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Earthquake Tectonics and Hazards on the Continents

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Perspective on the hazard problem

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Earthquakes hazards, Earthquake risks and a History of the Future

Overview and summary

Earthquake hazards are historical observations of the effect, or potential effects, of earthquakes on society in a specified region. *Earthquake hazards* are quantified by the severity and duration of shaking produced by an earthquake (local accelerations, velocities and displacements), and the indirect effect of these accelerations at the earth's surface (landslides, tsunami and liquefaction). *Earthquake risks* are estimates of the effects of future earthquakes in specified regions, based on insights from a catalog of historical hazards.

Although earthquake risk can be reduced by human intervention, hazards cannot. However although hazards cannot be changed, one can often improve the accuracy with which historical earthquakes have been reported, because written history is a fickle data logger subject to human memory and perception. Earthquakes hazards prior to 1900 are largely known from their preceived effects, with their location and magnitude quantified crudely using various intensity scales.

The first recording seismometer was constructed in 1887. By modern standards it was not very precise, but within 15 years there were enough of these early seismometers in the world to locate the positions of earthquakes and to estimate their relative sizes. This was the beginning of what we call the instrumental catalog. By 1920 the energy released by individual earthquakes had been calculated by Galitzin and Jeffreys and others. In 1956 Richter introduced a magnitude scale that is now routinely used to quantify earthquake energy release, and which can be used to interpret the historical record of the preceding many thousands of years of earthquakes, from which earthquake risks can be calculated.

Earthquake risk is a fundamental parameter used by engineers to construct buildings or structures (bridges, power-stations, dams and pipelines) to survive future earthquake shaking. The mandate of engineers is to construct buildings that do not collapse in earthquakes and therefore do not harm their occupants. A building can be constructed to withstand the strongest shaking, but the cost of a building increases with its resistance to collapse. Hence engineers are required to minimise the cost of a structure as a function of its use. Hospitals, schools and fire stations must be constructed to withstand the strongest shaking, and are expected to remain functional immediately shaking has ceased. At the other extreme it is possible to construct a building with minimal strength that will survive an earthquake permitting its occupants to escape injury, but which must be extensively repaired following the earthquake. The cost of a building immune to earthquake damage may be ten times the cost of of a building with minimal resistance that must be repaired after an earthquake. The cost of minimal earthquake resistance (ie sufficient resistance to guarantee occupant survival) is often less than 10% of the cost of the similar structure that would otherwise collapse without earthquake resistant features.

Earthquake risk is of major importance to insurance companies who must estimate their exposure to losses in regions where buildings have not been constructed specifically to resist future shaking. Regions of higher risk require higher insurance premiums. For this reason insurance companies are eager to fund scientists who are able to improve estimates of future risk.

Earthquake risk is rarely considered by home owners or people renting dwellings. Most of you who are reading these sentences will have zero knowledge of how your house or apartment was constructed. Some of you may have added to, or modified, your homes without thinking whether the changes have made your homes more. or less, resistant to future earthquakes

More importantly, although construction guidelines exist in all parts of the world, and in many places these guidelines include codes related to earthquake risk, in most parts of the world these guidelines were, and still are, not considered important by contractors or by authorities responsible for regulating building construction. A few hundred years ago this was not as much a problem as it is now, because populations were sufficiently sparse for most people to live in single story structures in rural communites. In the past hundred years populations have not only increased by an order of magnitude, populations are now concentrated in cities. The dense packing of people in cities caused by rural to urban migration has required a change from single family homes to multi-family housing in tall buildings made of concrete and steel.

Earthquake risk has been discussed for more than 100 years, but in the developing world where most of the population increase has occurred, it has not been an important factor in the assembly of dwellings. In most of the world it has been ignored, through ignorance or through a necessity linked to poverty. In some cases earthquake resistance has been deliberately avoided (corruption) to maximise construction profits. Thus in the major cities and megacities of the developing world, the current building stock is fragile and is an easy target for earthquake damage.

A measure of our awareness of the present vulnerability of the world building stock is that when an earthquake occurs near a major city, seismologists can calculate using empirical methods how many people are injured, how many are dead and approximately the cost of reconstruction, within half an hour of the mainshock (in fact a few seconds after depth, magnitude and location are recorded by the worlds seismometers). Yet despite the rapidity of these empirical calculations, it will take many days before survivors at the epicenter can count the dead and wounded, and many months before the true costs of reconstruction are known.

The title of this segment of your course includes the curious phrase "the history of the future". By this I wish to convey the following important message to the attendees of this short course - that despite the best intentions of seismologists, earthquake geologists and earthquake engineers, I foresee an immediate future that differs little from our immediate past. Thus were I writing in the year 2084 a history of earthquake disasters from 2013 to 2084 it would include a dozen earthquake disasters with death-tolls of 30,000 to 100,000 people. It may also include one with a deathtoll of more than 1 million. The only thing missing in this history of the future are the names of the destroyed cities where these events occurred.

The reason for this distressing view of our seismic future is summarised as follows. The world failed to incorporate ubiquitous earthquake resistance at a critical time when its population increased by a factor of ten. As a result many urban populations are now exposed to earthquake risks in structures that are not able to survive future shaking. Worse, the scale of future disasters may be far more costly and deadly than the worst disasters in our previous history, because populations are denser and more numerous than ever before. The following pages are presented in support of the above conclusions. They are taken from several published articles.

Ambraseys, N. and Bilham, R. (2011) Corruption Kills, *Nature* **469,** 143-145. 13 Jan 2011.

Bilham, R., (2012.)Societal and Observational Problems in earthquake risk assessments and their delivery to those most at risk, *Tectonophysics*, 584, 166-173. 10.1016/j.tecto.2012.03.023

Bilham, R., The seismic future of cities, Twelfth annual Mallet Milne Lecture. Bull. Earthquake Engineering, 2009, 7(4), 839-887. DOI 10.1007/s10518-009-9147-0

England, P. and J. Jackson, (2011) Uncharted seismic risk, *Nature Geoscience* **4**, 348–349 (2011) doi:10.1038/ngeo1168,

Holzer T.L. and J. C. Savage, Global Earthquake Fatalities and Population, Earthquake Spectra, Volume 29, No. 1, pages 155–175

Summary: The projected doubling in Earth's population in the next half century, requires an additional 1 billion housing units, more dwellings constructed in a single generation than at any time in Earth's history. Earth's tenfold increase in population has occurred during a time that is short compared to the return time of damaging earthquakes. In the next century, therefore, earthquakes that had little impact on villages and towns, will be shaking urban agglomerations housing upwards of 12 million people. An epicentral hit on a megacity has the potential to cause 1 million fatalities. The incorporation of earthquake resistant structures in the current global building boom, despite successes in the developed nations, has been neglected in the developing nations where historically earthquake damage has been high. The reasons for this neglect are attributed to indifference, ignorance and corrupt practices, not due to an absence of engineering competence. Never has a generation of earthquake engineers been faced with such a grave responsibility to exercise their skills, both political and technical, as now.

Introduction

Homo Sapiens is unique on our planet in its need to construct dwellings, to aggregate those dwellings in cities, and to construct both, largely oblivious of their vulnerability to earthquake damage, or for that matter any other kind of infrequent catastrophe. It is easy to protest that, no, we have learned how to construct buildings that don't collapse, and that we know where to construct to minimize the impact of earthquakes, but recent history shows that earthquake resistance is a local exception rather than a global rule. A slow steady increase in deaths and economic losses from earthquakes is interspersed with remarkable catastrophes that remind us of how far the gap between knowledge and its application has widened in those countries most disadvantaged by earthquakes.

It is the historical record that provides us a clue as to what lies in our future, and I propose to devote most of this article to an examination of this aspect of the human predicament. From our past we can glimpse the perils to an increasingly urban society indifferent to a guaranteed seismic future. Though it is accidental that the notion of an urban earthquake is built into the word seismicity - "seismic-city" - it is no accident that the only earthquakes that are of real concern to society are those that destroy buildings. The more buildings that are damaged the more certain is the earthquake to be remembered, and the more likely is the reconstruction of that city to incorporate a measure of resilience to the next earthquake. The notion of urban earthquakes - those that shake a city with damaging accelerations – say those exceeding Intensity VII on the Modified Mercalli scale, has thus been around since earthquakes were first described in biblical times. Historical earthquakes are remembered for the ruins they caused.

Nine thousand years ago humankind formed the world's first cities, colonies of dwellings, each family dwelling surrounded by four walls and a roof. The dwelling units of these early cities were formed from the materials available to hand: straw, twigs, and mud. The earliest Neolithic cities that we know of (Mellaart, 1967) were constructed of mud, a material that can be moulded when wet, yet becomes brittle when dry. For these early city dwellers mud provided two additional benefits -low thermal conductivity and high thermal capacity - thereby providing rudimentary air conditioning - cool in summer, warm in winter. Mud can be painted, swept and easily repaired. Mud houses don't burn. But most of all, mud is dirt cheap, and to this day mud is the construction method of choice in low income families throughout the developing world. But mud is a killer - mud houses collapse in earthquakes. One of the questions that we can ask concerns why the knowledge of 9000 years of city collapse in earthquakes, and a known cumulative death toll of more than 10 million people in the past millennium, has not led to safer construction everywhere.

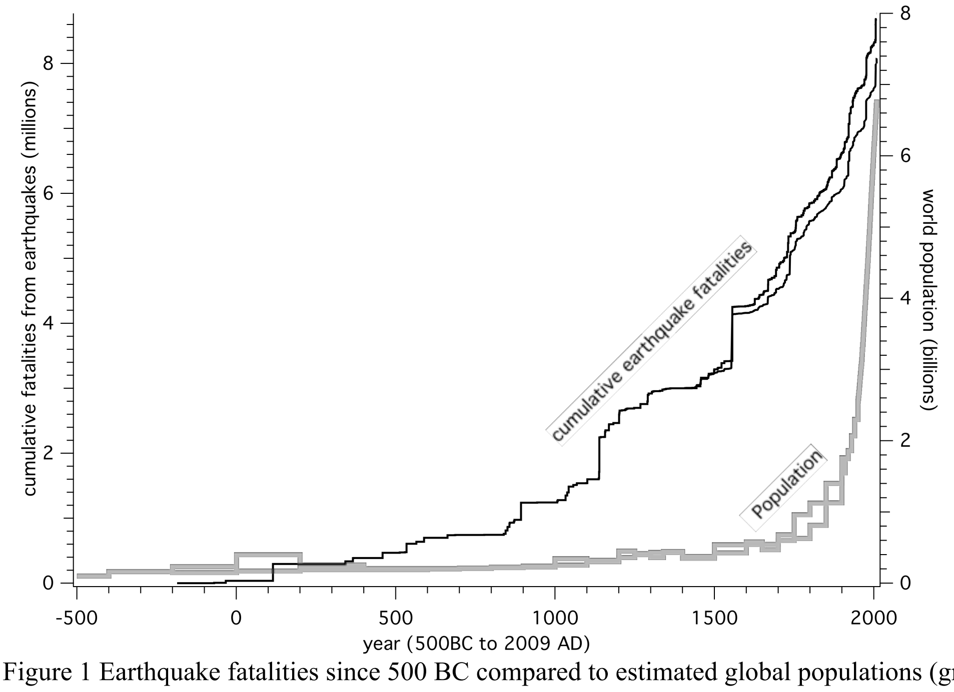


Figure 1 Earthquake fatalities since 500 BC compared to estimated global populations (grey). High and low estimates for global population are from McEvedy and Jones (1978) and Thomlinson (1975) (Tab;e 1). High fatality count edited from Dunbar et al. (1992). Low fatality counts since 1500 from Utsu (2002). Milne's (1912) compilation lists 6000 entries with a cumulative death toll of around 12 million.

Population Demographics

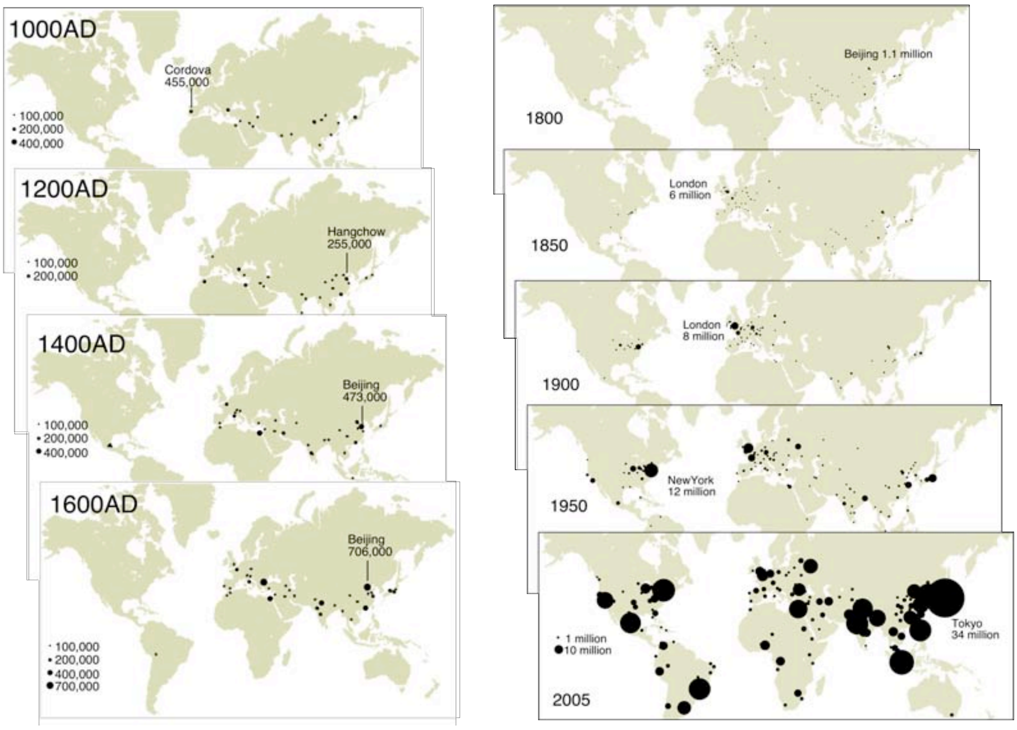
At the time of the first cities roughly 10,000 years ago world populations have been estimated as between 1 and 10 million (McEvedy and Jones, 1978; Thomlinson, 1975). The transition from Neolithic hunter-gathers to Bronze-age pastoral and farming communities led to a need for permanent structures, traces of which are increasingly evident starting roughly 5000 years ago, an approximate date for the start of urbanization. It is clear, however, that city life, though made possible by an abundant supply of food supplied by the surrounding rural populations, was an unhealthy environment, with communicable diseases holding populations firmly in check. Thus populations grew erratically from 7000 to 0 BC, interrupted by periodic epidemics in different continents that continued in the next 1500 years. These epidemics led to dramatic (30%-90%) but transient local reductions in population. Fewer than 400 years ago advances in medicine reduced the mortality rate, raising life expectancies from around 20 to more than 60 years. The extended life span caused by the increased availability of medicine, improved sanitation, and clean water, caused world populations to rise rapidly, starting in the 18th century (Figure 1) and continuing at present (Table 1).

The following table gives low and high estimates for global population in millions for the period 10,000 BP to 1950 (McEvedy and Jones, 1978 and Thomlinson, 1975).

Year	Lower	Upper	Year	Lower	Upper
-10000	1	10	1100	301	320
-8000	5	5	1200	360	450
-6500	5	10	1250	400	416
-5000	5	20	1300	360	432
-4000	7		1340	443	432
-3000	14		1400	350	374
-2000	27		1500	425	540
-1000	50		1600	545	579
-500	100	100	1650	470	545
-400	162	162	1700	600	679
-200	150	231	1750	629	961
1	170	400	1800	813	1125
200	190	256	1850	1128	1402
400	190	206	1900	1550	1762
500	190	206	1910	1750	1750
600	200	206	1920	1860	1860
700	207	210	1930	2070	2070
800	220	224	1940	2300	2300
900	226	240	1950	2400	2,556
1000	254	345			

World populations even now in the presence of mandatory census compilations are inaccurate, and estimates of early populations are doubly so based as they are on numerous assumptions. The data used for Figure 1 show high and low estimates (Durand, 1974; Thomlinson, 1975; McEvedy and Jones, 1978; Biraben, 1980; Haub,1995; United Nations, 1999, U.S. Census Bureau , 2008). Populations since 1950 are documented reasonably accurately. The show a rapid increase in urban populations and a much slower increase in rural populations.

It is convenient to consider the doubling time for world populations to realize how unusual is our present predicament. The first doubling occurred between 500BC and around 1000AD when estimated populations increased from ≈120 million to ≈250 million. It took a further 650 years to double the population to 500 million. Populations had doubled again to ≈1000 million by 1800, and redoubled in 1920 to 2000 million. A further doubling had occurred by 1975, and populations are expected to slowly double again reaching a 2020 population of 8000 million. The successive time intervals between each of these population doubling times - 1500, 650, 150, 120, 55 and 70 years - have decreased from taking place over thousands of generations (pre-1600 life expectancies were less than 30 years), to occurring in a single generation.



Figures 2 and 3. Snapshots of the world in thepast 1000 years showing the world's largest cities .Although Rome (AD 14 population 4.9 million) and Bagdad (AD 900 population 900,000) exceeded the size of all those depicted, not until 1800 did any other city attain a population of 1 million. Data adapted from Chandler and Fox (1974). Urban populations have increased tenfold since 1900.

Urban growth has absorbed most of the world's increased population. Cities not only host more families but act as a magnet drawing in rural populations who are unable to survive in rural communities. There is nothing new in rural to urban migration, but prior to 1800 the city acted as a black-hole killing off its inhabitants and keeping pace with both the flux of new births and influx of rural populations seeking life (but often finding death) in the cities. After the widespread application of medicine c. 1800 the city ceased to be setting where life expectancy was short, and as a result urban populations began to rise (Figures 2-4). In 2009 the world officially became an urban planet when city dwellers for the first time in history outnumbered rural dwellers.

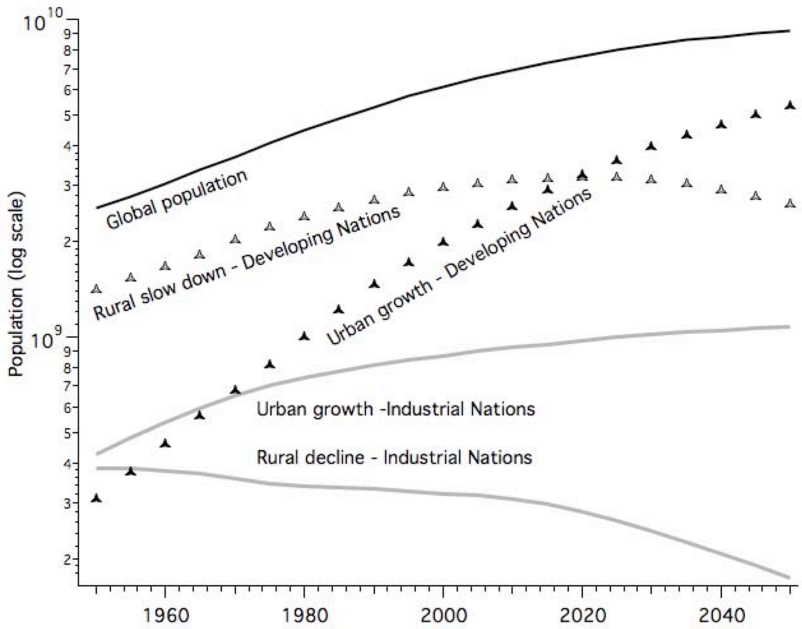


Figure 4. Urban and rural populations in the Developing and Industrial nations 1950 projected to 2050 (United Nations, 2008). Most the world's population recent increase has been absorbed by the doubling and re-doubling of city populations in the Developing Nations, a trend that will continue into the second half of this century.

Since 1950 the contribution to increasing global populations has occurred mostly in the cities of the developing world where it has doubled every 20 years or so, fueled by an annual population increase of 2-3%. According to UN predictions, rural populations in the developing nations are close to an anticipated peak of about 3200 million people, roughly ten times that in the Industrial Nations where rural populations continue to fall. The modest increase in urban population in the Industrial nations is expected to continue to rise, but by 2030 the total population in the Industrial nations is expected to peak and then decline (United Nations, 2009). A corresponding peak in the total population of the Developing Nations is not expected for a further quarter century.

In the past 200 years populations on Earth have increased by an order of magnitude. One consequence of this tenfold increase is that whatever we conclude about past risks from historical earthquakes our findings must be adjusted to account for this remarkable demographic change.

Fatalities from earthquakes

This article may be faulted for its morbid obsession with fatalities, rather than other aspects of earthquake damage – injuries, economic losses and urban renewal. The reason for this focus is that most fatalities are caused by the collapse of buildings. They thus provide a quantum measure of structural failure, something that can be addressed by improved engineering. The secondary effects of earthquakes – landslides, rock-falls, tsunami – have occasionally dominated the fatality count, and are not directly the result of flawed engineering. Two of the largest disasters in the past 500 years fall into this category: the 1556 earthquake in China when many deaths were caused by ground instability and hillside collapse, and the 2004 Indian ocean tsunami with its selective death toll on and near beaches on a public holiday. One can argue in hindsight that many of these accidents could have been avoided had appropriate planning preceded these catastrophes. Few societies are willing to restrict the right of its citizens to construct in vulnerable settings. Fatality counts for early earthquakes are often inflated since they are frequently estimated by historians writing many years after the event, with relatively modest access to contemporary materials. These materials are preserved most accurately in societies with central administrations, who have maintained written records of repairs, taxes, and sometimes tax-relief, following the earthquake. For pre-19th century earthquakes, the death-toll, location and the date of the earthquake are the only quantifiable parameters associated with the earthquake. A very readable summary of the attributes of a dozen early and recent earthquake catalogues of earthquakes can be found in the appendix of Ambraseys et al., (2002).

Mallet’s original catalogue of >5000 earthquakes was compiled with the help of his eldest son, and printed over a period of five years in the annual reports of the British Association for the Advancement of Science starting in 1850. The first two sections of their report (137 pages) describe methodology, and the listings of earthquakes (597 pages) since biblical times record physical phenomena but are sparse on fatality counts. The Mallet's catalogue (Mallet, 1852-54) includes entries from the earlier catalogues of Hoff, 1840 and Perrey c. 1848, and includes numerous new materials, from ship’s logs and from the writings of travelers and historians ending in 1842, at which point Mallet points the reader to Perrey's annual catalogues from 1842 onward. These have been subsequently incorporated into later listings. The catalogue compiled by Thomas Oldham and his son Richard, for earthquakes in India, for example, extracts materials of relevance to India, and adds others (Oldham,1893). Milne’s 1912 eighty-page somewhat telegraphic catalogue repeats data from these earlier compilations, omitting small earthquakes from Mallet's catalogue but adding additional events compiled from an enquiry to officials in all parts of the British Empire. These and later catalogues for various parts of the world have now been superseded by studies in which great care has been devoted to avoiding the repetition of error (Ambraseys et al., 2002; Stuchi et al., 2008). The success of these recent studies depends on the thoroughness with which each earthquake is linked to source materials that can be verified. For many earthquakes this requires the reproduction of primary accounts and a commentary on their interpretation.

However, despite these careful studies numerous recent catalogues have perpetuated errors, and reinserted items that were removed from previous catalogues. The readily available NOAA catalogue first published by Ganse and Nelson (1982) and updated by Dunbar et al., (1992) compiles data from numerous sources and subsequent catalogues and incorporates data available in accounts of earthquakes written by some primary and numerous secondary authors, who in turn cite previous summaries. As a result, the compilation contains duplicate entries and conflicting information for many events, and must be used with caution. Despite its shortcomings on the critical evaluation of what to believe and what to ignore, the published NOAA catalogue provides a listing of source materials from which the reliability of the data can sometimes be evaluated. An online version of this catalogue has now been reduced in length by the critical assessment and removal of numerous dubious accounts, but unevenly incorporates materials and case histories of earthquakes published in the past several decades:
http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1.

A carefully evaluated listing of historical earthquakes has also been published by Utsu (2002) and this too is available digitally, updated to the present with >10,000 entries http://iisee.kenken.go.jp/utsu/index_eng.html. This on-line catalogue includes many duplicate reports of events with "flags" alerting the unwary to the possibility that some entries may be based on unsound reporting. The most recent catalogue of these post-1900 earthquakes – *Pager-Cat* (Allen et al, 2009) is based on eight earlier catalogues http://earthquake.usgs.gov/research/data/pager/ and makes no attempt to evaluate original accounts. Instead, Allen et al. (2009) define rules for the quantification of fatality counts from poorly specified raw data, to provide a measure of uncertainty to the data.

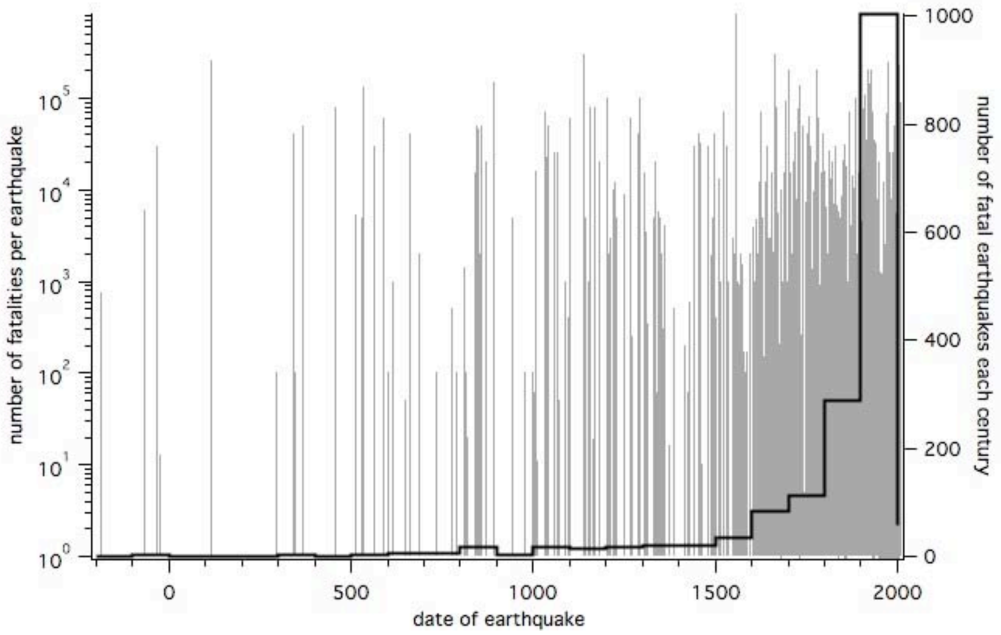


Figure 5. Earthquakes with known fatalities. The staircase plot indicates estimated numbers of fatal earthquakes per century plotted as a function of time. The record is clearly incomplete prior to 1600.

Why do catalogues of historical earthquakes abound in error?

"It is not for one moment supposed that this Catalogue is free from omissions and mistakes".
John Milne, 1912.

In Figure 1 the cumulative death toll from earthquakes shows two curves that diverge after 1500. Other catalogues that could have been plotted would show an even greater divergence. The essential problem with catalogues of historical earthquakes is that unlike lists of triangulation observations in which systematic and random errors can be rigorously quantified, none of the parameters of historical entries come with an estimate of uncertainty. Mallet (1851) observes that often in different accounts of the same earthquake "*the descrepancies are marvellous*". Some earthquakes in early catalogues are pure fiction. Ambraseys et al, (2002) argue that more than 50% of all historical earthquakes listed in pre-common-era catalogues are untrustworthy. I provide below some examples from the past 400 years illustrative of problem entries.

Detection threshold and incompleteness: The contribution to the total fatality count is systematically underestimated by the absence of information for the hundreds of earthquakes for which no numerical fatality count is given by historians, and for the even greater number unknown to historians. The question arises, as in earthquake magnitude, is there an earthquake whose death toll cannot escape global notice? The answer is, of course, that this detection-threshold has decreased through time. Although it is now essentially impossible for the worldwide news media to omit recording a single fatality in an earthquake, in the past it was quite common, especially in regions of low population density. Early earthquakes with low impacts on a literate society tend to be forgotten and their records lost.

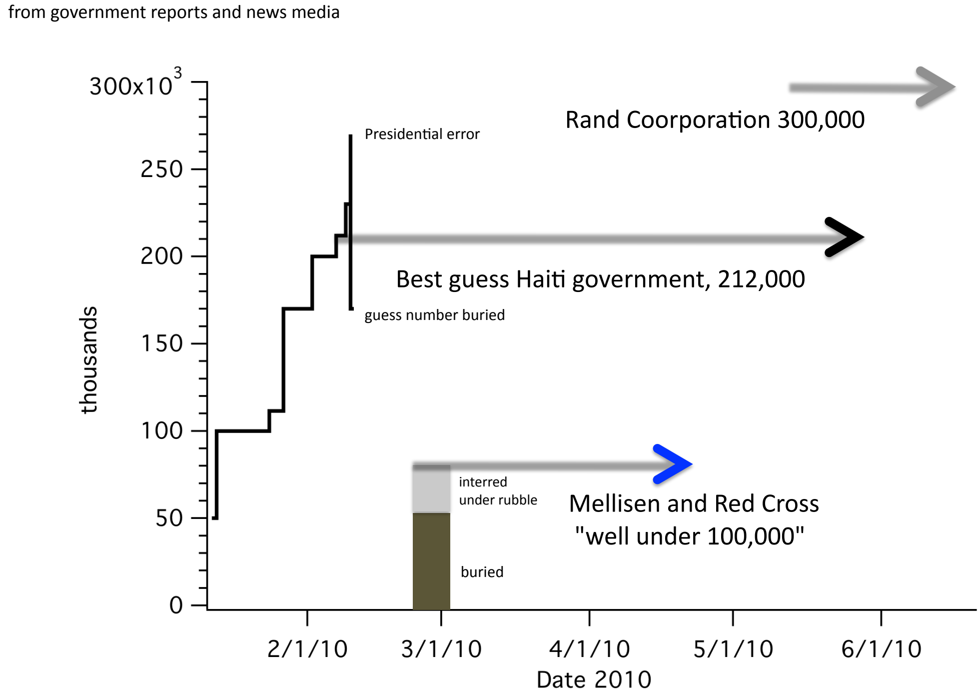
Chronologies- arithmetic and misunderstandings: On each continent, and sometimes in different parts of that continent, early societies developed their own methods of reckoning time, all linked to astronomy, but all with differing starting points, and each regulated by different celestial clockwork (Duncan, 1998). The links between these chronologies can be established by synchronizing eclipses, meteors and comets described in each (e.g. Gouin, 1979) and scholars have become adept at translating dates into local times and GMT. Richard Oldham encountered this problem in ascertaining the times of arrival of waves from the 1897 in India where as late as 1906 local time was set by the sundial at midday throughout most of the country. Although, catalogue problems can occur due to arithmetical errors in date conversions, a more frequent problem in earthquake compilations occurs where seismologists, eager to record new earthquakes, have entered the same earthquake as two earthquakes oblivious to the existence of these different chronologies. Ambraseys (1962) points at this grave error in a catalogue by Willis which duplicates many earthquakes by catalogueing the same event as occurring in AD (*anno Domini*) and also in the same numbered (unconverted) year in AH (*anno Hegirae* - in the year of the Hijra). In some instances Willis triplicated the earthquake as the result of a ±1 year arithmetic conversion error between the two calendars.

Conflation- the earthquake occurred there, not here.
The evolution of place names since classical times (Anthon, 1850; Cunningham, 1924), and the existence of many cities with similar or identical names means that some earthquakes can be assigned two (or more) locations, only one of which is correct. Once this conflation has been initiated it requires a considerable effort to eradicate spurious location errors from a catalogue. An example is the 28 Dec 893 Daibul earthquake in Armenia (Dvin, 40.02°N, 44.58°E), that appeared in Oldham's (1883) Indian catalogue as a result of a passage in one account mentioning "outer India" (Ambraseys, 2003). The ruin of Daibul in Armenia was identified erroneously with the ruins of Debil (Daybul, Bhanbore) near Karachi in Sindh province, and although there is evidence that earthquakes may have shaken this part of the Indus delta, and Kufic inscriptions found there have been interpreted as indicating reconstruction (Ghafur, 1966; Kovach, 2007), there is no evidence for earthquake damage to Banbhore in AD 893 (Khan, 1964).

Tangshan 1976, Izmit 1999, and Haiti 2010 – elusive numbers: For very destructive earthquakes, even in recent time, it is possible that numbers may be wrong by very large amounts For example, the numerical death-toll for the Mw=7.6 Tangshan earthquake of 27 July 1976 is listed in many catalogues somewhere between the official count of 242,419, the high initial estimate of 655,000, and early, educated guesses, of visitors to the area of 750,000. The elusive number was initially inflated by uncertainty in estimating the number of dead in families in which there were no survivors, and from a consideration of estimated head-count of the pre-earthquake population (Yong et al. 1988). In 7218 households all the family members were killed by the earthquake. Most catalogues now list the official count of 242,419.

Marza (2004) questions the death-toll of Izmit/Kocaeili earthquake of 1999 (also Mw=7.6 suggesting that the true numbers may have exceeded twice the official count of 17,127.

A more recent example of fatality inflation is the Haiti earthquake where a deathtoll of 85,000 was incremented without substantiation over the following several months to more than 300,000 by Haitian officials. The numbers were repeated uncritically by world relief organisations, with the one exception of the Red Cross who concurred with the findings of Mellisen. The following figure illustrates this incremental growth in the fatality count.



Assam, 1943 – a secret earthquake: In rare cases fatality counts may be suppressed for political expediency, for example, as occurred in Assam 23 Oct 1943 in World War II. Earthquake damage from this M≈7 earthquake was withheld from letters home and local news reports in case it proved of strategic advantage to the opposing side. Doug Warr writes in 2002 *"At the time I was with a medical unit stationed on the Manipur road, seven miles from Dimapur. I was awakened in the night by violent shaking - so violent that I found myself clinging desperately to the charpoy to avoid being shaken off. There was a rumbling noise. I don't know how long it lasted - perhaps a few minutes - and then it subsided to occasional slight tremors. In the morning we discovered that there were fissures and great unevenness in what had previously been level ground, trees had fallen and buildings had been damaged. There was some damage to the Manipur road, I think to the bridges on either side of my unit, but for security reasons a complete ban was imposed on the mention of any consequences of the quake so we never heard precise details. Of course, rumour was rife and we heard lurid accounts of fissures that had opened and swallowed men and vehicles but these were never substantiated and may have been figments of somebody's imagination. We shall never know"* (letter to Stacey Martin, 2009)

News of large fatality early earthquakes tend to be spoken about and recorded in more sources, and hence their survival is more likely, but the chances are thereby increased that numbers become subsequently inflated, sometimes to mythical proportions. My last examples are of what many now call *fake-quakes* - entries about disasters that are not earthquakes, but which have been recorded as such (Musson, 2004).

1662 Beijing – a mythical earthquake: An earthquake allegedly occurred near Beijing in 1662 and appears in many catalogues associated with 300,000 deaths. It is mentioned in a book by Ball (1904) introduced by the following remarks: *"As a general rule earthquake shocks would not appear to be infrequent in China, and not of serious import."* The following entries on his list are entered without attribution: *AD1662 - One in China, when 300,000 persons were buried in Beijing alone, AD 1731 - Another, when 100,000 persons were swallowed up in Beijing.* Drake (1912) reluctantly repeats the first of these earthquakes in his book, with an (almost) verbatim, but qualified entry- *June 1662-Chihli- According to Ball an earthquake during this year was so violent at Peking that "300,000 people were killed at that place alone." I have not been able to verify this report.*- but he adjusts the date of the second adding information from an unnamed source: *30 Sep 1730 – Chihli -This earthquake was followed by after-shocks until October 8th. At a place twelve miles west of Peking the earth cracked open. In Peking and the surrounding country 100,000 people were killed.* The 1662 and 1731 earthquakes listed by Lee et al., (1976) are relatively modest and their catalogue is devoid of fatalities. Ganse and Nelson (1982) reduce the fatalities in the June 1662 event to 600 but list 100,000 for the 1731 earthquake citing "*US Congress: Great earthquakes, March 1888 Volume 1*". This 1888 listing by Congress was extracted from the *Baltimore Sun* 1888 and does not mention the 1662 earthquake. Latter(1968) lists 300,00 deaths citing Daly. Dunbar et al., (1996) lists both of Ball's high numbers, but remove both events from the 2009 on-line NOAA searchable catalogue. Utsu's catalogue lists the 1662 earthquake as "mythical" and casts doubt on the year and number of deaths for the 1731 earthquake.

1618 Mumbai and 1737 Calcutta – fake-quakes: Striking examples of earthquakes that never happened but which appear in some catalogues mistakenly listed with M>7 are the 1618 Bombay and 1737 storms. These are first listed in the historical catalogue of Oldham(1883). The 1618 account of a storm is reproduced below:

"In May 1618, six years after the settlement of the English at Surat, "a general and diabolical storm" occurred in the neighbourhood of Bombay (Bombaim as it is termed by old writers). It began at Baçaim on the 15th of that month, and continued with such violence that the people hid themselves in cellars, in continual dread lest their dwellings should be levelled with the earth; The sea, according to the historian of the time, was brought into the city by the wind; the waves roared fearfully; the tops of the churches were blown off, and immense stones were impelled to vast distances; two thousand persons were killed; the fish died in the ponds; and most of the churches, as the tempest advanced, were utterly destroyed. Many vessels were lost in the port. At Bombaim, sixty sail of vessels, with their cargoes and some of their crews, foundered. At Agaçaim, a boat was blown by the force of the wind from the sea into a house, where it killed a woman and her child, and the trees were torn up by their roots."

[Faria Y. Souza "Ásia Portugueza", Lisbon, 1666-1675, translated under the title "The History and Conquest of India by the Portuguese" by J. Stevens, London, 1695. The text was researched by Stacey Martin who identifies the location of Agaçaim with Agashi, and Baçaim with Bassein]

A spurious event still listed by some web sites and text books among the world's worst earthquakes is a 1737 storm surge and cyclone in Calcutta, that is alleged to have killed 300,000 people. Whether or not an earthquake, the numerical count is clearly bogus because the population of Calcutta in 1737 was less than 30,000, and the number of burials in the local church increased by a mere handful in 1737, compared to previous and succeeding years. In this case of this storm the error can be traced to magazine accounts based on reports from captains of ships returning from

Calcutta the following year (Bilham, 1996). In some of these accounts the number of deaths is listed as 3000, a number that is consistent with the Fort William records of the East India Company as an estimate of the number *drowned* in the low lying areas of Calcutta by a cyclone. If there were an earthquake during the storm it is likely to have been quite modest (e.g.M<4.5) to have not been worth mentioning by the East India Company. The event is missing in Mallet's catalogue and enters the world's catalogues following Oldham's (1882) entry. Milne (1912) adopts it and only recently have catalogues begun to omit it.

1668 Samawani, Sindh – an unquantifiable earthquake: In many cases an historical earthquake will occur whose primary source material conveys indisputable evidence for a damaging earthquake, but contains insufficient information to assign a magnitude, a date, a geographic location, or even certainty as to the name of the town involved. Despite this ignorance the 1668 earthquake can be found in present day catalogues assigned with one, or all, of these parameters. Once these materials have been provided by one author they tend to taken in good faith by the next investigator, each repetition adding layers to a false cloak of credibility. The primary source of information for the Samawani earthquake comes from the Persian historian Musta'idd Khan who in the reign of the Emperor Aurangzeb notes that in May 1668 a report was received from the Mughal province of Thatta that an earthquake had damaged the town of Samawani. The account first appeared in earthquake catalogues in Oldham (1883) and reads as follows "*At this time (between the 1st and 10th Zí hajja, 1078 A.H) a report was received from the Soobah of Tattah that the town of Samawani (or Samanji) which belongs to the Parganah of Láhori had sunk into the ground with 30,000 houses, during an earthquake"*. Other translations are reproduced by Ambraseys (2004) and Bilham and Lodi (2009). In none of these translations is the day of the earthquake stated, and although it is bracketed by the dates of the preceding and following entries (2–11 May 1668), it may have occurred several days or weeks earlier as a result of the transit time of the information. In 1596 Samawani was the fifth largest revenue-producing city in the administrative province of Nasarpur, surrounding the present day location of a town of that name (25°31′N, 68°37′E). The precise position of ancient Samawani remains presently conjectural, but was known to Hodivala (1939) as a village of 500 houses. Unfortunately Hodivala omitted its coordinates from his account, and since we have no definitive location and only one observation, the assignation of coordinates or a magnitude is conjectural, yet several authors have felt compelled to provide both, with magnitudes in the range $7<Mw<7.6$. Some authors have even seen fit to invent an ocean tsunami as the cause for damage to Samawani (Murty et al., 1991) but its probable location places it NE of Hyderabad on a former course of the Indus more than 100 km inland (Bilham and Lodi, 2010).

Future findings of historical earthquakes?

Carefully researched reports of newly discovered information concerning the occurrence of earthquakes in Europe, China and Japan have now been published (Ambraseys and Melville (1982); Ambraseys (2009) and references therein; Guidoboni et al, 1994). We can anticipate that the historical record in many parts of the world will continue to improve from this archival research. The Vatican library, for example, remains a largely untapped resource for earthquake information that may eventually be examined by earthquake historians. However, in many parts of the world the survival of quantifiable accounts of earthquakes has been compromised by climatic and insect attack, fire and warfare.

Although regional catalogues based on the work of historians vigilant to first-hand accounts of earthquakes have now superseded earlier catalogues of uneven credibility, the suppression of incorrect information remains an ongoing task. One feature of new catalogues is to *include* bogus events with clear statements of the reasons for doubting their validity. Since an unqualified statement of error itself can be viewed later as an opinion subject to discussion, these faulty entries must be supported by a transparent and often tedious exposition of the reasons for the error. A satisfactory approach to this problem has been to lay out a hierarchy of citations demonstrating the dendritic growth of repetition and insertion from earlier source materials. This can be a lengthy and painstaking proposition requiring many pages devoted to identifying the source materials available to subsequent writers, and for this reason it has not been completed for many earthquakes. Stuchi et al. (2008) provide several case studies and Albini (2004) provides examples of the derivative nature of historical materials in the eastern Adriatic coast.

Working with what we have.

An idea of the incompleteness of the historical record can be gained by a glance at **Figure 5**, where the data available to the present are plotted as a function of time. All earthquakes for which no fatality count has been preserved are omitted. Two things are immediately obvious from this graph: its incompleteness especially before 1600, and an approximate correlation between the instantaneous world population and the number of reported fatal earthquakes. This correlation is readily apparent in figure 4. Most of the world, however, is spared fatal earthquakes, and a dozen or so nations are responsible for the rising global death toll.

Several developments occurred in human history in the 15th and 16th century that are responsible for the sudden increase in information on earthquakes and their effects. The development of printing made possible the widespread replication of travel accounts, the voyages of discovery awakened communications between Europe the Americas and Asia, with the attendant worldwide transfer of written information to and from colonies, by administrators and by individuals. Newspapers, diaries and letters home provide many first hand accounts of earthquake damage.

Figure 6 shows global trends in population and earthquake fatalities. Figure 6a suggests a correlation between the number of earthquake fatalities and world's increasing population. Figure 6b indicates that globally the odds of an individual dying in an earthquake were higher in previous centuries than now (Bilham 2003). It is tempting to speculate that the implementation of earthquake resistant construction methods is responsible for this decline, however, these global conclusions are unrepresentative of regional trends, for the risks to an individual vary significantly from nation to nation, and the quality of buildings stock in that country. The next section addresses this uneven distribution of earthquake fatalities and identifies those countries where city populations are most at risk.

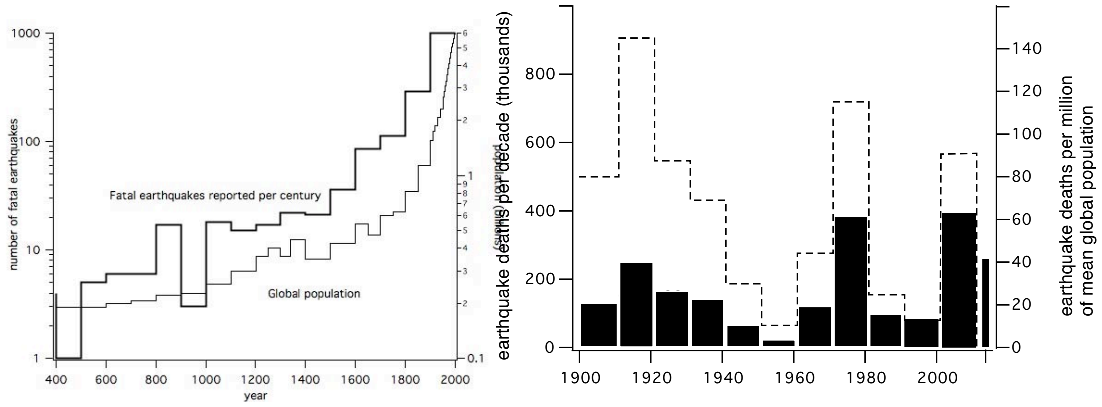


Figure 6a World population and numbers of fatal earthquakes per century increase steadily together. In this plot earthquakes are *counted* ignoring the numbers of fatalities in each earthquake (1 to >100,000). In **Figure 6b** the number of earthquake fatalities per decade normalized to the decadal global population averaged in 5 decade blocks. This view of earthquakes shows that earthquake risk to the individual averaged in a global sense has reduced in recent time.

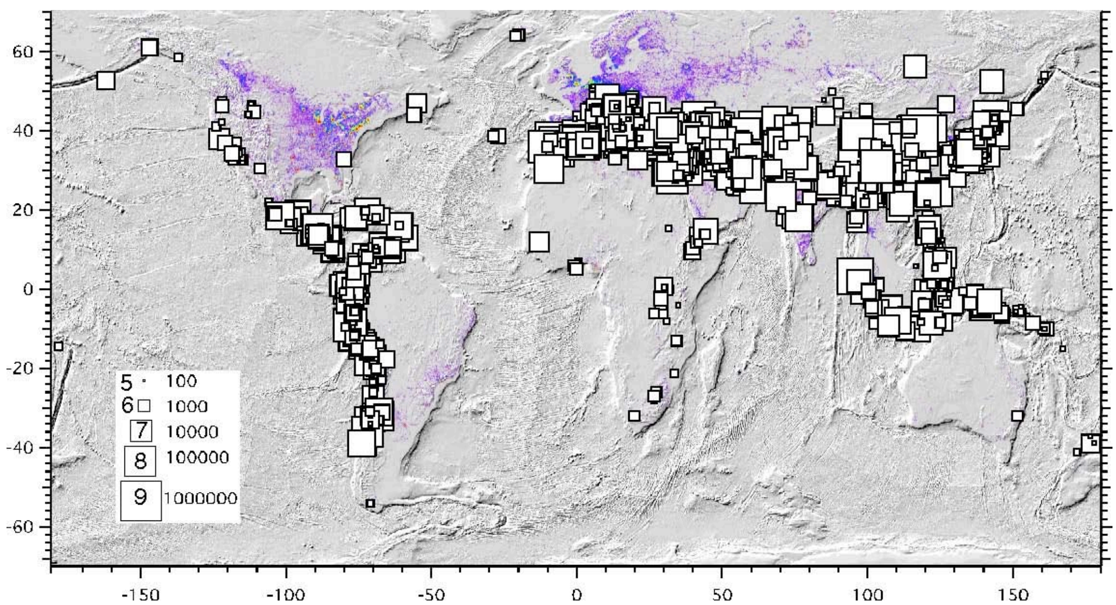


Figure 7 The past thousand years of earthquakes scaled according to a fatality magnitude scale, Mf=log(deaths)+3 (data edited from Dunbar et al, 1992). 85% of the world's fatal earthquakes have occurred in the Alpine/Himalayan collision zone from Europe to Indonesia, and 12% in the circum–Pacific including the Americas, Japan and New Zealand. The background map shows night-time luminosity of cities superimposed on global relief (Amante and Eakins, 2008)

Global distribution of fatal earthquakes

Figure 7 illustrates the distribution of earthquakes that have resulted in loss of life in the past 1000 years. Earthquake severity is indicated by plotting a symbol whose size is represented by the logarithm of the number of deaths in each earthquake. In view of the public acceptance of the Richter scale as a measure of the magnitude of an earthquake, and public perceptions of a Magnitude 8 earthquake as something exceptional, one may define a fatality scale M_f where a fatality magnitude of $M_f = 8$ represents exceptional loss of life: i.e. $M_f = \log(\text{fatalities}) + 3$. The most fatal earthquake on record (830,000 deaths in China in 1556) thus would have a M_f value of 8.9, and the minimum fatality count (1 death) would be M_f=3, with the millions of daily earthquakes that do no damage qualifying for M_f =2. A similar scale without the constant was proposed by Nishenko and Barton (1996). Neither scale has much utility, since unlike earthquake energy release, public perceptions of loss of life as a straight numerical count are immediate and direct.

It is immediately apparent from Figure 7 that the odds of a city being damaged by an earthquake are not evenly distributed on our planet (McGuire et al., 2004; Dilley, 2005). 12% of all fatal earthquakes are found along the margins of the eastern Pacific, and fully 85% of the world's earthquake fatalities have occurred in the Alpine/ Himalayan collision belt between western Europe and eastern Asia. This comparison is based on earthquakes since 1570, i.e. since the earliest historically recorded earthquakes in the Americas. Since then roughly 1100 people have died in earthquakes each year in the western Americas and Carribean, compared to 8900/year along the southern edge of the Eurasian plate. This concentration of most of the world's fatal earthquakes occurs in less than 12% of Earth's surface area - a 150° longitude band between London and Tokyo, between the equator and 45°N.

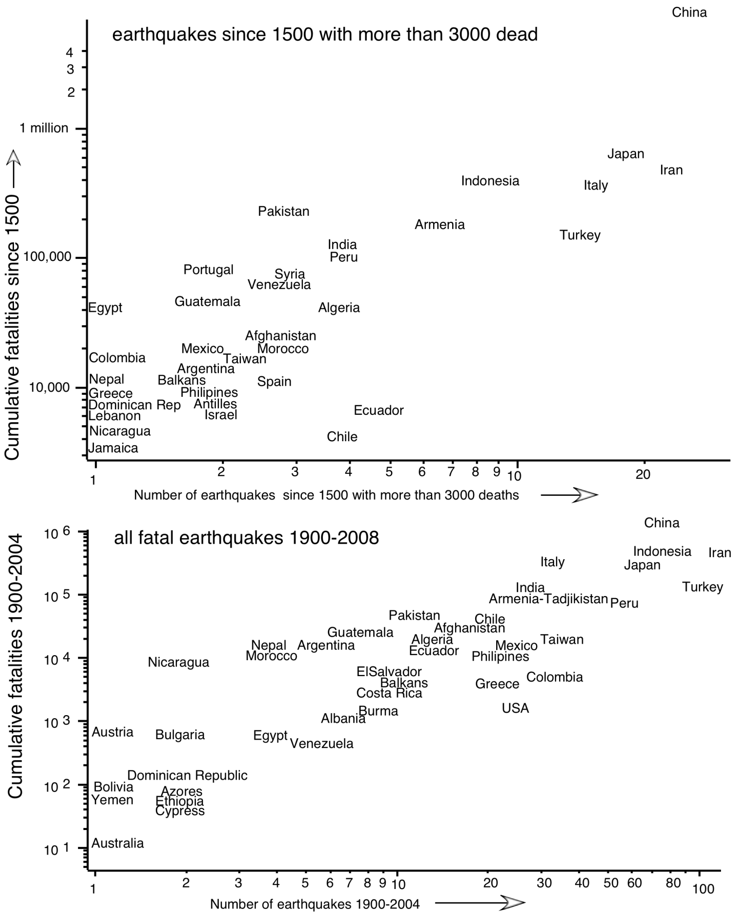


Figure 8 In the past 500 years, and in the past century, a handful of nations can be identified that have hosted both the world's most fatal earthquakes, and greatest number of them. The lower plot includes all fatal earthquakes, whereas the upper plot includes those that have resulted in more than 3000 deaths (updated from Hough and Bilham, 2006).

A consequence of this uneven distribution of historically fatal earthquakes is that some nations are at much greater risk than others. In both the past 500 years and in the most recent century we are forced to the same conclusion, that a handful of nations are selectively responsible for most of the world's earthquake fatalities. In Figure 8 the number of severe events in each country is plotted vs. the severity of these events. Nations that occupy the lower left hand corner of these graphs have few earthquakes of low severity, those that plot in the upper right corner have the misfortune to host frequent severe earthquakes. The least fortunate of these countries are China, Japan, Taly, Iran, Indonesia, and Turkey.

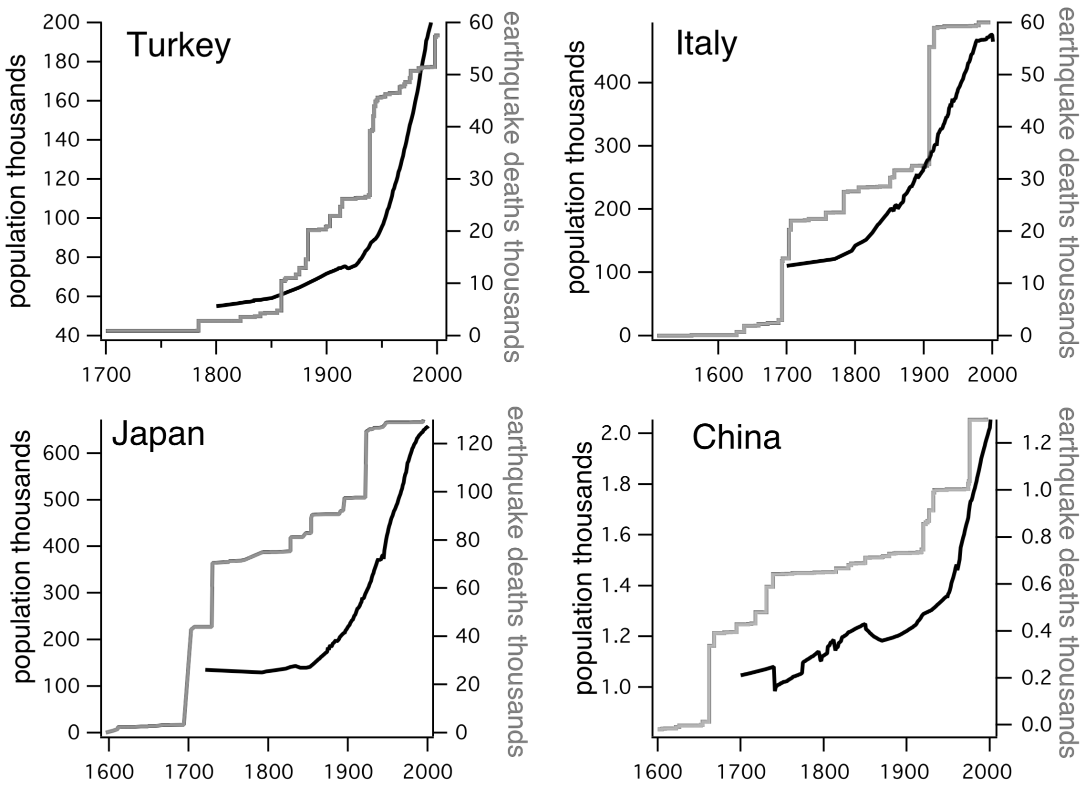


Figure 9 Fatality rates compared to instantaneous populations in four of the nations worse afflicted by earthquakes (from Bilham, 2004).

Nations who lose large numbers of their citizens to earthquakes every century recognize the seriousness of the problem they face, though the response in these nations has done little to stem the rise in the number of fatalities (In a later section we address the reasons for this). For example, the mean 20th century recurrence interval for killer earthquakes in half of the 42 nations depicted varies from once each year, to once per decade. This time interval is short compared to the average renewal time of building stock in cities (e.g. 30 years), and in some cases is short compared to the tenure of political office in these countries (3-10 years). Despite the repeated occurrence of earthquakes in 20th century Turkey, and a remarkably well-documented historical record of earthquake disasters, a Turkish politician when interviewed publically after the Izmit earthquake (Mw=7.6 & death-toll 17,127) voiced the opinion that the earthquake had no precedent in Turkish history. Such ignorance is surely unforgivable for an elected official. The rise in population and accompanying rise in fatalities for earthquakes for Italy, Japan, China and Turkey is depicted graphically in Figure 9. The past four hundred years of data for the four countries in

Figure 9 show that as expected, the fatality rate from earthquakes keeps pace with rising populations. The relationship though is quite erratic, dominated as it is by infrequent large earthquakes in each country. For 20th century Iran, however, because of the remarkable incidence of fatal earthquakes, the association between rising populations and increasing numbers of fatalities from earthquakes is clear (Figure 10).

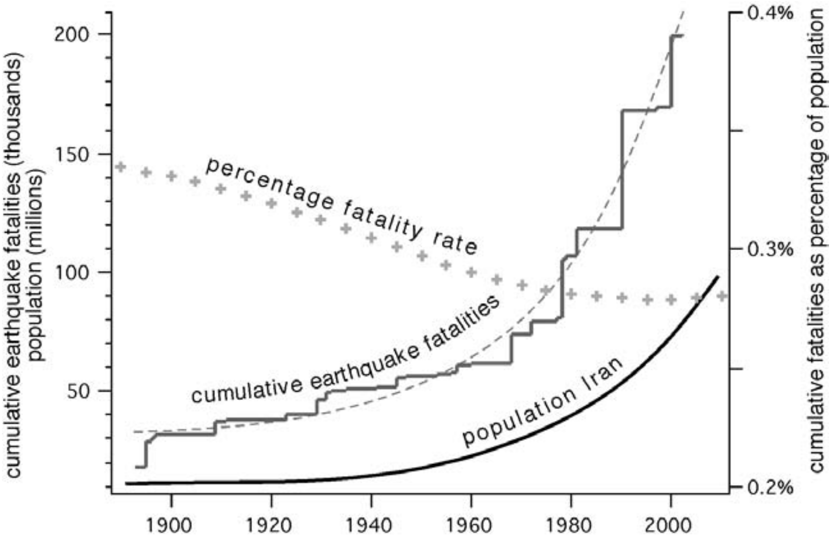


Figure 10 Earthquake fatalities and populations in Iran. A power law is fit to the fatality data, and the population curve is a least squares power-law fit to data from Klein-Goldweijk and Battjes (1997). The percentage fatality rate curve (right hand axis) shows that the ratio of the two curves has changed little in a hundred years despite earthquake awareness in Iran.

The ratio of earthquake-related fatalities in Iran to Iran's growing 20th century population indicates the two growth curves track each other with a scaling factor (0.3±0.05%) that changes little in the hundred years considered. This is grim statistic since it suggests that the introduction of earthquake resistant structures in the past several decades has had little effect in reducing fatalities from earthquakes. The scaling factor is large because it relates the cumulative death-toll to the instantaneous population, not the instantaneous death toll to the instantaneous population. The % fraction of the total population killed by individual earthquakes is, however, significant. For example the fraction of Iran's total population killed in the 2003 Bam earthquake was ≈0.06%.

On a brighter note, many countries are absent from Figure 8. Most of the African nations, the eastern Americas, northern Asia and Australia do not appear on the graph because earthquakes there are infrequent, or occur in sparsely inhabited regions. Antarctica occupies the extreme end of the spectrum of irrelevance – few earthquakes and fewer people. Earthquakes of course do occasionally occur in these mid-continent settings and their study is undertaken with great difficulty due to their rarity and the consequent sparcity of quantitative or descriptive data. Had the multiple New Madrid earthquake sequence of 1811 and 1812, with their many-thousand year recurrence interval, occurred just one or two centuries later, there would have been no speculation about the magnitudes of these earthquakes and their inter-relationships, and a much less hazy notion of an appropriate engineering response (Johnston and Schweig, 1996; Hough and Martin, 2002). In terms of their contribution to future earthquake losses, mid-continent earthquakes are likely to provide exceptional interest because of their uniqueness. Their infrequent historical occurrence in mid-plate settings in the eastern Americas, and Australia (eg a Mw=5.8 earthuqkae June, 2013) means that they have contributed insignificantly to the global death-toll from earthquakes.

Trends in global earthquake fatality rates

The erratic growth of fatalities with time shown in Figure 1 prevents any simple forecast of future fatality rates. Large steps in the cumulative total are caused by occasional catastrophes that occur as a result of a “direct hit”, when an earthquake occurs close to a large, poorly-constructed city. However, if we remove these larger events from consideration we are left with well-behaved curves from which forecasts of the loss of life in these smaller, more frequent catastrophes, can be made (Bilham,1995; 2004). Figure 11 illustrates the residual curves derived from removing statistically large outliers. Two residual curves are shown, for earthquakes that cause fewer than 30,000 deaths, and for a second subset that cause fewer than 5000 deaths.

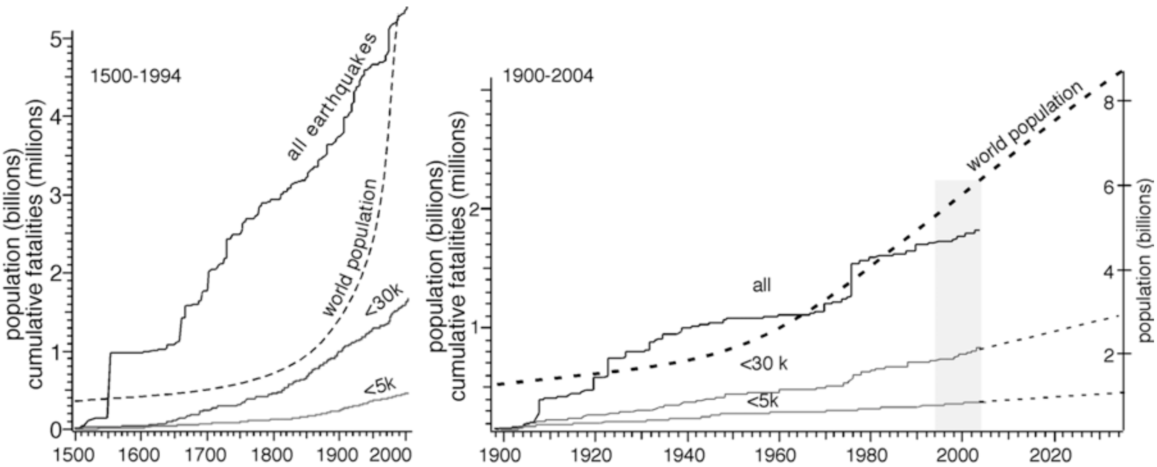


Figure 11 Growth of fatalities with time for all earthquakes, and for subsets of earthquakes in which fatalities are fewer than 30,000, and fewer than 5000 respectively. Forecasts based on these less extreme events made two decades ago (shaded region right) have erred on the low side .

Power law fits made to these two subsets of data (Figure 12 and Table 1) show that predictions based on early data tend to underestimate later fatality rates (Bilham 2004). Thus the global fatality rate for earthquakes with fewer than 5000 deaths per event was forecast from pre-1994 data to be 2355±130/year for the decade 1994-2004, and the observed rate was 2726±50. For earthquakes with ≤30,000 deaths per earthquake the rate was forecast as 7000±1000/year and the actual decadal average was 9548±198/year. These are grim statistics since they appear to be conservative and robust.

If we assume a world in which earthquake resistant construction is not generally implemented we may hazard a guess at future fatalities from earthquakes. The 2000-2009 forecast for all earthquakes was for 17,094 deaths per year (Bilham, 2004). The actual rate, however, was 58,000 year. If we ignore the coastal deaths caused by the 2004 Indian ocean tsunami the fatality rate reduces to 38,000/year, still twice the forecast rate. The rates for less severe earthquakes are over-estimated (Table 2). It is possible that the past decade of earthquakes represents a freak period of fatal earthquakes and that the rate will fall. I show below that this optimism may in fact be unwarranted.

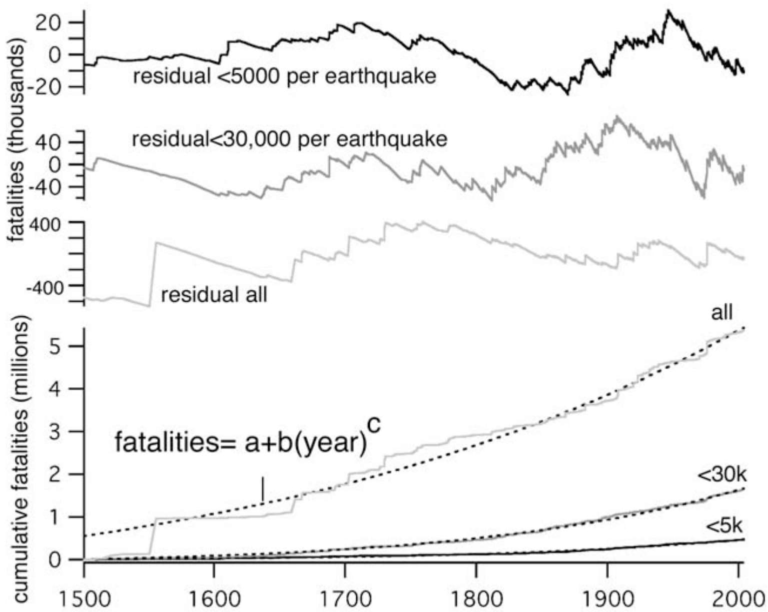


Fig 12 Power law fits (lowest graph) and residuals to earthquake fatality data for the period 1500-1999. The parameters of these fits are listed in Table 2.

Table 1 Decade-interval forecasts (1900-2030) for annual fatality rate (deaths/year) based on power law fits to 5 centuries of data. The constants a, b and c correspond to the power law variables in figure 3.

	1900-99	2000/09	2010/19	2020/29	a	b	C±0.1
all	16703	17094	17492	17897	$-(6.4\pm0.7).10^{5}$	$(1.6\pm1.3).10^{-12}$	5.6
<30k	8609	9015	9439	9881	$-(8.4\pm1.6).10^{3}$	$(2.9\pm1.7).10^{-28}$	10.2
<5k	2702	2849	3004	3166	$-(10.5\pm2).10^{3}$	$(2.2+1.6).10^{33}$	11.6

Table 2 Least-squares linear fits to fatality rates (deaths/year) in successive centuries (± standard deviation).

Time interval	all earthquakes	<30,000deaths/event	< 5,000deaths/event
1500-1599		313 ±31	213 ±8
1600-1699		2225 ±44	578 ±14
1700-1799		2098 ±41	482 ±8
1800-1899		5522 ±33	1324 ±16
1900-1999		6129 ±36	1996 ±6
forecast 95-2005		*6000-8000*	*2020-2690*
observed 94-2004		9548	2726
forecast 2000-9	*17094 per year*	*9015*	*2849*
observed *2000-9*	52,000 per year*	8320	1226

* ≈38000 if 2004 tsunami deaths are ignored.

The above estimates suggest around 20,000-50,000 deaths will occur each year (2-5 million in the next century). Holzer and Savage (2013) repeat the foregoing arguments using the same source materials and forecast that there will be 5-12 fatal earthquakes with greater than 100,000 deaths in the 21st century given current global population trends. Their total numbers of fatalities in the next century are similar.

Fatalities and earthquake magnitude

As a general rule the larger the earthquake the more people are killed by it. In practice the historical relationship is far from simple (Figure 13) especially when it is recalled that population sizes have increased significantly during the past several centuries, and the building fragilities and densities vary widely. Historical precedents permit us to conclude that Mw=8 earthquakes near urban agglomerations can kill upwards of 300,000 people, and none at all when they occur in sparsely inhabited regions. According to Figure 13 the upper limits for Mw=7, Mw=6 and Mw=5 earthquakes are 40,000, 10,000 and 100 respectively. That structures collapse in Mw=5 earthquakes is unexpected but it must be remembered that we live in a world where some structures can collapse without help from an earthquake at all. In 2013 Bangladesh, India, Pakistan and even the US have reported the collapse of buildings in what Ambraseys calls zero-intensity shaking. Maximum fatality counts occur for larger magnitude earthquakes when the footprint of maximum intensity shaking coincides closely with the maximum densities of population in an urban agglomeration.

Far fewer fatalities occur in similar sized earthquakes in the industrial nations than in the developing nations. The Mw=6.9 Loma Prieta earthquake resulted in ≈60 deaths (Eberhardt-Phillips, 1994; Vranes and Pielke, 2006), whereas the Mw=5.7 earthquake in Agadir, Morocco earthquake in 1960 killed more than 10,000. The Landers Mw=7.3 earthquake resulted in 1 death whereas the 2004 Kashmir Mw=7.6 earthquake killed 83,000. The reasons for this remarkable contrast concern the construction methods found in different nations, and the mandatory application of building codes in most industrial nations.

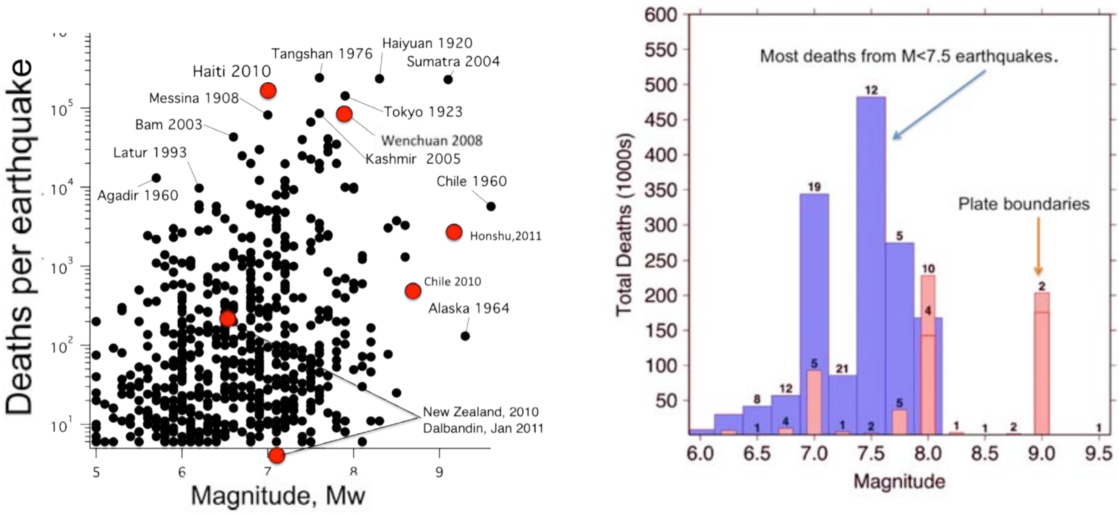


Figure 13 (Left) Earthquake fatalities as a function of earthquake magnitude. Post-2000 large events (red circles) are named. Updated 2013 from Hough and Bilham (2006). (Right) England and Jackson make the important observation that most deaths from earthquakes occur in Mw≤7.5 earthquakes in continental settings far from plate boundaries.

How bad can it get?

The rate of occurrence of earthquakes is essentially steady but the number and size of human settlements has grown. With earthquake fatalities counts of 830,000 in our past when low populations and predominantly rural populations prevailed, what lies ahead in our future urban world? One way to approach this question is to produce computer models of scenario earthquakes, as is currently being undertaken by USGS and WAPMERR (see later section on "fatality tools"), and FEMA using the loss estimation program known as HAZUS. A difficulty with this approach is that we seek information on events that may have no precedent, and "predicted-shaking" methodologies currently require calibration events in order to hone their estimates of fatalities.

Fatality estimates have been published for cities in India south of the Himalaya for Himalayan earthquakes based on scenarios in which ≈150-km-long segments of the Himalaya are proposed to have ruptured (Wyss, 2005), as is believed to have occurred in the past two centuries (Bilham et al, 2001; Bilham and Wallace, 2005). Fatality counts of 150,000 are derived using the 2004 Kashmir earthquake (5 m of slip) as a calibration event. However, prior to these most recent Mw≈8 earthquakes, two or three large earthquakes occurred (Mw≥8.4), only one of which has left its trace in the historical record (Bilham and Szeliga 2008). What would happen if a repeat of one of these Medieval earthquakes occurred? The rupture length could exceed 600 km and the slip could exceed 20 m. This would tend to bring the total fatality count to ≥600,000 based on rupture area, a number that might easily increase by 50% based on the increased slip in the earthquake.

An alternative method to evaluate the potential fatality count of a future earthquake is to examine the fractal attributes of our existing data. This was first attempted by Nishenko and Barton (1996) who found that disasters of all kinds appeared to obey fractal distributions. The number of earthquakes that cause a given number of fatalities shows a curved relationship in the past five centuries (Bilham, 2004). The curve may be interpreted in two ways: that an extreme event results in a million fatalities every 500 years with an average population of approximately 2 billion people, or that with our present global population of 10 billion people, an earthquake could result in a million fatalities every century. Century-long data from the world, or from individual nations show similar curves, but with lower intercepts (Figure 14).

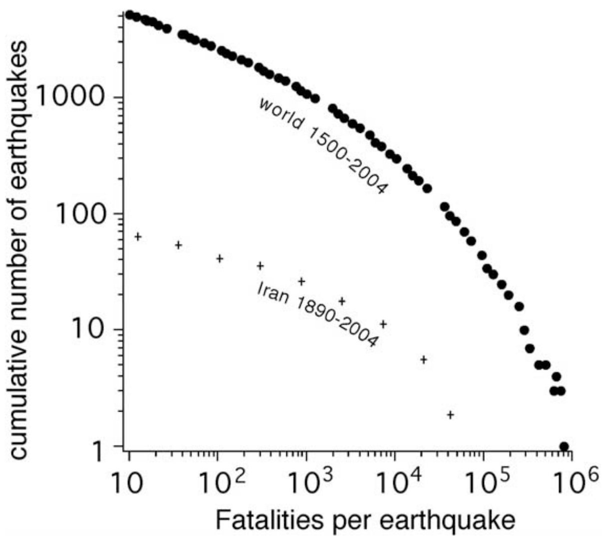


Figure 14 A fractal curve for earthquake fatalities in the past 500 years shows a curve that cuts the y=1 axis at approximately 1 million (from Bilham, 2004). The data from Iran (from Figure 6) are shown on the same plot to illustrate that the fractal curve for different nations has similar curvature but a lower intercept than the global curve.

Although we might conclude from the curve in Figure 14 that once in 500 years an earthquake with a million fatalities is likely, the average population at risk for most of these 500 years was 0.5 to 0.1 of the present population, and urban agglomerations in the largest cites were typically smaller than in our present-day smallest cities. With a present-day total population exceeding 6 billion, and with two dozen cities hosting populations exceeding 8 million we may reasonably anticipate an earthquake that could kill more than a million people every 100 years or so. Although such an event has not occurred in the past, never before have there been urban agglomerations of sufficient size to permit such a disaster. A case study of the likely damage to one megacity confirms these general conclusions. Netaghi (2001) calculates that in Teheran (2001 population 10 million) more than 1.4 million deaths and 4.3 million casualties may accompany a Ms>7 earthquake.

Strain rates, Supercities and Earthquakes

From geodetic observations of plate velocities, fault slip rates and the rate of seismic moment release it is possible to calculate mean strain rates near and across plate boundaries (Haines and Holt, 1993, Haines et al 1998; Beavan and Haines (2001); Kreemer et al, 2000; 2003). Strain rates (see Figures 15,17 and 18) provide a simple measure of earthquake productivity because most rocks fail at epicentral strain levels close to 10^{-4}. Although this empirical rule-of-thumb is based on the mean geodetic strain released by an earthquake (Rikitake, 1976), it lies at the heart of most earthquake scaling laws; e.g. maximum co-seismic slip of a fault 10 km long is typically 1 m (c.f. Wells and Coppersmith, 1998; Scholz, 2001), equivalent to a shear strain of 10^{-4}. The rule is an approximation, and earthquakes release lower or greater amounts of slip depending on the frictional conditions in the rupture zone and the stresses released at the time of failure. However, the approximation is of utility because it provides a rough guide to the recurrence interval between successive earthquakes. A strain rate of 10^{-6}/year is able to renew the strain released by an earthquake in 100 years.

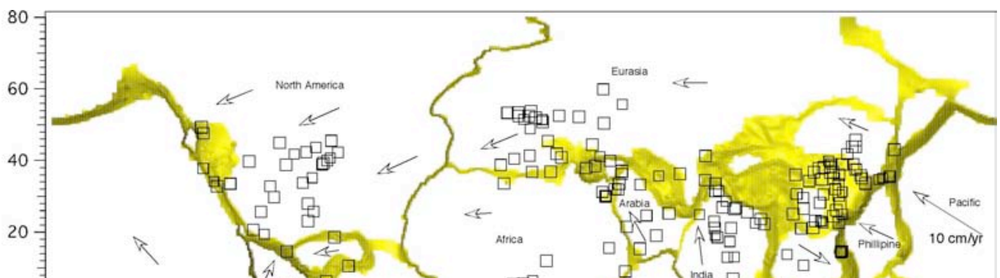


Figure 15 The location of 194 supercities (each with a 2005 population exceeding 2 million) and their proximity to zones of high plate boundary strain rate (shaded from Kreemer et al.

2002 ; see also Figure 16). The total population in these cities and urban agglomerations is 1.2 billion. Velocities of the plates are shown in a hot-spot fixed frame (Gripp and Gordon, 1990). The arrow showing the motion of the eastern Pacific provides a velocity scale. The plates are named but the continents are not shown.

The areas shaded in brown on Figure 15 are those where strain rates average $\approx 10^{-6}$/ year and in which the recurrence intervals of large earthquakes are of the order of 100-200 years. These regions of most rapid deformation occur at the world's plate boundaries. Spreading centres are rare on land (Iceland, Afar, northern Gulf of Mexico) and earthquakes there are associated with normal faulting through relatively thin elastic crust and hence typically do not exceed Mw=6. The thickened crust, where transform faults link these spreading centres host larger earthquakes with Mw≤7.5. The very largest earthquakes occur at the world's subduction zones. Here the Earth's crust is thick and the ruptures that permit the plates to converge involve areas that may exceed 1000 km along the plate boundary and more than 150 km down-dip. The 2004 Sumatra-Andaman Mw=9.1 earthquake ruptured a 1600 km x150 km segment of the eastern plate boundary of India.

Typically the world's plate boundaries are relatively narrow (<100 km) but in some plates zones of diffuse deformation have been identified. The Indian/Australian plate, for example, is deforming in the Indian ocean causing buckling of the plate and distributed seismicity (DeMets et al., 2005). The fragmentation of the African plate along the east African rift, is typically associated with moderate and somewhat sparse seismicity (Mw<6.5), but large (M>7.5) normal-faulting earthquakes also occur (Jackson and Blenkinsop, 1993). The frequency of damaging earthquakes in regions of distributed deformation, however, is much lower than at plate boundaries because strain rates are low, and the time taken to renew the epicentral region to failure is long. Regions of the earth where strain rates are of the order of 10^{-6}/year can be expected to produce Mw≈7 earthquakes once a century. Regions where the strain rate is 10^{-7}/year will not regenerate sufficient strain to generate a similar earthquake in less than a millennium. This does not mean that an intraplate setting near a recent damaging earthquake will not repeatedly experience damaging earthquakes in a period of several decades. If the rupture areas of historical earthquakes are small, for example as in the Bhuj region of India, where the rupture area of the 2001 earthquake was less than 20 km along-strike, contiguous regions may repeatedly shake nearby towns in a time period much shorter than the renewal time.

At a global level the distribution of the world's largest cities, supercities and megacities, shows an unexpected preference for plate boundary settings where strain rates are high. More than 55% of supercities are located within 200 km of a plate boundary. A *supercity* is defined by the UN population statistics division as a city with a population exceeding 2 million. Almost two dozen of these cities now host populations exceeding 8 million, the UN qualifier for *megacity* status. These definitions were invoked when populations exceeding 8 million were exceptional. They are now somewhat dated given the existence of cities with populations exceeding 20 million. Figure 15 shows the present disposition of supercities relative to plate boundaries. When this global view of cities and seismic belts was depicted two decades ago (Bilham, 1988) UN forecasts suggested that 40 supercities with a total population 290 million were located in seismically vulnerable locations. Of these, 80% (232 million people) were forecast to live in the developing nations. In 2005 seventy-nine supercities can be identified in seismically vulnerable settings with a total population of 472 million. 68% of these populations are found in the developing nations, 81% of which are found the southern edge of the Eurasian plate. The total number of supercity-dwellers at risk in the cities of the developing nations is 272 million. Thus the 1988 forecast based on UN growth statistics underestimated the 2005 number by 17%.

Why do cities favor seismically vulnerable locations? Cities often owe their origins to sites that are easily defended (Hurd, 1903, Brunn et al., 2003; Clark, 2003). Many cities thus once started on elevated regions of coastlines or inland hills. The growth of cities, however, could not occur without advantageous supply routes and abundant water. Many of the world's supercities are ports at the edge of continents, or on large rivers. Not all continental shorelines are plate boundaries, but a significant number are, notably the circumPacific belt, the islands of the Caribbean, and some of the shorelines of the Mediterranean. Exceptions are the passive margins of the eastern Americas, northern Eurasia and West Africa, that are not plate boundaries. Another subset of supercities are located near the foothills of mountain ranges that have been formed by localized or distributed plate convergence. A mountain range brings with it the combined attraction of a trade route through the mountains and typically a supply of fresh water (Hurd, 1903; Jackson, 2006). Again, not all mountain ranges are active plate boundaries, but many of them are: the Alps, the Andes, the Himalaya, and the Elburz to name the most prominent. Exceptions are the eastern edge of the Rocky Mountains and the Urals.

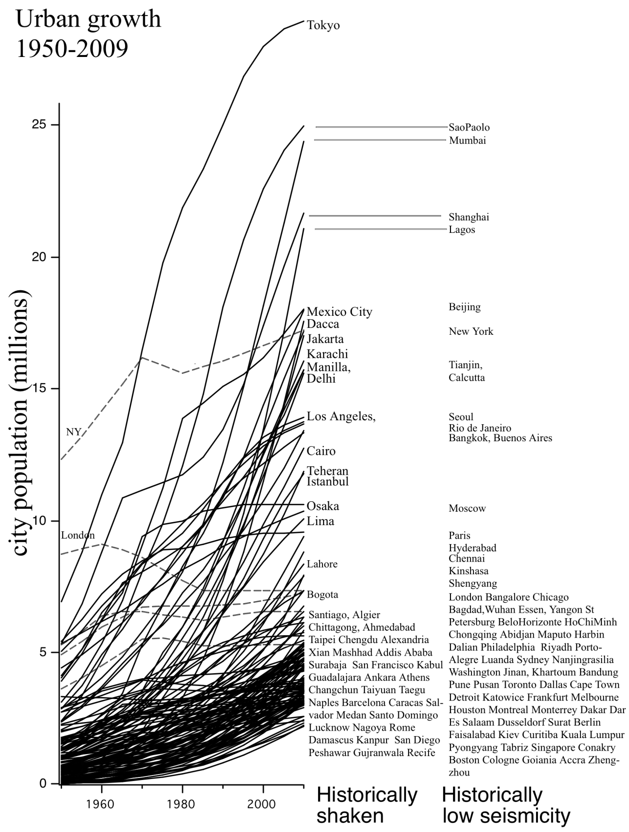


Figure 16 The growth of the worlds largest cities 1950-2009. The cities are separated into two columns identified by whether or not historically damaging earthquakes have occurred nearby (revised from Hough and Bilham, 2006). Data from the UN Population division. 65% of all supercities (total population 403 million) are currently exposed to seismic shaking. Dashed lines illustrate the substantially slower rates of growth, and occasional decline in populations, in cities in the developed nations.

Once established, the destiny of all settlements is to grow in size. As they grow they become part of a hierarchy of cities with a rank-ordering by population size that is established in ancient times and which is retained in subsequent centuries (Gabaix & Ioannides, 2003). Hamlets and villages lie at the base of this hierarchical structure, subordinate to towns and a larger dominant city. Although the populations within the components of this city hierarchy all grow (the villages become townships, the towns become cities, and the cities become supercities), the overall ranking shows a remarkable resilience to change. Roman France has much the same city-ranking as Medieval France, which persists to the present day (Pumain, 1981).

There are few matters of greater concern than identifying those cities that are vulnerable to future earthquakes. Figure 16 illustrates the growth of supercities and divides them into two categories – those that have a known history of earthquakes and those where earthquakes in their past are sparse or non-existent. The cities so identified include some that are clearly vulnerable, and others whose vulnerability may be subject to dispute. Many cities have a tradition of earthquake damage and are unquestionably on the "hit-list": Tokyo, San Francisco, Catania, Lisbon come easily to mind. The presence of others on the "hit list" may be questioned because of their uncertain distance from a potential future epicentre. For example, Chengdu was identified as a potentially vulnerable supercity in 1988 and again in 2003 (Bilham, 1988; Hough and Bilham, 2003) although the city itself has no established history of catastrophic earthquakes. On 12 May 2008, however, it was shaken by the Mw=7.9 Wenchuan earthquake whose epicentre was 80 km to the NW. Of the ≈70,000 killed in the earthquake 4,276 lived in Chengdu.

The disastrous southern edge of the Eurasian plate

We now returning to the distribution of cities between the Mediterranean and Myanmar, China and Indonesia, a zone of seismicity that broadens eastward as it follows the southern edge of the Eurasian plate, and is responsible for 85% of the world's historical earthquake fatalities. Strain rates here are caused by the approach of the African, Arabian and Indian plates from the south towards EuroAisia at rates from less than 1 mm/yr to rates exceeding 6 cm/year. The Arabian and Indian plates both rotate counter-clockwise slowly relative to Asia causing the velocity of convergence to increase eastwards (Figure 17). Recall that a relative velocity of 1 mm/yr applied to 100 km/wide zone (a strain rate of 10^{-8}/year) does not mean that an earthquake cannot occur, but merely that the interval between the repeated rupture of faults in earthquakes in such regions is 50 times longer than in regions where the convergence rate is 5 cm/yr. For example, the high fatality earthquakes near Chengdu (2008) and near Bhuj (2001) both occurred in regions where convergence rates are slow (≈1 mm/yr).

A striking feature of the continental collision process (Figure 17) is the extrusion of the Aegean and Turkey to the west (McKenzie, 1978), and the corresponding extrusion of eastern Tibet and Myanmar to the east (England and Molnar, 1990). These two extrusion processes are almost equidistant from a promontory of the Asian plate that extends southward through Afghanistan and Baluchistan towards the Makran coast. A Mw=8.1 earthquake occurred at the southern tip of this promontory in 1945 (Byrne et al, 1998; Bilham et al, 2008). In the west the net result of this extrusion has been to establish substantial rates of convergence between the Aegean and Africa near Crete. In AD365 this convergence was manifest in a M≈8 earthquake that raised the western coast of Crete, and the surrounding sea floor, generating a Mediterranean-wide tsunami with huge loss of life in coastal cities (Shaw et al., 2008, Bilham, 2008). Strain rates are high along the Anatolian fault and the Dead Sea rift, and these high rates have been responsible for documented destruction of cities in Turkey, Syria, Cypress, Greece and Israel since biblical times (Guidoboni et al., 1994; Ambraseys et al., 2002). Correspondingly high rates occur in the east in Myanmar but the written historical record of earthquakes here is surprisingly brief (≈300 years).

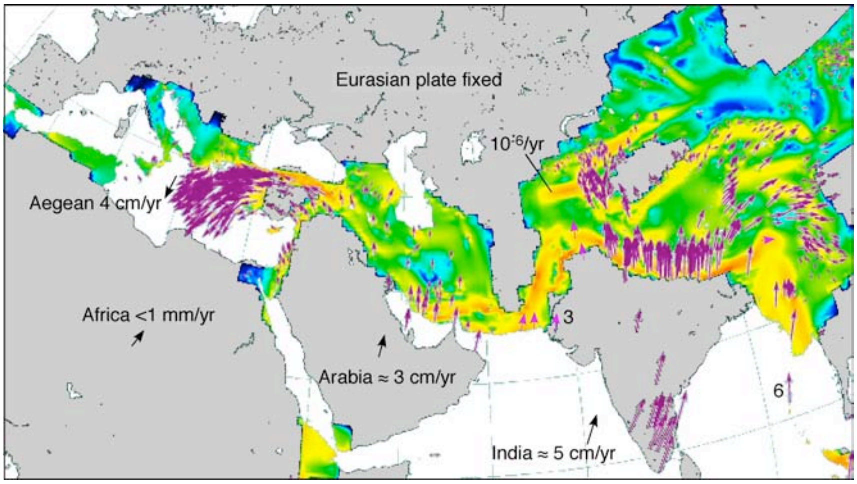


Figure 17. Plate velocities relative to Asia show a slow northward motion of Africa, and the substantially faster approach of the Arabian and Indian plates http://jules.unavco.org/VoyagerJr/Earth . As a result of the collision, Turkey and the Aegean are rotating counter-clockwise and extruding to the SW, and eastern Tibet and Myanmar is rotating clockwise and extruding to the SE. Strain rates: blue/green<10^{-6}/yr, yellow=10^{-6}/yr, and red>10^{-6}/yr (from Kreemer et al., 2000, 2003). Violet arrows indicate GPS observations of plate motion, black arrows show generalized velocities.

Where strain rates are high, and where a two thousand or more year record of earthquakes exists, and where city populations have been persistently large, as in Italy or the eastern Mediterranean, we find both a larger number of fatal earthquakes, and larger fatality events. Conversely, in regions where the historical record is short (India and Burma), relatively few fatal earthquakes have occurred in the historical record. This is very much a simplification of the various factors that influence our record of the fatality rate. For example, no account is made for building fragility, and its change through time.

The cumulative loss of life from earthquakes varies significantly with longitude, with peak fatalities in the Middle East and China. The minimum at 60-65° is clearly related to the low population-density along the Makran coast, and the low rates of strain in central Afghanistan. The low cumulative fatality count in India contrasts markedly with the seismic potential of the Himalaya and subcontinent, and with the existence of large current populations. This is partly attributable to the somewhat short historical record, partly to the prevalence, until recently, of thatch and wattle-and-daub type structures, and partly due to the spatial changes in distribution of dense populations. Given the recent tenfold increase in population and the current prevalence of poorly-assembled concrete-frame structures in many of these countries, it is possible that future earthquakes in India will result in significant loss of life.

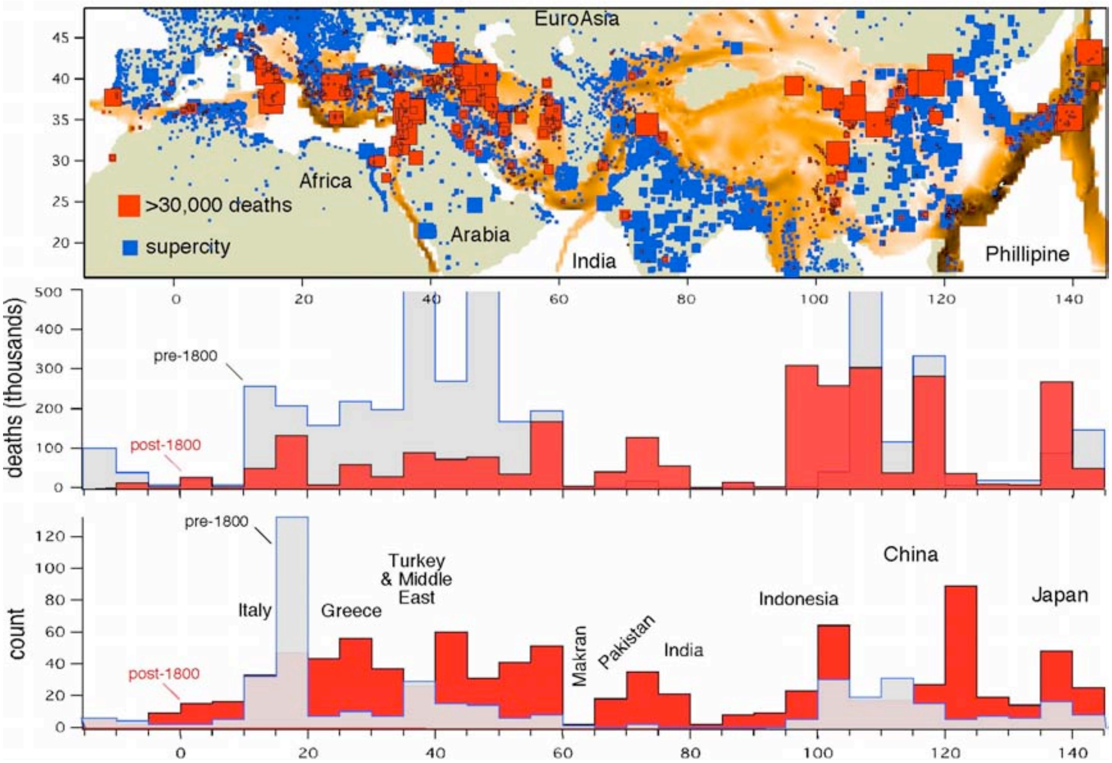


Fig 18. Present day cities and supercities (blue) compared to earthquake fatalities in the past millennium (red), showing plates and strain rates (light- to dark-brown shading). The centre plot shows the cumulative death-toll from these earthquakes in 5° longitude bins (truncated ≥500k). The lowest panel shows the number of fatal earthquakes in these 5° bins. Pre-1800 (grey) and post-1800 (red) earthquakes are summed separately to highlight incompleteness in the data in some areas, and fluctuations in earthquake productivity in others.

A quarter of the world's population now live in Iran, India, Pakistan, Nepal, Bhutan and Bangladesh, five nations surrounded by active plate boundaries. Several studies have shown that recent earthquakes in the Himalaya have not kept pace with plate motions, and that one or more seismic gaps appear to be sufficiently mature for rupture. Fig. 19 shows depicts the recent increase in fatalities east of Afghanistan compared to the past 1000 years of earthquake fatalities in the region.

A thought experiment is of value at this point. Suppose, instead of the recent arrivals of supercities depicted in Figures 15 & 18, that we were viewing a map of uniform distributed cities spaced evenly at, say, 50 km intervals for three millennia. The earthquakes that occurred near these cities in the past 3000 years would have resulted in far more fatalities than we observe. How would the present-day fatality map appear? The answer is clear. There would be many more large red squares (>30,000 fatalities) representing direct hits of supercities by earthquakes. The red squares in Figure 18 would form a continuous carpet from Europe to Sumatra.

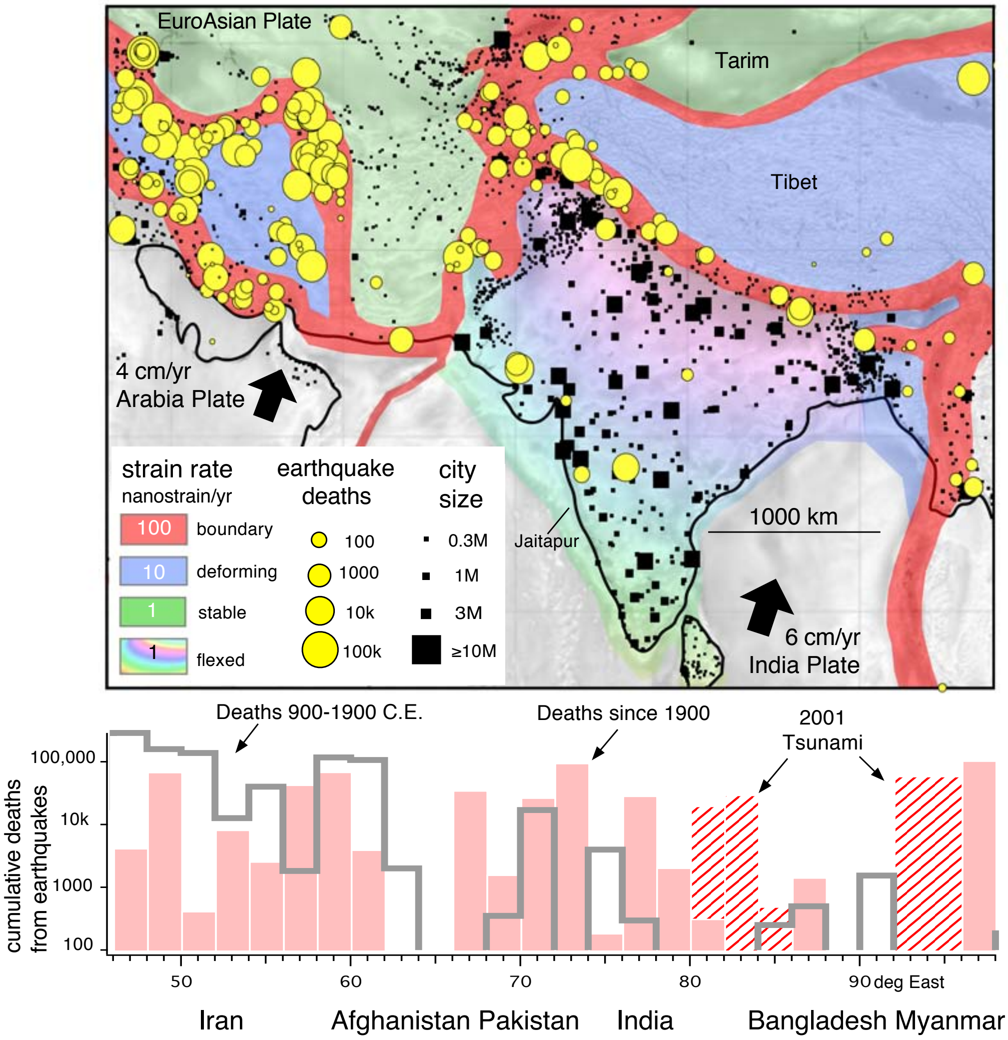


Figure 19 A comparison of the spatial change in earthquake fatalities in Iran with those east of Afghanistan before and after 1900 (Bilham and Gaur, 2013) Yellow circles are deaths in individual earthquakes, black squares are cities, and the shaded areas depict zones of comparable internal strain quantified in nanostrain per year. Earthquakes occur when the local strain approaches failure conditions of 10-100 microstrain.

An appalling conclusion from this line of reasoning is that if we allow supercities to continue to grow from former villages and do nothing to make them less vulnerable to earthquake shaking we shall eventually attain the results of our thought experiment – a continuous 12,000-km-long swath of death and destruction. One may protest that strain rates are too low in places to fill in the blanks with earthquakes, or that some parts of the southern edge of Eurasia will never fill in with supercities. The low-strain-rate argument can be dispelled by prolonging the thought experiment to say 10,000 years or 50,000 years. The present, and possibly future, absence of supercities in parts of the Eurasian belt is one that doesn't alter the main conclusions of this thought-experiment. Nor does a low strain rate, as mentioned earlier, prevent an earthquake occurring. If an earthquake's recurrence interval is 10,000 years and it last occurred 10,000 years ago, its epicentral process zone has attained maturity, and rupture must be considered imminent. We simply do not know how many areas like New Madrid, Bhuj or Chengdu exist on Earth.

The conclusion is obvious - that earthquake resistant construction is essential. Earthquake risk studies that are designed to refine our knowledge of the probability of future shaking severity of specific structures or parts of individual cities, are merely footnotes in the general scheme of earthquake fatalities on earth.

The cost of earthquakes

Earthquakes pose a difficulty for the insurance industry because they are infrequent and result in a huge variation in losses. The median loss is low but extreme events can expose the insurance companies to large losses (Scawthorn et al., 2003).

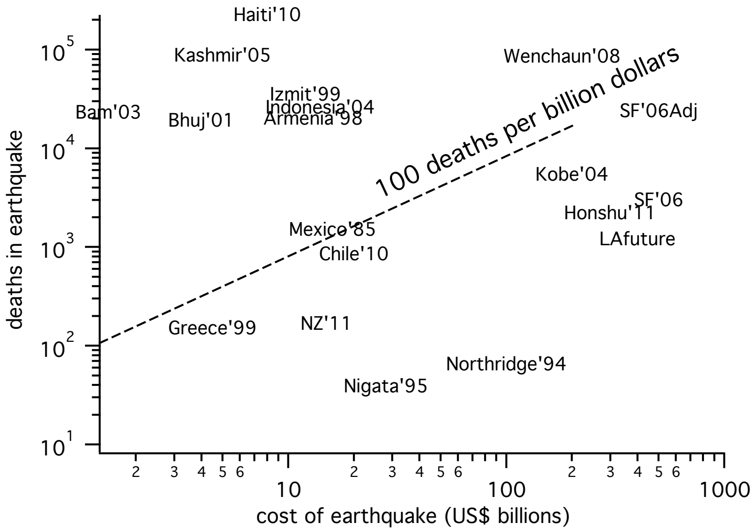


Figure 20 Earthquake fatalities vs. repair costs to 2005 US$ (Vranes and Pielke, 2009). supplemented by recent earthquakes to 2013 The high pseudo-death-toll for the 1906 San Francisco earthquake plotted here is extrapolated for present-day population and vulnerability. The LA future event is based on estimated $ losses from a hypothetical M7.8 earthquake near Los Angeles (http://pubs.usgs.gov/of/2008/1150/). Tsunami-related deaths from the Sumatra 2004 earthquake are omitted.

To compare earthquakes at different times, in the presence of inflation and changing demographics it is necessary to normalize both populations and values to a common number. Vranes and Pielke (2009) normalized the costs of 20th century earthquakes to 2005-US dollars, and fatality counts to current populations (adjusted for city vulnerabilities). After these adjustments they find that the San Francisco earthquake and fire of 1906 was the most costly earthquake in US history weighing in at $284 billion, followed by the Northridge earthquake of 1994 at $87 billion, followed by the 1964 Alaska earthquake at $16 billion, and a handful in the range 7-15$ billion (Long Beach 1933, Loma Prieta 1989 and San Fernando 1971). Their estimates are updated in Figure 20.

The total twentieth century US earthquake loss in 2005 dollars exceeded $448 billion, with a cumulative adjusted death toll of 25,000. A future M=7.8 earthquake in the Los Angeles region (the LA scenario event) were it to occur today was estimated recently to probably result in a death toll of 1800, accompanied by $200 billion in damages. This is comparable to the cost of 1995 Kobe earthquake in Japan ($63-$173 billion in reconstruction) that was accompanied by 5000 fatalities.

These calculations divide the rich from the poor. Earthquakes in the developed nations are expensive but are accompanied by low fatality counts. In contrast, earthquakes in the developing nations cause immense loss of life and cost relatively little. The Kashmir 2005 earthquake, for example, resulted in more than 80,000 deaths and a $4 billion reconstruction cost. The Indonesia/Andaman earthquake with its 290,000 death toll was associated with a $12 billion recovery cost. Much of these costs were covered by international aid. The 2011 Tohoku earthquake is the most expensive thus far with an estimated cost of $150-$308 billion (think $20-$40 for every single person on Earth).

The trends depicted in Figure 20 can be reduced to single numbers by taking the ratio of the fatality count to the cost in dollars. A vulnerability ratio can be defined as the number of fatalities x 10^6 divided by the $ damage cost (Vranes, personal communication, 2009). The vulnerability ratio (units are inverse dollars) for developed nations lies in the range 0.01/$-0.03/$, while for the developing nations the ratio is *three orders of magnitude* worse - in the range 2/$-27/$.

Corruption, Ignorance and Poverty

Of the several factors responsible for the rising death-toll from earthquakes we can identify three within society that prevent the lessons of earthquake engineering from being universally applied: *corruptio*n in the building industry, an absence of earthquake *education*, and the prevalence of *poverty* in earthquake zones. The contrubutions of these three societal phenomena to the building insdustry are defined below. They often act together such that their effects cannot easily be separated one from another, but it is not generally appreciated that these three societal flaws can negate the entire process of earthquake risk estimation and earthquake engineering.

1. Corruption in the building industry can lead to the issuance of illegal permits or unauthorized inspection certificates at all levels of the construction process. The building industry is one of the largest sectors of the global economy and is particularly alluring to ruthless individuals interested in maximizing profits at the expense of cutting corners in construction guidelines. The concept of "*cover-up*" is particularly appropriate in the building industry since it is possible to conceal unethical construction at every stage in assembly: inappropriate foundations can be hidden beneath walls, shoddily assembled steel work can be hidden beneath concrete, poorly mixed concrete can be hidden behind paint. The cost of correctly engineered construction means that large profits can be made by contractors willing to risk the use of substandard assembly methods, or weak materials. For specific examples of the processes of corruption the reader is referred to articles by Green (2005), Stansbury (2005), DelMonte and Papagni (2007), Bilham (2009) and Transparency International (2010).

2. Poverty is both responsible for people constructing buildings from inexpensive materials (adobe, weak concrete, or brittle steel), and for people renting accommodation in buildings assembled by corrupt contractors who have deliberately used inferior construction methods to maximize profits. The world's poor will often build in places that are considered undesirable by earthquake engineers- steep slopes, regions prone to liquefaction etc.

3. The absence of *education* about earthquake risks in a country can be responsible for home occupants not knowing that earthquake resistance should be considered in their choice of dwelling, but it is ultimately responsible for weaknesses at several levels of society. Children are not told how to mix concrete in school, these

same children as adults may remain ignorant of the earthquake history of their country because this is rarely taught in school curricula, the future leaders of society remain ignorant of earthquake risks and fail to impose laws on earthquake construction methods, contractors are unable to evaluate the consequences of cutting corners in construction methods.

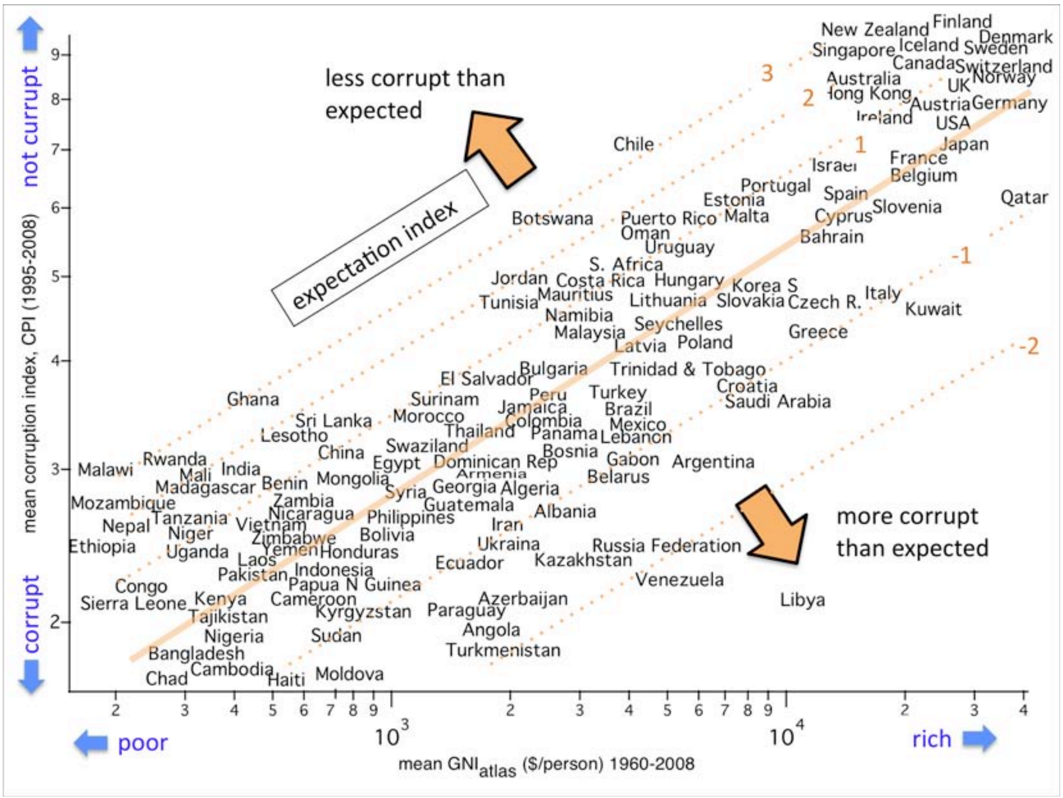


Fig 21 Corruption and per capita income in a country are closely linked (From Ambraseys and Bilham, 2011), yet those countries below the regression line are more corrupt than they should be given their per capita income. We characterize the departure of each country from this mean expectation as an expectation index. A Corruption Index of 10 means that no corruption is perceived in that country. An expectation index of +3 signifies (e.g. Chile and Botswana) that it is three corruption units less corrupt than that expected from its per capita income.

Another way of looking at the corruption and earthquakes is to plot these two measures as a function of geographic location (Figs 22 & 23). These plots show the remarkabe decrease in CPI eastwards from Europe to South Asia (Fig. 22) but show no simple numerical relation between seismogenic areas and deaths from earthquakes (Fig 23).

Because levels of education are tied to poverty, and poverty is closely correlated correlated with perceptions of corruption, it is not possible to be certain how these three factors impact on earthquake resistance. However we note that in Figure 21 some countries lie above the regression line, and can thus be considered less corrupt that they should be given the apparent regression coefficient.

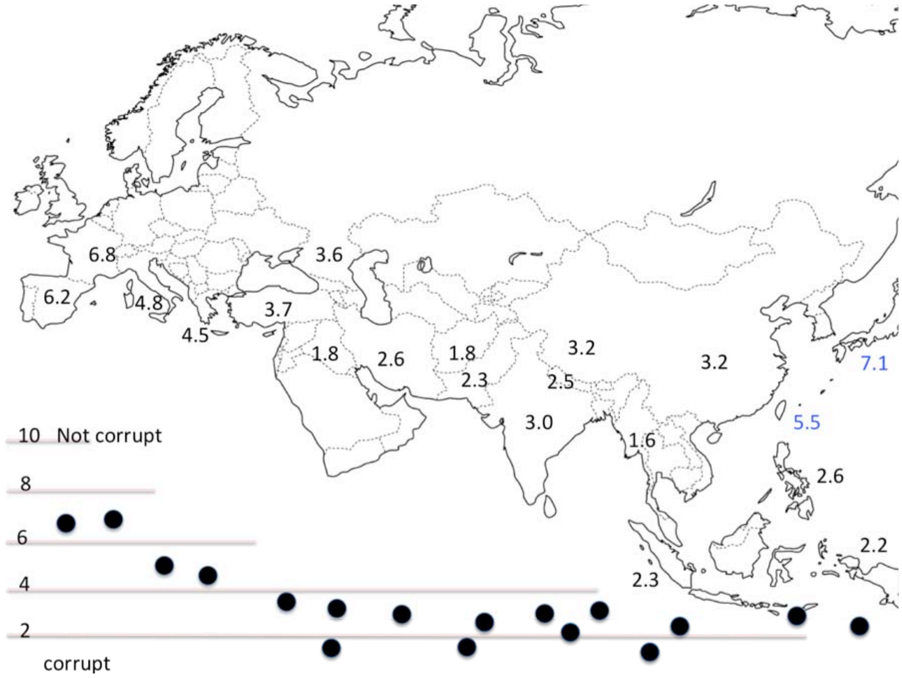


Figure 22 The last decade of the Perceived Corruption Index (plotted as the left ordinate in this graph) declines eastward along the Alpine Himalayan collision zone. 10 is not corrupt (transparent with no bribes) and 1 is very corrupt (opaque with widespread covert bribery).

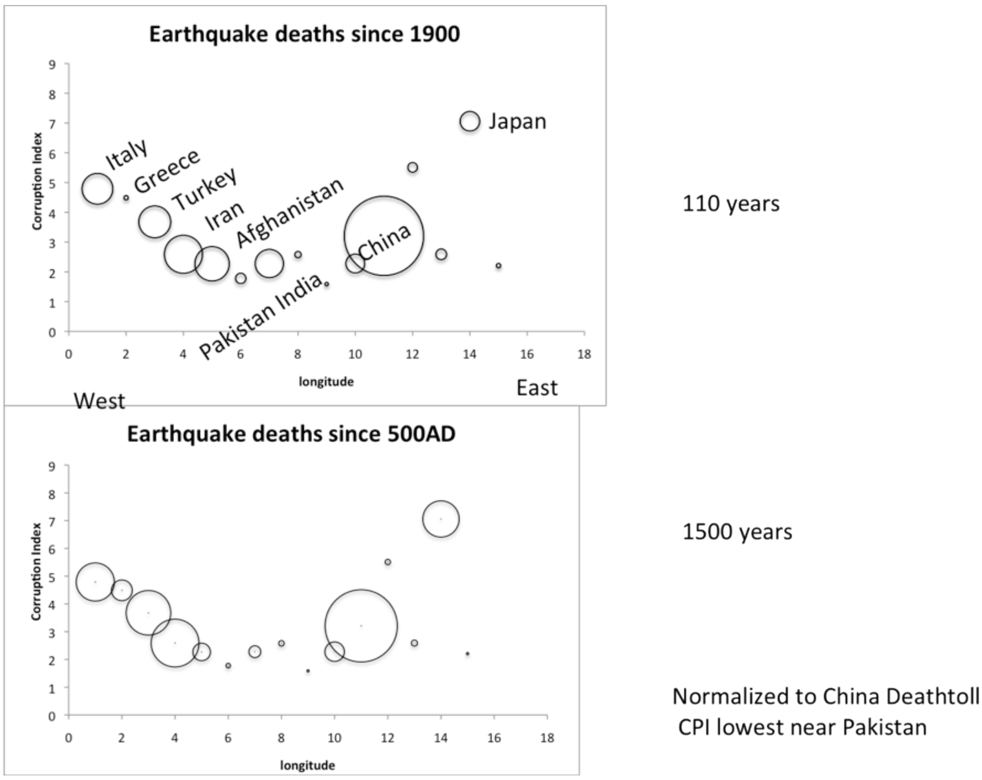


Figure 23 The Perceived Corruption Index (CPI) and the number of earthquake deaths normalized to the Chinese deathtoll in two time windows 110 years (top) and 500 years (bottom). There is no simple relationship between CPI and deathtoll.

We term a country's position above or below the regression line of Figure 21 an *expectation index*. Thus an expectation index of +3 signifies (e.g. Chile and Botswana) that it is three corruption units less corrupt than expected from its per capita income. When this corruption index is used to plot earthquake fatalities (Figure 24) we note that 90% of all deaths from earthquakes in the past 30 years have occurred in poor countries (per capita income less than \$3k/yr) with a lower than expected (negative) CPI (Ambraseys and Bilham, 2011).

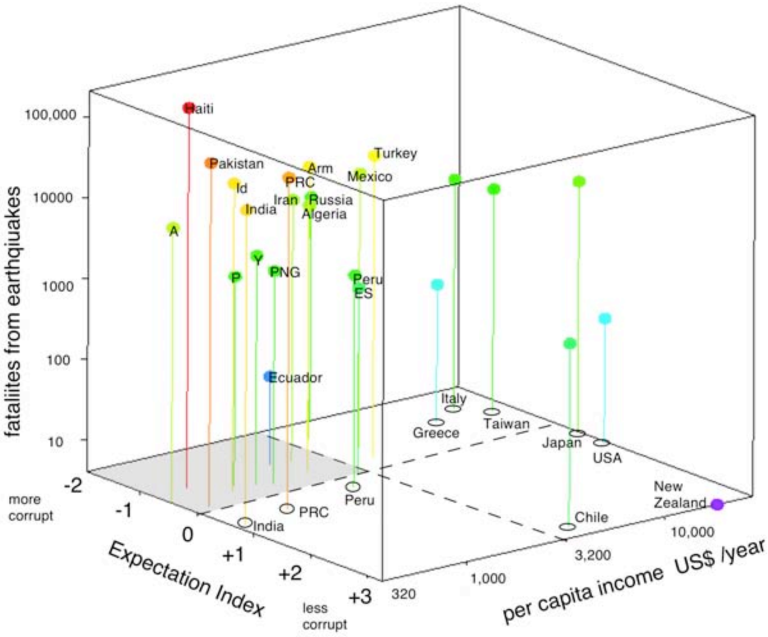


Figure 24 Ninety per cent of all deaths from earthquakes occur in low income countries (<\$3200/yr) and/or where corruption is worse than expected from per capita incomes (grey area on left hand side of the plot) A=Afghanistan, Y=Yemen, P=Philippines, PNG=Papua New Guinea, ES =ElSalvador, Id=Indonesia, Arm=Armenia. (after Ambraseys and Bilham, 2011).

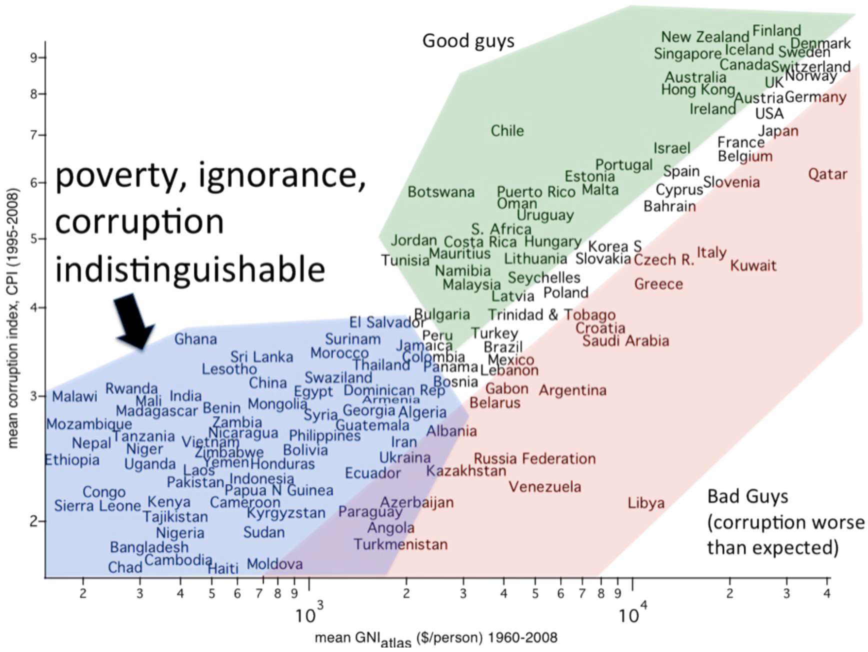


Figure 25 Figure 24 attempts to tease the effects of poverty and education from the direct effects of corruption, but this is not completey satisfactory, and no simple test of the result has been satisfactorily considered. The graph is divided into shaded regions that indicate subjectively in the lower left, a region where poverty, ignorance and corruption are considered indistinguishable.

A bias in the application of earthquake resistance

Thus far we have reviewed the procedures and pitfalls that we as scientists have undertaken to characterise earthquake hazards, which are in turn used to estimate earthquake risks. We then reviewed three factors that are sociological or pathological aspects of society that in a very real way act in a reverse direction. These pathological conditions overtly or covertly act to obstruct earthquake risk being implemented.

But there is an inbuilt flaw in the way that we have structured our efforts at mitigating earthquake risks, which is very easy to overlook. This flaw amounts to a disconnect between earthquake engineering community and society. The ideas developed in this section are summarized schematically in Figure 26. Put simply, there exist few outlets for the application of the results of most state-funded earthquake research findings, to the most in need of protection from earthquake shaking - the worlds poor.

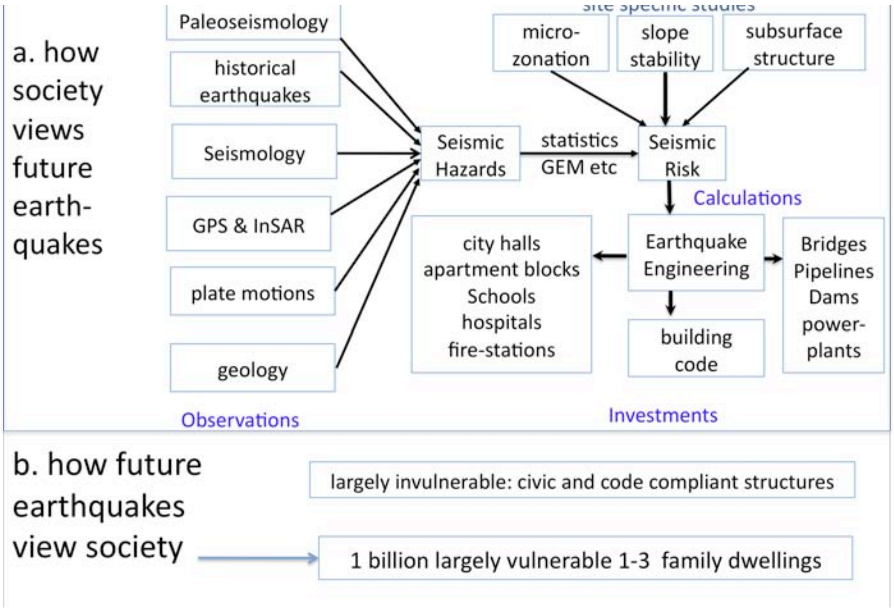


Figure 26. A comparison between (a) Mitigation strategies - the box encapsulates the cerebral response of the earthquake community to understanding and mitigating the effects of earthquakes (b) Disaster scenarios - how earthquakes view society. Mitigation efforts successfully protect community investments, but disastrous earthquakes in the past few years suggest that large death tolls are attributable to weak vulnerable structures inhabited by the world's poor.

The activities of seismologists and earthquake engineers are typically aimed at characterizing earthquake risk in a communicable form that permits a building to be sufficiently strong to resist damage in a future probable earthquake. Funding agencies (banks and governments) wish to optimize their investment in structures. The more precisely maximum expected accelerations for a given structure can be forecast, the more economically can a structure be constructed given a specified safety margin. The structure could be a bank, a hospital, a bridge or a dam. In each case knowledge of local seismic hazards are converted into potential future accelerations, or frequencies, or durations of shaking anticipated in the lifetime of a building. The engineer uses these data to strengthen the structure accordingly. The insurance industry wants to know how much their insured buildings are exposed to risk.

Engineered structures are usually state-owned, or bank investments, or city infrastructure, all structures that might be termed civic investments, and for very good reasons these structures must be well built for many of them are expected to function during and after an earthquake. The few such structures that do collapse in earthquakes are the exception rather than the rule. A review of recent earthquakes shows some remarkable successes. For example, the almost complete absence of damage to engineered structures in Tokyo during the 2011 Tohoku Mw=9 earthquake was a success that was overshadowed by the disastrous tsunami and its effects on coastal commuities. However, the Haiti 2009 earthquake tells a different story, as do earthquakes in Iran, Pakistan, India and other non-industrial countries. Earthquakes in these countries have resulted in huge loss of life because elementary information concerning construction and assembly of buildings is simply unavailable to most of the population.

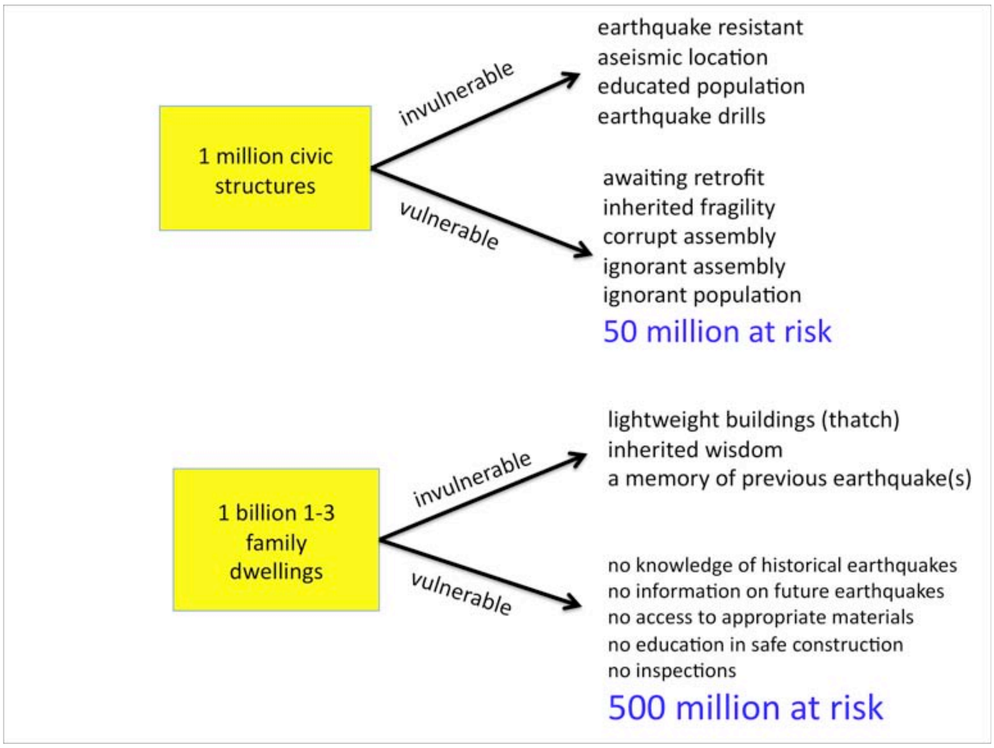


Figure 27 The influence of earthquake engineering on building safety is effective only where earthquake resistant codes are applied throughout society. In a few societal settings earthquake resistant engineering sometimes prevails despite the absence of codes and their enforcement. It is estimated that ten times more people worldwide live outside the protection of code enforcement, than within its safety net.

The most important outcome from societal investments in earthquake science and engineering is the design of earthquake codes. Where codes are enforced without adulteration, the successes of earthquake engineering trickle down to the dwelling unit level, protecting families and infrastructure. In contrast, although engineering codes may exist in the developing nations, mechanisms to implement these codes are largely unavailable. Deaths from earthquakes in the developing nations occur largely due to the collapse of owner-occupied structures or low-rent apartments, or because they have been constructed on unstable ground, or in the paths of tsunami or landslides. Earthquake engineers have not been consulted in their design or placement. In many cases the structures have been assembled without any kind of oversight. This is not caused by corrupt practices, and although it can be attributed to ignorance by the owner or renter, it is more generally attributable to indifference by local building regulators. It occurs because construction has usually evolved, rather than followed a blueprint. Banks may not have been involved in financing the dwelling. The dwelling may not be insured. The local building authority may not have been asked to inspect it during its assembly. The building may have been constructed before earthquake resistant codes were enforced. The building may have been built illegally without permission, and without laws to enforce its removal.

The apparent bias by the earthquake community that has resulted in a focussed attention to the investments of city centers at the expense of ignoring large numbers of people in the countryside and suburbs is clearly unintentional and is by no means universal, nor is it as simple as Figure 26 suggests. However, the ratio of those at risk within the controlled infrastructure of earthquake codes in the developed nations, compared to those in the developing nations unaware of the importance of earthquake resistant construction is large (Figure 27).

Conclusions

Earthquake risks can be mitigated where earthquake hazards have been documented over a period long compared to the recurrence interval of earthquakes, but can be polluted by a lack of attention by the earthquake community to the quality of the historical data used in its assembly. A common practice prevalent in Pakistan and India is to think that a reliable seismic risk analysis can be undertaken once a suitable program has been acuired and got running on their office computer. The entry of imperfect hazard data will not result in improved estimates of earthquake risk. (Garbage in=garbage out.)

The products of seismic risk analysis when applied to the design of local codes, or local buildings moderated by these codes, will result in a safer world for those fortunate enough to live and/or work in those buildings that have received the attention of the engineers. Many millions of people, however, live in structures that have never been engineered, and/or have been assembled by contractors intent on cutting corners. Earthquake resistant codes are of no utility if their application and enforcement can be subverted by indiffernce or corruption.

The seismic hazard/risk community of scientists and engineers have a built-in bias to help governments and insurance companies build cities in the industrial nations to resist earthquakes and protect investments. This is obviously necessary. Many millions of the world's poor in the developing nations, however, will never live in a house that has been built to any kind of construction code, earthquake resistant or otherwise. We can be reasonably certain that these will not be scheduled for retrofits in the next several decades. These are the people who will die in the next many decades from earthquakes.

The history of our future will thus resemble the history of our past. Given that we are aware of this tragedy, it is appalling to recognize that as scientists and engineers we are largely impotent to mitigate against its realization. We are not equipped to modify human nature.

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