Earthquake Risk Reduction

1.1 Introduction

Earthquake risk reduction is a complex affair involving many people of many vocations, much information, many opinions and many decisions and actions. The relationships between the contributing sets of information and people is illustrated schematically by the flowchart given in Figure 1.1. Considering that this diagram is necessarily simplified, it is clear that managing the changes needed to reduce earthquake risk is a challenging task in which all of the people in any given region are explicitly or implicitly involved.

1.2 Earthquake Risk and Hazard

In normal English usage the work risk means exposure to the chance of injury or loss. It is noted that the word hazard is almost synonymous with risk, and the two words are used in the risk literature with subtle variations which can be confusing.

Fortunately, an authoritative attempt has been made to overcome this difficulty through the publication by the Earthquake Engineering Research Institute’s glossary of standard terms for use in this subject (EERI Committee on Seismic Risk, 1984). Their terminology will be used in this book.

Thus, the definition of seismic risk is the probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at several sites, or in an area, during a specified exposure time. Risk statements are thus given in quantitative terms.

Seismic hazard, on the other hand, is any physical phenomenon (e.g. ground shaking, ground failure) associated with an earthquake that may produce adverse effects on human activities. Thus, hazards may be either purely descriptive terms or quantitatively evaluated, depending on the needs of the situation. In practice, seismic hazard is often evaluated for given probabilities of occurrence, for example as for ground motions in Figure 4.41.
It follows that seismic risk is an outcome of seismic hazard as described by relationships of the form

\[
\text{Seismic risk} = (\text{Seismic hazard}) \times (\text{Vulnerability}) \times (\text{Value})
\]  

where \text{Vulnerability} is the amount of damage, induced by a given degree of hazard, and expressed as a fraction of the Value of the damaged item under consideration. Referring
to Figure 6.6(a), the Monetary Seismic Risk to a building could be evaluated by taking the Seismic Hazard to be the MM intensity of the appropriate probability of occurrence, the Vulnerability would then be taken as the damage ratio on the appropriate curve for that intensity, and the Value would be the Replacement Cost.

For design or risk assessment purposes the assessment of seismic hazard consists of the following basic steps:

1. Definition of the nature and locations of earthquake sources;
2. Magnitude-frequency relationships for the sources;
3. Attenuation of ground motion with distance from source;
4. Determination of ground motions at the site having the required probability of exceedance.

Because seismic risk and hazard statements are essentially forecasts of future situations, they are inherently uncertain. Seismic hazard assessments are attempts to forecast the likely future seismic activity rates and strengths, based on knowledge of the past and present, and significant uncertainties arise partly because the processes involved are not fully understood and partly because relevant data are generally scarce and variable in quality. For reasonable credibility considerable knowledge of both historical seismicity and geology need to be used, together with an appropriate analysis of the uncertainties. Seismicity is defined as the frequency of occurrence of earthquakes per unit area in a given region, and is illustrated in non-numerical terms by the seismicity map of the world presented in Chapter 2 (Figure 2.1). Where available, other geophysical or seismological knowledge, such as crustal strain studies, may also be helpful, particularly in evaluating regional seismic activity patterns. Once both the estimated future seismic activity rates and the acceptable risks are known, appropriate earthquake loadings for the proposed structure may be determined, e.g. loadings with mean recurrence intervals of, say, 100 to more than 10,000 years, depending on the consequences of failure.

Because of the difficulties involved in seismic hazard evaluation, earthquake design criteria in different areas of the world vary, from well codified to inadequate or non-existent. Hence, depending on the location and nature of the project concerned, seismic risk evaluation ranging from none through arbitrary to thorough-going may be required.

The whole of this book is essentially to do with the explicit or implicit management of seismic risk, and hence the foregoing brief introduction to risk and hazard will be expanded upon in the subsequent text.

1.3 The Social and Economic Consequences of Earthquakes

1.3.1 Earthquake consequences and their acceptability

The primary consequence of concern in earthquakes is of course human casualties, i.e. deaths and injuries. According to Steinbrugge (1982), the greatest known number of deaths that have occurred in a single event is 830,000, in the Shaanxi, China, earthquake of January 24, 1556. Thus the number of casualties in any given event varies enormously, depending on the magnitude, location and era of the earthquake. This is illustrated by a selection of 26 of the more important earthquakes of the 20th century,
Table 1.1  Numbers of deaths caused by a selection of larger 20th century earthquakes in various countries (from Steinbrugge (1982) and NEIC web page)

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Magnitude</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1906 Apr 18</td>
<td>USA, San Francisco</td>
<td>7.8</td>
<td>800</td>
</tr>
<tr>
<td>1908 Dec 28</td>
<td>Italy, Messina</td>
<td>7.5</td>
<td>83,000</td>
</tr>
<tr>
<td>1923 Sep 1</td>
<td>Japan, Tokyo</td>
<td>7.9</td>
<td>142,807</td>
</tr>
<tr>
<td>1927 May 22</td>
<td>China, Nan-Shan</td>
<td>8.3</td>
<td>200,000</td>
</tr>
<tr>
<td>1935 May 31</td>
<td>India, Quetta</td>
<td>7.5</td>
<td>30,000 – 60,000</td>
</tr>
<tr>
<td>1939 Jan 24</td>
<td>Chile, Chillan</td>
<td>8.3</td>
<td>28,000</td>
</tr>
<tr>
<td>1939 Dec 26</td>
<td>Turkey, Erzincan</td>
<td>7.9</td>
<td>30,000</td>
</tr>
<tr>
<td>1949 Aug 5</td>
<td>Ecuador, Pelileo</td>
<td>6.8</td>
<td>6,000</td>
</tr>
<tr>
<td>1956 Jun 10–17</td>
<td>N. Afghanistan</td>
<td>7.7</td>
<td>2,000</td>
</tr>
<tr>
<td>1957 Dec 4</td>
<td>Outer Mongolia, Gobi-Altai</td>
<td>8.6</td>
<td>1,200</td>
</tr>
<tr>
<td>1960 Feb 29</td>
<td>Morocco, Agadir</td>
<td>5.6</td>
<td>12,000</td>
</tr>
<tr>
<td>1962 Sep 1</td>
<td>Northwestern Iran</td>
<td>7.1</td>
<td>12,230</td>
</tr>
<tr>
<td>1963 Jul 26</td>
<td>Yugoslavia, Skopje</td>
<td>6.0</td>
<td>1,100</td>
</tr>
<tr>
<td>1970 May 31</td>
<td>Northern Peru</td>
<td>7.8</td>
<td>66,794</td>
</tr>
<tr>
<td>1972 Dec 23</td>
<td>Nicaragua</td>
<td>6.2</td>
<td>5,000</td>
</tr>
<tr>
<td>1974 Dec 28</td>
<td>Pakistan</td>
<td>6.2</td>
<td>5,300</td>
</tr>
<tr>
<td>1976 Feb 4</td>
<td>Guatemala</td>
<td>7.5</td>
<td>23,000</td>
</tr>
<tr>
<td>1976 Jul 28</td>
<td>China, Tangshan</td>
<td>7.9</td>
<td>245,000 – 655,000</td>
</tr>
<tr>
<td>1976 Aug 17</td>
<td>Philippines, Mindanao</td>
<td>7.9</td>
<td>8,000</td>
</tr>
<tr>
<td>1977 Mar 4</td>
<td>Rumania, Bucharest</td>
<td>7.2</td>
<td>1,500</td>
</tr>
<tr>
<td>1978 Sep 16</td>
<td>Northeast Iran</td>
<td>7.7</td>
<td>25,000</td>
</tr>
<tr>
<td>1980 Oct 10</td>
<td>Algeria</td>
<td>7.2</td>
<td>3,000</td>
</tr>
<tr>
<td>1985 Sep 19</td>
<td>Mexico</td>
<td>8.1</td>
<td>9,500 – 30,000</td>
</tr>
<tr>
<td>1995 Jan 10</td>
<td>Japan, Kobe</td>
<td>6.9</td>
<td>5,500</td>
</tr>
<tr>
<td>1999 Aug 17</td>
<td>Turkey, Koeceli</td>
<td>7.4</td>
<td>17,439</td>
</tr>
<tr>
<td>1999 Sep 20</td>
<td>Taiwan, Chi-Chi</td>
<td>7.6</td>
<td>2,400</td>
</tr>
</tbody>
</table>

(mostly drawn from Steinbrugge (1982)) as listed here in Table 1.1. These earthquakes occurred in 24 countries from most parts of the world, and range in magnitude from 6.0 to 8.6. Many of the higher casualty counts have been caused by the collapse of buildings made of heavy, weak materials such as unreinforced masonry or earth.

In Figure 1.2 are plotted the approximate total numbers of deaths in earthquakes that occurred world-wide in each decade of the 20th century. This histogram highlights the randomness of the size and location of the earthquake occurrence process, as well as the appalling societal cost, and implied economic cost, of earthquakes. The totals were found by summing the deaths in major earthquakes listed by Steinbrugge (1982) and the NEIC. The totals for each decade do not include deaths from events with less than 1000 casualties, one of the larger omissions being the 1931 Hawke’s Bay New Zealand earthquake in which about 260 people died.

The physical consequence of earthquakes for human beings are generally viewed under two headings:

(A) Death and injury to human beings;
(B) Damage to the built and natural environments.
These physical effects in turn are considered as to their social and economic consequences:

1. Numbers of casualties.
2. Trauma and bereavement.
3. Loss of employment.
4. Loss of employees/skills.
5. Loss of heritage.
6. Material damage cost.
8. Consumption of materials and energy (sustaining resources).
9. Macro-economic impacts (negative and positive).

The above physical and socio-economic consequences should all be taken into account when the acceptable consequences are being decided, i.e. the acceptable earthquake risk.

Both financially and technically, it is possible only to reduce these consequences for strong earthquake shaking. The basic planning aims are to minimize the use of land subject to the worst shaking or ground damage effects, such as fault rupture, landslides or liquefaction. The basic design aims are therefore confined (a) to the reduction of loss of life in any earthquake, either through collapse or through secondary damage.
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such as falling debris or earthquake-induced fire, and (b) to the reduction of damage and loss of use of the built environment. (See also Section 6.3.7.)

Obviously, some facilities demand greater earthquake resistance than others, because of their greater social and/or financial significance. It is important to determine in the design brief not only the more obvious intrinsic value of the structure, its contents, and function or any special parts thereof, but also the survival value placed upon it by the owner.

In some countries the greater importance to the community of some types of facility is recognized by regulatory requirements, such as in New Zealand, where various public buildings are designed for higher earthquake forces than other buildings. Some of the most vital facilities to remain functional after destructive earthquakes are dams, hospitals, fire and police stations, government offices, bridges, radio and telephone services, schools, energy sources, or, in short, anything vitally concerned with preventing major loss of life in the first instance and with the operation of emergency services afterwards. In some cases, the owner may be aware of the consequences of damage to his property but may do nothing about it. It is worth noting that, even in earthquake-conscious California, it was only since the destruction of three hospitals and some important bridges in the San Fernando earthquake of 1971 that there have been statutory requirements for extra protection of various vital structures.

The consequences of damage to structures housing intrinsically dangerous goods or processes is another category of consideration, and concerns the potential hazards of fire, explosion, toxicity, or pollution represented by installations such as liquid petroleum gas storage facilities or nuclear power or nuclear weapon plants. These types of consequences often become difficult to consider objectively, as strong emotions are provoked by the thought of them. Acknowledging the general public concern about the integrity of nuclear power plants, the authorities in the United Kingdom decided in the 1970s that future plants should be designed against earthquakes, although that country is one of low seismicity and aseismic design is not generally required.

Since the 1960s, with the growing awareness of the high seismic risks associated with certain classes of older buildings, programmes for strengthening or replacement of such property have been introduced in various parts of the world, notably for pre-earthquake code buildings of lightly reinforced or unreinforced masonry construction. While the substantial economic consequences of the loss of many such buildings in earthquakes are, of course, apparent, the main motivating force behind these risk-reduction programmes has been social, i.e. the general attempt to reduce loss of life and injuries to people, plus the desire to save buildings or monuments of historical and cultural importance.

While individual owners, designers, and third parties are naturally concerned specifically about the consequences of damage to their own proposed or existing property, the overall effects of a given earthquake are also receiving increasing attention. Government departments, emergency services, and insurance firms all have critical interests in the physical and financial overall effects of large earthquakes on specific areas. In the case of insurance companies, they need to have a good estimate of their likely losses in any single large catastrophe event so that they can arrange sufficient reinsurance if they are over-exposed to seismic risk. Disruption of lifelines such as transport, water, and power systems obviously greatly hampers rescue and rehabilitation programmes.
1.3.2 **Economic consequences of earthquakes**

Figure 1.3 plots the costs of earthquake material damage worldwide per decade in the 20th century, where known. The data for the second half of the century comes from Smolka (2000) of Munich Reinsurance. The first half of the century is incomplete; only the material damage costs for the 1906 San Francisco and the 1923 Kanto earthquakes being readily found. As with the 20th century deaths sequence plotted in Figure 1.2, the costs sequence is seen to be random. However, there is no correlation between the deaths and costs sequences. It appears that if the costs were normalized to a constant population, and if the 1995 Kobe earthquake was not included, there would be no trend to increase with time. However, the global seriousness of earthquake damage losses is undisputed. The economic consequences of earthquakes occur both before and after the event. Those arising before the event include protection provisions such as earthquake resistance of new and existing facilities, insurance premiums, and provision

![Figure 1.3](chart-url)
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of earthquake emergency services. Insurance companies themselves need to reinsure against large earthquake losses, as mentioned in the previous section.

Post-earthquake economic consequences include:

2. Cost of damage.
3. Losses of production and markets.
4. Insurance claims.

The direct cost of damage depends upon the nature of the building or other type of facility, its individual vulnerability, and the strength of shaking or other seismic hazard to which it is subjected.

During the briefing and budgeting stages of a design, the cost of providing earthquake resistance will have to be considered, at least implicitly, and sometimes explicitly, such as for the upgrading of older structures. The cost will depend upon such things as the type of project, site conditions, the form of the structure, the seismic activity of the region, and statutory design requirements. The capital outlay actually made may in the end be determined by the wealth of the client and his or her attitude to the consequences of earthquakes, and insurance to cover losses.

Unfortunately it is not possible to give simple guides on costs, although it would not be misleading to say that most engineering projects designed to the fairly rigorous Californian or New Zealand regulations would spend a maximum of 10% of the total cost on earthquake provisions, with 5% as an average figure.

The cost of seismic upgrading of older buildings varies from as little as about 10% to more than 100% of the replacement cost, depending on the nature of the building, the level of earthquake loadings used, and the amount of non-structural upgrading that is done at the same time as the strengthening. It is sad to record that many fine old buildings have been replaced rather than strengthened, despite it often being much cheaper to strengthen than to replace.

Where the client simply wants the minimum total cost satisfying local regulations, the usual cost-effectiveness studies comparing different forms and materials will apply. For this a knowledge of good earthquake-resistant forms will, of course, hasten the determination of an economical design, whatever the material chosen.

In some cases, however, a broader economic study of the cost involved in prevention and cure of earthquake damage may be fruitful. These costs can be estimated on a probabilistic basis and a cost-effectiveness analysis can be made to find the relationship between capital expenditure on earthquake resistance on the one hand, and the cost of repairs and loss of income together with insurance premiums on the other.

For example, Elms and Silvester (1978) found that in communal terms the capital cost savings of neglecting aseismic design and detailing would be more than offset by the increased economic losses in earthquakes over a period of time in any part of New Zealand. It is not clear just how low the seismic activity rate needs to be for it to be cheaper in the long-term for any given community to omit specific seismic resistance provisions. The availability or not of private sector earthquake insurance in such circumstances would be part of the economic equation.

Hollings (1971) has discussed the earthquake economics of several engineering projects. In the case of a 16-storey block of flats with a reinforced concrete ductile
frame it was estimated that the cost of incorporating earthquake resistance against collapse and subsequent loss of life was 1.4% of the capital cost of building, while the cost of preventing other earthquake damage was reckoned as a further 5.0%, a total of 6.4%. The costs of insurance for the same building were estimated as 4.5% against deaths and 0.7% against damage, a total of 5.2%. Clearly, a cost-conscious client would be interested in outlaying a little more capital against danger from collapse, thus reducing the life insurance premiums, and he or she might well consider offsetting the danger of damage mainly with insurance.

Loss of income due to the building being out of service was not considered in the preceding example. In a hypothetical study of a railway bridge, Hollings showed that up to 18% of the capital cost of the bridge could be spent in preventing the bridge going out of service, before this equalled the cost of complete insurance cover.

In a study by Whitman et al. (1974), an estimate was made of the costs of providing various levels of earthquake resistance for typical concrete apartment buildings of different heights, as illustrated in Figure 1.4. Until further studies of this type have been done, results such as those shown in the figure should be used qualitatively rather than quantitatively.

**Figure 1.4** Effect on cost of earthquake resistant design of typical concrete apartment buildings in Boston (after Whitman *et al.*, 1974)
It is most important that at an early stage the owner should be advised of the relationship between strength and risk so that he can agree to what he is buying. Where stringent earthquake regulations must be followed the question of insurance versus earthquake resistance may not be a design consideration: but it can still be important, for example for designing non-structural partitions to be expendable or if a ‘fail-safe’ mechanism is proposed for the structure. Where there are loose earthquake regulations or none at all, insurance can be a much more important factor, and the client may wish to spend little on earthquake resistance and more on insurance.

However, in some cases insurance may be more expensive, or unavailable, for facilities of high seismic vulnerability. For example, the latter is often the case for older unreinforced masonry buildings in some high seismic risk areas of New Zealand, i.e. those built prior to the introduction of that country’s earthquake loadings code in 1935. The costs of earthquake damage are discussed further in Chapter 7.

1.4 Earthquake Risk Reduction Actions

To reduce earthquake risk, each country needs to examine its strengths and weaknesses, build on the strengths, and systematically take actions which reduce or eliminate the weaknesses. An example of such an approach comes from New Zealand where a list of weaknesses was identified (Dowrick, 2002).

Over a score of weaknesses were identified there in a preliminary list of weaknesses of a wide range of types. The weaknesses have been initially divided into two main categories, named strategic and tactical, as listed in Tables 1.2(a) and 1.2(b), respectively. This division in some cases is somewhat arbitrary, but it helps in comprehending the considerable detail implied by the abbreviated descriptions given to the tabulated weaknesses.

Consider the 11 strategic weaknesses listed in Table 1.2(a). The first of these is clearly strategic, noting that New Zealand has no national strategy for managed progressive reduction of earthquake risk. What was needed were monitored goals of target risk reductions in a series of (say) five-year plans, with priorities assigned at both a national and a local level.

As well as listing weaknesses, Tables 1.2(a) and 1.2(b) attempt to list all parties who contribute to remedying each of the weaknesses. The first of these is Advocacy by earthquake professionals (engineers, geologists, seismologists, architects, economists, planners, risk managers and others), and one is Funding (rather than people). The remaining nine entities, ranging from engineers to central government, illustrate the complexity of the workings of modern society, which by fragmentation constitutes a considerable difficulty (i.e. a weakness) as listed in Item A3. As given in Table 1.2(a), Central Government (G), government departments (g), local government (L) and planners (P), all are needed to address this problem, in addition to the advocacy role of earthquake professionals.

Item A10, over-design in New Zealand’s lowest seismic hazard zones results from the historical excessive conservatism of design loadings for northern regions of the North Island, a situation which was expected to be resolved in the then proposed revision of the loadings standard. This is listed as a weakness in order to illustrate the need to spend New Zealand’s limited national financial resources wisely, and emphasize the need for national priorities for risk reduction as discussed above for Item A1.
Table 1.2(a) Part 1 of the list of New Zealand’s weaknesses in earthquake risk reduction (from Dowrick, 2002)

<table>
<thead>
<tr>
<th>A</th>
<th>Undesirable situations — strategic</th>
<th>Remedial action by whom</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>No national strategy and targets for managed incremental risk reduction with time</td>
<td>A E — — M — G g L — —</td>
</tr>
<tr>
<td>A2</td>
<td>Too much national vulnerability to a ‘king-hit’ earthquake on Wellington</td>
<td>A — — — M — G — L — —</td>
</tr>
<tr>
<td>A3</td>
<td>Fragmentation of the many endeavours contributing to earthquake risk reduction</td>
<td>A — — — — P G g L — —</td>
</tr>
<tr>
<td>A4</td>
<td>Underfunding of production of design codes and standards</td>
<td>A — — — — — G — — F —</td>
</tr>
<tr>
<td>A5</td>
<td>Systematic reduction of the numbers of hospitals/beds nationwide</td>
<td>A — — — — P G g — F —</td>
</tr>
<tr>
<td>A6</td>
<td>Too little management/modelling of business interruption losses</td>
<td>A — — — I M P G g L — O</td>
</tr>
<tr>
<td>A7</td>
<td>Slow uptake of some new research findings</td>
<td>A — — — — P G g L F O</td>
</tr>
<tr>
<td>A8</td>
<td>As yet no official process for retrofitting of non-URM earthquake risk buildings</td>
<td>A E — — — — G g L — O</td>
</tr>
<tr>
<td>A9</td>
<td>Too much emphasis on life safety at the expense of high damage (e.g. EBFs)</td>
<td>A E — — — — — — — — O</td>
</tr>
<tr>
<td>A10</td>
<td>Over-design in New Zealand’s lowest seismic hazard regions</td>
<td>— E — — — P — — L — —</td>
</tr>
<tr>
<td>A11</td>
<td>Architects who don’t collaborate with engineers structural form needs</td>
<td>A — a — — — — — — — O</td>
</tr>
</tbody>
</table>

Notes: A = Advocacy by earthquake professions; a = Architects; E = Engineers; F = Funding needed; G = Central Govt; g = govt dept; I = Insurance industry; L = Local govt; M = Economists; O = Owners of property; P = Planners.

Let us now turn to the 12 tactical weaknesses, listed in Table 1.2(b), which generally involves more technical detail than the strategic weaknesses of Table 1.2(a). This is illustrated by the fact that in the Actions by whom lists, Engineers (E) appear in 11 items of Table 1.2(b) and only four of Table 1.2(a). As indicated by Items B1-B4, many components of the built environment are inadequately regulated for earthquake risk purposes. The lack of mandatory regulations for earthquake protection of most built or
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#### Table 1.2(b)  Part 2 of the list of New Zealand’s weaknesses in earthquake risk reduction (from Dowrick, 2002)

<table>
<thead>
<tr>
<th>B</th>
<th>Undesirable situations—tactical</th>
<th>Remedial action by whom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>B1</td>
<td>No EQ regulations for most equipment and plant</td>
<td>A</td>
</tr>
<tr>
<td>B2</td>
<td>Inadequate EQ regulations for building services in buildings</td>
<td>A</td>
</tr>
<tr>
<td>B3</td>
<td>Inadequate EQ regulations for storage of stock in shops and warehouses</td>
<td>A</td>
</tr>
<tr>
<td>B4</td>
<td>No adequate regulatory framework for existing high risk concrete and steel buildings</td>
<td>A</td>
</tr>
<tr>
<td>B5</td>
<td>Weak powers and weak action for pre-emptive land-use planning</td>
<td>A</td>
</tr>
<tr>
<td>B6</td>
<td>Buildings astride active faults</td>
<td>A</td>
</tr>
<tr>
<td>B7</td>
<td>Modern buildings built without measures for liquefiable ground</td>
<td>A</td>
</tr>
<tr>
<td>B8</td>
<td>Inadequate enforcement of some regulations</td>
<td>A</td>
</tr>
<tr>
<td>B9</td>
<td>Incomplete and/or inadequate microzoning maps nationwide</td>
<td>A</td>
</tr>
<tr>
<td>B10</td>
<td>Some councils renting out or using Earthquake Risk Buildings</td>
<td>A</td>
</tr>
<tr>
<td>B11</td>
<td>Are all new materials and techniques adequately researched before use? (e.g. ‘chilly bins’)</td>
<td>A</td>
</tr>
<tr>
<td>B12</td>
<td>No regular checks on seismic movement gaps for seismically isolated structures</td>
<td>A</td>
</tr>
</tbody>
</table>

Notes

(1) ($f, l, l, m$) = faults, landslides, liquefaction, microzoning;

(2) $EG =$ Engineers + geologists. For explanation of other abbreviations A, E, etc. see Table 1.2(a).

Manufactured items other than buildings is a historical situation (common world-wide) which strongly merits rectification in the interests of earthquake risk reduction. The case of stored goods (stock) in shops, Item B3, is a curious and alarming example. Consider the way that goods are stacked in some shops. Lethally heavy goods are
stacked needlessly high overhead in the most dangerous fashion to anyone below. The fact that loose goods or contents of buildings fall to the floor in moderate or strong shaking is common knowledge.

These situations are, in fact, a breach of the New Zealand law regarding the safety of the shop employees, and it was surprising and disappointing that the government agency, Occupational Health and Safety (OSH), had not stamped out this practice. The deaths and injuries of workers and public alike would will be on the slate of the owners, OSH staff and the government, if this situation is not eliminated before the next damaging earthquake. Oddly, the New Zealand public had no statutory protection from this source of danger at the time of this study.

In the more seismic parts of New Zealand two types of older buildings, of unreinforced masonry (URM) and some concrete buildings (Item B4), pose a serious threat. While many brick buildings have been demolished or strengthened in some parts of the country, the process is somewhat erratic. Even in Wellington where the City Council has been a leader in this field since about 1980, many old unreinforced brick buildings are still in use, death traps to occupants and passers-by. We might also ask why long-vacated brick buildings should not be demolished forthwith? They pose a great threat to passers-by.

The older concrete buildings that are at risk of serious earthquake damage (Item B4), comprise mainly pre-1976 multi-storey buildings, which have beam and column frames rather than structural walls. In the past several years much work has been done by the NZSEE Study Group (2002) on studying the problems posed by such buildings, and their proposed regulations for assessing and strengthening them were submitted to the New Zealand Government late in 1998. The issue of what to do about these buildings is rightly contentious as the costs of strengthening will be considerable in many cases.

An important aspect of Tables 1.2(a) and 1.2(b) is the influence of duty of care on who could be involved in remedial actions. Duty of care is the common law responsibility of a person or body to do something, such as warning others about a situation that they know to be dangerous, even if they are not involved, or if there is no statutory requirement. For example building on an active fault (Item B6) is known by most people to be dangerous, so that in addition to geologists, those who could act on this danger to people and property include engineers, architects, insurers, planners, government departments, local government and the owner of the building.

As the duty of care is surprisingly pervasive, Tables 1.2(a) and 1.2(b) should be widely distributed to all concerned.

References


9 Earthquake Risk Modelling

9.1 Loss Estimation

The estimation of probable future losses is of great importance to those concerned with the management of facilities or public administration in earthquake-prone regions. Future loss estimates are of interest to:

- those responsible for physical planning on an urban or regional scale, particularly where planning decisions can have an effect on future losses;
- economic planners on a national or international scale;
- those who own or manage large numbers of buildings or other vulnerable facilities;
- the insurance and reinsurance companies which insure those facilities;
- those responsible for civil protection, relief and emergency services;
- those who draft building regulations or codes of practice for construction, whose task is to ensure that adequate protection is provided by those codes at an acceptable cost.

A variety of different types of loss estimation studies are used depending on the nature of the problem and the purpose of the study. These include:

- **Scenario studies**: Calculation of the effects of a single earthquake on a region. Often a ‘maximum probable’ or ‘maximum credible’ magnitude earthquake is assumed, with a best-guess location, based on known geological faults or probabilistic seismic source zones. Historically significant earthquakes, such as the 1906 San Francisco event, or the 1923 Great Tokyo earthquake are commonly used as scenarios to assess their effects on present-day portfolios. Scenario studies are used to estimate the likely losses from an extreme case, to check the financial resilience of a company or institution to withstand that level of loss, and also to estimate the resources likely to be needed to
handle the emergency, i.e. for preparedness planning. The number of people killed, injured, buried by collapsing buildings or made homeless is estimated. From these can be estimated the resources needed to minimise disruption, rescue people buried, accommodate the homeless, and minimise the recovery period.

- **Probabilistic risk analysis:** Calculation of all potential losses and the probability of those losses occurring from each of the different sizes and locations of earthquakes that can occur. For an individual building or for a portfolio of buildings or other assets in a region, this generates a loss exceedance probability (EP) curve, defining the level of loss that would be experienced with different return periods. The EP curve is used to calculate the average annual loss, to use in financial reserving, insurance rate setting or risk benchmarking. The EP curve provides the probability of different levels of loss being achieved, such as the probability of the losses exceeding financial reserves, bankrupting a company, or triggering a reinsurance contract. Probabilistic risk analysis can be used to estimate EP curves for the numbers of buildings destroyed, lives lost and total financial costs over a given period of time. With sufficient detail in the calculation, the likely effect of mitigation policies on reducing earthquake losses can be estimated and costed. The relative effects of different policies to reduce losses can be compared or the change in risk over time can be examined.

- **Potential loss studies:** Mapping the effect of expected hazard levels across a region or country shows the location of communities likely to suffer heavy losses. Usually the maximum historical intensity or a level of peak ground acceleration associated with a long probabilistic return period is mapped across an area. The effect of the intensity on the communities within that area is calculated to identify the communities most at risk. This shows, for example, which towns or villages are likely to suffer highest losses, which should be priorities for loss reduction programmes, and which are likely to need most aid or rescue assistance in the event of a major earthquake.

Table 9.1 summarises the different users of loss estimation and the types of output required.

Because of the importance of loss modelling to so many different groups, and its complexity, the last decade has seen the development of many sophisticated computer models for the computation of likely losses, using scenario studies or on a probabilistic basis. The most advanced of these models have been developed to help the international insurance and reinsurance industry, which has huge financial exposure in earthquake zones, to assess its probable and maximum possible losses. Several specialist companies have developed to supply this demand, and recent earthquakes, particularly the 1994 Northridge earthquake and the 1995 Kobe earthquake, have provided detailed loss data to test and calibrate their
Table 9.1 Users of loss estimation and the information they need.

<table>
<thead>
<tr>
<th>Who</th>
<th>Why</th>
<th>Information needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical planners</td>
<td>Identify high-risk locations</td>
<td>Risk mapping</td>
</tr>
<tr>
<td>Building owners</td>
<td>Identify high-risk buildings</td>
<td>Building-by-building vulnerability studies</td>
</tr>
<tr>
<td>Insurers and reinsurers</td>
<td>Plan mitigation strategies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Set insurance premium rates</td>
<td>Annualised loss and exceedance probability curves</td>
</tr>
<tr>
<td></td>
<td>Structure risk transfer (reinsurance) deals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Identify possible losses</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce risks</td>
<td></td>
</tr>
<tr>
<td>Civil protection agencies</td>
<td>Plan size and location of emergency services</td>
<td>Estimates of fatalities and injuries, damage, homelessness</td>
</tr>
<tr>
<td>Building regulators</td>
<td>Determine optimum resistance levels</td>
<td>Cost–benefit studies</td>
</tr>
</tbody>
</table>

models. This has led in turn to the development of some of the new techniques described later in this chapter for estimating physical and other losses.\(^1\)

Because of the uncertainty of the knowledge available about earthquakes and their recurrence patterns, all loss estimates are necessarily extrapolations into the future of the observed statistical distribution of earthquakes and their effects in the past, and are based on attempts to determine the earthquake risk on a probabilistic basis. The term risk, and the associated terms hazard and vulnerability, have been formally defined by international agreement, and these agreed definitions, which are set out in the next section, will be used in this book.

### 9.2 Definition of Terms

#### 9.2.1 Risk

The term earthquake risk refers to the expected losses to a given elements at risk, over a specified future time period.\(^2\) The element at risk may be a building, a group of buildings or a settlement or city, or it may be the human population of that building or settlement, or it may be the economic activities associated with either. According to the way in which the element at risk is defined, the risk may be measured in terms of expected economic loss, or in terms of numbers of lives lost or the extent of physical damage to property, where appropriate measures

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\(^1\) The November 1997 issue of the *Journal of Earthquake Spectra* was devoted to loss estimation, and is a useful summary of recent progress in the United States.

\(^2\) According to the international convention agreed by an expert meeting organised by the United Nations Office of the Co-ordinator of Disaster Relief (UNDRO) in 1979 (UNDRO 1979, Fournier d’Albe 1982).
of damage are available. Risk may be expressed in terms of average expected losses, such as:

- 25 000 lives lost over a 30-year period, or
- 75 000 stone masonry houses experiencing heavy damage or destruction within 25 years,

or alternatively on a probabilistic basis:

- a 75% probability of economic losses to property exceeding $50 million in the City of L within the next 10 years.

The term specific risk is used to refer to risks or loss estimations of either type which are expressed as a proportion or percentage of the maximum possible loss. Specific risk is commonly used for financial losses to property, where it usually refers to the ratio of the cost of repair or reinstatement of the property to the cost of total replacement, the repair cost ratio.\(^3\)

### 9.2.2 Hazard

Hazard is the probability of occurrence of an earthquake or earthquake effects of a certain severity, within a specific period of time, at a given location or in a given area. According to the type of analysis that is being made, the earthquake may be specified in terms of either its source characteristics or its effect at a particular site. The source characteristics of earthquakes are most commonly specified in terms of magnitude (see Chapter 1). When considering the hazard of ground shaking, the site characteristics of the earthquake are expressed in terms of an intensity or a parameter for severity of ground motion, such as EMS or modified Mercalli intensity, or in terms of peak ground acceleration (PGA), or some other parameter derived from measured characteristics of the motion. Like risk, hazard may be expressed in terms of average expected rate of occurrence of the specified type of event, or on a probabilistic basis. In either case annual recurrence rates are usually used. The inverse of an annual recurrence rate is an average return period. Examples of hazard defined in terms of the earthquake source are:

- there is an annual probability of 8% of an earthquake with a magnitude exceeding 7.0 in region E.

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\(^3\) The term earthquake risk is still sometimes used to refer not to expected losses but to the expected future occurrence of given levels of earthquake ground shaking. According to the UNDRO definitions, the term ‘hazard’ is to be used with this meaning, as will be defined below. This is clearly a potential source of confusion, and as both usages are likely to continue for the near future, it is essential to be cautious in reading documents, particularly from US sources, which deal with earthquake risk. The UNDRO definition will be used here.
This is effectively the same thing as saying:

the average return period for an earthquake of $M \geq 7.0$ in region E is 12.5 years, or there is a probability of 85% that an earthquake with a magnitude exceeding 7.0 will occur in region E within the next 25 years.$^4$

Examples of earthquake hazard expressed in terms of its site characteristics are:

an annual probability of 0.04 (or 4%) of an earthquake of EMS intensity VI in the town of N (or expected return period of 25 years for the same event – an equivalent definition),

or:

an annual probability of 0.20 (or 20%) of a peak ground acceleration exceeding 0.15% g in M City.

The hazard expressed in this way is of course only a partial definition of the ground shaking hazard, related to events of a particular size range. The definition of the hazard for all possible size ranges cannot be done by a single statement of the type given above, but can be presented graphically, as a relationship between the annual probability and the size of the event. An example of a hazard definition in terms of the regional frequency of recurrence of earthquakes of different magnitude is given in Figure 9.1 for several broad regions of the world.

In addition to ground shaking, the potential for other collateral hazards from ground liquefaction, from landslide, dam failure or tsunami, and from direct damage in the fault rupture zone need to be considered at any site; in each case a characteristic hazard parameter needs to be defined, and expressed in a similar way to that for ground shaking hazard.

### 9.2.3 Vulnerability

Vulnerability is defined as the degree of loss to a given element at risk (or set of elements) resulting from a given level of hazard (i.e. from the occurrence of an earthquake of a given severity). The vulnerability of an element is defined as a ratio of the expected loss to the maximum possible loss, on a scale from 0 to 1 (or 0 to 100%). The measure of loss used depends on the element at risk, and accordingly may be measured as a ratio of numbers killed or injured to total population, as a repair cost ratio or as the degree of physical damage defined on an appropriate scale. In a large population of buildings it may be defined in terms of the proportion of buildings experiencing some particular level of damage.

$^4$Using the assumed Poisson distribution of earthquake occurrence, explained in Section 9.9.
Figure 9.1  Relative seismic activity rates in different parts of the world. In an area of moderate to low seismicity, such as the eastern United States, the probability of an earthquake of magnitude 6.0 or above is little more than one-hundredth of the probability of such an event in Japan.

The vulnerability of a set of buildings to an earthquake of intensity VIII may be defined as:

70% of buildings suffering heavy damage or worse, at intensity VIII, or average repair cost ratio of 55% at intensity VIII.

Specification of average vulnerability alone is rarely adequate for making loss assessments, however, because the distribution of losses within the set of elements at risk is generally very wide, with some elements sustaining very high degrees of damage, others very little. Thus the vulnerability of elements such as buildings, where a degree of damage may be assessed, is generally expressed by means of a damage distribution which may be expressed as a histogram. The derivation of such distributions is further discussed in Section 9.3.

As in the case of hazard it is clear that the vulnerability to one size of event is only a partial definition of the total vulnerability, which needs to be specified for all possible events which may cause any loss or damage. The complete vulnerability for an element at risk is therefore an assembly of the separate vulnerability distributions for each size of event which may need to be considered. Table 9.5 below shows an example of such a damage probability matrix. Damage probability distributions are defined for events of intensity V or VI to X.

Vulnerability functions such as that shown in Figure 9.2 may be combined with the hazard data defined as shown above in order to estimate the probable distribution of losses for all possible earthquake events in a given time period.
and thus to determine the risk to that element or set of elements at risk. How this is done in particular cases is discussed in Section 9.5 below.

9.2.4 Mathematical Definitions

The definitions given above may also be expressed mathematically, in a way which facilitates the computation of risk. The general equation for the calculation of risk can be given as:

\[ R_{ij} = H_j V_{ij} \]

where, for an element at risk (e.g. an individual building) \( i \):

\( R_{ij} \) is the risk, the probability or average rate of loss to element \( i \) due to earthquake ground motion of severity \( j \).

\( H_j \) is the hazard, the probability or average expected rate of experiencing earthquake ground motion (or other earthquake related damaging event) of severity \( j \).

\( V_{ij} \) is the vulnerability, the level of loss that would be caused to element \( i \) as a result of experiencing earthquake ground motion of severity \( j \) (where loss is the specific loss; loss as a proportion of the total value of element \( i \)).

By summing the risk from all levels of hazard \( (\min \leq j \leq \max) \), the total risk to any individual element can be derived (see Figure 9.2). The specification of hazard has been discussed in Chapter 7, and that of vulnerability is discussed in more detail in the following sections.

9.3 Vulnerability Assessment

9.3.1 General Approach

Vulnerability is the degree of loss to a given element at risk resulting from the occurrence of a specified earthquake. For assessment of losses due to ground shaking over a population of buildings (or other elements at risk) we need:
1. A means of specifying the earthquake hazard, as discussed in Chapter 7.
2. A classification of the building types or other facilities into distinct types whose performance in earthquakes is likely to be similar both in nature and degree.
3. A method of defining loss so that the extent of loss to a particular building or population of buildings can be quantified.
4. A means of estimating the distribution of losses to each building type for each discrete level of ground shaking (if intensity scales are used), or as a function of ground shaking (if a continuous parameter of ground shaking is used).

A similar approach needs to be used for estimating losses to other collateral hazards.

There are two principal methods of vulnerability assessment, which may be referred to as predicted vulnerability and observed vulnerability. Predicted vulnerability refers to the assessment of expected performance of buildings based on calculation and design specifications, or, if no other method is available, on judgement based on the assessor’s experience. Observed vulnerability refers to assessment based on statistics of past earthquake damage. The former method is suitable for use primarily with engineered structures and facilities, where a reasonable estimate of earthquake resistance may be made, but for which only a limited amount of damage data, if any, is available. The latter method is more suitable for use with non-engineered structures made with low-strength materials such as timber or unreinforced masonry, whose earthquake resistance is more difficult to calculate, but for which substantial statistical damage data may be available. The use of observed vulnerability is increasingly relevant in the case of very common forms of engineered construction, such as reinforced concrete frame structures, as the amount of damage data increases over time. For the most common building types, observed vulnerability methods will continue to be used, but increasingly predicted vulnerability will be needed to assess the performance of newer and better built structures which have not yet been tested in severe earthquake shaking.

### 9.3.2 Building Type and Facility Classification

The building type and facility type classification to be adopted in any study will depend not only on those characteristics which are expected to influence the earthquake performance of the structure but on the extent of data available. Most studies of earthquake damage have concluded that the form of construction used

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5 Sandi (1982).
6 A relatively new approach is to combine observed and predicted vulnerability measures, as described by Bommer et al. 2002.
7 The effects of changing building stock on vulnerability assessment are discussed by Spence (2000).
for the primary load-bearing structure is the most important factor affecting earthquake damage; in some instances the _vertical structure_ (‘load-bearing masonry’, ‘timber’ or ‘reinforced concrete frame’) is a sufficient definition, but in other cases the _horizontal structure_ used for floor and roof (timber joists or reinforced concrete slab, for example) may be equally important. In any particular area the definition of the form of construction in this way will embrace the entire building practice associated with it, thus providing a reasonably homogeneous class of buildings in a particular region, but ‘load-bearing masonry’ buildings located in different regions will not necessarily be similarly well constructed or perform in a similar way in earthquakes.

Because of changing building practices over time, the definition of the _date or period of construction_ may be an equally important element of the building classification. Building practices can change radically within a short space of time as a result of economic changes, changes in regulations or building code, rebuilding after earlier disasters or political upheavals. A knowledge of these changes is essential to establish an effective building stock classification. For modern engineered buildings the earthquake performance is likely to be strongly affected by other aspects of the form of construction such as ‘moment-resisting frame’ or ‘shear wall’ for reinforced concrete buildings, and by the number of storeys; the building type classification may therefore need to include these factors.

Many other aspects of a building’s construction have been shown to have an influence over its performance in earthquakes, some of which are listed in Table 9.2. These have already been discussed in Chapter 8. A classification of common building types in seismic areas of the world is presented in Table 8.1. However, finer and finer subdivision of the building classification would require correspondingly more vulnerability relationships to be defined, and quantitative measures of the separate influence of these factors are difficult to obtain. Their influence is better assumed to be taken account of by the distribution of expected damage within each class, discussed below.

Table 9.3 shows the classification of building types proposed for use with the HAZUS loss estimation methodology (FEMA 1999). This defines 16 model building classes, with further subdivision by numbers of storeys, giving 36 classes in all.8

For each country and region, building types will differ, and the classification needed will depend on the range of building uses to be included in the study. For example, where only residential buildings are to be studied, the range of building types considered may not need to include high-rise steel or concrete frames.

### 9.3.3 Damage Evaluation

Quantification of structural damage presents a number of difficulties. The mechanisms of damage are different for each building type; the cracking and

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8 See FEMA (1999).
Table 9.2  Secondary vulnerability factors (i.e. factors apart from construction type and local subsoil condition) known to influence earthquake damage to structures.

(a) Structural form

Non-symmetrical or irregular plans
Differences in the architectural plans and stiffnesses of different stories (especially framed buildings)
Total number of storeys and stiffness of structure and its effect on natural period and dynamic characteristics of the building
Single directions of strength (e.g. load-bearing walls all in same direction, or frame buildings with a unidirectional structure) and orientation of building with respect to direction of seismic force
Excessive wall openings leaving insufficient wall area to resist lateral shear (masonry)
Heavy roof forms and disposition of loads with height
Foundations; depth, adequacy, protection from frost, etc.
Design faults. Good practice not followed, e.g. vertical load-bearing elements not aligned from one floor to the next

(b) Site planning

Mutual stiffening effects of adjoining buildings
‘Pounding’ effects of adjacent buildings colliding
Slope effects causing subsidence and weakening buildings before earthquakes
Local ground failure under buildings, triggered or exacerbated by earthquake

(c) Construction quality

Low quality of building materials and failure to comply with specifications (e.g. during wartime construction)
Low quality of work. Good practice not followed or ignorance of the need for details
Deliberate neglect of conforming to design specifications (e.g. misappropriation of concrete reinforcement)
Mixtures of construction materials with different seismic performance (e.g. in load-bearing masonry).

(d) History

Age. Decay and weakening of materials
Pre-existing damage weakening structure, from previous earthquakes, war damage, foreshocks, etc.
Repair, maintenance and strengthening of structure
Modifications to structure (e.g. addition of another storey, extension of plan, alteration of structure to fit services, etc.)

disintegration of load-bearing masonry, for example, is a significantly different process to the deterioration and failure of a reinforced concrete frame. In some cases it is possible to avoid these differences by quantifying and comparing damage in financial terms. The most commonly used economic measure of repair is repair cost ratio (or RCR). This is the ratio of the cost of repair and
Table 9.3 Building structure type classification used in the HAZUS earthquake loss estimation methodology (FEMA 1999).

<table>
<thead>
<tr>
<th>Label</th>
<th>Building class</th>
<th>Subdivisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Wood, light frame</td>
<td></td>
</tr>
<tr>
<td>W2</td>
<td>Wood, commercial and industrial</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>Steel moment frame</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>S2</td>
<td>Steel, braced frame</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>S3</td>
<td>Steel light frame</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>Steel frame with cast-in-place concrete shear walls</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>S5</td>
<td>Steel frame with unreinforced masonry infill walls</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>C1</td>
<td>Concrete moment frame</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>C2</td>
<td>Concrete shear walls</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>C3</td>
<td>Concrete frame with unreinforced masonry infill walls</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>PC1</td>
<td>Precast concrete tilt-up walls</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>PC2</td>
<td>Precast concrete frames with concrete shear walls</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>RM1</td>
<td>Reinforced-masonry-bearing walls with wood or metal deck diaphragms</td>
<td>Low and mid-rise</td>
</tr>
<tr>
<td>RM2</td>
<td>Reinforced-masonry-bearing walls with precast concrete diaphragms</td>
<td>Low, mid- and high rise</td>
</tr>
<tr>
<td>URM</td>
<td>Unreinforced-masonry-bearing walls</td>
<td>Low and mid-rise</td>
</tr>
<tr>
<td>MH</td>
<td>Mobile homes</td>
<td></td>
</tr>
</tbody>
</table>

Low rise = 1–3 storeys
Mid-rise = 4–7 storeys
High rise = more than eight storeys.

reinstatement of the structure (or building) to the cost of replacing the structure (or building). The evaluation of damage in terms of repair cost is unsatisfactory for many purposes, though, because of its dependence on the economy at that time and place. Repair cost ratio varies because there are different ways of repairing and strengthening, and because construction costs vary from place to place and through time – they often rise steeply after an earthquake has occurred. Repair cost ratio is also significantly affected by the type of building, and repair cost for serious damage may be more than replacement cost.

For these reasons, structural damage state is a more reliable measure of damage. If defined with sufficient accuracy, structural damage states can be converted into repair costs in any economic situation. Thresholds of structural damage also correlate with other indirect consequences such as human casualties, homelessness and loss of function, in ways that economic parameters of damage cannot. The definition of structural damage generally used involves a sequence of structural damage states, with broad descriptors such as ‘light’, ‘moderate’, ‘severe’, ‘partial collapse’, elaborated with more detailed descriptions which may use quantitative
Table 9.4 Definition of damage states for masonry and reinforced concrete frame buildings: brief damage definitions (see also full definitions in Section 1.3).

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Definition for load-bearing masonry</th>
<th>Definition for RC-framed buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0 Undamaged</td>
<td>No visible damage</td>
<td>No visible damage</td>
</tr>
<tr>
<td>D1 Slight damage</td>
<td>Hairline cracks</td>
<td>Infill panels damaged</td>
</tr>
<tr>
<td>D2 Moderate damage</td>
<td>Cracks 5−20 mm</td>
<td>Cracks &lt;10 mm in structure</td>
</tr>
<tr>
<td>D3 Heavy damage</td>
<td>Cracks &gt;20 mm or wall material dislodged</td>
<td>Heavy damage to structural members, loss of concrete</td>
</tr>
<tr>
<td>D4 Partial destruction</td>
<td>Complete collapse of individual wall or individual roof support</td>
<td>Complete collapse of individual structural member or major deflection to frame</td>
</tr>
<tr>
<td>D5 Collapse</td>
<td>More than one wall collapsed or more than half of roof</td>
<td>Failure of structural members to allow fall of roof or slab</td>
</tr>
</tbody>
</table>

measures such as crack widths. A commonly used set of damage states is the six-point scale defined in the EMS scale described and illustrated in Section 1.3,\(^9\) since the damage states defined in this scale are relatively easy to assess. A more detailed elaboration appropriate to assessing the performance of particular building types may sometimes be used; damage states, derived from the EMS scale, suitable for assessing the damage to masonry structures and reinforced concrete frame structures, are shown in Table 9.4.

Some damage evaluation methods assess damage levels separately for different parts of the structure and then use either the highest or average values for the overall damage state classification of the structure.

9.3.4 Damage Distribution

In any single location after an earthquake, buildings suffer a range of different types and levels of damage. Surveys record the distributions of structural damage states (numbers of buildings in each damage state) for each building type in each location. The format used for the definition of the probable distribution of damage depends on the method of defining the earthquake hazard parameter. Each of the basic methods of defining the earthquake hazard parameter described in Section 7.3 requires a different format.

Where the hazard is defined from macroseismic site shaking characteristics in terms of intensity, which is a discrete scale, the most widely used form is the damage probability matrix (DPM). The DPM shows the probability distribution of damage among the different damage states, for each level of ground shaking; DPMs are defined for each separate class of building or vulnerable facility.

Table 9.5  Typical example of a damage probability matrix for Italian weak masonry buildings (based on Zuccaro 1998) % at each damage level.

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Intensity (European Macroseismic Scale) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V</td>
</tr>
<tr>
<td>D0 No damage</td>
<td>90.4</td>
</tr>
<tr>
<td>D1 Slight damage</td>
<td>9.2</td>
</tr>
<tr>
<td>D2 Moderate damage</td>
<td>0.4</td>
</tr>
<tr>
<td>D3 Substantial to heavy damage</td>
<td>0.0</td>
</tr>
<tr>
<td>D4 Very heavy damage</td>
<td>0.0</td>
</tr>
<tr>
<td>D5 Destruction</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 9.5 shows an example. In this case, the range of expected damage cost (as a repair cost ratio (RCR)) is sometimes also given for each damage state, along with the estimated mean or central damage factor which may be assumed for each damage state; this makes it possible for the physical damage to be reinterpreted in terms of repair cost ratio.

Where the hazard is defined in terms of an engineering parameter of ground motion such as peak ground acceleration (PGA), similar information may be presented as a continuous relationship, defining, for the particular class in question, the probability that the damage state will exceed a certain level, as a function of the ground motion parameter used. An example of vulnerability defined this way is shown in Figure 9.5. In this case and the above, the damage distribution so defined is assumed to be a unique property of the particular building class, relevant in any earthquake, given the same defined level of ground shaking.

Where the hazard is defined in terms of the spectral displacement of a particular building type, vulnerability is expressed in terms of a set of fragility curves defining the probability of any building being in a given damage state after shaking causing a given spectral displacement. Such fragility curves are based on a standard distribution function, enabling them to be defined by the parameters of the distribution. The approach is discussed in more detail in Section 9.5.

Clearly, to define any such relationships on the basis of observed vulnerability, a substantial quantity of data is required; where data is missing or inadequate, a method is required to enable reasonable assessments to be made. Two such methods will be discussed in this section—the use of standard probability distributions, and the use of expert opinion survey. An alternative approach is described in Section 9.4.

### 9.3.5 Probability Distributions

In any location affected by destructive levels of earthquake ground motion, buildings will be found in a range of damage states. Surveys of damage, classifying buildings into building type categories and recording damage states for each, can
be presented in the form of histograms showing the damage distribution for each building type. This distribution of damage is related to the intensity of ground motion so that, for example, where high intensities have been experienced, the damage distribution shifts towards the higher levels of damage. In the analysis of the damage data from past earthquakes, it has been observed that the distributions of damage for well-defined classes of buildings tended to follow a pattern which is close to the binomial distribution.\(^{10}\) Using this form, the entire distribution of the buildings among the six different damage states D0–D5 could be represented by a single parameter.\(^{11}\)

The parameter \(p\) can take any value between 0 (all buildings in damage state D0, undamaged) and 1 (all buildings in damage state D5, collapsed). The distributions generated for particular values of \(p\) are shown in Figure 9.3. Defining damage distributions in terms of \(p\) both simplifies these definitions (replacing a six-parameter specification with a single parameter for each building class and level of ground motion) and provides a better basis for the use of limited damage data in generating distributions. The binomial parameter \(p\) may be used in the generation of either DPMs or continuous vulnerability functions.\(^{12}\) Observations suggest that damage distributions of masonry buildings appear to conform quite well to the binomial model. Other building types, such as frame structures, may have a more varied distribution, requiring a more complex description. A similar characterisation of damage distribution in terms of the beta distribution has also been used,\(^{13}\) which uses two parameters, and hence allows for more flexibility in the shape of the distribution to fit different circumstances.

Figure 9.3 Theoretical distributions for each damage level D0–D5 defined by different values of binomial parameter \(p\)

\(^{10}\) Braga et al., (1982)

\(^{11}\) According to this distribution, the proportion of the total building stock falling into damage state D1 is defined by \(V_1 = \frac{5!}{1!(5-1)!} \times p^1(1-p)^{5-1}\).

\(^{12}\) Braga et al. (1982).

\(^{13}\) For example, by Spence (1990) and Applied Technology Council (1985).
9.3.6 Expert Opinion Survey

The technique of expert opinion survey may be useful in generating vulnerability functions or DPMs for classes of structures which are reasonably well defined in structural terms, but for which limited damage data is available.

In essence the method is as follows. A number of experts are asked to provide independent estimates of the average damage level (defined in a predetermined way) for each class of building at each level of intensity; the answers are circulated to all the experts, who are then asked to revise their assessment in the light of the responses of others, and by this means a consensus is approached. The average damage levels agreed are then converted into damage probabilities using a standard distribution technique. One use of this method was in developing earthquake damage evaluation data for California.14

9.4 The PSI Scale of Earthquake Ground Motion

In many earthquake regions much of the building stock is not built to any code of practice, and there are no instruments available to measure ground motion. Thus, the use of damage data to assess the intensity of shaking at any location is likely to continue to be important both as a measure of the strength of the shaking and as a means to assess likely future losses.

But the use of macroseismic intensity scales as a ground motion parameter for this purpose has a number of difficulties:

- Intensity is a descriptive not a continuous scale, which makes it difficult to use for predictive purposes.
- Significant variations are found to exist between one survey group and another in identifying intensity levels.
- Intensity scales assume a relationship between the performance of different building types which is not found in reality.

The parameterless scale of seismic intensity (PSI scale) has been devised to avoid these problems. It is a scale of earthquake strong motion ‘damagingness’, measured by the performance of samples of buildings of standard types. It is based on the observation that, although assigned intensity in different surveys varies widely even with the same level of loss, the relative proportions of a sample of buildings of any one type in different damage states are fairly constant, and so are the relative loss levels of different building classes surveyed at the same location.

14 Applied Technology Council (1985).
Figure 9.4 shows, for example, the average performance of samples of brick masonry buildings at and above each level of damage D0 to D5, given the proportion of the sample damaged at or above level D3.

The PSI scale is based on the proportion of brick masonry buildings damaged at or above level D3; it is assumed that this proportion is normally distributed with respect to the ground motion scale. The PSI parameter $\psi$ is defined so that 50% of the sample is damaged at level D3 or above when $\psi = 10$, and the standard deviation is $\psi = 2.5$. Thus about 16% of the sample is damaged at D3 or above when $\psi = 7.5$, 84% when $\psi = 12.5$, etc. The curve for D3 thus has the form shown in Figure 9.5(a). Using this curve as a basis, the curves for other damage levels are defined from the relative performance of buildings in a large number of damage surveys. Likewise, vulnerability curves for other building types have been derived from their performance relative to brick buildings in surveys.

Since the vulnerability curves are of cumulative normal or Gaussian form, the proportion of buildings damaged to any particular damage or greater is given by the standard Gaussian distribution function.\textsuperscript{15}

Values of the Gaussian distribution parameters $M$ and $\sigma$ for a range of common building types and damage states have been derived from the damage data in the Martin Centre damage database. These are shown in Table 9.6, with confidence limits on $M$ where appropriate. Some examples are illustrated in Figure 9.6. A fuller description and justification for the PSI methodology is given elsewhere.\textsuperscript{16}

### 9.4.1 Relating PSI to Other Measures of Ground Motion

Figure 9.5(a) shows how the PSI scale relates to the intensity scale defined in the EMS 1998 scale.

\textsuperscript{15}A normal distribution is defined by a mean, $M$, and a standard deviation, $\sigma$, as:

$$
 y = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[ -\frac{1}{2} \left( \frac{x-M}{\sigma} \right)^2 \right]
$$

The cumulative distribution function, $D = \text{Gauss}[M, \sigma, \psi]$, is then defined by:

$$
 D = \int_{-\infty}^{\psi} \frac{1}{\sqrt{2\pi}\sigma} \exp \left[ -\frac{1}{2} \left( \frac{\psi-M}{\sigma} \right)^2 \right]
$$

where $D$ is the percentage of the building stock damaged (0–1.0) and $\psi$ is the intensity. The inverse function, $\psi = \text{Gauss}^{-1}[M, \sigma, D]$, can also be used to derive an intensity value from a level of damage.

\textsuperscript{16}Spence et al. (1998).
Figure 9.4  Analysis of brick masonry damage distributions
Correspondence of PSI to Intensity Definitions

Figure 9.5  (a) Damage distributions of brick masonry buildings arranged as a best fit against Gaussian curves are used to define the parameterless scale of intensity (PSI or $\psi$). (b) An analysis of the scatter from this gives the confidence limits on predictions using this method.

Where it has been possible to carry out statistical damage surveys in the immediate vicinity of recording instruments (within a radius of maximum 400 metres where soil conditions remain constant) it is possible to obtain an approximate correlation between PSI and various ground motion parameters. Figure 9.7 shows data points and linear regression analyses carried out for two particular parameters: peak horizontal ground acceleration (PHGA) and mean response spectral acceleration (MRSA). Peak horizontal ground acceleration is the most commonly used parameter of ground motion, and although the dataset is small, Figure 9.10
Table 9.6  Vulnerability functions for worldwide building types.

<table>
<thead>
<tr>
<th>Building Type</th>
<th>M</th>
<th>σ</th>
<th>Conf. limits (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High confidence (20 to 100 damage survey data points)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB1 Brick masonry unreinforced</td>
<td>4.9</td>
<td>7.8</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>CC1 RC frame, non-seismic</td>
<td>7.9</td>
<td>10.3</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>AR1 Rubble stone masonry</td>
<td>3.2</td>
<td>5.9</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Good confidence (up to 20 damage survey data points)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA1 Adobe (earthen brick) masonry</td>
<td>3.9</td>
<td>6.6</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>BB2 Brick with ringbeam or diaphragm</td>
<td>6.5</td>
<td>9.4</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>BC1 Concrete block masonry</td>
<td>5.6</td>
<td>8.5</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>BD1 Dressed stone masonry</td>
<td>4.0</td>
<td>7.1</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>DB1 Reinforced unit masonry</td>
<td>7.5</td>
<td>10.6</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Moderate confidence (extrapolated from published estimates by others)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT1 Timber frame with heavy infill</td>
<td>8.8</td>
<td>10.5</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

There is good evidence from surveys of earthquake damage in Italy (1980) and Turkey (1983) that a reinforced concrete ringbeam or floor diaphragm in load-bearing masonry structures A and B decreases their vulnerability by about 1.6 \( \psi \) units (add 1.6 to \( \psi \)50 values for these building types).

(continued overleaf)
Table 9.6  (continued)

<table>
<thead>
<tr>
<th></th>
<th>RC frame seismic design</th>
<th>$M$</th>
<th>$\sigma$</th>
<th>9.4</th>
<th>11.1</th>
<th>13.0</th>
<th>14.7</th>
<th>16.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>UBC3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>RC frame seismic design</td>
<td>$M$</td>
<td>$\sigma$</td>
<td>10.6</td>
<td>12.4</td>
<td>14.7</td>
<td>17.0</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>UBC4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conf. limits (SD)

Figure 9.6  Vulnerability functions for some common building types
Figure 9.7 The relationship between PSI and instrumental parameters of ground motion, peak horizontal ground acceleration (PHGA) and mean response spectral acceleration (MRSA), over the 0.1–0.3 second period range. Correlation coefficients for the data from the 14 sites are not high, but MRSA is a somewhat better predictor of PSI than PHGA. (Data from Spence et al. 1991a)

below shows that it correlates reasonably well with PSI in this dataset: the coefficient of correlation is 0.77. The majority of the masonry buildings in the 14 sites examined here are residential houses one to three storeys high, and it could be expected that a good parameter to describe the ‘damagingness’ of ground motion to these buildings would be the mean response spectral acceleration over the range of the natural periods of such buildings, i.e. 0.1 to 0.3 seconds. This correlation has also been plotted in Figure 9.7 and was found to give a correlation coefficient of 0.81, slightly better than that for PHGA. Using this relationship and vulnerability functions such as those of Figure 9.6 offers a good basis for estimating losses when ground accelerations or intensities can be predicted.

The PSI scale can also be used to assist in the analysis of post-earthquake damage surveys. Figure 9.8 shows the results of surveys of buildings damaged in a number of locations, as surveyed after the 1999 Kocaeli earthquake.¹⁷ Each of these surveys has been located on the appropriate set of damage curves determining the best-fit value of PSI at that location, and from this an understanding

¹⁷ Johnson et al. (2000).
Figure 9.8  Use of the PSI scale in post-event damage survey. Plotting of surveyed damage to mid-rise reinforced concrete frame buildings in the locations of worst damage in the 1999 Kocaeli, Turkey, earthquake. (Risk Management Solutions)
of the geographical distribution of PSI and hence macroseismic intensity was deduced. A similar approach was used for mid-rise reinforced concrete frame buildings damaged in the 2001 Gujarat, India earthquake.\(^{18}\)

### 9.5 The HAZUS Methodology

The HAZUS methodology is a predictive method of loss estimation based on recent performance-based procedures for the design of new buildings and for retrofitting existing buildings. For any individual building, these procedures enable levels of earthquake ground motion to be defined which correspond to a range of post-earthquake damage states, from undamaged to complete collapse. The use of such procedures is as applicable to evaluation as it is to design: that is, they can be used for assessing the probable state of an existing building after a given earthquake motion as well as for designing new (or strengthening existing) buildings. The HAZUS methodology has been developed in the United States as part of a FEMA-supported national programme to enable communities or local administrations to assess and thereby reduce the earthquake (and other) hazards they face.

The resulting HAZUS earthquake loss estimation methodology is a systematic approach which combines knowledge of earthquake hazards (from ground shaking, fault rupture, ground failure, landslide, etc.) with building and other facility inventory data and building vulnerability data to estimate losses for a community. One of its strengths is its comprehensiveness: estimation of losses includes losses to lifelines, industrial facilities, etc., and goes beyond direct damage to include estimates of induced damage (fire, hazardous materials release), and to estimates of casualties, shelter requirements and economic losses. But for these modules to be used, there is a large demand for inventory and other data appropriate to each locality. At the heart of the HAZUS loss estimation methodology is a process for developing vulnerability or fragility curves for buildings and other facilities, to estimate the losses from ground shaking, which has been used to define likely losses for a range of different building types found in the United States. Altogether it defines 36 different classes of buildings (Table 9.3) and many other facility classifications, distinguished according to age, height and level of seismic resistance designed for. For each building class a set of parameters defines the expected average earthquake capacity curve for the class. This curve, together with further parameters, then defines the displacement response to any given earthquake ground motion, resulting in an expected loss distribution for a typical population of buildings of any class.

The procedure needed to define the displacement response is rather more complex than that used to develop loss estimates based on MM or EMS intensity as the

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\(^{18}\) EEFIT (2002b), Del Re et al. (2002).
governing ground motion parameter. However, in many situations its advantages will outweigh the extra computational effort considering that:

- Engineering seismology internationally has for some years been directed towards defining earthquake ground motion in terms of instrumental parameters rather than macroseismic intensity.
- No satisfactory way to incorporate the interaction of earthquake ground motion characteristics (amplitude, frequency, duration) with soil type and building response is possible using intensity or any other single ground motion parameter.
- Intensity-based loss estimation methods are primarily derived from past damage data; this makes it difficult to estimate the losses to newer building types which have not experienced damage.
- The calculated displacement-based procedure can readily be extended to study the effect on losses of strengthening existing buildings in alternative ways, which is not easily achieved using intensity-based procedures.

9.5.1 Damage States

The essence of the HAZUS methodology for estimating losses from ground shaking is that the damage state of a building is taken to be defined by the interstorey drift ratio at the most deformed level of the building. A series of damage states is defined (called slight, moderate, extensive, complete) with detailed descriptors of the state of damage which corresponds with each state for each class. Figure 9.9 shows for example the damage states appropriate for mid-rise reinforced concrete frame buildings. For each separate class of building, each of these damage states is taken to correspond to a threshold level of interstorey drift ratio, at which this damage state would just be triggered.

Performance Point

For a single building, and for any given earthquake ground motion, the interstorey drift is derived from the spectral displacement of the building as a whole in response to the motion. This spectral displacement, at what is described as the ‘performance point’ for the building, is defined by the interaction of the ‘demand’ on the building created by the ground motion, and the ‘capacity’ of the building in terms of a response or capacity curve, which is derived from the elastic response of a single degree-of-freedom system by taking account of the degradation of the building as shaking progresses. Both demand and capacity are defined by curves of spectral acceleration $S_a$ against spectral displacement $S_d$, and the performance point $(S_a, S_d)$ is taken to be at the intersection of these two curves. This process is illustrated in Figure 9.10.
<table>
<thead>
<tr>
<th>Damage state</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight structural damage</td>
<td>Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks a frame—infill interfaces</td>
</tr>
<tr>
<td>Moderate structural damage</td>
<td>Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam—column connections. Diagonal shear cracks may be observed in concrete beams or columns</td>
</tr>
<tr>
<td>Extensive structural damage</td>
<td>Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; few walls may fall partially or fully; few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation</td>
</tr>
<tr>
<td>Complete structural damage</td>
<td>Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and non-ductile failure of the concrete beams and columns</td>
</tr>
</tbody>
</table>

Figure 9.9  Damage states for low- and mid-rise reinforced concrete buildings used: the HAZUS loss estimation methodology

### 9.5.2 Capacity Curve

Detailed rules for the construction of standard capacity curves for each building class are given in the HAZUS manual.\(^{19,20}\) The capacity curve is derived from static pushover curves using concepts explained in more detail in ATC-40\(^ {21}\) and FEMA 273.\(^ {22}\) For each building type the capacity curve for \(S_a\) vs \(S_d\) has an initial linear section where the slope depends on the typical natural frequency of the building class, and rises to a plateau level of \(S_a\) at which the maximum attainable resistance to static lateral force has been reached (Figure 9.10).

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\(^{19}\) FEMA (1999).
\(^{20}\) Kircher et al. (1997).
\(^{21}\) Applied Technology Council (1996).
\(^{22}\) FEMA (1997).
9.5.3 Demand Curve

The demand curve derives from a damped elastic spectral response curve built from spectral parameters of the ground motion, as modified according to soil type. This is done by incorporating spectral reduction factors to account for the increased hysteretic damping as the building shifts from elastic into inelastic response (Figure 9.10). Rules for constructing these spectral reduction factors are also given in the HAZUS manual: a different spectral reduction factor is associated with each value of spectral displacement; it depends on the shape of the capacity curve up to that displacement level, and also on a degradation factor, to account for the reduction in hysteretic damping occurring in poorly designed buildings, which depends in turn on the duration of shaking and the state of the building.

9.5.4 Damage Distribution

To estimate the performance of a group of buildings of a particular class under given ground shaking, the spectral response of the building at the performance
point for the standard building of that class, as defined above, is used in conjunction with a set of four fragility curves (Figure 9.11) for that class, which estimate the probability of any particular building being in each of the four damage states after shaking at any given spectral response level. Each of these curves is assumed to be lognormal in form, and is defined by two parameters: a *median value* and a *coefficient of variation*. These curves are used to define the distribution of a set of buildings among the four damage states. The HAZUS manual gives parameters for the construction of these fragility curves for each of the 36 major building classes defined for the US building stock and for zones with different seismic design regulations.

For most building types, the spectral response to be used is the spectral displacement as defined above (such building types are considered ‘displacement-sensitive’, or ‘drift-sensitive’), but some classes of facilities, and some building elements and equipment, are taken to be damaged as a result of the spectral acceleration rather than the spectral displacement (they are ‘acceleration-sensitive’), and this is reflected in fragility curves defined in terms of this parameter. For the United States, a set of parameters to construct each of the curves required for each building type has been defined in the HAZUS manual. The method has also been applied for loss estimation studies in Turkey.23

![Figure 9.11](image-url)  
**Figure 9.11** Example fragility curves for a particular building type used in the HAZUS loss estimation methodology

23 Bommer *et al.* (2002).
9.6 Human Casualty Estimation

The purpose of most earthquake protection programmes is to save life. For loss estimation studies to be useful for earthquake protection they need to include an assessment of the probable levels of human casualties, both deaths and injuries, which will be caused by the earthquake.

Casualty estimation is notoriously difficult. Casualty numbers are highly variable from one earthquake to another and data documenting occurrences of life loss in earthquakes is poor. During an earthquake the chaotic disruption and physical damage causes loss of life in many different ways: building collapse, machinery accidents, heart attacks and many other causes. Some earthquakes trigger follow-on secondary hazards which also cause loss of life, like landslides, mudflows and fires.

An approximate classification of earthquake deaths by cause, during the twentieth century, is presented in Figure 1.1. Up to 25% of all deaths are from non-structural causes or follow-on hazards. In some cases, follow-on disasters like urban fires, mudflows, rockfalls and landslides can lead to many more deaths than those caused directly by the earthquake. Follow-on disasters of this type are extremely difficult to predict, but they normally cause only a small proportion of the earthquake casualties. For the large majority of earthquakes, deaths and injury are primarily related to building damage. Over 75% of deaths are caused by building collapse (and if secondary disasters are excluded, building collapse causes almost 90% of earthquake-related deaths). In Figure 9.12, the total number of people killed is plotted against the total number of buildings heavily damaged for earthquakes where both statistics are known with some reliability. Deaths can be seen to be broadly related to the destruction caused by earthquakes. However, casualty totals are much more variable in earthquakes causing low or moderate levels of damage, i.e. those where fewer than 5000 buildings were damaged.

An approach to estimating these casualties is by determining the ‘lethality ratio’ for each class of building present in a set of buildings damaged by an earthquake.\(^\text{24}\) Lethality ratio is defined as the ratio of the number of people killed to the number of occupants present in collapsed buildings of that class. Thus the estimation of casualties derives from an estimate of the number of collapsed buildings of each class, calculated using methods described above, and the lethality ratio for that class.

Lethality ratio has been found from an examination of data from past earthquakes to depend on a number of factors including building type and function, occupancy levels, type of collapse mechanism, ground motion characteristics, occupant behaviour and SAR effectiveness. To obtain overall casualty levels, information on the spatial distribution of earthquake intensity and building

\(^{24}\) Coburn et al. (1992).
damage, a suitable building classification, and statistics on the distribution of buildings of each type and their occupancy levels are required.

The lethality ratio for each building class can be estimated using a set of parameters defining the expected proportions of occupants who are trapped, the proportion of those trapped who are subsequently rescued, and the injury distribution in each group. A set of M-parameters is used to estimate the proportions of people rescued and trapped at each stage and the injury distributions among them. Figure 9.13 explains the meaning of these M-parameters. Each building class has its own specific set of M-parameters taking account of the likely collapse characteristics of that class of building and the SAR capability, which are derived from or compared with published casualty data.25

The proportion of occupants trapped by collapse (M3) is strongly influenced by building type, and also increases with building height. For tall reinforced concrete or masonry buildings it may reach as high as 50% or 60%. However, for the most numerous one- and two-storey buildings, even if they did collapse, it is unlikely that more than a very small proportion of occupants would be trapped. For collapsed residential timber frame buildings it is estimated that only 3% of occupants would be trapped. The proportion of occupants trapped by collapse is

Factors M1 to M5 are used in the estimation of the number of human casualties likely to occur in an earthquake. M3 is also affected by the type of ground motion. Table 9.7 indicates the range of available data.

The proportion of occupants killed at collapse (M4) is assumed to depend on building type. For the timber and masonry classes 20% are assumed killed, while for the concrete and steel classes 40% are assumed to be killed at collapse. Table 9.8 shows typical injury distributions for the major building classes.

The mortality post-collapse (M5) depends crucially on the effectiveness of SAR, which will vary considerably between countries and according to the scale of the earthquake and whether the rural or urban population is affected, but the speed of rescue would be slower for concrete and steel buildings for which heavy cutting and lifting equipment would need to be deployed. In timber buildings it
Table 9.7  M3: estimated average percentage of occupants trapped by collapse.

<table>
<thead>
<tr>
<th>Collapsed masonry buildings (up to three storeys)</th>
<th>Intensity</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5%</td>
<td>30%</td>
<td>60%</td>
<td>70%</td>
<td></td>
</tr>
</tbody>
</table>

| Collapsed RC structures (3–5 storeys)            | Near-field, high-frequency ground motion: | 70% |
|                                                  | Distant, long-period ground motion:      | 50% |

Table 9.8  M4: estimated injury distributions at collapse (% of trapped occupants).

<table>
<thead>
<tr>
<th>Triage injury category</th>
<th>Masonry</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Dead or unsaveable</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>2. Life-threatening cases needing immediate medical attention</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>3. Injury requiring hospital treatment</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>4. Light injury not necessitating hospitalisation</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

is assumed that most of those trapped would be quickly rescued; on the other hand, in any reinforced concrete buildings collapsing, rescue might come too late for 50% or more of those trapped. Thus values of M5 range from 10% for residential timber frame to 67% for the tallest pre-code reinforced concrete buildings. Figure 3.3 presents some indicative data on fade-away times for injured trapped victims, and Table 9.9 summarises aggregated data on survival rates from a number of earthquakes.

The injury distribution among those eventually rescued will also depend on the type of building. For steel and concrete buildings it has been assumed that 66% are uninjured, while for masonry and timber only 25% would be uninjured. The injured are roughly equally divided between serious and moderate injuries.

Table 9.9  M5: percentage of trapped survivors in collapsed buildings that subsequently die.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Masonry</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community incapacitated by high casualty rate</td>
<td>95</td>
<td>–</td>
</tr>
<tr>
<td>Community capable of organising rescue activities</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Community + emergency squads after 12 hours</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Community + emergency squads + SAR experts after 36 hours</td>
<td>45</td>
<td>70</td>
</tr>
</tbody>
</table>
Table 9.10  Casualty distributions for collapsed buildings for key building types in the case of Wellington, New Zealand.

<table>
<thead>
<tr>
<th>Class</th>
<th>Killed (%)</th>
<th>Seriously injured (%)</th>
<th>Moderately injured (%)</th>
<th>Lightly injured or uninjured (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry (2–3 floors)</td>
<td>17.5</td>
<td>10</td>
<td>17.5</td>
<td>55</td>
</tr>
<tr>
<td>RC frame (2–3 floors)</td>
<td>21</td>
<td>0.8</td>
<td>9.2</td>
<td>70</td>
</tr>
<tr>
<td>RC shear wall (2–3 floors)</td>
<td>10</td>
<td>0.7</td>
<td>9.3</td>
<td>80</td>
</tr>
<tr>
<td>Steel (2–3 floors)</td>
<td>16</td>
<td>0.6</td>
<td>9.4</td>
<td>75</td>
</tr>
<tr>
<td>Timber (1 floor)</td>
<td>0.6</td>
<td>0.2</td>
<td>10.2</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 9.10 shows the resulting distribution of injuries among occupants of collapsed buildings for a few common building types based on the special circumstances of Wellington, New Zealand.\(^{26}\)

The casualties calculated in this way will constitute most, but not all, of the expected casualties. In addition to the casualties caused by building collapse, other possible causes of casualties need to be considered, including the major secondary catastrophes mentioned above, the collapse of large civil engineering structures, the direct effects of the fault rupture, and miscellaneous other causes.

### 9.7 Other Losses

The techniques discussed in Sections 9.4 and 9.5 are suitable for the assessment of the physical damage to buildings and other fixed and structured facilities, including the infrastructure of services, roads, power supply networks, resulting from ground shaking. But losses resulting from earthquakes extend well beyond these direct consequences of the ground shaking, and any adequate assessment must take these indirect or secondary effects and their consequences into account, and attempt to evaluate them. In particular it is important to evaluate:

- losses from collateral earthquake hazards such as ground failure, flooding and fire;
- non-structural losses to the buildings and facilities, their equipment and fittings;
- economic loss resulting from loss of function of the facility for the period of time needed to restore its use.

Techniques for the assessment of these losses are much less developed than those for the assessment of structural damage due to ground shaking, since there is much more limited data available, and rather crude assessments must be made,

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\(^{26}\) Spence et al. (1998).
generally relying extensively on professional judgement. Methods of assessing these losses are discussed briefly below.

9.7.1 Collateral Hazards

Collateral or secondary hazards are those earthquake-related hazards other than the shaking of the ground itself which threaten life and property. The hazards which usually need to be considered can be grouped under three headings: ground failure, flooding and fire.

Ground Failure

Several types of ground failure can occur in earthquakes. Landslides, rock slides and mudflows are frequently triggered and can be very destructive. The principal factors affecting the occurrence of landslides are the surface geology (including the presence of pre-existing slides), the slope gradient, the water content of the soil, and the intensity of ground shaking. The first two of these factors can be mapped in such a way as to identify different degrees of landslide susceptibility, each associated with a critical level of ground shaking; the level of destructiveness of the potential landslide can also be evaluated by defining damage states ranging from light (insignificant movement) to catastrophic (movement sufficient to carry everything large distances). For each level of landslide susceptibility, a landslide probability matrix can thus be defined, identifying the probability of occurrence of each damage state, for each intensity of ground shaking. In practice the data for the construction of such matrices is insufficient, and those so far produced rely heavily on professional judgement.

A second type of ground failure is earthquake-induced liquefaction. Loose fine sands which are in a saturated state are most susceptible, and these can generally be identified from existing subsoil maps. The probability of liquefaction for any susceptible deposits is greater the greater the level of ground shaking, and liquefaction probabilities can be estimated for particular known deposits based on in situ soil testing and professional judgement.27

A third type of ground failure is that which occurs as a result of ground disturbance at or close to a fault break. The disturbance can take the form of a local deformation, often a clean linear break in the ground surface, with the two sides moving relative to each other. The relative movement at a fault break can be either horizontally along the fault or vertically, or a combination of the two. Alternatively the ground disturbance may take the form of a more general regional deformation. Local deformations may be severe up to a few hundred metres at most from the fault, and are potentially highly destructive to any facilities in this area. If the location of a potential fault is known, the approximate

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27 FEMA (1999).
length of fault break and the extent of movement on the fault as a function of magnitude can be estimated, and this can be used to judge the damage potential.\textsuperscript{28} This is of minor importance for buildings but of great significance in the case of subsurface lifelines and roads. In most cases a knowledge of the precise location of the potential fault is not available, but this may not be important for assessing its effects on lifelines. Another local hazard commonly associated with fault breaks is the amplification of ground motion in a region near the end of the fault break in the direction of propagation of movement along the fault.

Flooding

Flooding in earthquakes can result from tsunamis and seiches, or from dam or reservoir failure. The damage potential from tsunamis and seiches in low-lying coastal areas may be considerable, and can result from large undersea earthquakes with very distant epicentres. Damage assessment requires a knowledge of the potential height of the waves, velocity of the water, the topography of the coastal areas, and the damageability of the facilities in these areas to saturation and to water at various velocity rates. The assessment of damage potential from dam failure requires a knowledge of the vulnerability of the dam to earthquake ground shaking, the area susceptible to flooding in the event of the failure, and the vulnerability of the facilities in these areas to flooding.\textsuperscript{29} If a reservoir is at a low level at the time of the earthquake, dam failure may occur several months later as seasonal rainfall refills it.

Fire

Fire following earthquakes is a common occurrence, and can be a major cause of damage as described in Section 3.5. Some fires are started in almost every damaging earthquake, but losses become significant only in cases where fire spreads in an uncontrolled manner. There are many factors influencing the probability of such a ‘conflagration’. The first is the number of fires started initially, which will depend on the type of heating and cooking equipment in use and fuel storage and distribution methods; the second is the density of combustible material available, and the rate of spread which will also depend on the weather and climatic conditions; finally, the action of the firefighting services in suppressing fires will be a key factor. This will in turn depend on the capability of those services, the availability of water, accessibility of the fires, and the extent of involvement of the firefighting services in parallel activities such as SAR. Because of this large range of variables, it has proved exceptionally difficult to develop useful

\textsuperscript{28} FEMA (1997), p. 4–40.
\textsuperscript{29} FEMA (1997), Chapter 9.
quantitative procedures for predicting fire losses. Models have been developed for low- and mid-rise buildings in Japan, where available data is sufficient to justify the use of empirical relationships between the numbers of collapsed timber frame buildings.\textsuperscript{30} A method has also been proposed for use in the western United States where timber frame single-family dwellings and apartment blocks are common, though its application depends on many assumptions about density of development, windspeed, temperature and so on.\textsuperscript{31} Prediction of fire losses in earthquakes is likely to be highly uncertain.

\section*{9.7.2 Non-structural and Economic Losses}

Non-structural losses are of two types: first, losses to the non-structural elements and components of the actual building, such as cladding, partitions, windows and services; and, secondly, losses to the building contents, such as furniture and equipment. The losses to non-structural components are usually included with those to the structure itself, since they are often indistinguishable, and these may be measured either in terms of direct physical damage (damage level D0–D5) or in terms of repair cost or damage factor. The damage probability matrix (DPM) or other vulnerability functions generally include such non-structural damage.

Losses to contents can usually be measured only in terms of value; the degree of loss can be expected to relate not only to the extent of physical damage to the building, but also to the use to which the building is put. Thus to determine damage probability distributions for contents a social function classification of buildings is required in addition to their structural vulnerability classification. For residential buildings, contents losses are relatively predictable as a function of damage state. The HAZUS manual, for example, gives mean estimates of 1\% for slight damage, 5\% for moderate damage, 25\% for extensive damage, and 50\% for complete damage.\textsuperscript{32} For other uses a detailed understanding of the nature of the contents, and for industries their inventories or stocks of raw materials or unsold products, is needed to assess probable contents losses.

Economic losses arising from an earthquake are not limited to the monetary value of the physical damage, but must also include losses of industrial production, commercial and other economic activities consequent on the physical damage, which have been discussed in Chapter 2. These economic losses are associated with (or the consequences of) the loss of function of the buildings or the unavailability of employees, and to assess probable economic losses it is important to try to assess the degree of loss of function of each building and facility, and the length of time needed for partial and complete restoration of function.\textsuperscript{33} This will depend not only on the degree of physical damage (to

\textsuperscript{31} FEMA (1997), Chapter 10.
\textsuperscript{32} FEMA (1997), Chapter 15.
\textsuperscript{33} FEMA (1997), Chapter 15.
building and contents), but also on the degree of damage to lifelines (roads, power networks and other infrastructure) on which the building depends, and other external factors such as casualties among the workforce. The loss of production of a large number of individual enterprises can have a significant effect on the economy of a whole region through broken chains of backward linkages (to suppliers) and forward linkages (to buyers or consumers).\textsuperscript{34} The scale and nature of these losses can be investigated by using input–output modelling, and standard procedures have been developed.\textsuperscript{35}

9.8 Applications of Loss Estimation

This section will discuss methods of combining hazard and vulnerability to undertake loss estimation applicable to different situations. Location, the type of buildings and facilities involved, the extent of data available and the purpose for which the loss estimation is being made all have an influence over the choice of the method used. The problems involved in estimating losses in rural and urban areas can be quite different, as the following examples of studies carried out by the authors will show.

9.8.1 Loss Estimation in Rural Areas

Estimates of probable future losses in rural areas may be needed in order to plan relief and emergency preparedness at a regional level, and in order to support and evaluate plans for upgrading traditional housing. Often traditional low-strength rural housing is the principal cause of earthquake loss.

To evaluate losses over a large, predominantly rural area an approximate first estimate of losses may be adequate, and it may be possible to assume:

- a single homogeneous seismic source zone
- a uniform population distribution
- a single predominant type of dwelling applicable to the majority of the population.

Further, if the form of construction used is not changing rapidly, it may be possible to develop damage–attenuation relationships for the predominant type of construction based on the distribution of damage from past earthquakes in the region. Using such assumptions relationships can be used either to estimate the total losses which can be expected in the event of earthquakes of different magnitudes, or, in conjunction with a magnitude–recurrence relationship such as

\textsuperscript{34} A major cause of economic loss following the Kobe earthquake was the closure of the key port of Kobe.

\textsuperscript{35} Brookshire \textit{et al.} (1997).
that shown in Figure 7.3, to estimate the total losses which can be expected from all earthquakes over a given period of time.

The number of people killed and injured in earthquakes depends on many variables, but within a particular rural region with unchanging building technology, it is primarily related to the number of buildings which totally collapse (D5). Estimates of numbers of people killed and injured can be derived using an empirical relationship derived from past experience in the area (as discussed in Section 9.6).

One of the most important uses of loss estimates of this sort is that they can be used to assess the impact of a building improvement programme of upgrading the traditional houses, and to compare the effectiveness of different levels of technology in upgrading, if the relative vulnerabilities are known or can be estimated. Figure 9.14 shows the impact, over 25 years, in the expected numbers of deaths and houses destroyed in eastern Turkey, if different levels of strengthening corresponding to some of those shown in Figure 8.12 were generally introduced. Data of this sort can be used in a cost–benefit or cost-effectiveness evaluation of alternative possible government intervention programmes. This is discussed in Chapter 10.

### 9.8.2 Loss Estimation in Urban Areas

For urban loss estimation it may be reasonable to assume that with the occurrence of an earthquake some distance away, the attenuation of ground shaking across
the breadth of the city will be insignificant. Thus standard methods of making a hazard assessment may be used, with whichever is the most appropriate ground motion parameter. Vulnerability assessment is likely to be much more complex than for a rural area because most urban settlements contain a wide range of building types of differing earthquake vulnerabilities and a variety of ground conditions.

One technique for making a loss estimation is to divide the urban area into a number of distinct vulnerability zones, within each of which the mix of building types may be assumed uniform, the ground conditions may be assumed uniform, and the total population (or number of dwellings) is known.

This subdivision into zones can be done using whatever large-scale mapping or aerial survey of the city is available, coupled with the use of subsoil maps and field investigation. Frequently administrative zones such as districts or subdistricts will be most appropriate, since these are the units within which building stock or population data will have been collected. Often it will be found that the zoning so far as building types is concerned closely follows the pattern of historical development of the city, with a higher proportion of older, more vulnerable buildings in the centre, and predominantly newer, less vulnerable buildings towards the periphery. There is often a close coincidence between the pattern of historical development and subsoil ground conditions, with the earliest settlement located on firm ground conditions and later development occupying progressively less satisfactory ground.\(^36\) The mix of building types in each zone can be established either using census data or by sample field survey if needed. The building types defined should correspond to those for which vulnerability data already exists in the form of damage distributions from previous earthquakes. The development and availability of damage distributions in the form of the DPM and vulnerability functions has been discussed in Section 9.3. The total number of buildings in each vulnerability zone can be estimated from maps and aerial photographs, from field survey or from census data depending on the size of the zone and the availability of mapping.

The effect of soil conditions can be dealt with either by using modified damage probability distributions for poor ground conditions, or by assigning one or more increments of MM or EMS intensity, or even an adjustment of the PSI for these sites to derive an appropriate damage distribution. Where damage distributions are based on spectral parameters of ground motion, the effect of soil conditions is incorporated as a site-specific or zonal modifier of the ground motion parameter used.

A useful technique for dealing with the variation of building types and soil conditions within a city is to divide it into a grid, and assume that the soil type, building type distribution and population density appropriate to the centre of each grid square apply to the whole of that grid square. The accuracy of such estimates

\(^{36}\) Coburn \textit{et al.} (1986).
can be improved by increasing the fineness of the mesh, but it has been found
that for a medium-sized city (0.5 million population) a grid square of 0.5 km side
gives sufficiently good results.\textsuperscript{37}

These sorts of estimates are useful for regional planning of emergency ser-
\textsuperscript{37} See Department of the Environment (1993).
\textsuperscript{38} Variations in the values of the constants $A$ and $b$ used in the Gutenberg linear regression relations-
\textsuperscript{39} The Poisson distribution gives the probability of just $k$ events in time interval $s$ as being $p(k) = (e^{-Ls}(L \cdot s)^k)/k!$, where $L$ is the average rate of occurrence of events (Ang and Tang 1976).
shown to be 22%, and the probabilities of one or more event occurring in a period of 2, 5 or 10 years are 39%, 71% and 87% respectively.

The Poisson model, by assuming independence of events. It does not allow for the inclusion of aftershocks, or the clustering of events. It also assumes a stationary process, with a constant average rate of occurrence of events, and therefore does not allow for the possibility of periodic changes in the seismicity of a region, or time-dependent changes in seismicity caused by strain energy build-up and release, which are known to occur (see Chapter 3).

In a study of the uncertainty in ground motion attenuation relationships, standard deviations on the logarithm of peak ground acceleration (PGA) and peak velocity were both around 0.25, implying a 66% probability of actual values between 0.55 and 1.8 of the mean value. Because the uncertainties in the different aspects of hazard estimation interact, the uncertainty in the final hazard assessment is best approached by studying its sensitivity to likely errors in the various assumptions made. Experience suggests that the uncertainty in the effect of sub-soil ground conditions on likely ground motion levels is likely to be particularly significant.

### 9.9.2 Vulnerability

Vulnerability relationships also involve a high degree of uncertainty. The uncertainties involved here are in the ‘damagingness’ of an event of a particular severity, the definition of the building stock, and the appropriateness of the chosen vulnerability functions to the particular building stock or other facilities involved. The uncertainty is even greater when indirect losses derived from the primary losses of building stock, such as human casualty and economic losses, are made.

It is possible to examine the effect of cumulative uncertainties in loss estimates using discrete event simulation (or Monte Carlo) techniques if it is assumed that the hazard is known and that the probability distribution of each of the constituent relationships is known. This was done for losses in eastern Turkey as a part of the study discussed above. The results are shown in Figure 9.15. Estimated total losses have a 90% probability of being within ±50% of predicted losses, when a damage–magnitude model is used. However, when losses are calculated for traditional construction using a magnitude–distance damage model, the probability of the actual losses being within 50% of the predicted losses falls to 73%, and when losses to other building types are inferred through relative vulnerability functions, the probability that the actual losses will be within 50% of predicted values drops further to 40%. Estimates of human casualties are derived by uncertain relationships from already uncertain building loss estimates,

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41 Coburn (1986a).
so the uncertainties in these estimates are compounded. The study concluded that casualty estimates have only 10% to 20% probability of being within ±50% of predicted values. Where further losses such as loss of function and economic losses are to be inferred from human casualty and building losses, the uncertainty of the prediction increases still further.

To date, there have been very few cases in which loss estimates have been tested by the subsequent occurrence of an earthquake. However, one study in Italy was able to compare predicted vulnerability with observed earthquake damage in two earthquakes.\(^{42}\) It was found that the correlation improved as the intensity of ground shaking increased with acceptable correlation for areas of intensity IX and X; however, for areas with intensity levels of about VII or less the correlation was too low to be satisfactory for use in loss prediction.

To date, it appears that earthquake loss estimation is a somewhat inexact science depending to a considerable extent on professional judgements. However,

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42 Vulnerability was measured using a vulnerability index which took into account 10 different contributing factors to the vulnerability of a building, whose contribution was determined by a weighting factor. This was calculated for a sample of over 1500 masonry buildings previously damaged by the 1976 Friuli earthquakes, and a separate survey was carried out in the small town of Gubbio in 1983, which subsequently experienced a moderately damaging earthquake in 1984. The damage level was thus in both cases able to be compared with the vulnerability index (Benedetti and Benzoni 1985).
within its limitations loss estimation can give considerable information for use in protection planning. The use of quantitative methods such as those described for assessing risk or the likely outcome of various scenario studies makes it possible to compare alternative protection strategies and to obtain maximum value for money in protection investment. The use of these techniques in making decisions on protection is discussed in the next chapter.

Further Reading


Earthquake Spectra, 1997. The whole of the November 1997 issue is devoted to the subject of Earthquake Loss Estimation.


