Chapter Five

Modelling Earthquake Losses

5.1 Theoretical Approach

The object of seismic risk studies is to estimate future levels of loss to particular elements at risk within known confidence limits. Such estimates may then be used to plan mitigation policies in such a way as to make optimum use of the resources available.

Two types of loss estimate are commonly made:

(1) Estimates of losses resulting from a probable large-magnitude earthquake located at a particular source.

(2) Annualised losses arising from all possible earthquake sources and magnitudes which could cause damage.

In either case there are two principal components to the risk analysis:

- the determination of the distribution in space and time of earthquakes of each possible magnitude or intensity (the hazard model).
- given a particular event, the determination of the distribution of damage to particular elements at risk (the vulnerability model).

The principal theoretical contribution of the present study has been the development of a new type of vulnerability model appropriate to seismic risk studies in Eastern Anatolia as well as elsewhere in Turkey. The model is based on damage attenuation functions derived from detailed study of the spatial distribution of damage to stone masonry buildings in past earthquakes in the study area. These damage attenuation functions can be used to assess the probability distribution of damage to stone masonry buildings given an earthquake of a certain magnitude at a certain distance. Relative vulnerability functions (RVF) have been developed using data from numerous damage studies reported worldwide to assess the damage distribution to buildings with other construction methods, including the strengthening technologies described in Chapter Three.[1]

These techniques have been combined with data from existing hazard models to determine expected future losses and casualties for the region, and to compare the costs and benefits of alternative possible strengthening methods. This chapter will summarise each of these aspects of the study.

5.2 Damage Attenuation

The standard method of deriving damage attenuation data is to use isoseismal maps showing the distribution of felt intensity in past earthquakes. Intensity is a poorly-defined and partly subjective measure of earthquake ground motion however. The assignment of intensities in past earthquakes has involved considerable individual bias, with the result that there has been only a poor correlation between recorded intensity and local damage. It has been shown that a much better correlation exists between the instrumental magnitude of an earthquake and the total damage caused, given an area with a more or less uniform building type.[2] In this study a model of the spatial distribution of damage has been developed which enables local damage to be assessed as a function of magnitude and distance from the earthquake source.

Since 1966 the Ministry of Reconstruction and Resettlement has compiled lists of the damage to every settlement affected by earthquakes in Turkey. Within the study area this includes seven events

[1] Coburn (1986).

[2] Ambraseys and Jackson (1981).

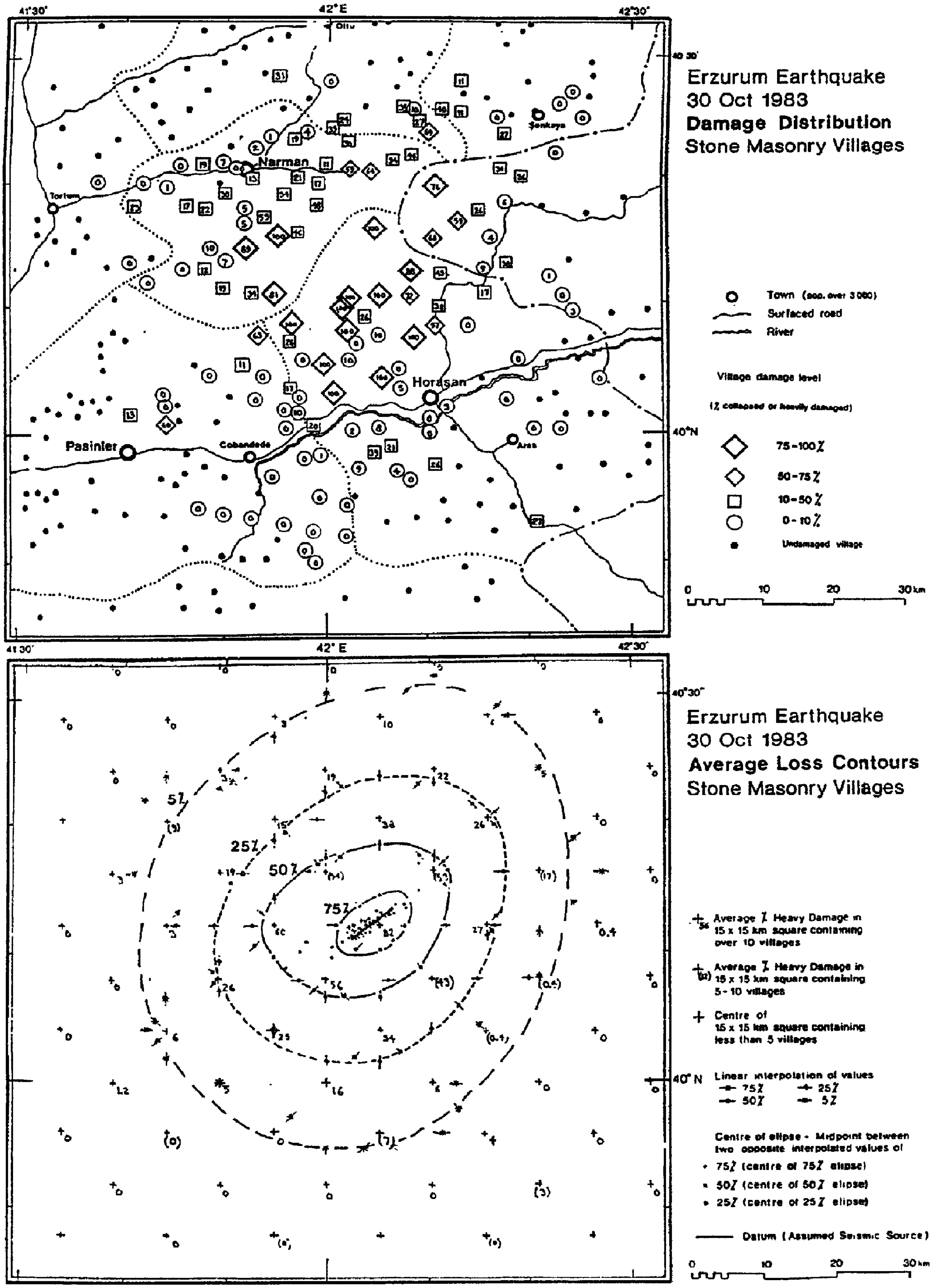


Figure 5.1 Spatial Analysis of Earthquake Damage: The Erzurum-Kars Earthquake

with magnitudes between 5.2 and 7.1. Data on affected villages known to have been predominantly stone masonry at the time of the earthquake have been used to examine their performance in each event.[3]

Analysis includes spatial distribution of damage, where the percentage heavy damage (% loss) of each village, mapped across the affected area, is analysed using 'Average Loss Contours'. Damage is averaged within a 15 km grid and interpolated between grid points to give contours of average loss as shown in figure 5.1. These contours also define a 'datum' or position of seismic source which is generally in good agreement with fault plane solutions and field determination of fault positions.

Attenuation of damage is analysed from the linear distance from seismic source to the location of each village. The distribution of damage with distance from the source is defined to obtain the probability of exceedence of a certain level of loss for a village at any distance away from the damage datum, figure 5.2(a). The average level of loss also represents the probability of heavy damage for any individual house at that distance, figure 5.2(b).

Damage attenuation has three major components:

(a) *The epicentral area*, where average loss is high and range of distribution around the mean is limited. The level of average loss appears relatively constant for some distance away from the datum.

(b) *The intermediate area*, where a relatively rapid attenuation of average loss occurs. This area is characterised by an extreme range of distribution of levels of loss. It is probable that effects of surface geology response and wave propagation in determining the severity of ground motion are most marked at this distance.

(c) *The fringe area*, where losses are generally light, and distribution is limited, but a small number of villages sustain some level of loss and this maintains a significant average level of loss for a considerable distance.

The six earthquakes from which it is possible to derive Damage:Distance relationships all have fairly similar characteristics. They are shallow earthquakes with depths around 15 km and they are all strike-slip mechanisms with near vertical dip. It is possible to use the analyses together to generalise Damage:Distance relationships with magnitude for similar events.

The Average-Damage:Distance for any magnitude event is shown in figure 5.3(a). The total number of houses that would be expected to be damaged at any magnitude can be calculated from these relationships, combined with the expected length of the seismic source and building densities in the affected area. These are illustrated in figure 5.3(b), compared with Total-Damage:Magnitude relationships derived in Ambraseys and Jackson.[4]

5.3 Relative Vulnerability Assessment

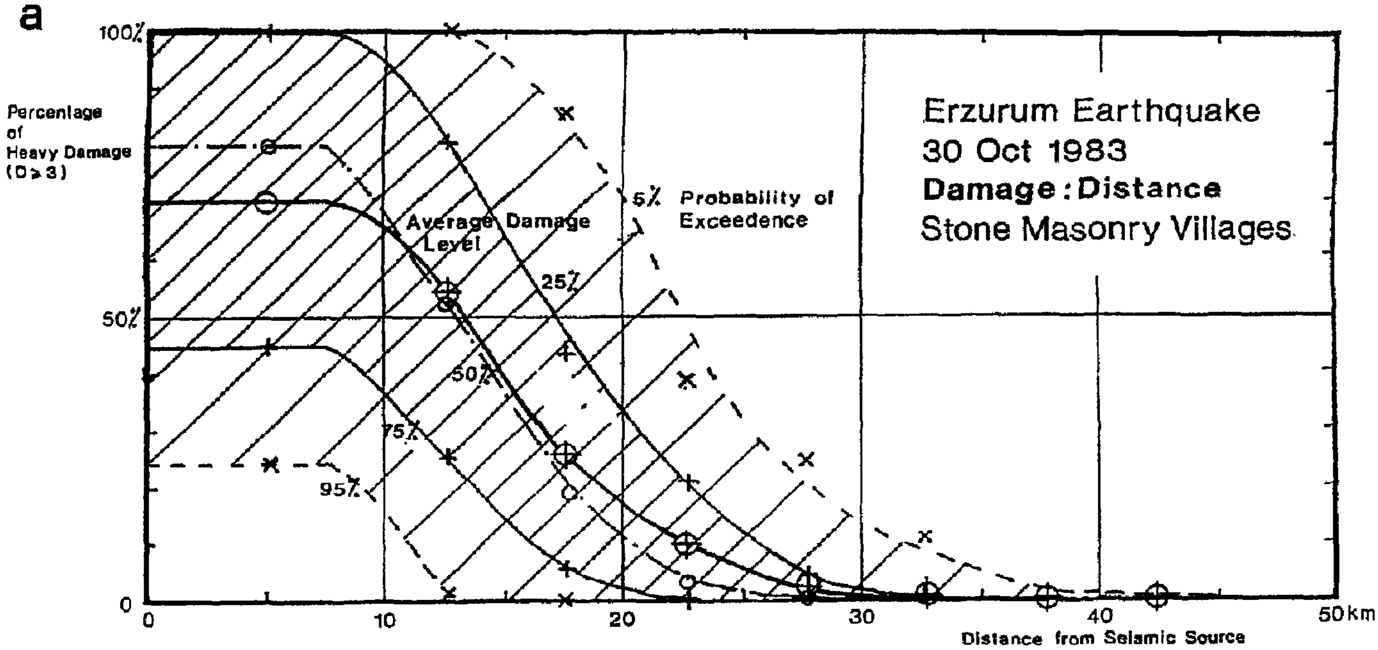
Published studies of damage surveys worldwide show wide variations in damage levels for similar construction types for the same designated intensity level. The use of intensity scales is consistent within each survey, but no two surveys interpret intensity scales in exactly the same way. Combining the results of surveys by different authors is therefore not a valid way to derive better vulnerability functions. However, the fact that the use of intensity scales is consistent within each survey means that the relative damage between building types can be compared across different surveys. This comparison has been found to work best when different types of building have been surveyed in the same locality.

Figure 5.4 shows the relative vulnerability, expressed in terms of repair cost ratio (RCR), of a number of different types of construction, using brick masonry as the measure of comparison; this

3 Coburn (1987).

4 Ambraseys and Jackson, ibid.

a



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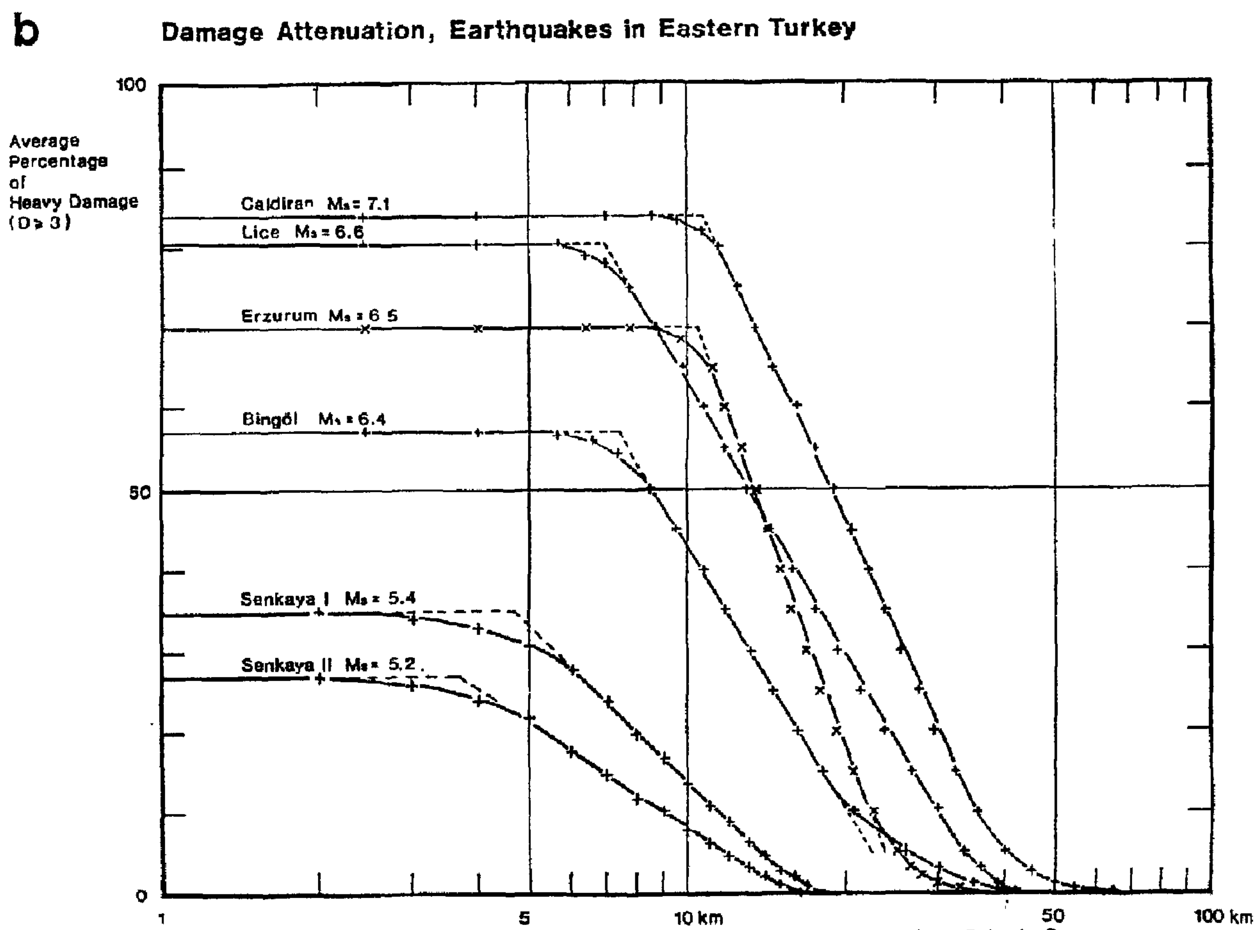

Figure 5.2 Damage:Distance Analysis for Stone Masonry Buildings
a) Variation with distance for a single event
b) Average damage distance relationships for all shallow events

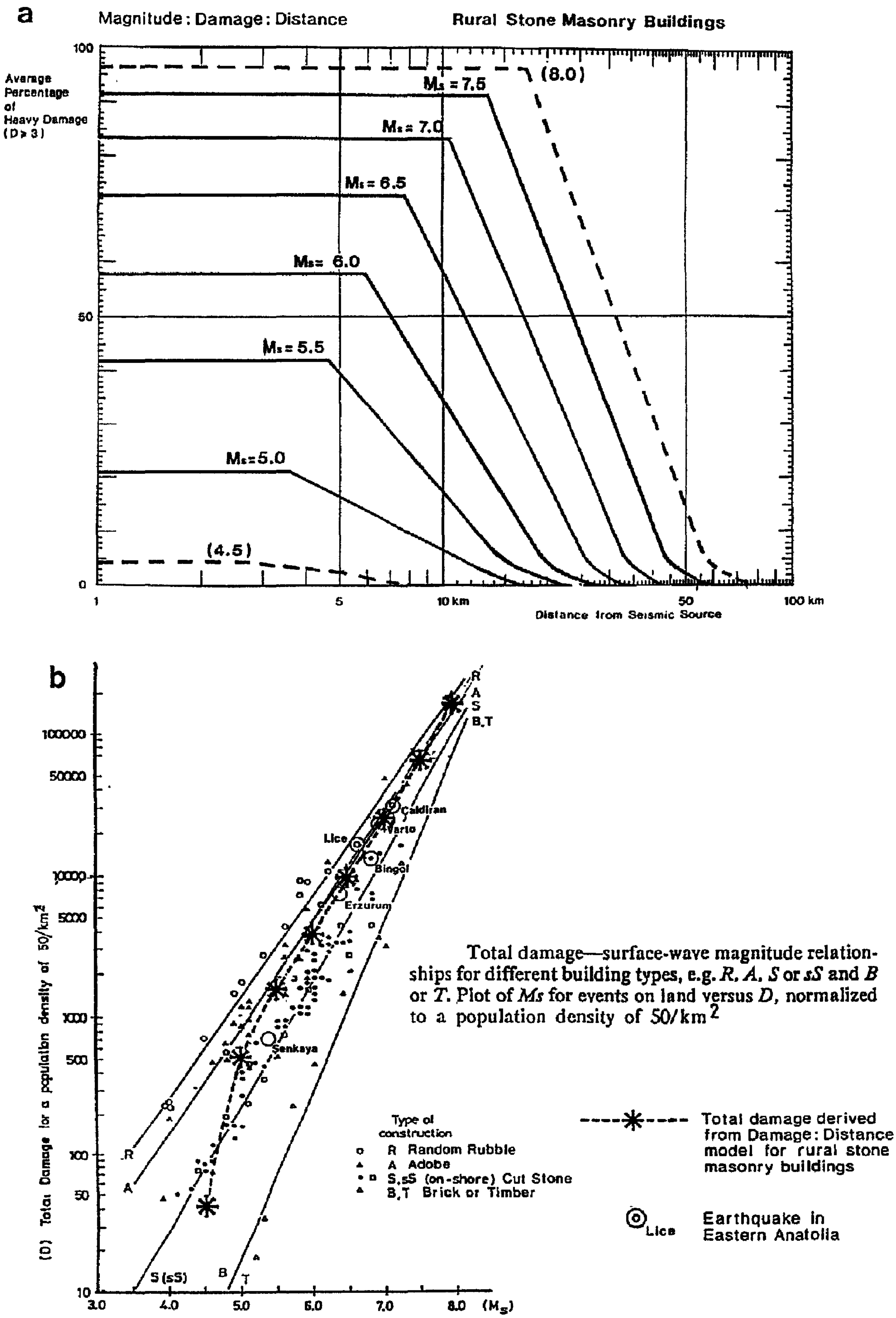

Figure 5.3 Magnitude:Damage:Distance Model
a) Average-Damage:Distance with Magnitude
b) Total Number of Houses Damaged with Magnitude

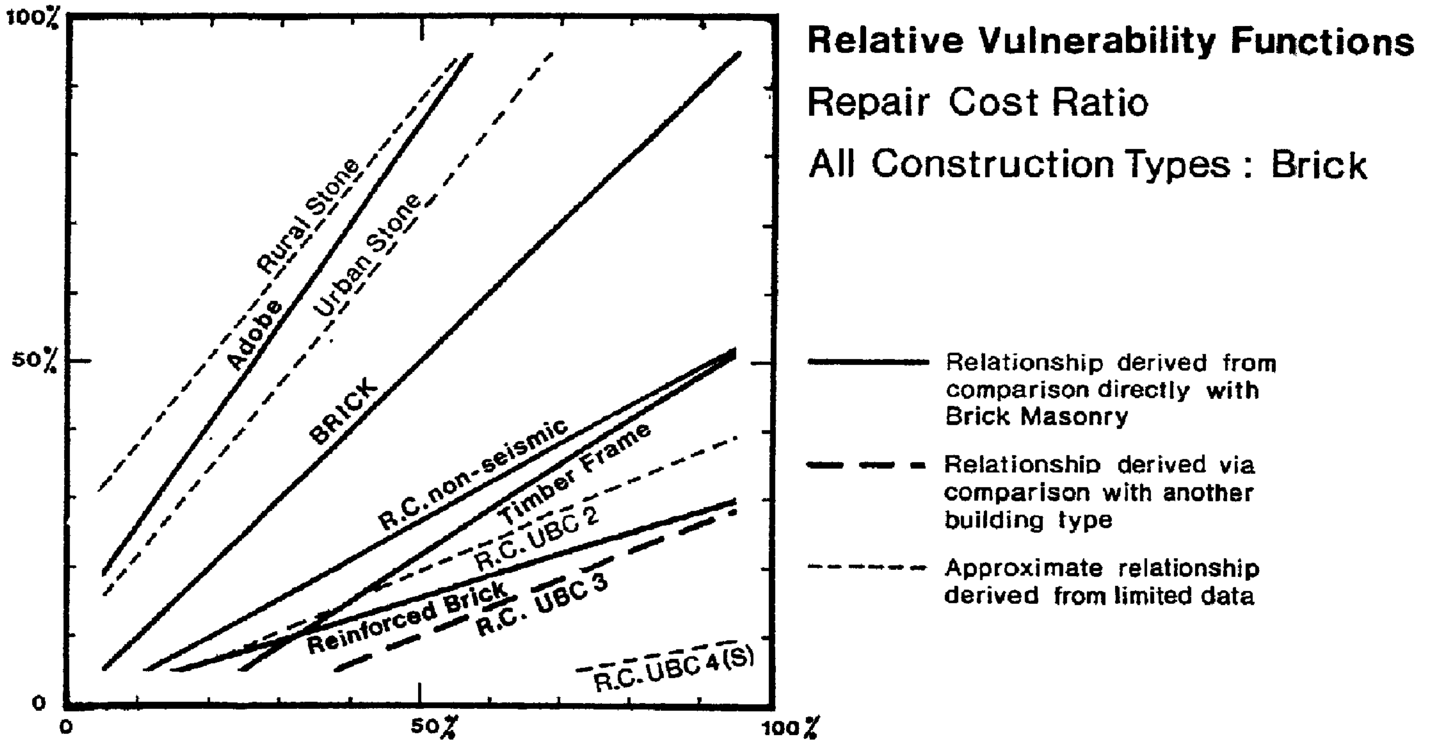

Figure 5.4 Relative Vulnerability Functions in terms of Repair Cost Ratio (RCR)

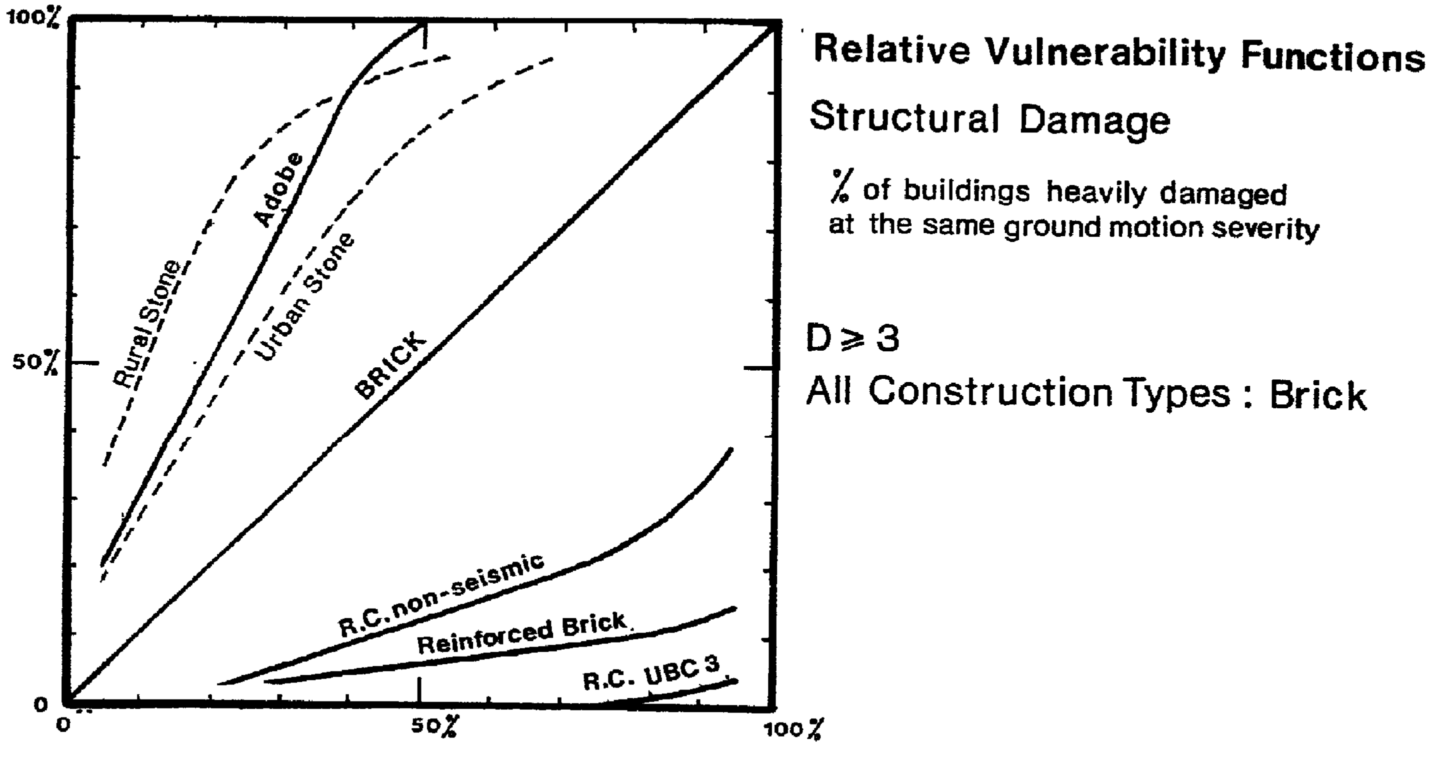

Figure 5.5 Relative Vulnerability Functions in terms of Structural Damage

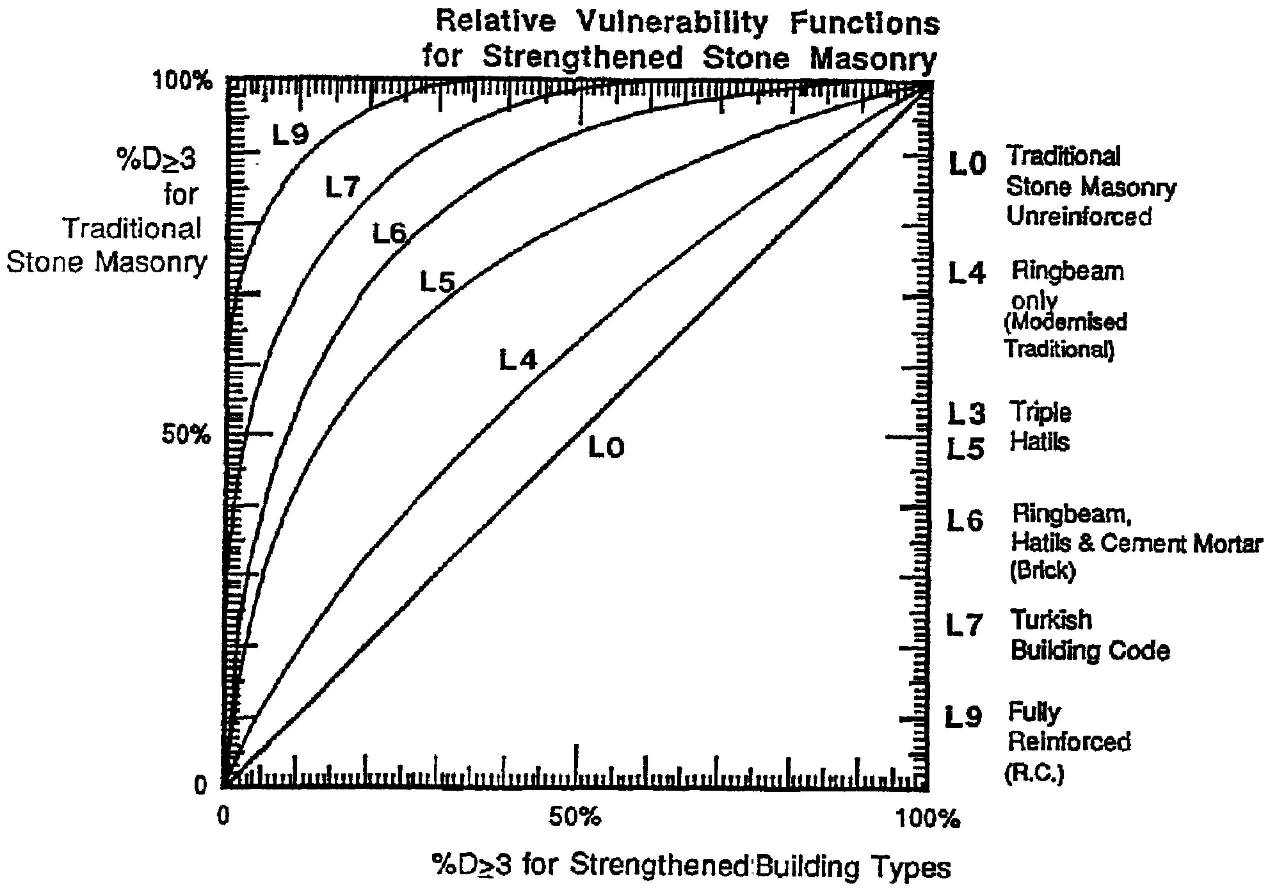

Figure 5.6 Relative Vulnerability Functions for Strengthened Stone Masonry

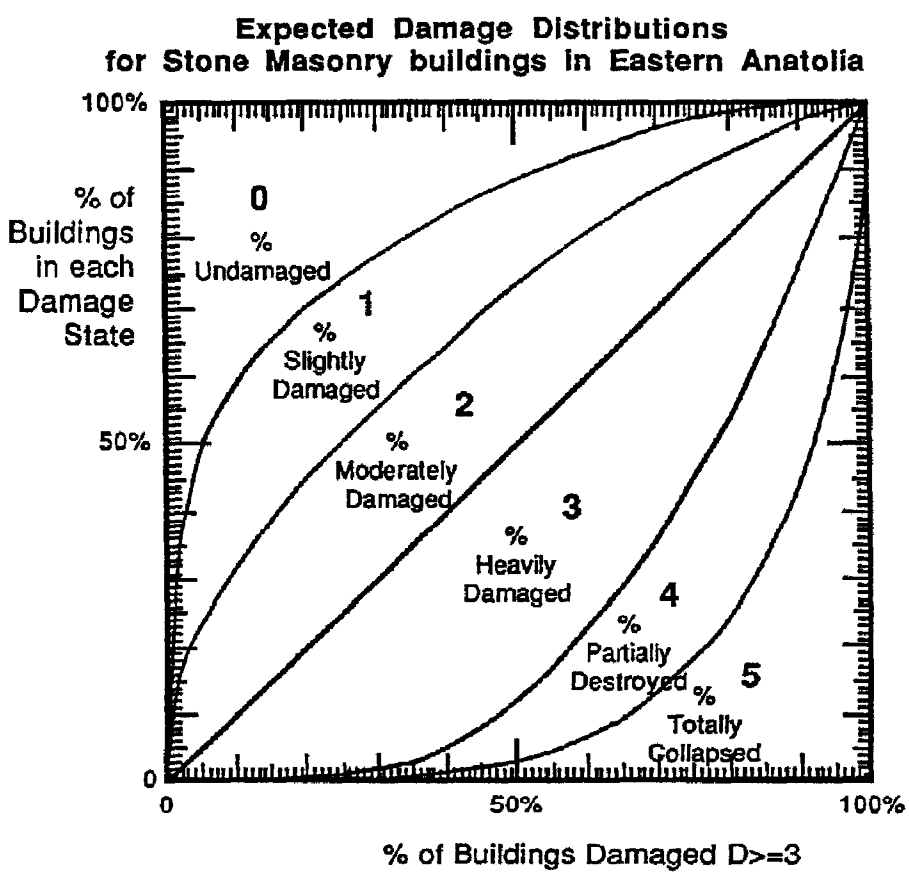

Figure 5.7 Expected Structural Damage Distributions for Stone Masonry Buildings

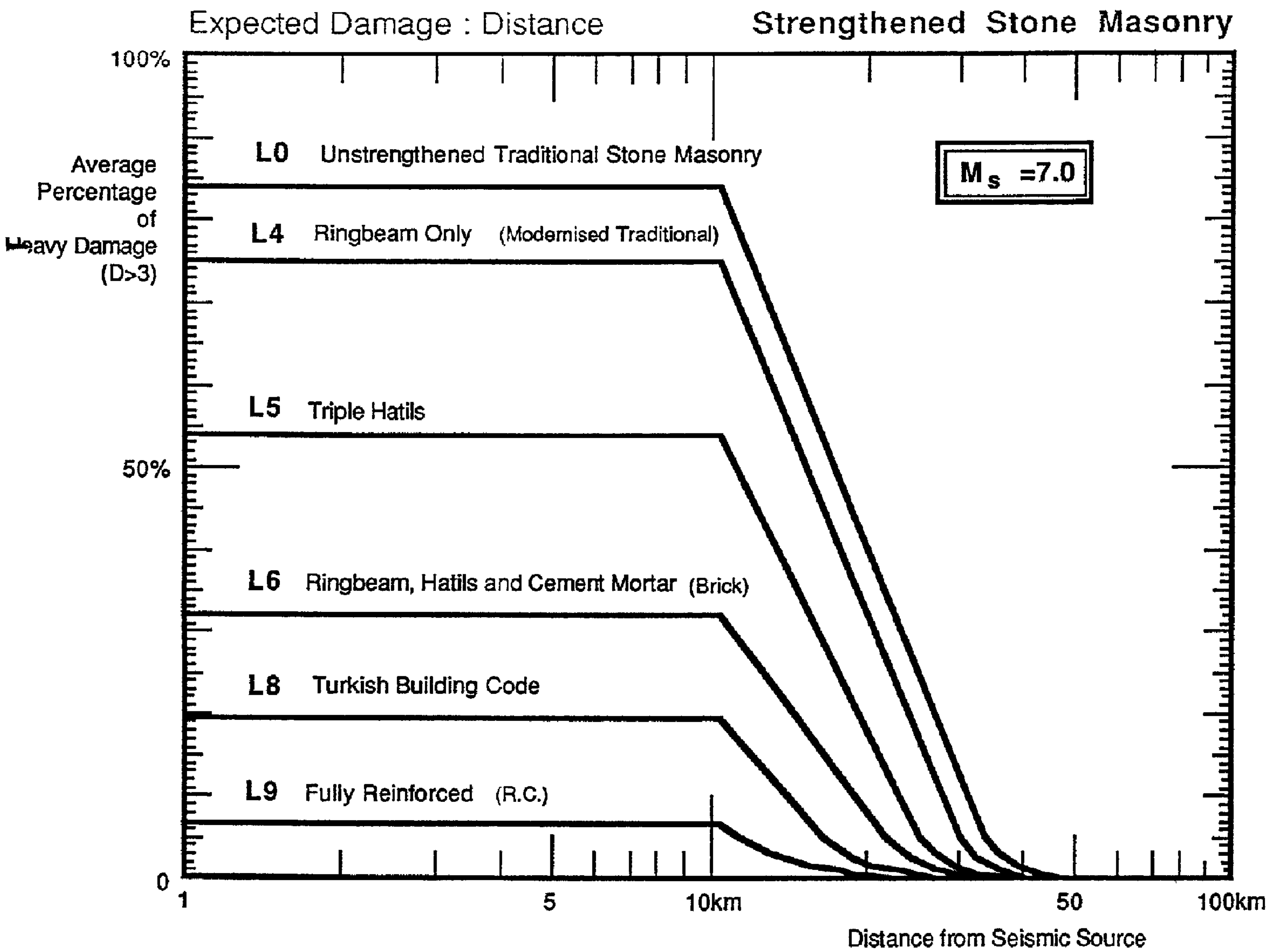

Figure 5.8 Damage:Distance Relationships for Strengthened Stone Masonry

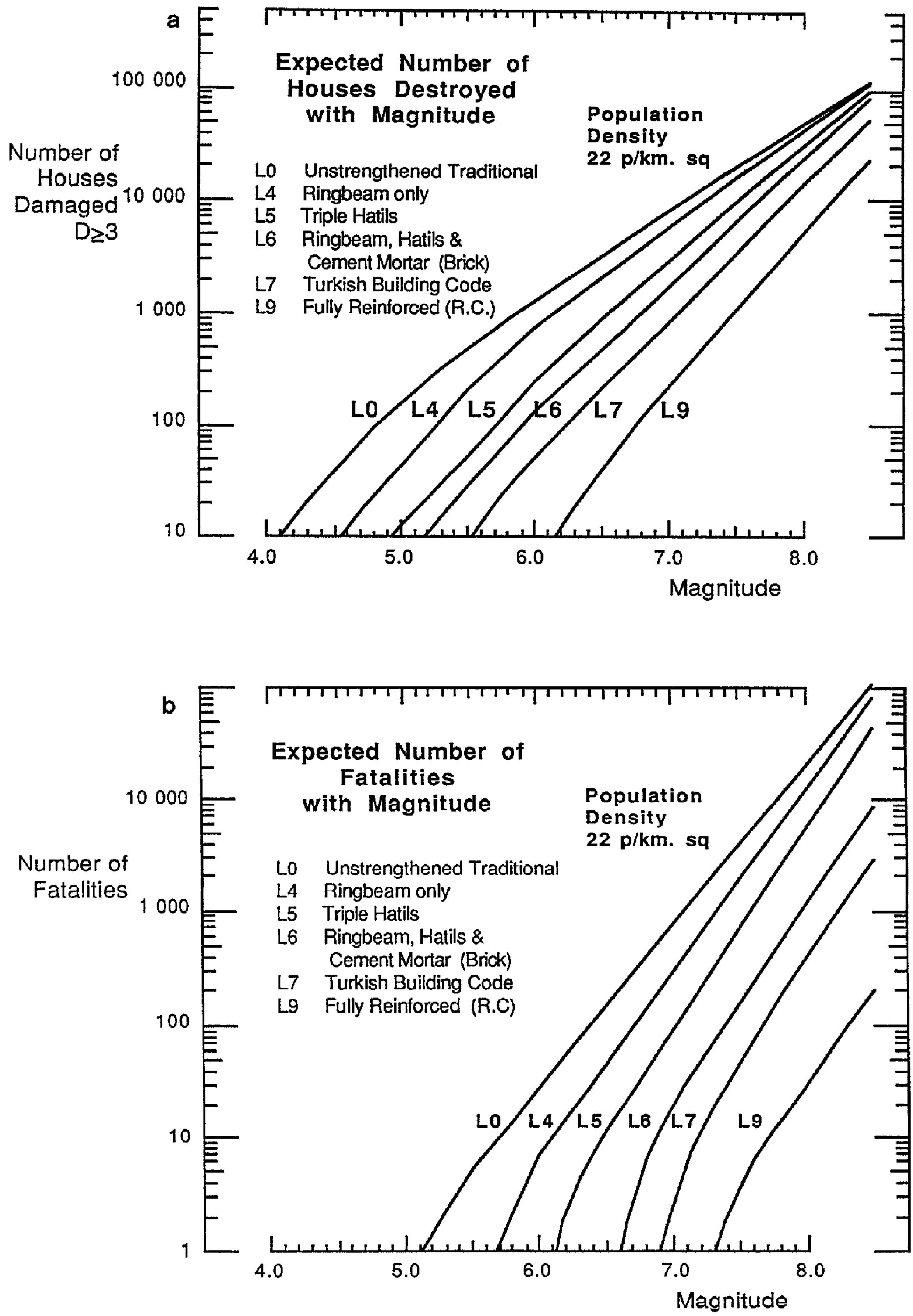

Figure 5.9 Total Damage as as a function of Magnitude for Strengthened Stone Masonry

figure is based on the results of over 30 reported damage surveys.

A more widely applicable measure of damage is the physical damage level expressed on the six-point MSK damage scale, which has been widely used in recent surveys. The damage distributions from large enough surveys can be taken to represent the probability distributions of different levels of damage to an individual structure, and are to some extent consistent from survey to survey. Distributions of structural damage can be converted into an average RCR by assuming a cost for each damage category. The relationship between RCR and structural damage may then be used to convert relative vulnerabilities in RCR to structural damage. Figure 5.5 presents relative vulnerabilities in terms of structural damage (measured in terms of the proportion of individual buildings with damage level D≥3) for those building types for which the conversion is possible.

A similar approach has been used to determine mean relative vulnerability functions for strengthened stone masonry and other possible modifications of rural housing technology compared with unstrengthened stone masonry, figure 5.6. The curves for the modified technologies are derived partly from the results of field studies carried out after the Şenkaya earthquakes, partly by interpretation from published data, and partly from the comparative performance of the modified techniques tested on the impulse table described in Chapter Four. Each curve represents the proportion of a large population of strengthened building damaged beyond repair, given a certain proportion of unstrengthened buildings damaged beyond repair (MSK scale damage level D≥3) The proportions of the population which can be expected to be in any other damage state can be assessed from figure 5.7 which is based on all published data on stone masonry as well as the field surveys reported in Chapter Two.

From the relative vulnerability curves of figure 5.6 new damage attenuation relationships for each of the modified technologies have been derived for each level of earthquake magnitude, such as figure 5.8. These new damage attenuation relationships may be used in loss estimation and seismic risk studies, if the distribution of building types and their density is known. The confidence limits of the analysis are discussed below.

If it is assumed that an earthquake of a given magnitude occurs in an area of uniform population density (and housing density), then the above relationships may be used to determine the expected total number of houses lost with each of the modified technologies. In deriving the loss magnitude relationships in figure 5.9(a) the assumption has been made that the average rural population density and house occupancy are those typical of present day Eastern Anatolia. The expected loss of life can also be calculated if it is assumed that the relationship between the number of houses destroyed and lives lost is typical of recent earthquakes in the region and independent of the construction technology. The results of this analysis are shown in figure 5.9(b).

From figure 5.9 it is clear that substantial reductions in both destroyed houses and loss of life can be expected from introducing strengthening technologies. The introduction of modification L6, (triple hatil construction), for instance, would reduce the number of destroyed houses in the event of an earthquake of magnitude M_s=6.5 from about 3500 to about 900; the number of lives lost would be similarly reduced from 150 to about 10. But the benefit to the whole area over a period of time depends both on the magnitude and frequency of occurrence of future earthquakes.

5.4 Earthquake Hazard Model

Figure 2.3 shows the location and severity of the earthquakes known to have caused damage in the study area in the 20th century. If the great Erzincan earthquake of 1939 is included, the death toll from all these earthquakes has certainly exceeded 50,000, nearly 1% of todays population. The extent of the area of significant building damage (Intensity > VI) in each earthquake is shown or estimated. In total over 150,000 houses have been destroyed in these events. The principal characteristics of all events within the study area this century are summarised in Table 5.1. The most recent seven earthquakes have caused the destruction of over 35,000 dwellings, with the loss of over 10,000 lives.

Date	Place	Epicentre E	N	Magnitude Ms	No. of Houses Destroyed	No. of People Killed	
1986	Malatya			5.4			
1984 18 Oct.	Şenkaya	40.6	42.4	5.2	198	0	
1984 18 Sep.	Şenkaya	40.7	42.3	5.4	187	3	
1983 30 Oct.	**Erzurum**	**40.2**	**42.3**	**6.5**	**3 241**	**1 155**	
1978 15 Feb.	Pülümür	39.7	39.9	4.4	0	0	
1977 25 Mar.	Palu	38.6	40.0	4.8	210	8	
1976 24 Nov.	**Çaldiran**	**39.1**	**44.0**	**7.1**	**10 500**	**3 840**	
1976 30 Apr.	Ardahan	41.0	42.9	5.0	c.300	4	
1976 2 Apr.	Agrı	39.8	43.7	4.8	236	5	
1976 25 Mar.	Ardahan	41.0	43.0	5.0	257	2	
1975 6 Sep.	**Lice**	**38.5**	**40.8**	**6.6**	**8 149**	**2 385**	
1972 16 Jul.	Van	38.4	43.2	5.0	400	1	
1972 22 Mar.	Şarıkamış	40.3	42.6	4.7	100	0	
1971 22 May.	**Bingöl**	**38.8**	**40.5**	**6.8**	**5 617**	**878**	
1967 26 Jul.	**Pülümür**	**39.5**	**40.4**	**5.9**	**1 262**	**97**	
1966 19 Aug.	**Varto**	**39.2**	**41.4**	**6.9**	**10 828**	**2 517**	
1966 12 Jul.	Varto	39.1	41.6	4.0	90	12	
1966 7 Mar.	**Varto**	**39.1**	**41.5**	**5.6**	**1 200**	**14**	
1965 31 Aug.	**Karliova**	**39.3**	**40.8**	**5.6**	**1 500**	**-**	
1964 14 Jun.	Adiyaman	38.1	38.5	5.9	878	8	
1964 24 Mar.	Siirt	37.9	41.6	4.0	c.100	1	
1964 14 Mar.	Palu	38.7	39.6	4.5	-	-	(EGU)
1962 4 Sep.	Iğdır	39.9	43.9	(5.3)	-	-	(EGU)
1962 10 Feb.	Muş	38.7	41.5	4.0	97	0	
1960 26 Feb.	Bitlis	38.4	41.9	4.0	80	0	
1959 25 Oct.	Hinis	39.2	41.6	5.0	c.300	18	
1957 7 Jul.	Başköy	39.3	40.4	5.1	c.300	0	
1954 28 Mar.	Hinis	39.2	41.4	6<	-	-	(EGU)
1952 3 Jan.	Hasankale	39.9	41.6	6.0	876	103	
1951 18 Mar.	Kayadere	40.0	41.8	4.9	500	0	
1950 4 Feb.	Kığı	39.5	40.6	4.6	c.100	20	
1949 17 Aug.	**Karliova**	**39.5**	**40.6**	**6.7**	**3 000**	**650**	
1947 14 Dec.	Pasinler	39.2	41.4	-	-	50	(EGU)
1946 31 May.	**Varto**	**39.3**	**41.2**	**5.9**	**1 986**	**832**	
1945 20 Nov.	**Van**	**38.7**	**43.3**	**5.8**	**c.1 000**	**-**	
1941 12 Nov.	Erzincan	39.7	39.7	5.9	-	15	
1941 11 Sep.	Başkale	39.1	43.4	5.8	600	194	
1939 27 Dec.	**Erzincan**	**39.7**	**39.7**	**7.9**	**c.74 800**	**32 741**	
1939 21 Nov.	Tercan	39.7	39.7	5.9	c.500	43	
1936 23 May	Kötek	40.1	43.0	4.5	c.100	-	
1935 1 May	**Diğor**	**40.5**	**43.3**	**6.2**	**1 300**	**200**	
1934 15 Dec.	Capacur	38.9	40.5	4.9	c.200	12	
1929 18 May	**Susehri**	**40.0**	**38.0**	**6.1**	**1 357**	**64**	
1924 13 Sep.	**Panisler**	**39.9**	**41.9**	**6.9**	**-**	**310**	
1924 13 May	Çaykara	40.8	40.4	5.3	c.700	50	
1906	Erzurum/Van	39.9	41.3	(I_o=VII)	-	-	(EGU)
1903 28 May	Ardahan	41.1	42.7	(I_o=VII)	-	-	(EGU)
1903 29 Apr.	**Malazgirt**	**39.2**	**42.9**	**7.0**	**-**	**6 000**	

Notes:

(EGU) indicates earthquake reported in catalogue of Ergin, Güçlü and Uz (1967) but not sufficiently verifiable for inclusion in catalogue of Ambraseys and Jackson (1981).

c indicates approximate number from records.

Events in bold type represent major damaging earthquakes of over 1 000 houses destroyed (usually M>6.0).

Table 5.1
Damaging earthquakes in Eastern Turkey 1900-1986
(After Ambraseys and Jackson (1981))

General conclusions from the study of earthquake hazard in Eastern Anatolia are:

(1) Eastern Anatolia is at the convergence of two major fault systems, each with a propensity for large magnitude energy release.[5]

(2) Despite fluctuations in the seismicity of Anatolia over long-term cycles of the order of 500-700 years,[6] it is unlikely that within the next century rates of earthquake occurrence will change appreciably. The present high rate of seismic activity - one of the highest in the European and surrounding area[7] - is likely to continue for the foreseeable future.

(3) Major damaging earthquakes may occur almost anywhere within the study area. They may occur outside the zones presently designated as First and Second Degree Zones on the 1973 earthquake zoning map. They can be expected within a broad zone which coincides largely with zones of Third Degree and above.

(4) From earthquake catalogues of events occurring in the past 80 years it is possible to estimate the number of events of different magnitude that are likely to occur within the study area, within the planning timescale. It is also possible to bracket the average expected number of events by a probabilistic assessment of there being more or less events than the average over the next 25 years (table 5.2).

(5) Studies of fault gaps and statistical analysis suggest that it is highly likely that Eastern Anatolia will experience a large magnitude earthquake (M>7.0) within the planning period of 25 years.[8]

For this study, the hazard model used is that proposed by Burton et al.[9] using a curved cumulative frequency law based on statistical analysis of historical earthquake occurrences. Figure 5.10 shows the comparison between this curved relationship and the actual number of recorded earthquakes. The curved formula is a very much better fit to the data than the more conventionally used linear Gutenberg-Richter formula also shown, which is significantly in error for magnitudes below 5.0 and above 7.5. From this the expected number (or average over a long period) of events of different magnitude within the study period for a 25 year period can be calculated. These are presented in Table 5.1.

	Number of Events in any 25 Year Period		
Magnitude Range	Expected (Average) Number of Events	95% probability of exceeding:	5% probability of exceeding:
4.0 - 4.5	**38.43**	32	60
4.5 - 5.0	**31.25**	27	51
5.0 - 5.5	**19.59**	12	28
5.5 - 6.0	**10.25**	7	14
6.0 - 6.5	**5.08**	1	9
6.5 - 7.0	**2.29**	0	4
7.0 - 7.5	**0.99**	0	2
7.5 - 8.0	**0.19**	0	1

Table 5.2
Number of earthquakes of each magnitude range expected in 25 years within Eastern Anatolia.

From analysis of samples of 25 year periods within the 80 years of data available, it is possible to estimate the variation around this average figure that may be expected in any future 25 year period, (which can be shown to conform to a Poisson distribution). This is also presented in Table 5.2, as the lower and upper limit of the 90% confidence range.

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[5] Jackson and McKenzie (1984).

[6] Ambraseys (1971).

[7] Kaila and Madhava Rao (1975).

[8] Toksöz, Shakal and Michael (1978) identify fault gaps on the North Anatolian Fault in Eastern Anatolia. Burton et al. (1984) estimates maximum magnitudes and cumulative strain energy release within the study area.

[9] Burton, McGonigle, Makropoulos and Üçer (1984).

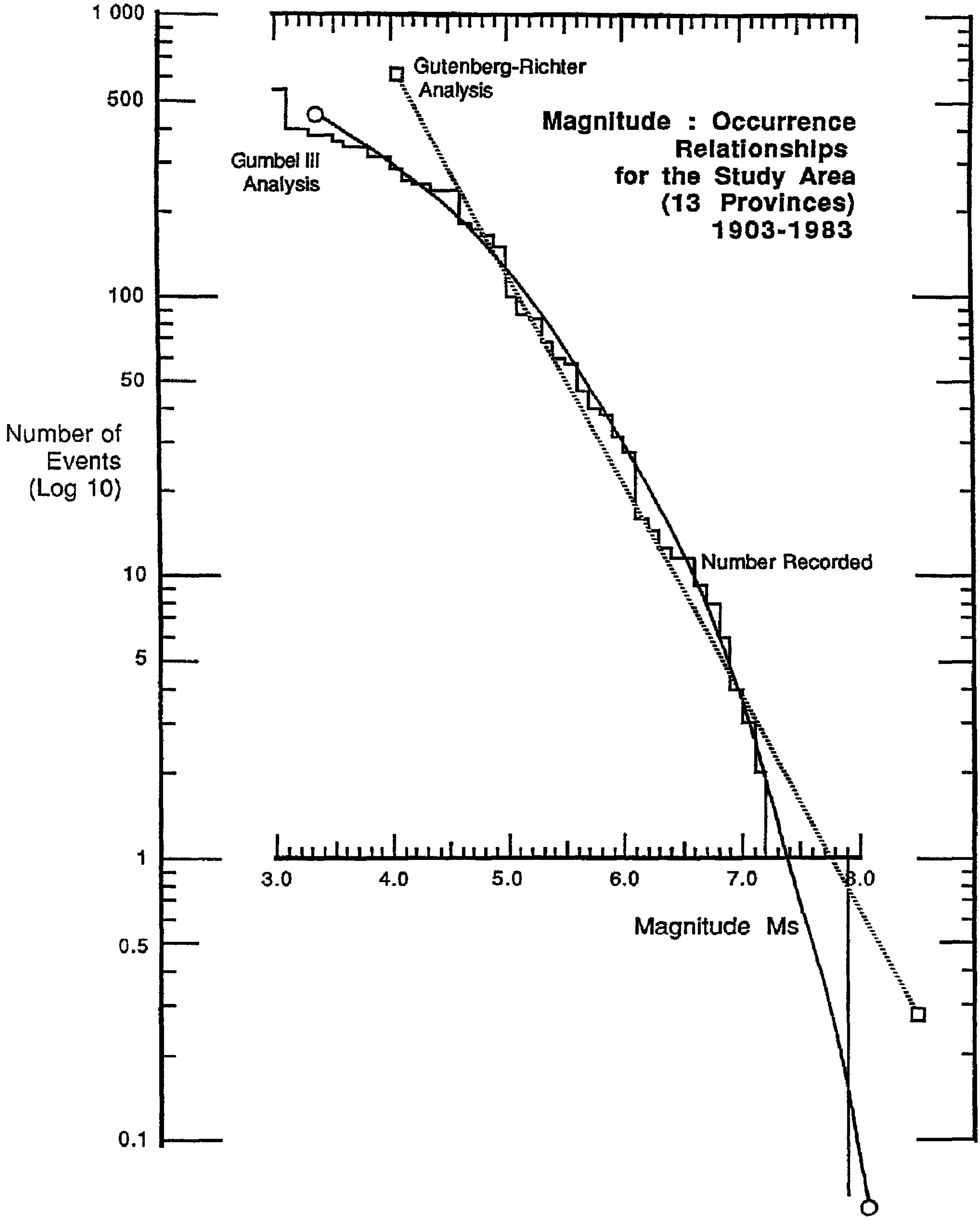


Figure 5.10 Earthquake Magnitude Frequency Relationships for the Study Area, 1903-1983

5.5 Loss Estimation Model

The recurrence relationship derived from figure 5.10, has been combined with the vulnerability relationships of figure 5.9 to calculate the total numbers of houses which can be expected to be destroyed over 25 years assuming that the whole housing stock were to be of present day stone masonry construction or of one of the modified technologies. The compilation of losses involves the summation of the expected losses across the whole range of possible earthquake magnitudes. This calculation was carried out using a computer programme called DEPREM (Damaging Earthquakes Probable Effects Model) recently developed at the Martin Centre.[10] Table 5.3 shows the expected total number of houses destroyed and the total number of lives lost over a 25 year period for each of the levels of technology shown in figure 3.2.

	Level of Strengthening	Expected Total Houses Destroyed	Expected Total People Killed
L0	Unstrengthened Traditional Stone Masonry	71,745	8,098
L4	Ringbeam Only *(Modified Traditional Construction)*	53,540	6,050
L5	Triple Hatil Reinforcement	22,378	1,657
L6	Ringbeam, Hatils and Cement Mortar *(Brick Masonry Buildings)*	13,683	329
L7	Turkish Building Code Specifications	7,080	101
L9	Fully Reinforced Stone Masonry *(Reinforced Concrete Frame)*	1,966	8

Table 5.3
Comparison of performance of different levels of strengthening:
Expected Losses for Eastern Anatolia over a 25 year period, assuming
a homogeneous building stock, static 1980 population levels and
seismicity given in table 5.2.

5.6 Costs and Benefits of Alternative Strengthening Strategies

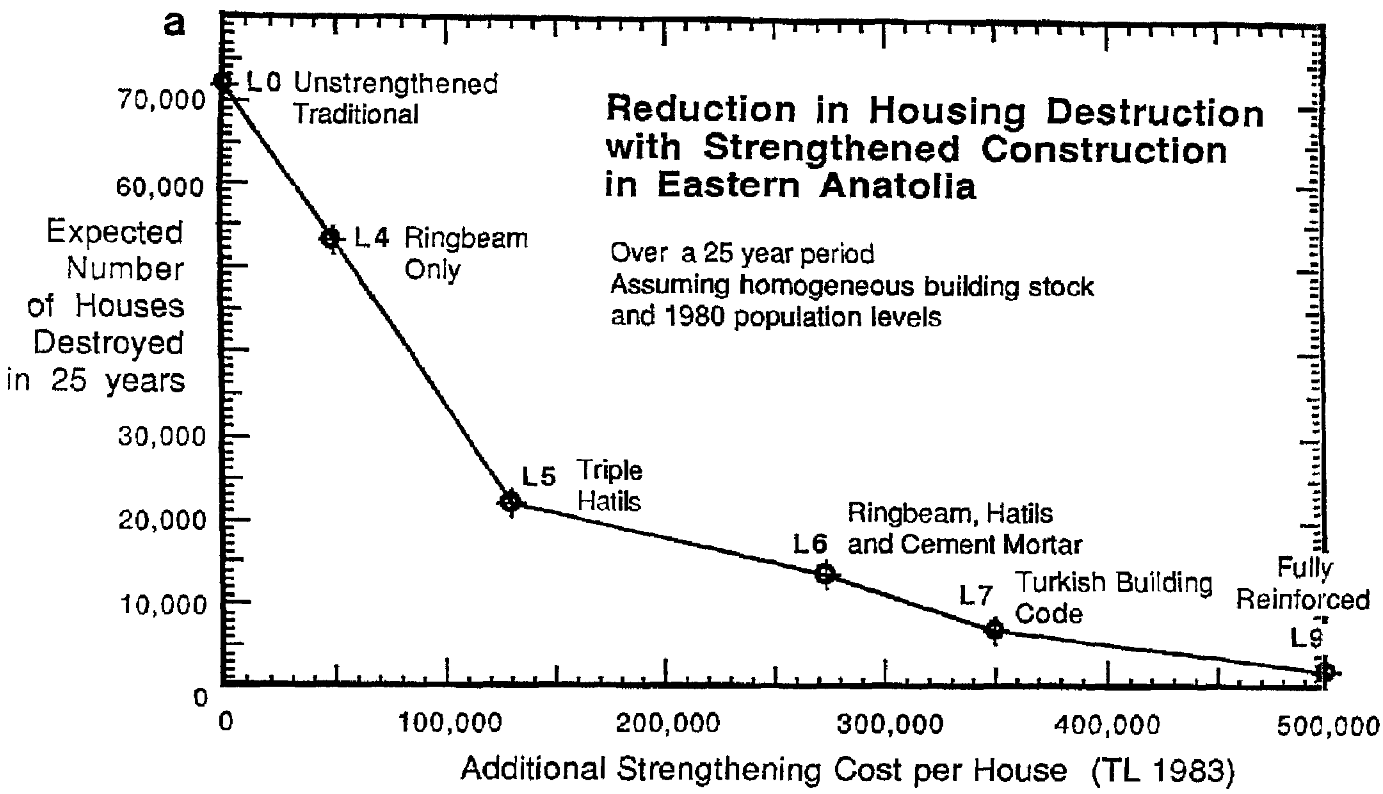
The cost data of Chapter Three have been used to plot figure 5.11(a) which shows the expected number of houses destroyed as a function of the cost of strengthening each house. Figure 5.11(b) shows in a similar way the expected number of lives lost.

From the figures shown in figure 5.11 the cost of each saved life and each saved building (compared with the use of unmodified stone masonry technology) can be calculated, again as a function of the expenditure on each house, figure 5.12. It is interesting to note that there is a least-cost technology in each case, but not the same one. For reducing housing loss, L4 (ringbeam only), is the cheapest technology at 2.5 million TL per saved house. This can be compared with the 3.5 million TL which in 1983 was spent by the Turkish Government to replace each lost house. Effectively this means that a programme to strengthen all houses in the study area by introducing modification L4 could be expected to pay for itself in the long term in reduced cost of reconstruction after future earthquakes. The same is true of modification L5, though in this case the financial benefit would not be as great. The other more expensive modifications would of course reduce losses still further, but at an increased overall cost.

If the criterion was to save lives at minimum cost then modification L5 would be marginally more cost-effective than modification L4; but in either case the cost would be substantially offset by the long-term saving in reconstruction costs.

These calculations are intended merely to compare the alternative possible modifications on a cost-benefit basis. But they are based on a number of unrealistic assumptions about strengthening programmes, namely that all houses are modified at once using the same modification; and no account has been taken of the discounted value of future savings. More plausible alternative possible scenarios are proposed and evaluated in the next chapter; and an alternative cost-benefit analysis

[10] Akbar (1987).



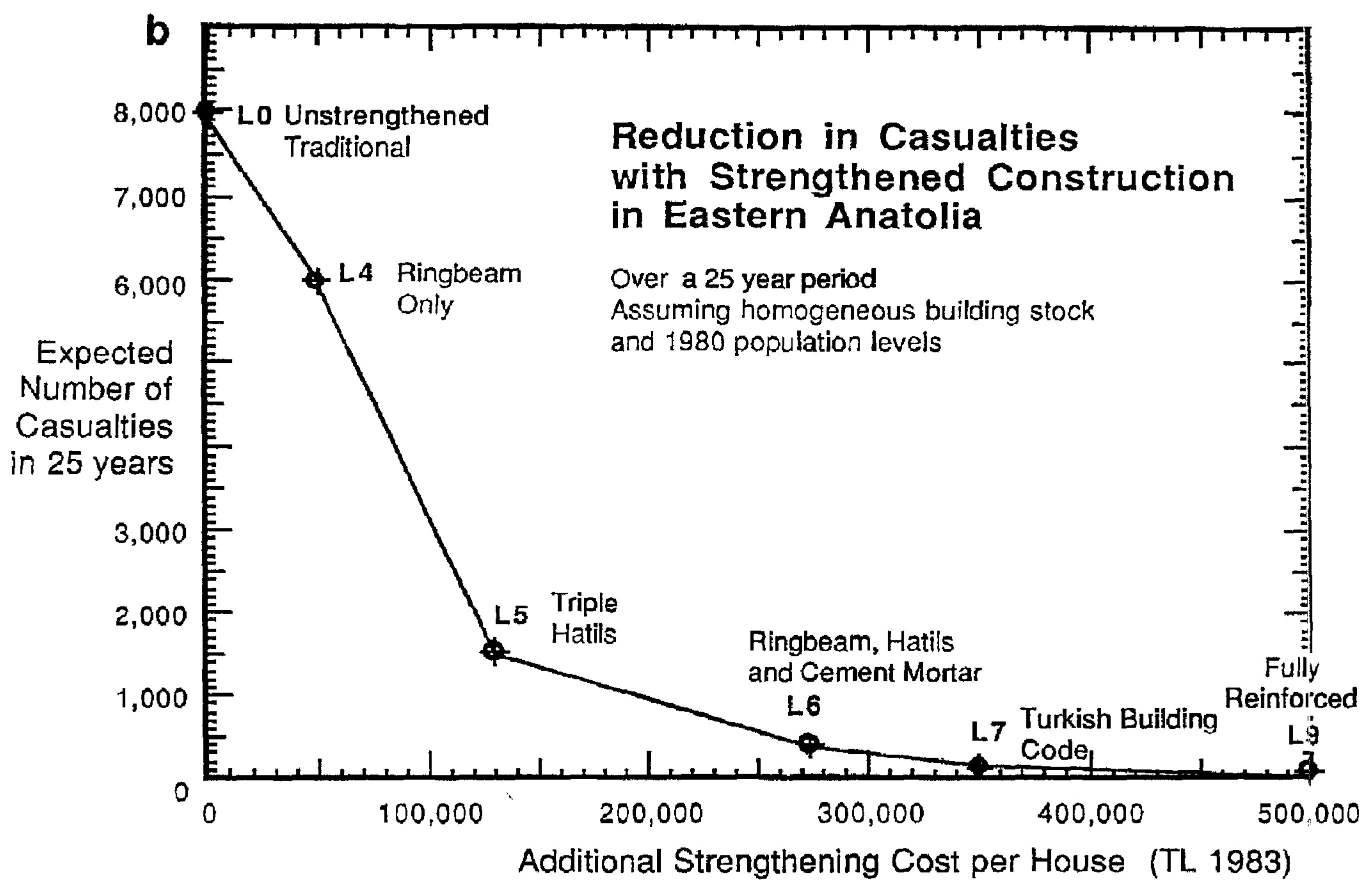


Figure 5.11 Destroyed Houses and Loss of Life over 25 Years with different Levels of Strengthening

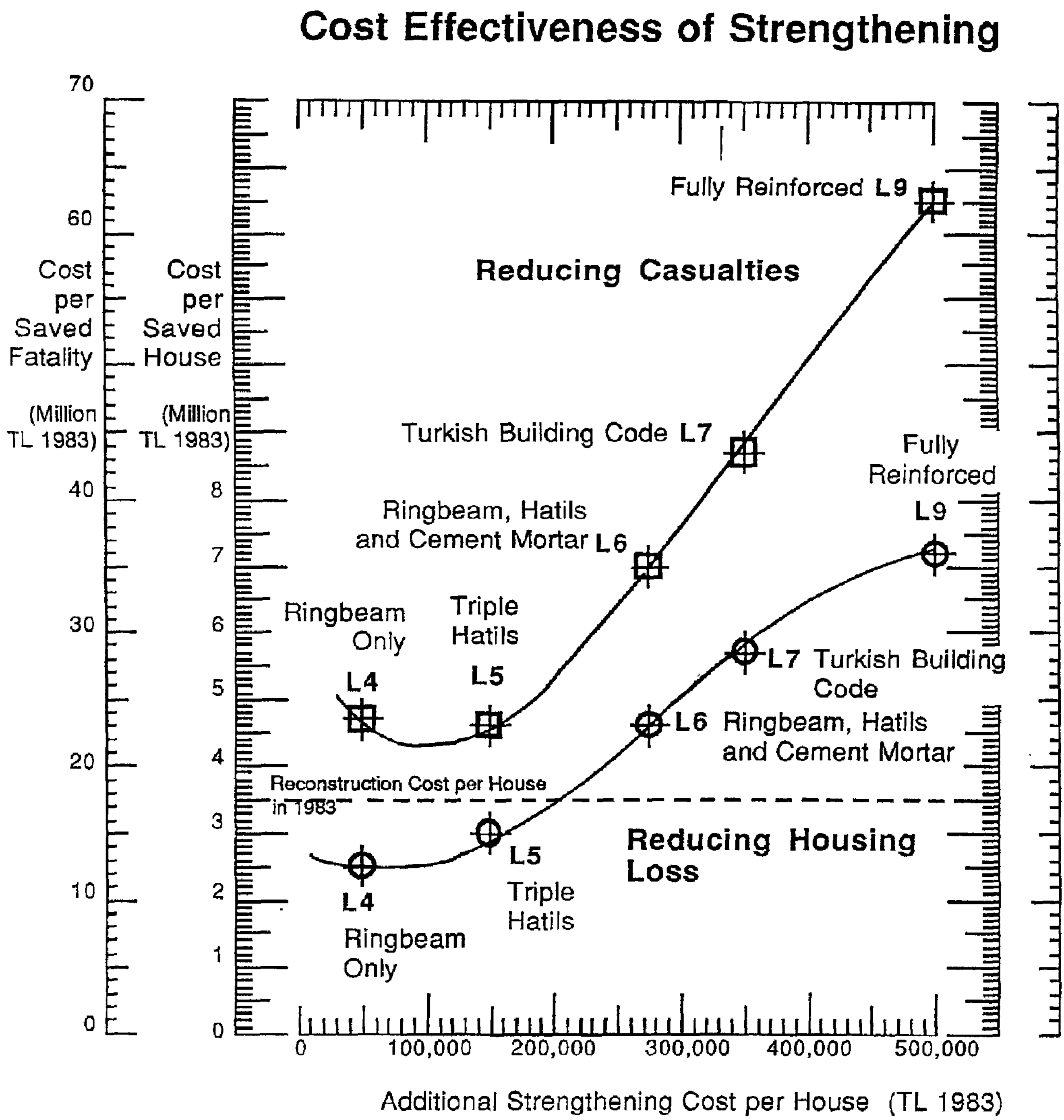


Figure 5.12 Cost-effectiveness of Strengthening Stone Masonry

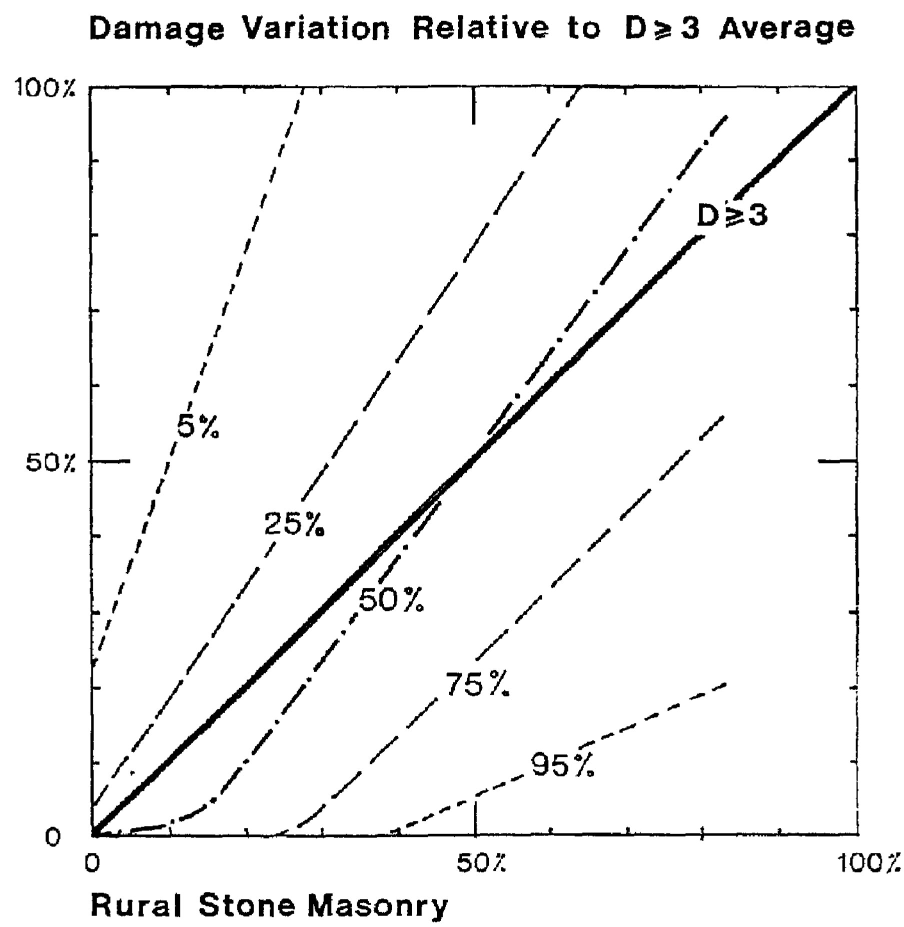


Figure 5.13 Relative Damage Probability Distributions for Stone Masonry

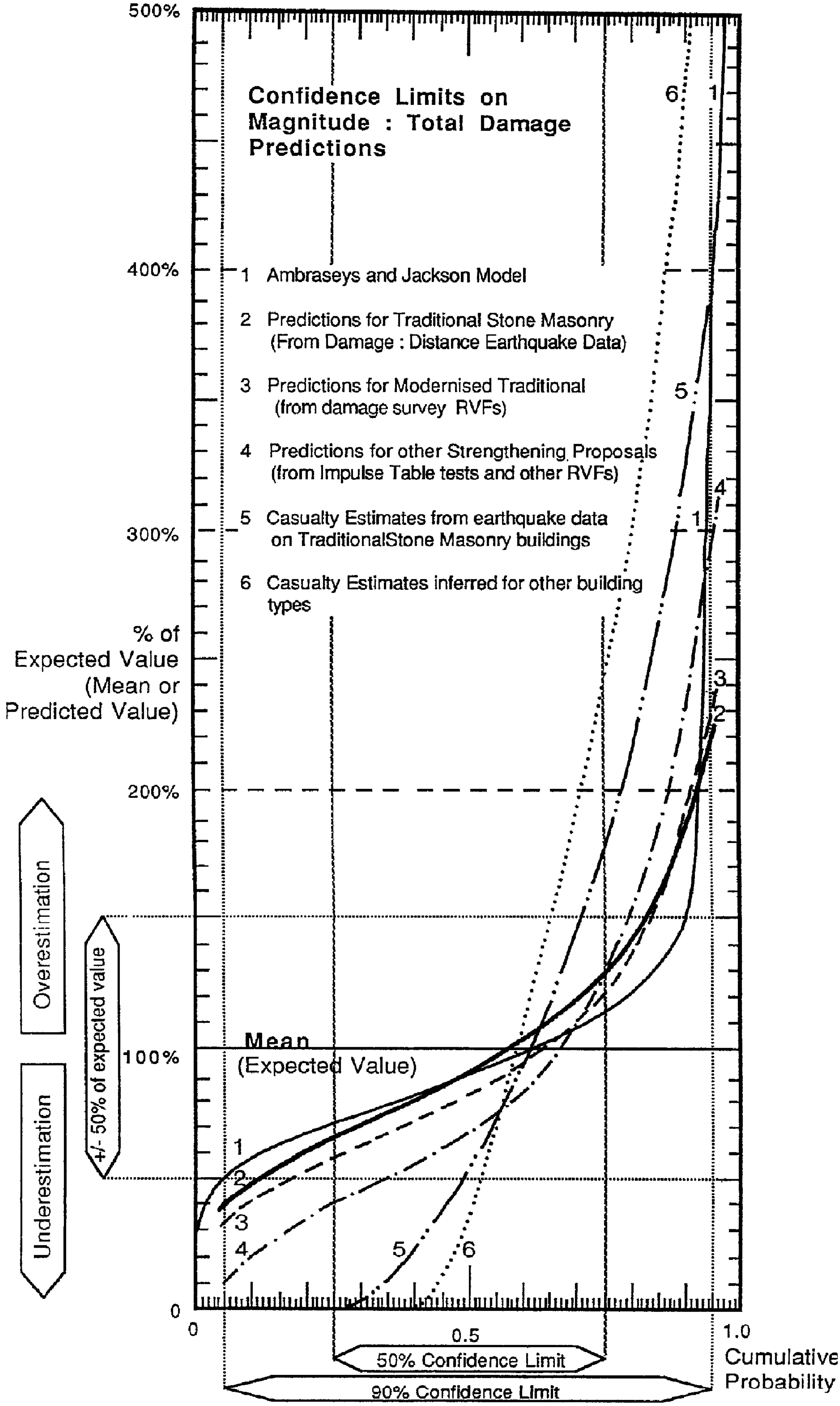


Figure 5.14 Confidence Limits on Loss Predictions

which considers discounted future costs has been presented elsewhere.[11]

5.7 Uncertainty

The above calculations have been carried out using expected values based on best-fit regression lines derived from very scattered data. Even given a future earthquake event of known location and magnitude, and assuming that the probability distribution of future losses will be similar to the observed distribution of past losses, a large measure of uncertainty exists and must be taken into consideration. The sporadic nature of earthquake occurrence, both in time and space, further adds to the uncertainty of predicting losses over a period of time.

At each stage of the above analysis, the probabilistic distribution of losses has been determined, as shown for example in figure 5.13.

The effects of combining the uncertainties from the attenuation relationships, the relative vulnerability functions, and the casualty estmation relationships has been studied using discrete event simulation (DES) techniques to derive confidence limits on loss estimates, figure 5.14. It will be seen that in the case of the expected losses in traditional stone masonry construction there is a 73% probability that the actual losses will be within +/-50% of the predicted losses. Where relative vulnerability functions are used to infer losses in other building types, the accuracy drops to a probability of only 40%; while estimates of loss of life have only 10 to 20% probability of being within 50% of the predicted values. These very low probabilities indicate the need for great caution in using the calculated numerical values of loss estimates for planning purposes, even though they may still be legitimately used in the comparison of alternative strengthening strategies.

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[11] Spence (1986).