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 emphasize this point (it is hard to write "VII"). Nowadays the use of Roman numerals is largely a matter of taste, and most seismologists find Arabic numerals easier to process by computer.

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 recognizable 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).

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) and became 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. More recent attempts to modernize the MM scale further, e.g., that of Brazee (1978) have not caught on.

In 1964 the first version of the MSK Scale was published by Medvedev, Sponheuer and Karnik (Sponheuer and Karnik, 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

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modifications in the mid 1970s and in 1981 (Ad hoc group, 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 organization 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).

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 macroseismics 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.

12.1.1 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.

An essential feature of this scale is that, whereas other intensity scales such as the Modified Mercalli scale (in its 1956 incarnation, see below) have attempted to distinguish between the effects of earthquake shaking on buildings of different construction types, using type as an analog of strength, the EMS 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 also handled in a new way, with discrimination 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.

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 that 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 also contains examples of intensity assignment and can be obtained in full at the following web address:

http://seismohazard.gfz-potsdam.de/projects/ems/index.html.

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 Europe, and has been used successfully for assessing modern earthquakes in many parts of the world.

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 generalized form for educational purposes.

EMS intensity	**Definition** (Description of typical observed effects (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.

12.1.2 Modified Mercalli (MM) Scale

Since none of the more recent versions of the MM Scale have found wide acceptance, the version that follows is Richter's 1956 draft, which is probably the most used version at the time of writing (some seismologists still use the 1931 version, however).

I Not felt. Marginal and long period effects of large earthquakes.

II Felt by persons at rest, on upper floors, or favorably placed.

III Felt indoors. Hanging objects swing. Vibration like passing light trucks. Duration estimated. May not be recognized as an earthquake.

IV Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.

V Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle).

VII Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluvial areas sand and mud ejected, earthquake fountains, sand craters.

X Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI Rails bent greatly. Underground pipelines completely out of service.

XII Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A: Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B: Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C: Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D: Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

(From Richter, 1958).

12.1.3 Accuracy of assessment

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 available information (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.

Intensity scales are therefore 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, 6, this would imply that a 23 degree intensity scale could be written, which is doubtful. In cases where one can not 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.

A suggested guideline in EMS 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 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.

12.1.4 Equivalence between scales

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 either by a straight equivalence of grades or by a series of rectangles overlapping to a smaller or larger extent. Such charts should be avoided if possible, as their results are not wholly reliable. It is much preferable to revisit the original data and make a fresh intensity assignment with the desired intensity scale. The same is true with respect to empirical equations which have occasionally been suggested in the past to relate one scale to another.

For the various twelve-degree scales, it is likely the case that differences in the way that different seismologists have used intensity scales in practice can substantially outweigh any actual differences in the scales themselves. In general the equivalence between MM56, MSK and EMS is roughly one to one. The principal difference between EMS and earlier scales is that it is more clearly written, and structured in such a way as to make it easier for different investigators to obtain consistent results.

A rough equivalence for the original JMA Scale is given in the Tab. 12.1 below.

Tab. 12.1 Equivalence between JMA and EMS scale.

JMA	EMS
1	2
2	3
3	5
4	6
5	8
6	10
7	11

12.2 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.

There is a third source - documentary material - 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.

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.

12.2.1 Macroseismic questionnaires

The request has often been made for someone to produce a standard macroseismic questionnaire that could be used by everyone and ensure compatibility of results from one investigation to the next. The reason that such a thing has never been achieved is simply because social and practical considerations vary from case to case and make a unified approach impossible. To some extent, different cultures require different questionnaires simply because of the different fabric of everyday surroundings upon which the effects of an earthquake will become manifest. But more fundamental are the practical considerations facing the seismologist who wishes to distribute questionnaires - to whom will he give them?

There are 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 favor of positive responses. Online Internet questionnaires have already been used with success in California (Wald et al., 1999) and this means of dissemination will become more important in the future as the proportion of the population with Internet access increases.

(ii) The randomly selected individual: there exists a methodology, highly developed in the social sciences, for disseminating questionnaires in such a way as to maximize 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 organize 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/post officer/police superintendent's officer 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 can not 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 have 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.

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/her 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 questionnaire, which is a synthesis of several in active use, is shown below.

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. Were any animals nearby frightened?
   No [ ] Yes, pets [ ] Yes, farm animals [ ] No animals nearby/don't know [ ]

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	[ ]	[ ]	[ ]
Small objects shifted or fell	[ ]	[ ]	[ ]
Books or similar shifted or fell	[ ]	[ ]	[ ]
Furniture shook visibly	[ ]	[ ]	[ ]
Furniture shifted out of place	[ ]	[ ]	[ ]
Furniture toppled over	[ ]	[ ]	[ ]
Pendulum clocks stopped	[ ]	[ ]	[ ]
Plants shook	[ ]	[ ]	[ ]
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?
    ……………………………………………………………………………………
    ……………………………………………………………………………………

12.2.2 Field investigations

Following a high intensity earthquake, a field investigation needs to be made as soon as possible. It is advisable to plan such investigations as much as possible before an earthquake even occurs, so that the investigation team (typically two to six people) can be assembled, together with necessary equipment, and leave for the affected area at very short notice. Team members should include people who have experience in earthquake engineering and geotechnical engineering as well as seismology. The following paragraphs draw largely on EEFIT (1993).

In the field, it is necessary to combine both detailed and general surveys of structural behavior. 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. External and internal damage should both be recorded, 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 poor 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.

12.3 Processing of macroseismic data

12.3.1 Assessing intensity from data

Although the conversion of descriptive information to numerical intensity data by use of an intensity scale is fundamental to macroseismic studies, the process has in general been rather poorly documented. This has led to considerable variations in practice from worker to worker, resulting in serious inconsistencies in results. It is widely recognized that assessing intensity is to some extent a subjective exercise, and that some variations between workers will always occur, but it is better if these are minimized 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.

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.

For each place, compare the picture of earthquake effects provided by the data with the idealized 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, 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 can not 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 pluralize things for effect, so a newspaper report that says "pictures fell from walls" may mean only one picture fell from a 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).

The use of automatic algorithms to assess intensity by computer has been experimented with since at least the mid 1980s (e.g., Zsiros, 1989). This has the advantage of removing any possible subjectivity or bias from the procedure. Such algorithms require careful calibration, and a certain amount of checking is still required. However, this is a developing field. Wald et al. (1999) demonstrate that the combination of algorithms for intensity assessment with on-line questionnaires allows the possibility of producing intensity maps extremely rapidly in the wake of a felt earthquake in areas where a very high proportion of residents have Internet connections.

12.3.2 Isoseismal maps

The presentation of intensity data is usually done in the form of a map. As well as plotting intensity points, it is usually useful to be able to draw contour lines of equal intensity, called isoseismals. 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 precise instructions can be given for drawing isoseismals as no definitive method 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, at present, the drawing of isoseismals is to some degree subjective.

However, some guidelines can be given. The degree of smoothing employed 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. It can be argued that highly detailed isoseismals present too many practical problems, and that microzonation is better served by damage maps.

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 epicenter is offshore, and only (say) a 120 degree arc of each isoseismal would fall onshore, it is not correct to project the whole of the remaining 240 degrees 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.

In a case where one has data for intensity 5 and intensity 8, and data points assessed at 6-7, it is possible to have isoseismals labeled 5, 6-7 and 8. For analytical purposes it is best to treat the 6-7 isoseismal as the 6 isoseismal, and conclude that the data are insufficient to draw the 7 isoseismal. In cases where it is possible to draw isoseismals for intensities 6 and 7, one should definitely not attempt to draw a 6-7 isoseismal between them.

Computer contouring programs usually do not give good results with macroseismic data. This is because local variations in intensity can easily upset contouring algorithms by suggesting a gradient that doesn't exist.

In plotting the intensity data points on a map, the most common practice is to use Arabic numerals for each data point. Roman numerals can become very confusing when data are close together. A set of international symbols (first introduced by the Commission of the Academies of Sciences of Socialist Countries for Planetary Geophysical Research (KAPG)) based on coloring in different proportions of small circles (Fig. 12.1) is a clear alternative; as is the use of colored dots. It is strongly recommended that isoseismal maps should always have the data points displayed on them.

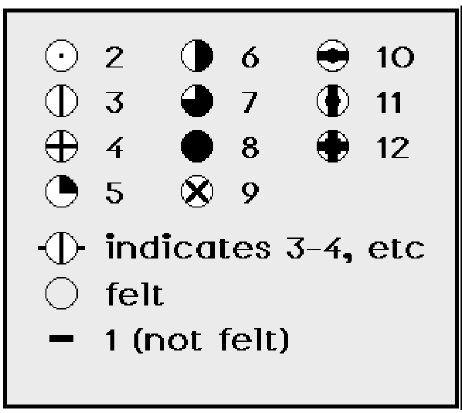

Fig. 12.1 Symbols for plotting intensity values. Those for intensities 2-9 are standard. There do not appear to be any recognized standard symbols for intensities 10-12, felt or not felt; the ones above are offered as suggestions.

The use of modern software, databases, GIS and Internet applications, combine to aid the display, analysis and communication of intensity data. Two examples are given in Fig. 12.2. These both show data from the 23 January 1980 Modica (Sicily) earthquake. The first (above) shows the data from the web-enabled DOM4.1 macroseismic database (http://emidius.mi.ingv.it/DOM/) displayed in both text and graphical formats. The second (below) shows the same data displayed using the Wizmap II seismological display program, with the KAPG symbol set as shown in Figure 12.1, and estimated isoseismals drawn purely from a standard Italian intensity attenuation formula (see 12.3.4). The Wizmap program can be downloaded from http://www.gsrg.nmh.ac.uk/hazard/wizmap.htm.

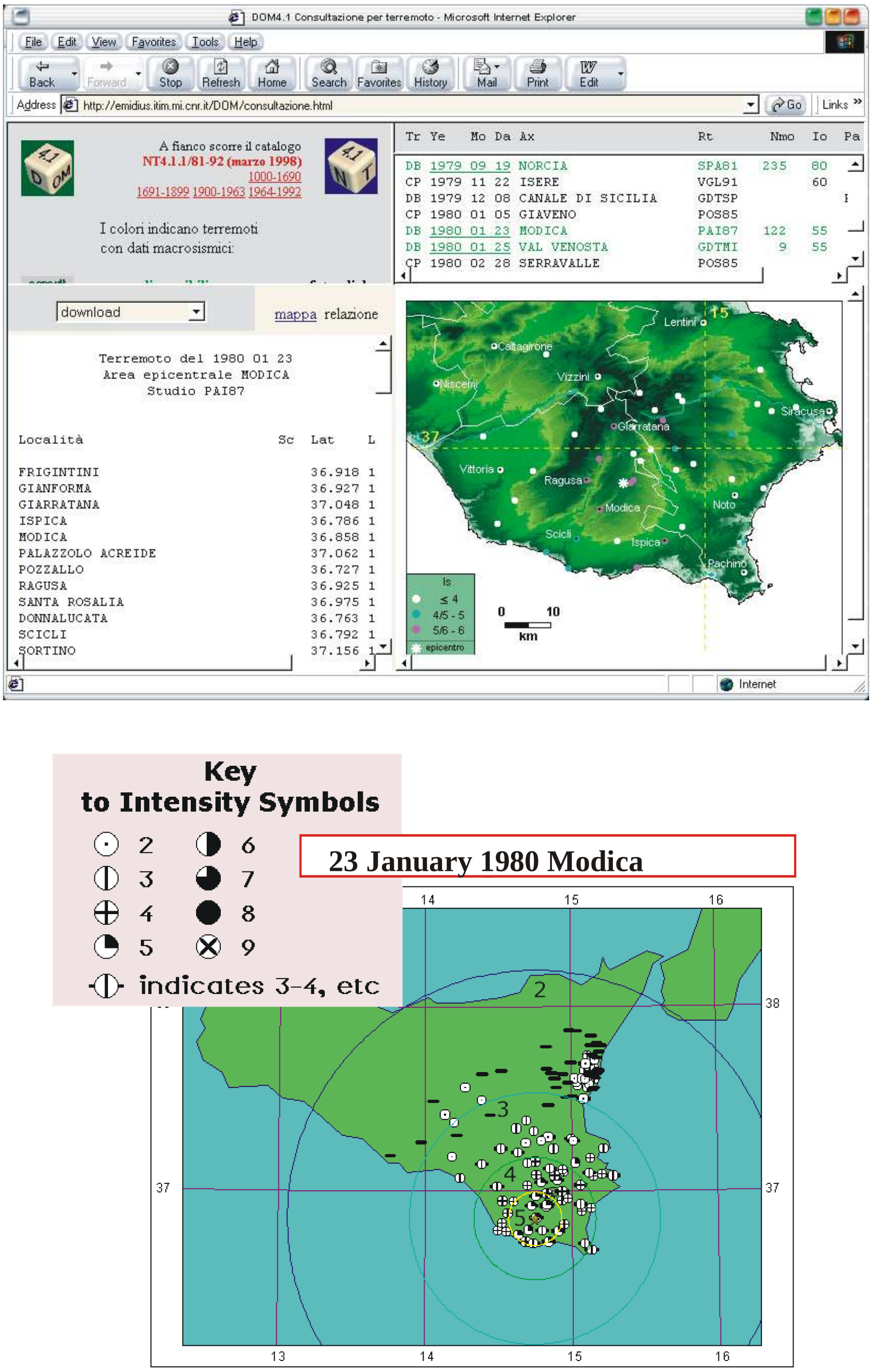

Fig. 12.2 Display of intensity data points using a web-enabled database (above), and a PC-based data exploration program (below).

It is recommended that seismologists preserve and publish tables of intensity data (place, geographical co-ordinates, intensity) whenever possible.

12.3.2.1 Example of an isoseismal map

In Fig. 12.3 a sample intensity/isoseismal map is shown. The earthquake in question is the small Lagrangeville (NY) earthquake of 26 February 1983 in the Eastern USA. This earthquake was chosen as one representing a fairly typical case for a small earthquake; since it doesn't have a very large number of data points, the whole intensity field can be seen clearly in just the one figure. The data were taken from the NOAA Earthquake Intensity Database, plotted using the KAPG symbol set, and the isoseismals added. Notice that the symbols are well mixed; between the isoseismals 4 and 5 are some data points for intensity 2, 3 and 5. This is quite normal and to be expected especially where data points represent only one or two questionnaires. It is not hard to see in this case that standard automatic contouring algorithms would have difficulty with this data set. However, the hand-drawn smoothed isoseismals in Fig. 12.3 represent quite well the general pattern of diminution of intensity with distance observed in this earthquake. It is not appropriate to try and draw an isoseismal 6 for only two data points. Nor can elaborate re-entrants be justified with the given data. The degree of smoothing is appropriate to the resolving power of the original data, and the contours are true to the expected underlying pattern of approximately elliptical areas of equal intensity.

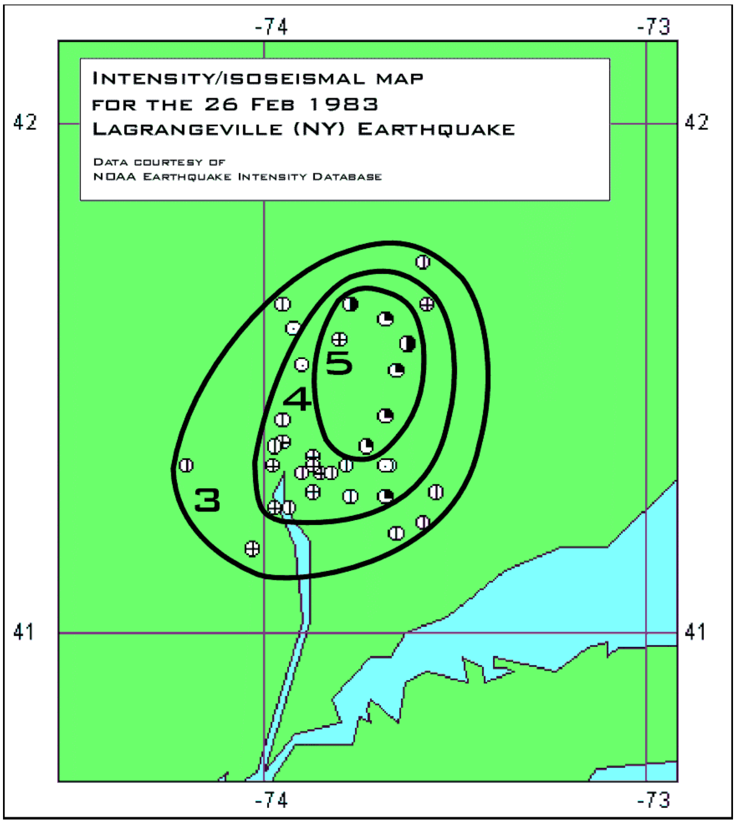

Fig. 12.3 Sample intensity/isoseismal map: the Lagrangeville (NY) earthquake of 26 February 1983.

12.3.3 Determination of earthquake parameters from macroseismic data

12.3.3.1 Macroseismic epicenter

This is an expression which has been used in the past to convey different concepts, never properly defined. The following usage is proposed for the future:

Macroseismic epicenter: The best estimate made of the position of the epicenter (i.e., the point on the Earth's surface above the focus of the earthquake) 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.

Barycenter: The point on the Earth's surface from which the macroseismic field appears to radiate. This is usually the center of the highest isoseismal or the weighted center of the two highest isoseismals. Advanced computational methods have also been demonstrated for calculating the barycenter from the whole macroseismic data set. (The terms macrocenter and macroseismic center have also been proposed.)

These two points are often the same, but need not be. As an example: In the case of the 1989 Loma Prieta earthquake the apparent point of origin of the macroseismic field, for various geological reasons, was well to the north of the actual instrumental epicenter. If one were to attempt to locate a similar event from macroseismic data alone (for example, a historical Californian earthquake), one might be inclined to compensate for this effect by choosing epicentral co-ordinates to the south of the highest isoseismal. This would not affect the location of the barycenter.

Both these concepts have their uses. For any study of the tectonics of an area, the macroseismic epicenter is more useful. For studies of seismic hazard, especially those using a technique like extreme value statistics, the barycenter gives a better indication of the hazard potential of an earthquake.

12.3.3.2 Epicentral intensity

Epicentral intensity, usually abbreviated I_o, is a parameter commonly used in earthquake catalogs 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 epicenter of the earthquake, but since it is likely that there will not be observations exactly at the epicenter 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 data to the epicenter 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 epicenter, the I_o value is also 9. If the epicenter is significantly offshore, I_o can not be determined;

2) calculating a fractional intensity at the epicenter from the attenuation over the macroseismic field, using a formula such as that by Blake (1941) or Kövesligethy (1906) - see 12.3.3.4 below. 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. This value can be determined for earthquakes with sufficient data to draw at least two (preferably three) isoseismals. This is only possible if one is using the concept of the barycenter (see 12.3.2.1 above), since the true epicenter may not be central to the macroseismic field. The term "barycentral intensity" may be preferable.

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 I_o value; the arbitrary amount is too subjective.

As well as epicentral intensity, a useful parameter is maximum intensity, abbreviated I_{max}. This is simply the highest observed intensity value anywhere in the macroseismic field. For onshore earthquakes, I_o and I_{max} may be equal. For offshore earthquakes it is often not possible to estimate I_o (never if method 1 is used), but I_{max} can be given.

12.3.3.3 Macroseismic magnitude

The use of macroseismic data can give surprisingly robust measures of earthquake magnitude. This is an extremely important part of macroseismic studies, as in this way earthquake catalogs can be extended into historical times with consistent magnitude values. Such extended earthquake catalogs are of great benefit to seismic hazard studies.

Early studies attempted to correlate epicentral intensity with magnitude; however, epicentral intensity is strongly affected by focal depth, so such correlation's perform poorly unless either (a) depths are known and taken into consideration, or (b) one is working in an area where seismogenic depth is narrowly constrained.

The total felt area (A) of an earthquake, or the area enclosed by one of the outer isoseismals (usually 3 or 4), is a much better indicator of magnitude, being not much affected by depth except in the case of truly deep earthquakes. For earthquakes below a threshold magnitude (about 5.5 Mw), the magnitude and log felt area scale more or less linearly, and so equations of the form

$$M = a \log A + b \qquad (12.1)$$

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

$$M = n \log\left(\frac{A}{\pi}\right) + \frac{2m}{2.3\sqrt{\pi}}\sqrt{A} + a \qquad (12.2)$$

is used to represent the full magnitude range, where n is the exponent of geometrical spreading and m = (π f)/(Q β) 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 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.

Other forms that have been proposed include

$$M = a I_o + b \ln r + c \tag{12.3}$$

where r is the radius, rather than the area, of the total macroseismic field, and

$$M = a I_o + \Sigma bi \ln ri + c \tag{12.4}$$

in which all isoseismals (values for each i) are used as well as the epicentral intensity (see Albarello et al., 1995).

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 (M_s, M_L, M_w etc.). It is also useful to determine the standard error, which will give a measure of the uncertainty attached to estimated magnitude values.

12.3.3.4 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

$$I - I_o = 3 \log \sin e - 3 \alpha(r/R) (1 - \sin e) \tag{12.5}$$

where sin e = h / r and R 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:

$$I - I_o = 3 \log \sin \varphi \tag{12.6}$$

where φ is the angle of emergence. Why the absorption term was dropped in this publication is unclear. Eq. (12.5) was subsequently rewritten and modified slightly by Jánosi (1907) to reach the now well-known formula

$$I_o - I_i = 3 \log (r / h) + 3\alpha M (r - h) \tag{12.7}$$

where r is the radius of the isoseismal of intensity I_i and M = log e. This work was developed further by Blake (1941) whose contribution was essentially a reduction and simplification of Eq. (12.7); 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 Eq. (12.7), 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 now been possible to unravel. A further confusion is that Jánosi (1907) attributes Eq. (12.7) to Cancani, transmitted by Kövesligethy; it seems that Kövesligethy named another of his equations in honour of Cancani and that Jánosi transferred this title to Eq. (12.7) (Zsiros, 1999, personal communication).

The constant value of 3 used in Eqs. (12.5) to (12.7) represents an equivalence value between the degrees of the intensity scale and ground motion amplitudes. Some workers accept it, others prefer to find their own values by fitting to data (Levret et al., 1996). In this case the formula could be written with a further variable in place of the constant 3. The attenuation parameter a is generally considered to be a regional value, reflecting the absorption of seismic energy by the crust; therefore, normally it should be determined regionally by group optimization on an appropriate data set - not for individual earthquakes.

I_o here is properly the barycentral intensity, which has to be solved for as well as solving for h. This is usually done graphically - one can fit the isoseismal data to all possible values of h and I_o and find a minimum error value consistent with the observed maximum intensity (e.g., Burton et al., 1985; Musson, 1996).

12.3.4 Intensity attenuation

Intensity attenuation, the rate of decay of shaking with distance from the epicenter, 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 Eq. (12.7); this form of intensity attenuation and depth determination from intensity are closely linked.

One can also express intensity attenuation as a function of magnitude and distance. Such formulae usually have the functional form

$$I = a\,M + b\log R + c\,R + d \qquad (12.8)$$

where R is hypocentral (slant) distance, and a, b, c and d are constants. (The third term is sometimes dropped, especially in intraplate areas). Since most earthquake catalogs include magnitude as a parameter, this form of intensity attenuation is extremely useful in seismic hazard studies. Intensity is a good parameter to use for expressing seismic hazard, since it relates directly to damage. It yields hazard values which are more relevant to planners and insurers than physical ground motion parameters. Some typical values are:

Interplate (New Zealand): $I = 1.41\,M_s - 1.18\ln R - 0.0044\,R + 2.18$

Intraplate (SE Australia): $I = 1.64\,M_s - 1.70\ln R + 4.00$

Such formulae also link magnitude with epicentral intensity; when epicentral distance = 0, then R = h. Since depth is now taken into account, much better results can be obtained than from simple I_o/M relationships.

More sophisticated models of attenuation, taking into account factors such as directionality, have been developed for seismic hazard work but are beyond the scope of this Manual.

12.3.5 Relationship with ground motion parameters

Attempts to equate intensity with physical parameters of ground motion, especially peak ground acceleration (PGA), are nothing new. One early scale (that of Cancani) amounted to little more than a table of intensity numbers and equivalent PGA values, and such tables are still often encountered in the literature. However, they can not be relied on; work in the 1970s (e.g., Trifunac and Brady, 1975) demonstrated that intensity and peak ground acceleration correlate very poorly, and any attempt to relate the two suffers from such severe scattering as to be practically useless.

There are a number of reasons for this. One is that other parameters of ground motion, such as peak ground velocity, may be just as important, if not more so, than acceleration. Another is that the duration of strong ground motion is obviously important; a high acceleration for a fraction of a second is not as damaging as a lower acceleration applied over a longer period. Thirdly, peak ground acceleration values often represent single spikes in an accelerogram record which are unrepresentative of the earthquake ground motion as a whole. Where accelerations have been recorded in excess of 1g, these have not been accompanied by any remarkably high intensity values.

Recent research has therefore turned to looking at other ways of relating intensity to physical ground motion parameters, including spectral accelerations and Arias intensity. A review of this subject is beyond the scope of this Manual.

Acknowledgments

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Recommended overview readings (see References, under Miscellaneous in Volume 2)

Burton, P. W. et al. (1985).
Cecić, I. et al. (1996).
Grünthal , G., ed. (1998).
Musson, R. M. W. (1996).
Richter, C. F. (1958).
Wood, H. O. and Neumann, F. (1931).