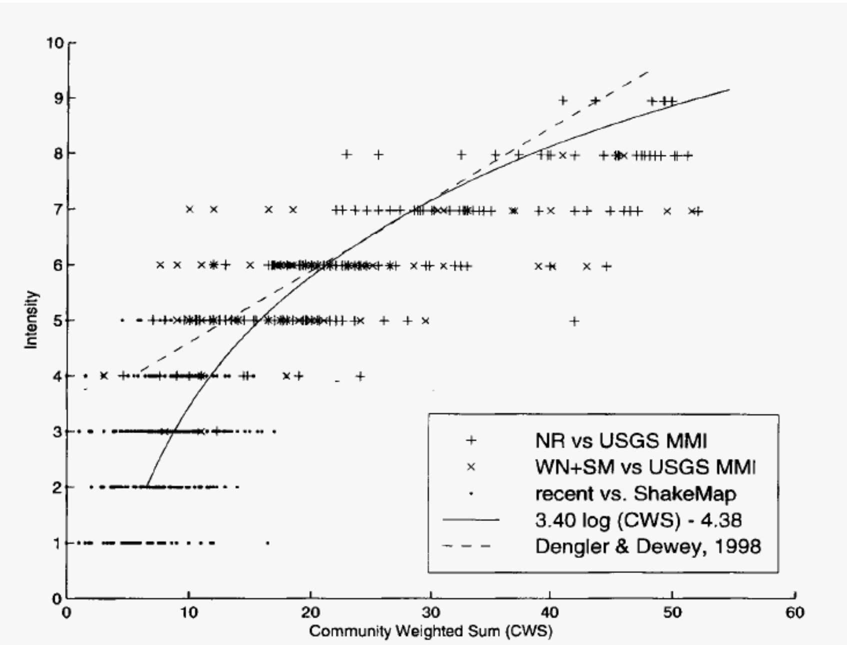


Fig. 12.3 Regression of community weighted sum against intensity; reproduced from Figure 1 in Wald et al. (1999). NR = Northridge, WN = Whittier Narrows, SM = Sierra Madre. For further information, see the original paper.

The system does not impose a minimum number of questionnaires before assigning an intensity, but the number received may be useful supplementary information in estimating uncertainty.

The expert systems approach is quite different, and seeks to emulate the thought processes of a seismologist using an intensity scale in the traditional way. Such a system is described by Musson (2006) for the EMS-98 scale. The basis of it is an assessment of the totality of reports received from a location compared to the requirements of the scale. For this purpose, for key effects, the proportion of observers at a location who reported the effect is computed. This might be, for instance, that 35% of questionnaires from a place answered yes to "did windows or doors rattle?". Such ratios cannot meaningfully be established from single or very few questionnaires, so for places with very few replies, only "felt" will be returned.

Once the ratios have been computed, the effects at each place are considered by a process of elimination. This runs as follows:

- First, was the earthquake felt at all? If all the reports are negative, the intensity is 1 EMS and processing stops. Second, are there many reports of substantial damage? If so, the intensity is 7 or 8 EMS (8 being the upper limit of the system) and more detailed tests are applied to choose which.
- If the intensity was not 1, 7 or 8, the next thing to look at is whether there is a high proportion of "strong" effects like objects falling, people running out, minor damage, and so on. If this is the case, the intensity is 5 or 6 EMS and more detailed tests are applied to choose which. If this is not the case, only intensities 2, 3 and 4 are left. If the preponderance of data suggests that many or most people felt the earthquake and there were some physical manifestations like rattling doors, the intensity is assessed as 4 EMS. If it is found that only people at rest on upper floors felt it, the intensity is 2 EMS. If neither of these is the case, the intensity is finally 3 EMS.

Both approaches have positive and negative features. Regression-based systems can be calibrated to past national data sets to maintain consistency; but they then inherit whatever subjective practices informed the intensity assessments of the calibration data set. The expert systems approach, in contrast, is tied to the interpretation of the actual intensity scale, and not any previous data sets (and therefore may not be precisely compatible with them).

The regression approach will always return a numerical intensity, where the expert systems approach will not. On the other hand, the uncertainty in intensity estimates from a regression-based system may be large, especially if based on few questionnaires. The expert systems approach effectively redefines the scale as a series of specific tests, from which it follows that there is no uncertainty at all in any assigned intensity value – at least, with respect to the data on which the assignment is made.

In both approaches, there is still the problem that a self-selected sample from a large population (the total number of inhabitants of the location) is likely to be unrepresentative. Therefore, besides any inherent uncertainty in assessment, there is an additional unquantifiable uncertainty as to the relation between the sample (the questionnaires received) and the total population.

Note that this uncertainty would be quantifiable if the sample was randomly drawn from the population, instead of being self-selecting. As well as a probable bias towards positive responses, there may also be a demographic bias, in that some categories of people are less likely to be internet users. These people are also likely to live in poorer housing, and there may in some cases be other influences on the data, for example in places where wealthy suburbs are built on high ground and poorer suburbs on reclaimed land.

More details on these two systems, and the actual software required to implement them, are available from USGS and BGS respectively, on request.

12.4.3 Accuracy of assessment

The previous paragraphs lead naturally into a consideration of what degree of accuracy in intensity assessment can be expected in general.

Given a certain strength of shaking, it is to be expected that buildings of equivalent strength will not respond in a completely uniform way. Rather, there should be a modal level of damage observed, with some buildings suffering less and others more. The net effect approximates to a normal distribution (as has often been seen in damage surveys). Thus, for any particular level of shaking, it is expected to be found that different percentages of the building stock of a given strength will suffer different degrees of damage. In assessing intensity (and this is true of the lower degrees as well as the damaging ones) one is usually dealing with a sample or estimate of the percentages that were observed, and attempting to match these to the expected ranges for one of the intensity degrees. In most cases, given a degree of robustness, an adequate fit can be found without much problem.

Difficulties can occasionally arise when this task is compounded, as it sometimes is, by one or other of two factors: (i) that the effects of an earthquake vary considerably over very short distances, due to a combination of local conditions and the complexity of earthquake ground motion; and (ii) information is often not complete. These two factors can have an effect on the level of accuracy that can be expected in intensity assessments. The variability of earthquake effects is well-known, as in cases where, of two identical houses side-by-side, one is heavily damaged and the other nearly intact. This may give a misleading impression of difficulty in assessing intensity which might actually disappear once a larger sample of houses was assessed. The difficulty with respect to information is that one is often working from an uncontrolled, possibly unrepresentative, sample of the whole data population (particularly when not working with data derived from a field investigation), and there may also be uncertainty about the condition of buildings before the earthquake. This can cause problems where the real percentage distribution of effects is obscured by the limited data. Also, even when the amount of data is good, there can be cases where the reported effects do not match unambiguously any of the "pen pictures" presented by the classes in the intensity scale.

In cases where one cannot determine intensities to a resolution of one degree, two degrees can be bracketed together to show the probable range. This can be particularly the case for lower intensity degrees; there are often cases where it is hard to be sure between intensity 2 or 3, or between 3 or 4, or between 4 and 5. In such cases one may write 4-5, meaning either intensity 4 or intensity 5.

One guideline that can be suggested is that the description of each degree should be considered the minimum case. For example, in a case in which the data satisfy the requirements for intensity 4, but certainly do not adequately satisfy the criteria for intensity 5, then the correct assessment is 4, even if the effects seem stronger than the basic intensity 4 description.

Intensity scales are designed to include the necessary degree of robustness to make identification of the different degrees as practical as possible. The number of degrees in a scale is controlled by the number of different levels that can be distinguished in normal use without too much difficulty. Experience shows that it is very unlikely that one could ever meaningfully discriminate intensities to a resolution of less than one degree of a twelve-degree scale. If one could state accurately in some case that the intensity was, for example, 6½, this would imply that a 23 degree intensity scale could be written, which is doubtful.

This reservation does not apply to algorithmically computed intensities; as shown above, a "DYFI?" intensity of 4.8 has a precise meaning – that the community weighted sum for the locality from the questionnaires received was 15. While it might not seem that "4.8 ± 0.5" is really more meaningful than "5" or even "4-5", it is reported that the fractional intensities computed this way do tend to show a smooth attenuation with distance (Atkinson and Wald 2007).

It may be no coincidence that modern intensity scales are converging on ten degrees as the optimal amount of discretisation possible. The JMA scale, with its degree 0 and split 5 and 6 degrees has ten degrees in total, and the major twelve-degree scales are effectively ten-degree scales, since in modern practice, intensity 11 and 12 are not used. At very high intensities, scales tend to saturate once all buildings have been destroyed. In areas where the building stock is very poor, this can be as low as 8 or 9 MMI-MSK-EMS. EMS-98 attempts to discriminate intensities 11 and 12 by extrapolating damage distributions to building stock with modern anti-seismic design, but this is largely untested in practice. Some other scales define intensity 11 and 12 in terms of secondary effects that are actually due to surface faulting, slope failure or liquefaction, and are not truly indicators of intensity.

12.4.4 Equivalence between scales

The translation of values from one scale to another has been discussed in detail by Musson et al. (2010), whose conclusions can only be summarised here.

It has often been the practice to attempt to express the equivalence between different intensity scales by way of a chart that compares different degrees of a scale by a series of rectangles overlapping to a smaller or larger extent. Such charts are unhelpful, partly because they imply that, for instance, intensity 5 in one scale may be "slightly higher" than intensity 5 in another scale, when in integer degrees there is no "slightly higher". Secondly, any set of intensities is a combination of the scale employed and the working practices used in the assessment. One worker may make the assumption that if there is any damage, the intensity must be at least 6, another worker may not, and the result will be consistent variation even if both are using the same intensity scale.

For practical purposes, therefore, it is much preferable to revisit the original data and make a fresh intensity assignment with the desired intensity scale. However, this may not always be possible.

Comparing the scales as written, rather than as used, Musson et al. (2010) found no significant differences between MM-56, MSK, MCS and EMS-98 This is in accord with the table of equivalences by Shebalin in the original MSOP (Willmore 1979) for MM-56, MCS and MSK. It is noted though, that in practice, intensity data points assigned with MCS have a tendency to be higher than those assigned using other scales. The Stover and Coffman (1993) scale breaks the pattern slightly, since 1 MM-93 could be 1 or 2 EMS-98, and more importantly, 4 MM-93 could be 4 or 5 EMS-98.

The higher degrees of scales cannot really be compared because of saturation problems, as discussed above.

A rough equivalence for the JMA (2009) Scale is given in Tab. 12.1 below. This varies significantly from the table given in Musson et al. (2010), due to the changes made in the 2009 revision of the JMA scale, after Musson et al. (2010) was submitted.

Tab. 12.1 Equivalence between JMA-09 and EMS-98 intensity values

JMA Scale	*EMS-98*
0	1
1	2
2	3
3	4
4	5
5 Lower	6
5 Upper	7
6 Lower	8
6 Upper	9
7	10

12.4.5 Presentation of intensity data

Practice in the earlier part of the 20th century was generally to publish intensity data in the form of an isoseismal map. An isoseismal can be defined as a line bounding the area within which the intensity is predominantly equal to, or greater than, a given value. No definitive method of contouring has ever been agreed. Some workers adopt a practice of overlaying a grid on the data and taking the modal value in each grid square prior to contouring, others prefer to work directly on the plotted intensity values. Workers have differing preferences for the amount of smoothing, extrapolation, etc, that is to be employed. Thus, the drawing of isoseismals has always been to some degree subjective.

While an isoseismal map often gives a good visual impression of the effects of an earthquake, and the areas within each isoseismal can be used for some purposes (e.g. estimation of focal depth; see 12.5.5.), such maps are inadequate for modern studies, partly due to the subjectivity problem, and partly because many applications of interest require point data (e.g. Bakun and Wentworth 1997, Gasperini et al. 1999, Musson and Jiménez 2008).

The primary requirement, therefore, is to publish the intensity data for any earthquake in the form of a table of intensity data points (IDPs), where each IDP has, as a minimum, latitude, longitude and intensity (using Arabic numerals, not Roman ones), and may also have locality name, some quality factor (for instance, the number of questionnaires contributing to the assessment) and other metadata. Such publication is now sometimes done in the form of an online database, much to be encouraged – SISFRANCE (www.sisfrance.net*)* is an example (Fig. 12.4).

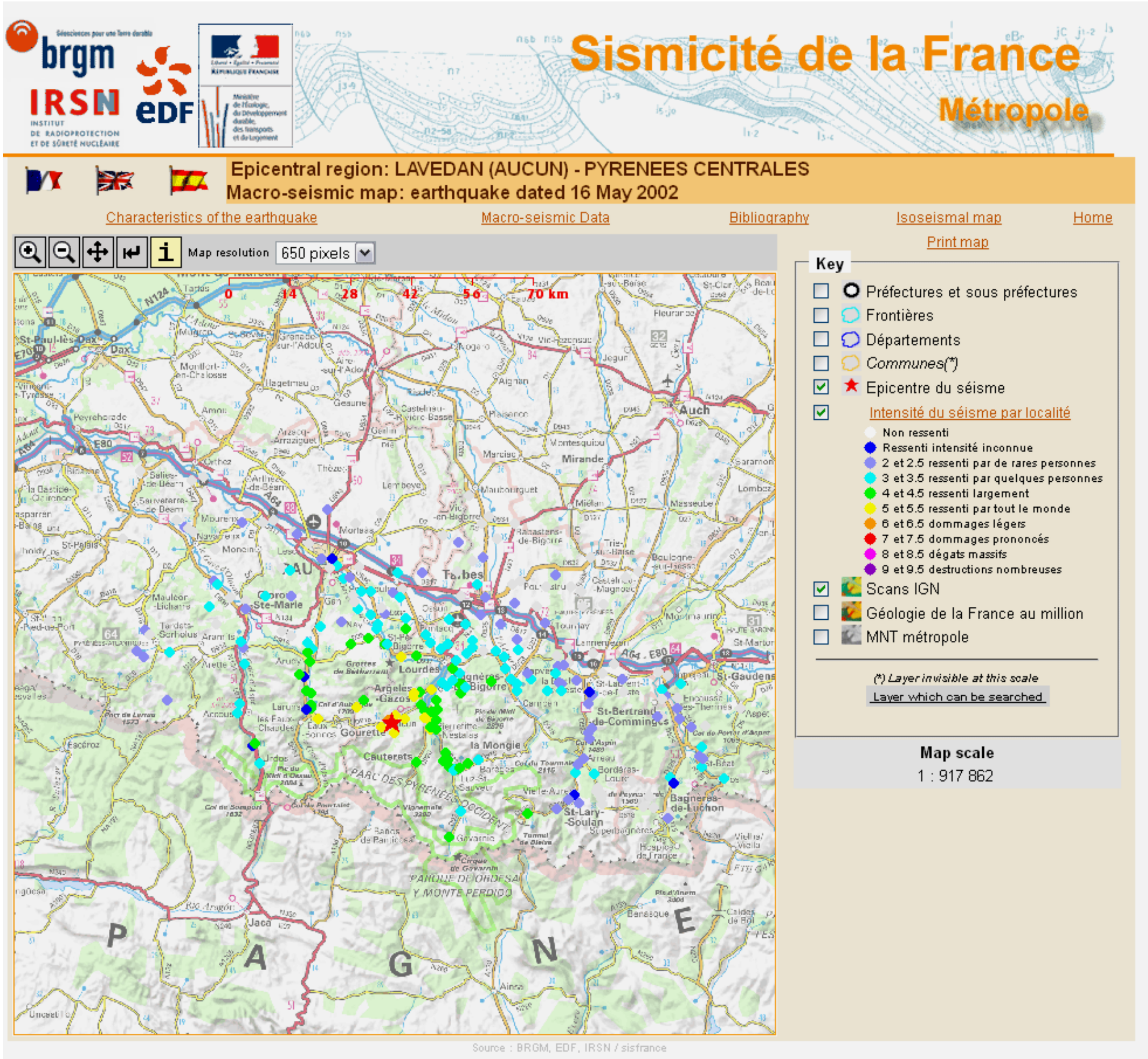


Fig. 12.4 Screenshot from the SISFRANCE website, showing a macroseismic display of a Central Pyrenees earthquake from 2002.

Mapping of intensity data is now predominantly done by showing maps of the IDPs themselves. There are three principal ways of representing IDPs on a map. The simplest is to plot each intensity as a number. This works adequately if there are only a few well-spaced points to be displayed, but if the point density is high, the map quickly becomes hard to read. Also, such a map does not give a very clear visual impression of the overall intensity distribution. A better alternative is the set of international symbols (first introduced by KAPG, the Commission of the Academies of Sciences of Socialist Countries for Planetary Geophysical Research) based on colouring in different proportions of small circles (Fig. 12.5). This gives more of a visual impression, and can be used in monochrome figures. The KAPG symbols are only really standard between intensities 2 and 8; outside this range they vary between different studies. Those shown in Fig. 12.5 are as used in Shebalin (1973).

With colour printing becoming more accessible in journals, and straightforward in internet publication, the most common system now is to use coloured dots for IDPs. While there is no single standard colour scale, the norm is to use a colour spectrum such that low intensities use blues and greens, middling ones use yellow and orange, and higher ones use reds, browns, purples and black. Fig. 12.5 shows such a scheme, devised for the Archive of Historical Earthquake Data (AHEAD), produced by the NERIES project in Europe (see http://www.emidius.eu/AHEAD/), which includes a convention for uncertain values split over two degrees. In this system, "felt" is plotted as an empty green circle. Also shown is the colour scale for use with the DYFI? System. The SISFRANCE colour scheme is visible in Figure 12.4.

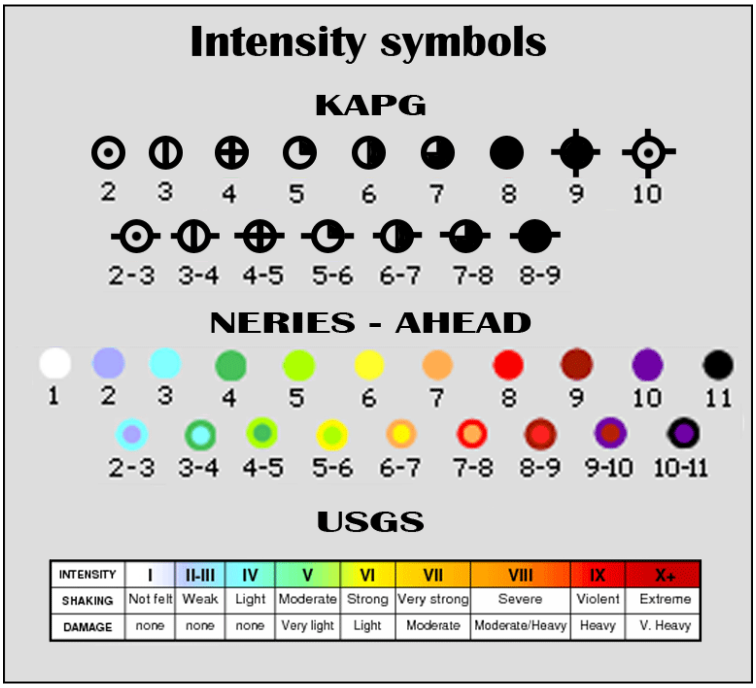


Fig. 12.5 Three different systems for plotting intensity values; monochrome symbols and two approaches to using colour.

Isoseismal maps still have their uses. The degree of smoothing employed in their construction should reflect the purposes to which the resulting map will be put. If the map is intended for microzonation work, i.e. to point up areas where seismic hazard may be enhanced owing to local soil conditions, then smoothing will be at a minimum, and isoseismals will be as convoluted as the data. If the map is intended for other purposes (calculation of earthquake parameters, attenuation studies, tectonic studies, etc) then the curves will normally be smoothed so that only major re-entrants and outliers are shown. In practice, smoothed isoseismals are much more common. As a general rule, re-entrants and outliers should not be drawn unless suggested by a grouping of at least three data points. If isoseismals have to be interpolated or extrapolated across areas of water, or areas without data points, these sections of the lines should be shown as dashed. In cases where, for example, an epicentre is offshore, and only (say) a 120^{o} arc of each isoseismal would fall onshore, it is not correct to project the whole of the remaining 240^{o} of each isoseismal on a map, even as a dotted line. Only the onshore section should be drawn, with each line tailing off with a short dotted section offshore if desired. Plotting isoseismals that are completely offshore and merely projections of an intensity attenuation curve should not be done. For onshore earthquakes with few data, it is not good practice to attempt to draw isoseismals conjectured from one or two points only; at least three mutually supporting data points for one intensity value should exist before one attempts to draw even a partial isoseismal for that value. Figure 12.6 shows some examples of acceptable and unacceptable drawing of isoseismals.

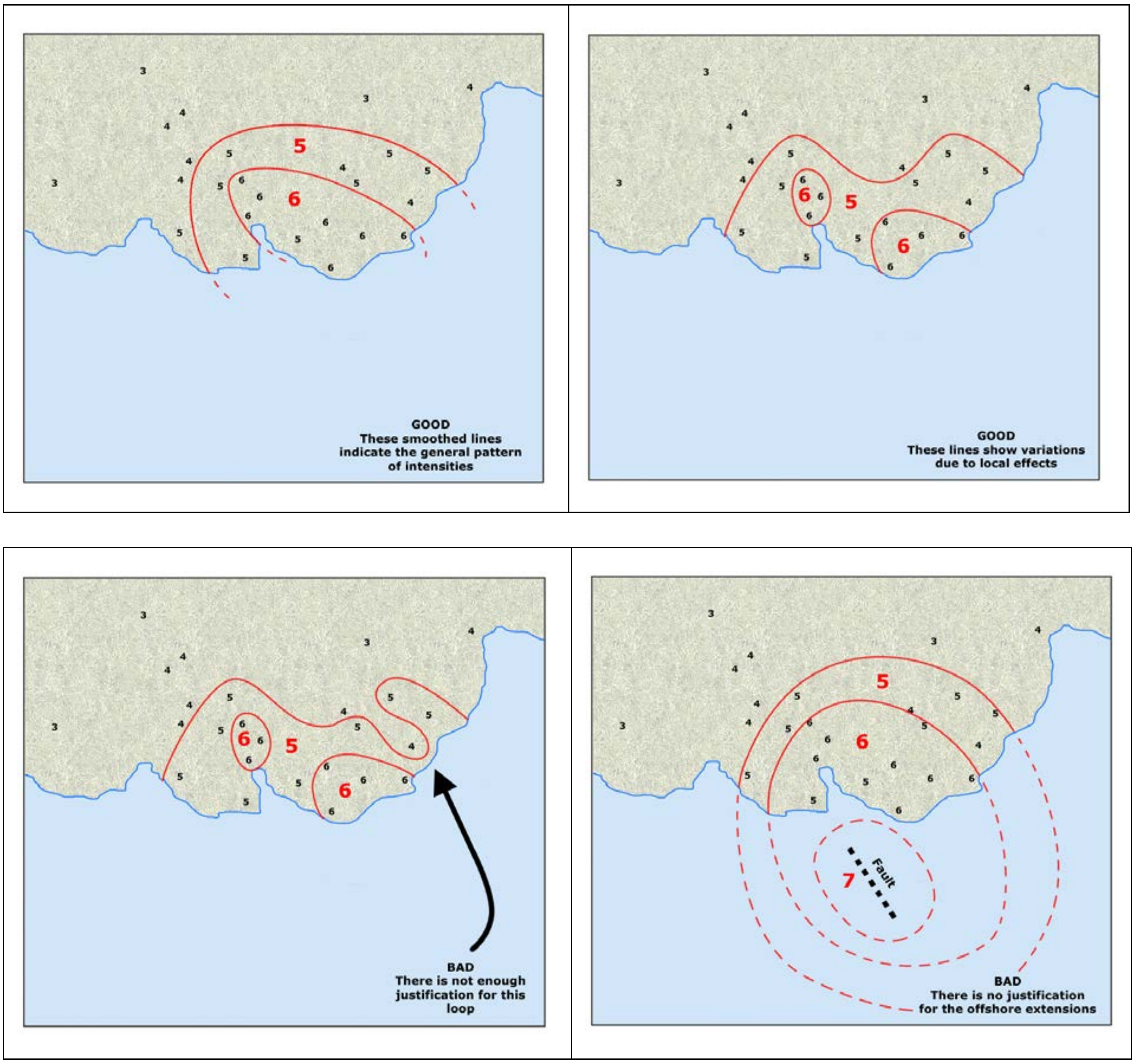


Fig. 12.6 Two **e**xamples each of acceptable (upper row) and unacceptable practice (lower row) in drawing isoseismals.

Computer contouring programs often do not give good results with macroseismic data, as too often parts of the macroseismic field are poorly constrained; though Schenková et al (2007) report good results from kriging (a linear least-squares method commonly used for interpolation of geospatial data in the earth sciences).

12.4.6 Exchange of macroseismic data

Earthquakes are obviously no respecters of international boundaries, and it is not uncommon for the felt area of a significant earthquake to extend into more than one country. In the case of the 1992 Roermond earthquake, macroseismic data was collected from the Netherlands, Germany, Belgium, Luxembourg, France, the UK, Switzerland and the Czech Republic (Haak et al 1995). Exchange of data is clearly important. However, problems can arise if what is exchanged is simply tables of IDPs, as these may be assessed using different scales or methods, and may not be compatible. Some means are necessary for exchanging data at a lower level – that of the original questionnaire, at least in some abstracted form. A format is needed that can provide a record for each questionnaire that includes, besides location, values representing the effects reported. The greater the degree of international standardisation of questionnaires, the easier such a format will be to construct, but clearly, it needs to represent a superset of the types of information collected by different questionnaires and used by different systems. At the time of writing, there are initiatives to develop such a format in the scope of QuakeML (https://quake.ethz.ch/quakeml/QuakeML).

12.5 Determination of earthquake parameters from macroseismic data

The determination of earthquake parameters (principally epicentre and magnitude, also depth in some cases) from macroseismic data is of critical importance for historical seismology, where it is the only way in which one can assess earthquakes of the pre-instrumental period. For observatory practice, these parameters will of course be determined from instrumental data, but it can be instructive to compute the macroseismic equivalents as well, partly as a means of checking how a recent earthquake would appear in the catalogue had it occurred before 1900. The highest intensities may in some cases be some distance from the instrumentally-determined epicentre (i.e. the point on the earth's surface above the focus of the earthquake where the rupture initiated).

There is also one purely macroseismic parameter, epicentral intensity (and its close relation, maximum intensity) to be considered.

12.5.1 Epicentral intensity

Epicentral intensity, usually abbreviated Io, is a parameter commonly used in earthquake catalogues but rarely defined, and it is clear that different usages exist in practice (Cecić et al 1996). The meaning of the term is clearly the intensity at the epicentre of the earthquake, but since it is likely that there will not be observations exactly at the epicentre itself, some way of deriving this value is necessary. The two main techniques that have been used in the past are:

1. Extrapolation from the nearest observed intensity data to the epicentre without changing the value, or use of the value of the highest isoseismal. Thus if there are a few data points of intensity 9 near the epicentre, the Io value is also 9. If the epicentre is significantly offshore, Io cannot be determined.

2. Calculating a fractional intensity at the epicentre from the attenuation over the macroseismic field, using a formula such as that by Blake (1941) or Kövesligethy (1906).

In this case, because this is not an observed value (and not a "true" intensity) it may be expressed as a decimal fraction without contravening the rule that intensity values are integer.

It is recommended that these two methods be discriminated between by the notation used. Thus an integer number (9 or IX) indicates method (1) and a decimal number (9.0 or 9.3) indicates method (2). It is recommended that one should not add arbitrary values to the maximum observed intensity when deriving an Io value; the arbitrary amount is too subjective.

As well as epicentral intensity, a useful parameter is maximum intensity, abbreviated Imax. This is simply the highest observed intensity value anywhere in the macroseismic field. For onshore earthquakes, Io and Imax may be equal. For offshore earthquakes it is often not possible to estimate Io (especially if method 1 is used), but Imax can be given for any earthquake.

12.5.2 IDPs and isoseismals

There are two basic strategies in determining parameters from macroseismic data – to work with the raw IDPs, or to draw isoseismals and work with those.

The reason for using isoseismals is this: they can reduce or eliminate effects due to population distribution. Consider Fig. 12.7, in which an earthquake produces its highest intensities at several places on the mainland and in one island location. A seismologist, knowing that the irregular distribution is due to topography, might estimate an isoseismal as shown, which might be a better expression of reality than that obtained from processing of the individual data points, in which the clustering due to population factors has an influence. From an isoseismal one could deduce an epicentre in the position of the solid star; from data points one would be likely to obtain the position of the open star.

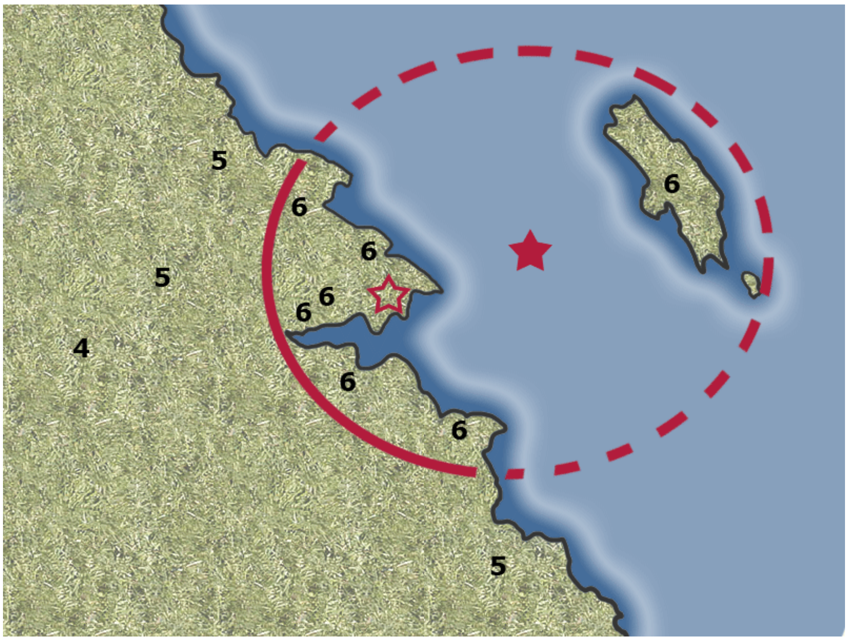


Fig. 12.7 Illustration of different macroseismic epicentres obtained from (a) intensity 6 data points (open star) and (b) a possible interpretation of isoseismal 6 (solid star).

However, because of the subjectivity in isoseismal construction, modern opinion favours the direct use of the IDP distribution, without any isoseismals. Currently three systems are available for the computation of the main earthquake parameters from IDP sets. These are the Bakun-Wentworth (B-W) method (Bakun and Wentworth 1997), the BOXER method (Gasperini et al. 1999) and MEEP (Macroseismic Estimation of Earthquake Paramaters, Musson and Jiménez 2008). These will be discussed further in the next sections. Fig. 12.8 shows a comparison of results from the three methods for a sample earthquake. In this case, the parameters obtained can be compared to instrumental values; for historical earthquakes it can be the case that location methods disagree with no clear indication which is more reliable.

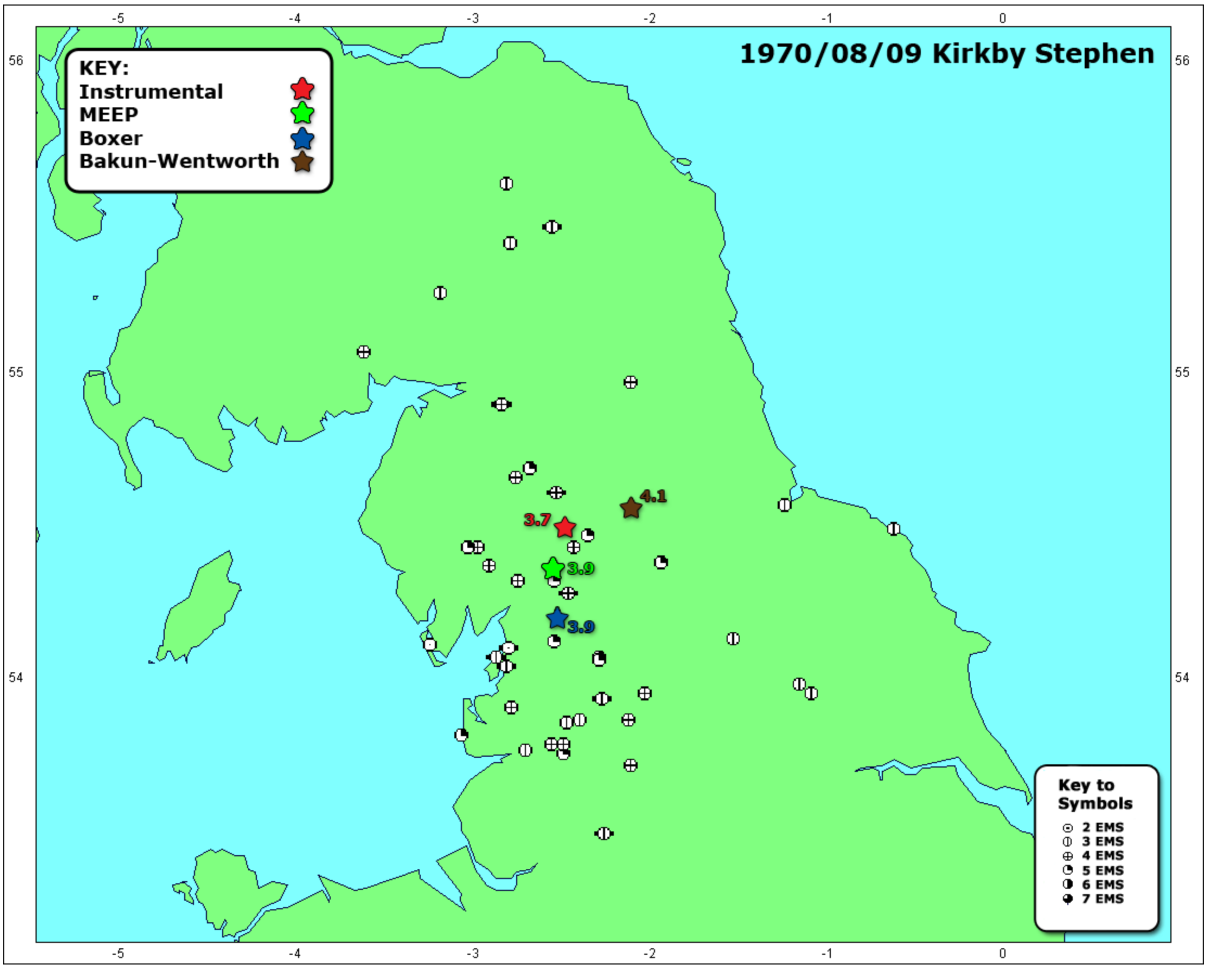


Fig. 12.8 Comparison of macroseismic parameter estimations for a British earthquake, together with the instrumental parameters.

12.5.3 Macroseismic epicentre

Macroseismic epicentre is an expression which has been used in the past to convey different concepts, never properly defined. On the one hand, the macroseismic epicentre can be considered to be the best estimate made of the position of the epicentre without using instrumental data. This may be derived from any or all of the following as circumstances dictate: position of highest intensities, shape of isoseismals, location of reports of foreshocks or aftershocks, calculations based on distribution of intensity points, local geological knowledge, analogical comparisons with other earthquakes, and so on. This is a rather judgmental process with some subjectivity, and does not lend itself to simple guidelines that can be applied uniformly in all cases.

More commonly, the term is used for the point on the Earth's surface from which the macroseismic field appears to radiate. In the past this was often the centre of the highest isoseismal or the weighted centre of the two highest isoseismals. The terms “barycentre” “intensity centre”, “macrocentre” and “macroseismic centre” have been proposed as alternative terms.

These two points are often the same, but need not be. For any study of the tectonics of an area, the macroseismic epicentre is perhaps more useful. For studies of seismic hazard, especially those using a technique like extreme value statistics, the barycentre gives a better indication of the hazard potential of an earthquake.

The BOXER method computes epicentres by taking the trimmed mean of the latitudes and longitudes of the highest intensity locations (using also the second-highest values if there are insufficient points otherwise). It also computes an estimate of the rupture dimensions of the fault; this is the only method that handles extended sources from IDP data.

The B-W and MEEP procedures both work on the basis of attempting to minimise residuals from a theoretical intensity distribution that can be derived from some attenuation model, a procedure first proposed by Perruzza (1992). In the case of the B-W method, the model used is of the type expressing intensity as a function of magnitude and distance. In MEEP, the model used is one expressing the reduction of intensity from the Io value as a function of distance. In both cases, a grid search is used to locate the position at which the misfit between the best set of predicted values and the actual values is minimised. Both these methods are capable of locating earthquakes offshore, which BOXER generally cannot do. However, especially with poor data sets, they can get trapped in false minima.

12.5.4 Macroseismic magnitude

The use of macroseismic data can give surprisingly robust measures of earthquake magnitude. Early studies attempted to correlate epicentral intensity with magnitude; however, epicentral intensity can be affected by focal depth or soil amplification, so such simple correlations may perform poorly.

The total felt area (A) of an earthquake, or the area enclosed by one of the outer isoseismals (usually 3 or 4), tend to be a better indicator of magnitude, being not much affected by depth (except in the case of truly deep earthquakes) or soil conditions, and since the relationship between the area and magnitude is logarithmic, even a substantial mis-estimation of the total felt area will not produce an overly large error in the magnitude. For earthquakes below a threshold magnitude (about 5.5 Mw) magnitude and log felt area scale more or less linearly, and so equations of the form

$$M = a \log A + b \qquad (12.2)$$

can be established regionally by examination of data for earthquakes for which macroseismic data and instrumental magnitude are both available. For larger earthquakes, differences in spectral content may affect the way in which earthquake vibration is perceived, and a different scaling appears to apply. In Frankel (1994) the form

$$M = n \log (A / \pi) + (2 m / (2.3 \sqrt{\pi}))\sqrt{A} + a \qquad (12.3)$$

is used to represent the full magnitude range, where n is the exponent of geometrical spreading, a is a constant, and

$$m = (\pi f)/(Q \beta) \qquad (12.4)$$

where f is the predominant frequency of earthquake motion at the limit of the felt area (probably 2-4 Hz), Q is shear wave attenuation quality factor and β is shear wave velocity (3.5 km/sec). Using this functional form and comparing world-wide intraplate earthquakes with interplate earthquakes from one region (California), Frankel found the difference in magnitude for the same felt area to be on average 1.1 units greater for California.

In the above equations, M has been used for generic magnitude; for any particular magnitude equation it is important to specify what magnitude type the derived values are compatible with (Ms, ML, Mw etc). It is also useful to determine the standard error, which will give a measure of the uncertainty attached to estimated magnitude values.

Magnitudes calculated by BOXER adapt a model proposed by Sibol et al. (1987):

$$M = a + b\, Io^2 + c \log^2 (A_I). \qquad (12.5)$$

Here A_I is the area of each intensity I, calculated from the median distance of IDPs of value I. The formula is applied for each intensity in the data set, and the magnitude is given by the weighted average.

For the B-W method, since it is based on the optimisation of a model including magnitude, the optimal magnitude is a by-product of the location procedure.

MEEP adapts the Frankel model given above to estimate the limit of intensity 3 for a hypothetical magnitude. The radii of higher “isoseismals” are then interpolated and compared to the data to find the optimal magnitude.

Common to all methods is the need to perform a regional calibration before magnitude can be calculated from intensity data, something not needed for computation of epicentres.

12.5.5 Estimation of focal depth

The estimation of focal depth from macroseismic data was first developed by Radó Kövesligethy. His first paper on the subject presented the formula

$$I - Io = 3 \log \sin e - 3 \alpha (r/K) (1 - \sin e) \qquad (12.6)$$

where sin e = h / r (h is depth, r is isoseismal radius) and K is the radius of the earth, and α is a constant representing anelastic attenuation (Kövesligethy 1906). A second paper, (Kövesligethy 1907) contains a different equation:

$$I - Io = 3 \log \sin \varphi \qquad (12.7)$$

where φ is the angle of emergence. Why the absorption term was dropped in this publication is unclear. Equation 12.6 was subsequently rewritten and modified slightly by Jánosi (1907), to reach the now well-known formula

$$Io - I_i = 3 \log (r / h) + 3 \alpha m (r - h) \qquad (12.8)$$

where r is the radius of the isoseismal of intensity I_i and m = log e (Euler's constant). This work was developed further by Blake (1941) whose contribution was essentially a reduction and simplification of equation (12.8); Blake's version is still used by some workers today, but Kövesligethy's original equation (in Jánosi's version) is more commonly encountered. Kövesligethy's equation became more widely known, in the form of equation (12.8), through the work of Sponheuer (1960). However, although Sponheuer references Kövesligethy (1906) in his text, he cited Kövesligethy (1907) in the reference list, and the relative inaccessibility of these papers, and this misreference, has caused some confusion which it has only recently been possible to unravel. A further puzzle is that Jánosi (1907) attributes equation to (12.8) to Cancani, transmitted by Kövesligethy; the involvement of Cancani in this is unclear (Zsiros 1999, pers. comm.).

The constant value of 3 used in equations 12.6 - 12.8 represents an equivalence value between the degrees of the intensity scale and ground motion amplitudes. This may vary regionally, and can be optimised (Levret et al 1996). The attenuation parameter α should be determined regionally by group optimisation on an appropriate data set - not for individual earthquakes; some proposed values for different parts of Europe are given in Karník (1969).

Io here is an interpolated value, not the highest observed integer value, and has to be solved for as well as solving for h. This can be done graphically - one can fit the isoseismal data to all possible values of h and Io and find a minimum error value consistent with the observed maximum intensity (e.g. Burton et al 1985, Musson 1996).

Macroseismic depth determination has attracted less interest than epicentre and magnitude, partly because for large earthquakes, focal depth is not of great practical importance. While the application of equation (12.8) can give quite good results for small crustal earthquakes, irregular data sets have a tendency to depress the depth estimate to the maximum allowed, and this is probably a worse problem when using IDPs rather than isoseismals. Of the three recent analysis methods from IDPs, MEEP is the only one that supports depth determination, using equation (12.8).

12.5.6 Intensity attenuation

Intensity attenuation, the rate of decay of shaking with distance from the epicentre, can be expressed in two ways. Firstly, there is the drop in intensity with respect to the epicentral intensity. This is shown by the Kövesligethy (1906) formula in equation (12.8).

It is generally more useful to express intensity attenuation as a function of magnitude and distance. Such formulae often have the functional form

$$I = a + b M + c \log R + d R \qquad (12.9)$$

where R is hypocentral distance, and a, b, c and d are constants. (The last term is sometimes dropped, especially in intraplate areas). Since most earthquake catalogues include magnitude as a parameter, this form of intensity attenuation is extremely useful in seismic hazard studies. This type of model is also that required by the Bakun-Wentworth method described above.

A particular use of this type of model is in estimating the expected impact of an earthquake that has just occurred. Since a magnitude will be available at once, an equation of the form of (12.9) can give an immediate idea of how far the earthquake will be felt.

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