Death Tolls in Earthquakes

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ABSTRACT

Death tolls in earthquakes arise from three main causes: structural collapses, non-structural causes and follow-on disasters. Structural collapses are responsible for 75% of deaths in earthquakes. The factors influencing the number of people killed per building collapse fall into five major categories M1 to M5. The number of people killed in the collapses of any particular building type, b, can be estimated from:

$$Ksb=D5b^* [M1b * M2b * M3b (M4b+M5b)]$$

where D5 is the number of collapsed buildings, M1 is Population per building, M2 is Occupancy at time of earthquake, M3 is Occupants trapped by collapse, M4 is Mortality at collapse and M5 is Mortality post-collapse. The model follows the logical process of casualty occurrence. Estimated values for parameters M1 to M5 are given for main classes of building types and certain typical situations. Further elaboration of the factors within this framework, the parameters that affect them and data needs for better resolution of such a model are described.

1 INTRODUCTION

So far this century there have been more than 1,100 fatal earthquakes causing a total loss of life exceeding 1.53 million people. Reducing the loss of life is the primary priority of most earthquake protection strategies, and yet the processes that contribute to death tolls and the best strategies for reducing injury levels are not well understood. Death tolls are highly variable from one earthquake to another and data documenting occurrences of life loss in earthquake are poor. This paper summaries the findings of a two year project on Reducing Human Casualties in Building Collapse undertaken at The Martin Centre for Architectural and Urban Studies, University of Cambridge, funded by the Science and Engineering Research Council. This was a collaborative project with the Universities of Hokkaido and Tokyo in Japan. Some of the work was also carried out in close contact with the project at John Hopkins University and Virginia Polytechnic Institute on Epidemiology of Injury in Earthquakes, funded by the National Center for Earthquake Engineering Research, USA.

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 hazards which also cause loss of life, like landslides, mud-flows and fires.

A worldwide database of 1,100 earthquakes causing loss of life has been compiled. An approximate classification of earthquake deaths by cause during this century is shown in Figure 1 (above). 25% of all deaths are from non-structural causes or follow-on hazards. In some cases, a follow-on disaster can lead to many more deaths than those caused directly by the earthquake.

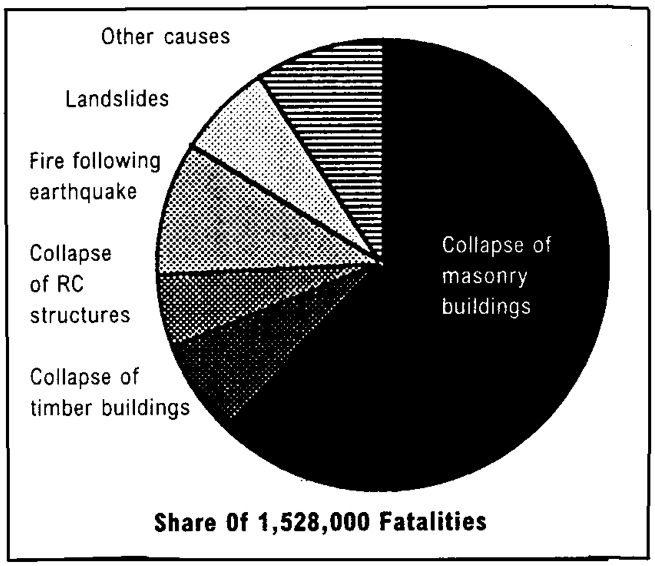


Figure 1 Causes of death by earthquake in the 20th century

Earthquakes in Japan that trigger urban fires can cause 10 times as many deaths as those that don't (Kobayashi 1982 and Coburn, Murakamai and Ohta 1987). Tsunami and floods have the capability of adding to the death toll. Mud-flows, rockfalls and landslides, can also cause very high mortality rates in communities affected and lead to large death tolls in earthquakes (e.g. the Ankash, Peru earthquake 1970). Follow-on disasters of this type are extremely difficult to predict, but fortunately are rare. For the large majority of earthquakes, deaths and injury are primarily related to building damage. Figure 1 shows that over 75% of deaths are caused by building collapse and almost 90% if follow-on disasters are excluded.

In Figure 2 (page 22, overleaf), the total number of people killed is plotted against the total number of buildings heavily damaged for 157 earthquakes where both statistics are known with some reliability (Coburn and Spence 1992). 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 (>5000 buildings damaged). In these earthquakes, the numbers of deaths and injury from non-structural causes, accidents and medical conditions are a significant proportion of the total. These are the result of combinations of factors and are largely unpredictable. The same causes of deaths also occur and on a larger scale in more destructive earthquakes, but a much higher proportion of deaths are due to building collapse, i.e. in earthquakes causing >5000 buildings heavily damaged, fatalities in building collapse dominate the total.

In most countries highly-destructive earthquakes constitute the most important part of earthquake risk and are the focus of concern in earthquake protection

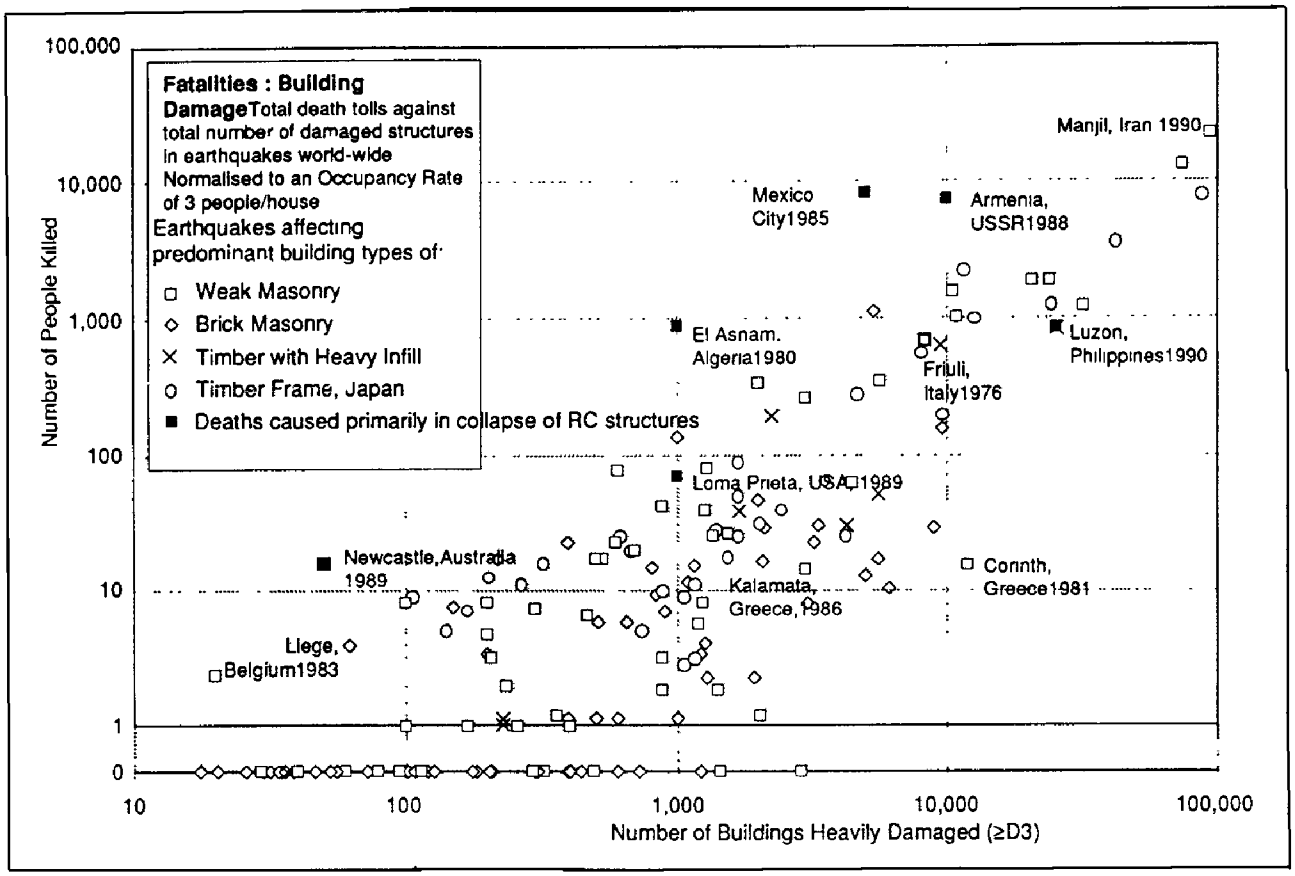


Figure 2 Relationship between total casualty figures and total building damage statistics

measures Casualty totals in large earthquakes can be predicted within certain confidence limits using models of casualty occurrence based on building collapse.

A generalised casualty equation for the total deaths resulting from an earthquake can be expressed as·

$$K=Ks+K'+K2 \quad [1]$$

where Ks is fatalities due to structural damage, K' is fatalities from non-structural damage and K2 is those arising from follow-on hazards Variable K2 is rare, but where it occurs this is likely to dominate the total K' is dominant at low levels of damage but highly variable and difficult to predict Ks is consistent and the controlling factor for most large and destructive earthquakes and contributes a large percentage of the total deaths from earthquakes The model for Ks is elaborated in the rest of this paper.

2 LETHALITY RATIO

An extensive review of literature on casualty occurrence (Sakai et al 1990) and a comparative analysis of some 16 casualty prediction models published by others (Coburn et al 1990) has helped identify a number of consistent and useable factors in casualty estimation. These have now been developed into a comprehensive casualty model which can be used to predict likely casualty levels in future events, to assess variations that are possible and confidence levels in existing data and to assess the effects of casualty-reduction activities. Much of the data examined in this project has been related to the number of people killed per building collapse. This 'Lethality Ratio' has been explored in a number of data sets to investigate several explanatory variables, which can be classified into five factors

3 CASUALTY MODEL

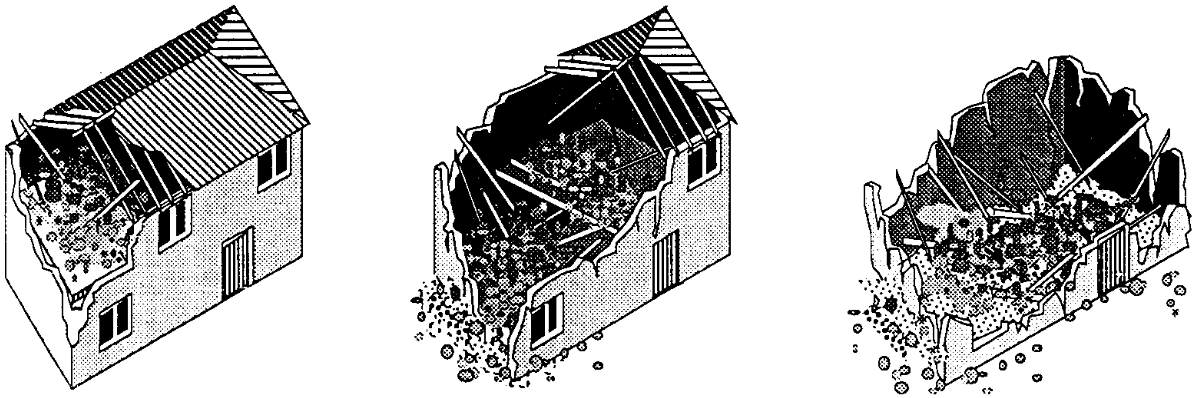
The casualty model can be stated as a series of five factors which are applied to classes of buildings For a class of building, b, the number of people killed can be expressed as:

$$Ksb=D5b * [M1b*M2b*M3b*(M4b+M5b)] \quad [2]$$

where D5b is the total number of collapsed structures (damage level 5) of buildings of type b, and factors M1 to M5 are a range of modifiers to a potential mortality figure Summing for all building types affected by the earthquake gives the total dead due to building collapse, Ks

Predictions of numbers of collapsed structures of various building types are the outputs of structural vulnerability and hazard models, such as that presented elsewhere in these proceedings (Spence et al. 1992) The additional mortality factors M1 to M5 can be used to assess the effects of such damage predictions on the human population accommodated in a known building stock.

Population per building (P/B), or M1, varies considerably from one place to another and can change significantly in a town or region in just a few years In residential building stock the P/B is equivalent to the average family size living in each house. In European cities, average residential P/B sizes are around 2 to 3



Damage Level: **D5 Collapse**Extent of Collapse: 10% of Volume**M3** (Occupants Trapped) **: 10%**

Damage Level: **D5 Collapse**Extent of Collapse: 50% of Volume**M3** (Occupants Trapped) **: 37.5%**(50% of ground floor occupants assumed escaped

Damage Level: **D5 Collapse**Extent of Collapse: 100% of Volume**M3** (Occupants Trapped) **: 75%**(50% of ground floor occupants assumed escaped before collapse)

Average M3 for these three buildings = 41%

Figure 3 Illustration of extent of collapse and its effect on M3

In cities with rapidly expanding populations, a large immigration of population or a shortage of building stock, P/B ratios can be much higher and can increase or decrease quite suddenly with changes of population movement. The rise of P/B in Japanese cities following the loss of large amounts of building stock in WWII has been shown to have had a demonstrable effect on the lethality ratio of earthquake damage into the mid 1950s (Coburn, Murakami, Ohta 1987). Many rural areas associated with high death tolls in earthquakes (Iran, Turkey etc) have very large family sizes – surveys show at 16 person households are not uncommon and average P/Bs in these areas are around 8. Other areas of low casualties in eathquakes, for example coastal towns of Greece, have low levels of P/B due to declining or out-migration of population and higher affluence generally. The population per building is a major variable in determining the number of people at risk in a building collapse and is established as the potential mortality for a building type.

The time of day that an earthquake occurs (M2: occupancy at time of eartquake) has long been known to affect the number of people killed. An earthquake occurring when a lot of the population is indoors kills more people in the buildings that collapse. In societies spending a lot of time outdoors, for example agricultural economies, the time of day can have a considerable effect on earthquake mortality. Studies examining the comparative influence of time of day on lethality ratios show measurable variations of a factor of about two in deaths per building during the day in rural areas, mirroring typical occupancy patterns. (Pomonis et al. 1991)

In urban areas and other types of community, more complex patterns of activity are found, with people moving from one building type to another, e.g. from residential to non-residential, during the day. If non-residential buildings are more vulnerable, then death tolls will be higher when they are more fully occupied and vice versa. Other temporal variations in occupancy occur seasonally (winter vs summer) and weekly (weekdays vs weekend). Where detailed information on occupancy cycles is not known for the relevant building types, average occupancy levels for the whole day, week or year can be assumed.

Although there is little detailed information or statistics to quantify it empirically, it is clear that not all the occupants that are inside a building when an earthquake occurs are trapped if it collapses. People escape before collapse, or the collapse of the structure is not total, or they are able to free themselves relatively easily by their own efforts.

It is not known for certain how long buildings take to collapse. A large magnitude earthquake can have a minute or more of strong ground motion but the strongest amplitude shaking often occurs during the early part of the earthquake. A ductile building may collapse over a period of several tens of seconds. A brittle building may collapse more quickly. In the epicentral areas of large earthquakes there are reports of weak buildings collapsing almost instantaneously. Tests of evacuation times show that people cannot get out of a building from anywhere above the first floor in less than thirty seconds, even if they are capable of walking during the violent shaking (Georgescu 1988). A reasonable assumption is that a certain percentage of occupants of the ground floor – e.g. 50% for a building of fairly shallow plan depth, will be capable of escape, all other occupants of the building will remain inside.

The main difference in M3 (occupants trapped by collapse) parameters between different buildings classified as collapsed is in the type and percentage of collapse. Buildings are classified as collapsed (D5) on the MSK scale, if they have "more than one wall collapsed or more than half of the roof dislodged or failure of structural members to allow fall of roof or slab" (Cambridge definition). Within this definition a range of types and extent of collapse can be found, from one or two walls to complete structural disintegration (Figure 3, page 23)

A measurement of the extent of collapse, based on the study of photographs of over 300 collapsed buildings, was developed in order to quantify the implications of M3 in the casualty equation (Okada et al 1991) From a range of proposed parameters, the volumetric reduction in the building form (W3 in Okada's study) is used to relate the extent of collapse to the entrapment rate of occupants In 'Collapsed' (D5) masonry buildings, volumetric reduction ranges from 10% to 100% The average extent of collapse at a location appears to be related to the ground motion intensity.

In weak masonry buildings close to the epicentre of a large magnitude earthquake it is clear that average reduction in volume of buildings can reach over 75% Buildings classified as collapsed in locations on the periphery of earthquake-affected areas, and at lower intensities may have average volumetric reductions of 30% or less

Soil-structure interaction, storey height, structural characteristics and location relative to other buildings all influence the collapse mechanism and pattern of multi-storey reinforced concrete frame structures The mechanism of collapse determines the volumetric reduction A study of over 100 collapsed RC frame buildings in Mexico City, Bucharest, Armenia, Greece and other earthquakes derived four primary collapse types (Pomonis 1991): 'Bottom-up' collapse starts from a failure in the ground floor, often caused by stiffness discontinuities, and often causes complete failure of the whole structure ('pancake collapse' or 100% volume reduction) Average volumetric reductions of all collapses classifield as 'Bottom-up' are around 75% 'Top-down' collapse is a progressive collapse downwards from failures due to large deflections at the top of the structure, common in multi-storey ductile structures. Top-down collapses are less severe with average volumetric reductions of around 50% 'Pounding' between adjoined buildings may cause collapse in some mid-level storeys with limited progression further average values of 30%. 'Overturning' of tall structures is often associated with torsional effects in corner buildings, particularly those with a large proportion of openings on the facades, and can be extensive – averaging 75%

The relative proportions of these collapse types among multi-storey RC structures appears to depend on the characteristics of ground motion. Near-field, high frequency motion appears to cause more 'Bottom-up' types of collapse, with average M3 values of around 70% Long-period motions from distant earthquakes appear to cause more 'Top-down' and 'Pounding' collapses, resulting in average M3 values around 50%.

Empirical evidence from the few reported cases of earthquake prediction or organised evacuations before an earthquake suggest that with sufficient warning and social organisation, M3 values in a city or region can be reduced significantly, but probably not lower than 10% The M3 values proposed here assume a direct correlation between the volumetric extent of building collapse and % of occupants trapped. Where collapse is near total, this is valid, but for lower volumes of collapse, occupants are capable, if awake, of escaping entrapment through their own efforts. Studies of occupant behaviour in earthquakes being undertaken by others will be able to provide better estimates of M3 as these factors become clearer. People caught in building collapses suffer a range of types of injury, including traumatic injuries, fractures, crushing contusions or lacerations of soft tissue and bronchial or thoracic injuries from dust inhalation.

The causes of death and reported injury type of those trapped inside damaged structures vary considerably and there is some evidence that different types of buildings (timber, masonry, reinforced concrete) inflict injuries in different ways and to different degrees of severity when they collapse. In masonry buildings, a primary cause of death is often suffocation from the weight and powder of wall or roof material which buries the victim There is also evidence that suffocation is a real danger to those trapped inside reinforced concrete structures from the large amount of dust generated by collapse

A proportion of the building's occupants are killed outright when collapse occurs This proportion (deaths at time 0 or T0 after the earthquake) is taken as the M4 factor in the casualty model Others are injured to various degrees of severity A number of injury severity scales have been proposed for quantifying earthquake epidemiological studies (Noji 1989), one of the simplest and most useful to emergency managers is the four-point standard triage categorisation of injuries.

There is very little data to indicate the distribution of severity of injury to occupants when a building collapses. However, studies back-figuring injury types and survival times from mortality data of people retrieved from building collapses several days later (Shiono and Krimgold 1989) suggest that in reinforced concrete structures, the M4 injury distribution is bi-modal, with most people being either killed or only lightly injured, with very few people badly injured in between. By contrast, injury distributions in masonry buildings appear more uniform, with high percentages of trapped victims having serious injuries

It has been speculated that the injury distribution may be a function of the degree of cavitation in collapse – the void-to-volume ratio of the collapsed rubble and the size of the cavities left within it (Sakai 1991).

Other parameters that could affect M4 include the mass and fragmentation sizes of building elements on collapse, the dust-producing potential of building materials, characteristics of stairways and circulation routes and other factors that affect cavity potential on collapse

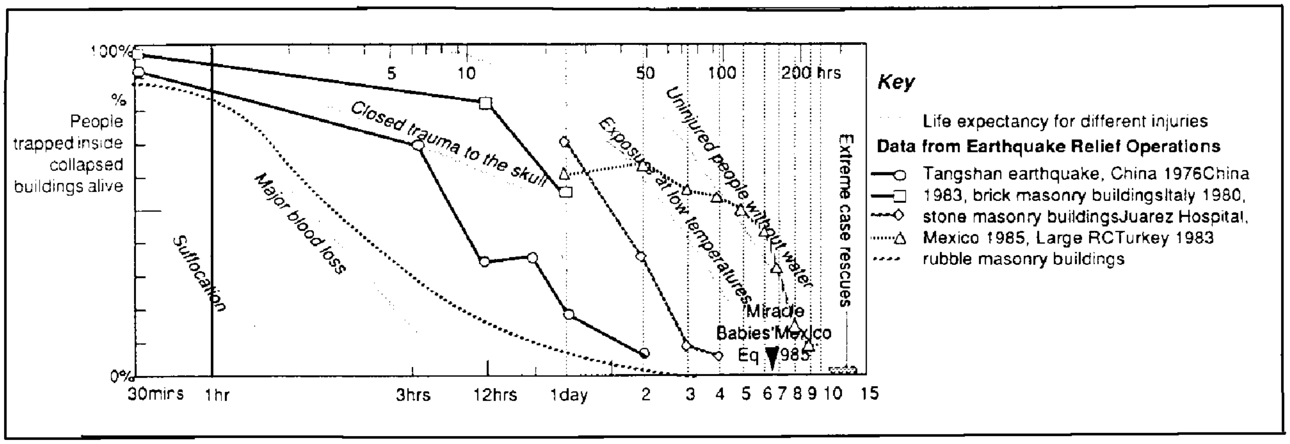


Figure 4 'Fade-away' times for trapped victims

In principle, the identification of these characteristics could be incorporated into the design of new buildings to make them safer in the event of a collapse – designs incorporating a structural core or deep-beam structure appear to have higher cavity potential on collapse for example. Certain building materials and finishes may be preferred that reduce dust-production – for example plasterboard may produce less dust on collapse than wet-applied plaster and may provide a safe building.

Those trapped in the rubble will die if they are not rescued and given medical treatment. Those who have serious injuries will die quickly. Less severely injured people can survive for longer. The unaffected community usually rally to the collapsed buildings and set to work to extricate trapped victims. Considerable resources are expended mobilising emergency services for search and rescue activities. In a large-scale disaster it is common for international search and rescue specialist teams to be flown thousands of miles to assist the rescue operations in gestures of inter-country solidarity. Considerable expertise has been developed in operational and medical management of a mass-casualty disaster.

Effective emergency activities will save the lives of many of those trapped in building collapses that would otherwise have died. Time is critical and death rates increase with every hour that passes.

The M5 factor – the additional mortality of trapped victims after collapse – is a measure of the effectiveness of post-collapse activities. It is clear that in cases of extreme destruction, where high percentages of the total population of a community are trapped in collapses (i.e. M1*M2*M3>50%) the M5 factor becomes very high: the community itself loses its capability of rescuing its own victims, both because its manpower is greatly reduced and because it is psychologically and socially incapacitated by the disaster. In very high casualty earthquakes ('hyper-fatality events' Coburn et al. 1989) this appears to be a major factor in the escalation of casualty figures.

The number of people saved after collapse is a function of the capability of the rescue and medical activities together with the survival time of those trapped in the rubble. Figure 4 (above) summarises available data on 'fade-away' time for people with different injuries and aggregated survival rates of people retrieved in a number of earthquakes. Models of rescue and life-saving achievement have been proposed (Shiono 1989, Sakai 1990) in which times are assumed for the injury distribution to deteriorate and manpower, equipment, search techniques, transport resources and other factors affect the extrication rates of victims. These models indicate the M5 is sensitive to improvements in rescue efficiency within the first 24 to 36 hours after the earthquake but that sensitivity diminishes extremely rapidly with time. The logistical difficulties of mobilising rescue reinforcements into the affected locations within hours of an earthquake's occurrence means that the potential for lifesaving in a stricken community relies heavily on the capabilities of the people on the spot. Specialist rescue teams arriving more than a few hours after the event are unlikely to make much of a difference to the overall death toll of a large earthquake.

Other factors known to affect fade-away time, and thus to influence M5, include climatic conditions, aftershocks, fire outbreaks and rainfall. Factors that affect search and rescue effectiveness include construction materials, collapse type, manpower, equipment, skills, and other factors.

5 CONCLUSIONS

A general model has been proposed to estimate the number of people killed by building collapse in an earthquake. Five factors M1 to M5 are identified which encompass the primary parameters affecting mortality in mass-collapse disasters, based on an extensive study of available data and systematic research into the process of casualty occurrence.

The model requires an estimate of the number of buildings collapsed, categorised into broader classes which at it simplest would consist of residential and non-residential and broad classes of structural type (such as masonry, RC frame and timber). Where it is possible to identify the number of collapses by the intensity of ground motion that caused it, this will assist the accuracy of defining M3 (otherwise average values can be used). For each of the building type classes, average values for person per building (M1) and occupancy patterns (M2) need to be estimated or obtained from detailed surveys The parameters M3 to M5 have been estimated here based on the best indication from such data and studies as can be found

The structure of the model allows considerable flexibility in examining the effects of a wide range of factors incorporating demographic, sociological and organisational parameters in addition to engineering knowledge about the seismic performance of the physical building stock. The costs of earthquake protection measures and their benefits in terms of life saving can be realistically assessed.

This simple model lends itself to considerable elaboration, with each of the parameters M1 to M5 capable of being varied by sets of sub-factors and more complex analytical procedures (such as the search and rescue models already referenced). The basic framework is capable of considerable further development as more becomes understood about the nature of casualty occurrence in building collapse

The greatest need is for systematic studies and data collection on mortality and morbidity incidence in earthquakes Coordination of medical and epidemiological data collection with engineering studies and damage surveys is essential to improve the science of reducing human casualties in earthquakes

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TABLES

M3

Average extent of collapse for all collapsed buildings and average % of occupants trapped by collapse

Collapsed Masonry Buildings (up to 3 Storeys)

MSK Intensity	VII	VIII	IX	X
	5%	30%	60%	70%

Collapsed RC Structures (3-5 Storeys)

Near-field, high-frequency ground motion	70%
Distant, long-period ground motion	50%

M4

Estimated Injury Distributions at collapse (% of M3)

Triage Injury Category		Masonry	RC
1	Dead or unsaveable	20	40
2	Life threatening cases needing immediate medical attention	30	10
3	Injury requiring hospital treatment	30	40
4	Light injury not necessitating hospitalisation	20	10

M5

(as % of M3-M4) Living victims trapped in collapsed buildings that subsequently die

Situation	Masonry	RC
Community incapacitated by high casualty rate	95	-
Community capable of organising rescue activities	60	90
Community + emergency squads after 12 hours	50	80
Community + emergency squads + SAR experts after 36 hours	45	70