Urban earthquake fatalities- a safer world or worse to come?

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The global fatality count from earthquakes continues to rise. This has occurred despite the adoption of earthquake resistant building codes in most countries where damaging earthquakes have historically caused loss of life. In the past five centuries the global deathtoll from earthquakes has averaged 100,000/year, a rate that is dominated by large infrequent disasters, mostly in the developing nations. Though an increased fatality rate might be expected from the steady increase in global population (Bilham, 1988), recent urban growth has been accompanied by a decline in the fatality rate as expressed as a percentage of instantaneous population. It is tempting to attribute this observation to the application of earthquake resistant construction code in new city construction. A more sinister interpretation, however, is that the apparent decline in risk is caused by the short exposure time (50 years) of the world's recently increased population to earthquakes with recurrence intervals of the order of centuries. Future extreme earthquake disasters in some of the world's megacities may arrest, or reverse, the current trend.

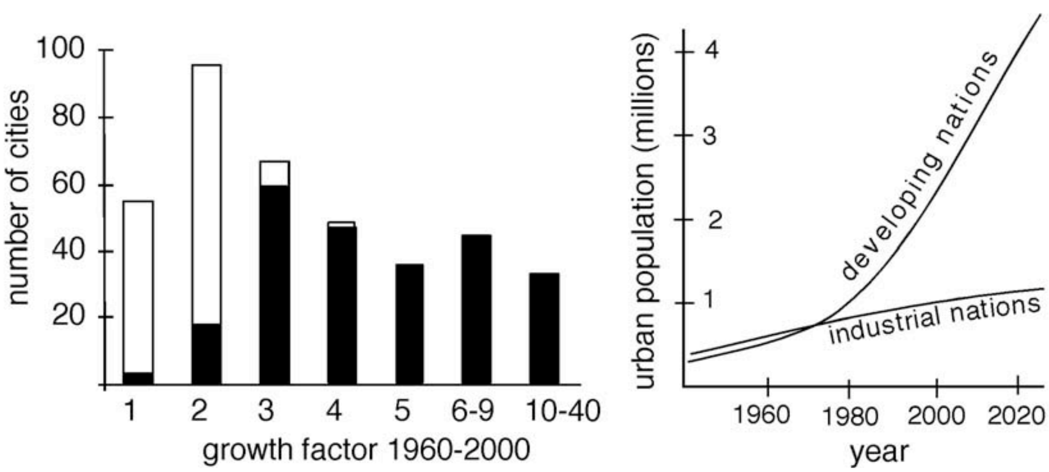

Figure 1 (Left) City populations between 1960 and 2000 grew on average by a factor of 2.55. The mean urban growth rate in the developing nations (filled bars) is twice this, largely in cities with present populations of less than 1 million. (Right) Global urban population grows mostly in cities in the developing nations.

URBAN POPULATION GROWTH

Global populations doubled between 1900 and 1960 and doubled again between 1960 and 2000 (United Nations, 2001). Most of this population growth has occurred in the cities of the developing nations in cities with populations 1 million or less. Although less than 4% (≈400 million) of the world's population live in megacities with 10 million or more inhabitants, half of these are located in earthquake vulnerable locations. Since 1960, one hundred cities with populations exceeding 1 million, increased their populations by an average factor of five, and a third of these increased in size by more than a factor of ten (Fig. 1). In the developed nations, with few exceptions urban populations have grown little, and in some cases have declined. The urban population now exceeds 3000 million. By the year 2007 more than half the world will live in cities.

FIVE CENTURIES OF URBAN EARTHQUAKES

Averaged over the past 500 years the deathtoll from earthquakes is approximately 100,000/year, a rate that is influenced by rare catastrophic events each of which have claimed the lives of 50,000-250,000 people. The fatality count associated with these large events is notoriously unreliable even for quite recent earthquakes. Moreover, because they occur erratically in the historical record their potential reccurence is not amenable to statistical forecasts. The most recent of these was the 1976 Tangshan earthquake with a deathtoll of the order of 242,000 though some sources have estimated twice as many people died. The analyses presented here used the Significant Earthquake data base compiled by Dunbar et al., (1992) supplemented by recent data compiled by the author. Dunbar et al.(1992) is an uncritical compilation and contains numerous multiple entries that must be removed prior to analysis.

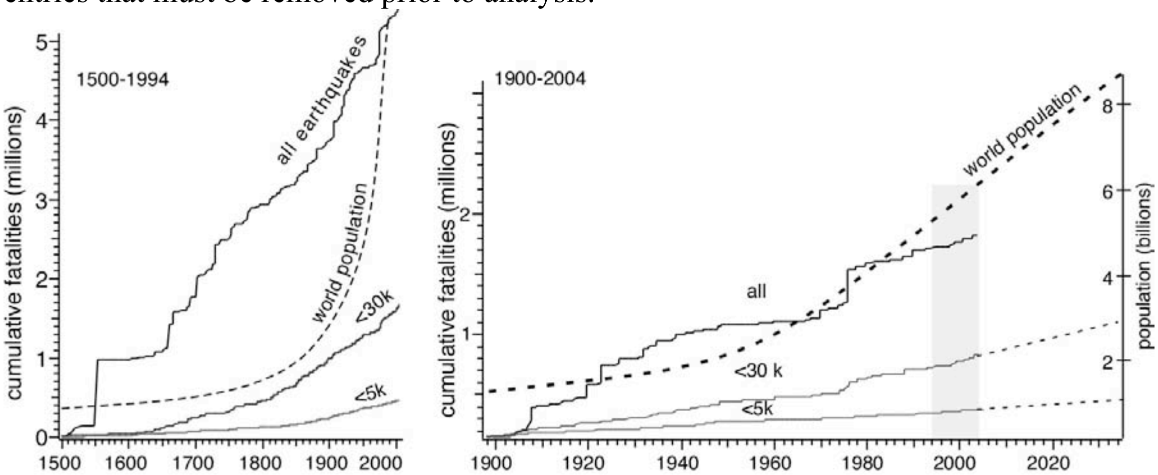

Figure 2. World population increase (UN data and predictions) compared to the cumulative fatalities from earthquakes in the five centuries. Whereas the cumulative fatality count from all earthquakes grows erratically, the count from moderately fatal events grows sufficiently smoothly for predictions. Trends to

1994 were used to anticipate a 7500/year annual fatality count from moderately fatal earthquakes. Actual losses (1994-2004, shaded) were 30% higher.

The fatality rate from numerous, less-severe earthquakes, however, provides sufficient numbers of events to permit numerical forecasts. Two populations were considered in 1994: 1216 earthquakes in which fewer than 30,000 died, and a subset of 1105 earthquakes in which fewer than 5,000 people died (Bilham, 1995). The growth in fatalites for these two classes of earthquake in the past 500 years suggested that the rate in the 30 years following 1995 should not increase more than 30%, that is from 6000-8000/year for <30k-fatality events, and from 2200 to 2690 for <5k-fatality events (Figure 2). Earthquakes that occurred since then, reveal that both forecasts were conservative (Table 1). In particular, despite multiple entries and inflated fatality counts for some earthquakes in the 1994 data set, the <30k-fatality-earthquake forecast maximum was 19% too low.

TABLE 1

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

Time interval	<30k old		<30k revised		<5k old		< 5k revised	
1500-1599	640	±59	313	±31	220	±8	213	±8
1600-1699	3119	±63	2225	±44	510	±12	578	±14
1700-1799	2297	±49	2098	±41	578	±14	482	±8
1800-1899	4715	±26	5522	±33	1370	±10	1324	±16
1900-1999	6675	±30	6129	±36	2028	±9	1996	±6
1995 forecast	6000-8000				2020-2690			
1994-2004 obs			9548	±195			2726	±50

"Old" uses data to 1994 (Bilham (1995). "Revised" uses edited data to 2004. Forecasts made in 1995 for the interval 1995-2025 (7500/year) are compared to the observed 1994-2024 rate (9548/year).

Table 2

Decade-interval forecasts (1900-2030) of annual fatality rate (deaths/year) based on power law fits to 5 centuries of data. Numbers on parenthesis in the first row represent the observed fatality rate 1900-2004, all lower than predicted. The constants a, b and c correspond to the power law variables in figure 3.

	1900-1999	2000-09	2010-19	2020-29	a	b	c
all	16703*(10991)*	17094	17492	17897	-(6.4±0.7)e+05	(1.63±1.3)e-12	5.62±0.1
<30k	8609 *(5991)*	9015	9439	9881	-(8.4±1.6)e+03	(2.9±1.7)e-28	10.23±0.1
<5k	2702 *(788)*	2849	3004	3166	-(10.5±2)e+03	(2.2+1.6)e-33	11.6±0.1

One reason for this error is possibly that the recent rate represents a statistical fluctuation of the kind that occurs throughout the past few centuries. To examine these fluctuations, the revised catalog of earthquake data, including earthquakes to August 2004, and excluding errors in the earlier catalog (Table1), has been re-evaluated using both linear fits (Table 1) and power law fits (Table 2 and Figure 3).

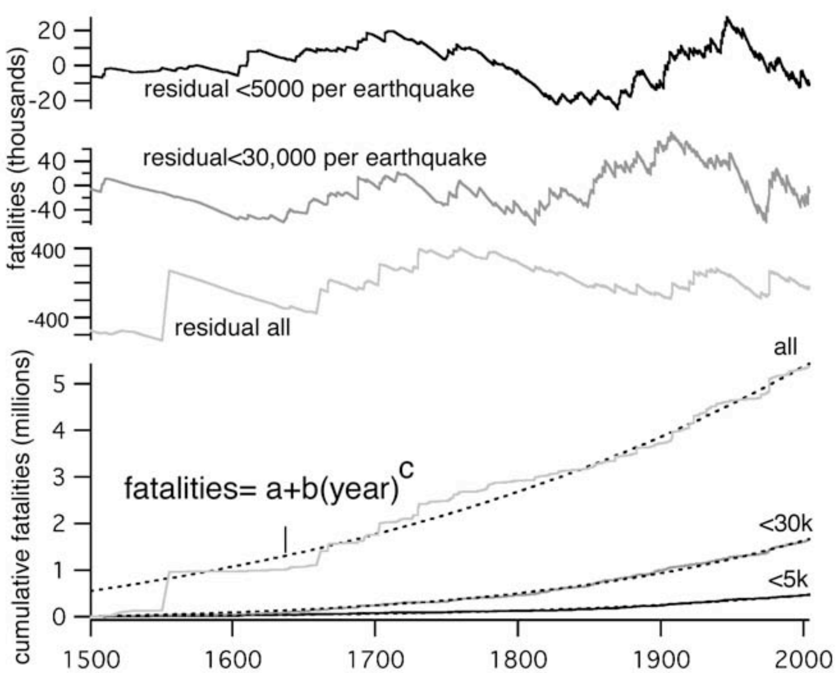

Figure 3 Power law fits (dashed lines) to observed data and residuals (upper three plots) for the three classes of earthquake severity considered. The power-law coefficients derived in this figure have been projected to the year 2030 in Table 2.

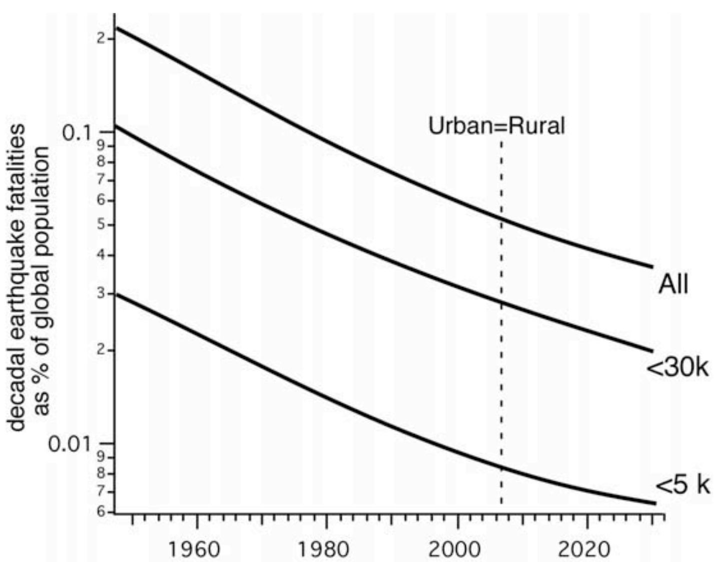

Figure 4 In contrast to the increasing annual deathtoll from earthquakes (Fig. 3) a global decline in the number of fatalities per decade is evident when earthquake fatalities are expressed as a percentage of instantaneous global population. Since 1950 the decline has been a factor of 2-3 for all classes of earthquake. Forward projections are based on power law fits to fatality data (from Table 2) and published UN population predictions. The dotted line indicates the time when the world's urban population equals, and subsequently exceeds, the world's rural population.

Tables 1 and 2 demonstrate that neither linear, nor power law fits to the data emulate the most recent decade of observed fatalities from earthquakes, a conclusion that is not unexpected from the decadal fluctuations in rate evident in the residuals in Figure 3. However, power-law fits to the data emulate the century-long trends reasonably well (Figure 3), and these are of utility in suppressing short-period fluctuations in global data discussed below.

Of interest is whether the fatality rate from earthquakes keeps pace with global populations, or whether improved building styles offer hope that the rate may be declining. A clue to this statistic lies in the relationship between the decadal average global population and the decadal number of earthquake fatalities. In Figure 4 United Nation's population statistics to 2002 are combined with their published median-level predictions to 2030. The ratio of the number of earthquake-deaths per decade to global urban population decline smoothly with increasing populations for all classes of earthquake.

Discussion

The decay in fatality rates as a percentage of world population (Figure 4) implies that the world is a safer place than it was before urban growth accelerated in the 1950's. In 2007, when urban dwellers will for the first time outnumber rural dwellers, the risk to an individual will have apparently declined by a factor of 3-4. The construction of megacities has apparently resulted in a mitigation of earthquake risk.

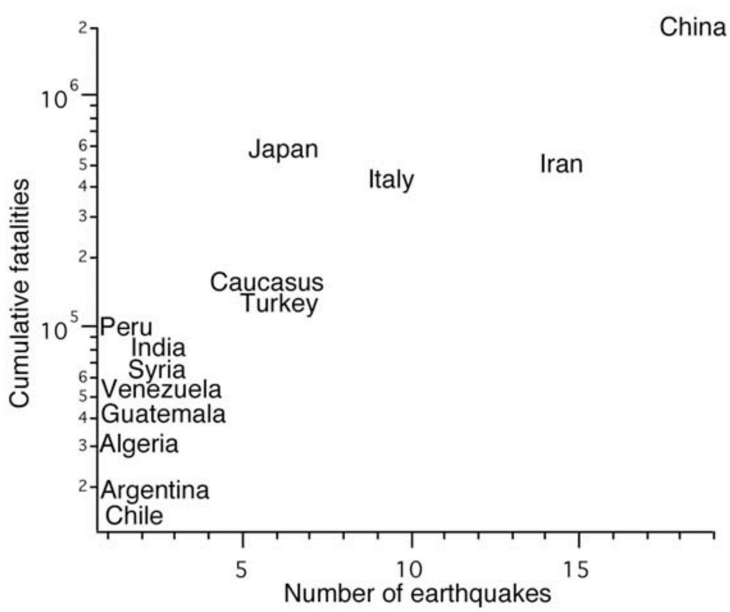

Figure 5. Location of the world's 71 worst earthquakes (>10,000 fatalities) since 1500. With the exception of a group of countries in the Caucasus, the figure excludes ten nations that have experienced only a single disastrous earthquake during this same time interval.

This is an appealing global conclusion, but most seismologists and earthquake engineers would consider it absurd. The conclusion conceals three important facts. The first is that although the risk to an individual has declined, the absolute number of earthquake fatalities per year is indeed increasing (Figure 3 and Table 2). The second is that the entire discussion thus far has neglected the potential size of future extreme events, except as a statistical least-squares fit. I discuss this below. The third is that fatalities from earthquakes are focussed not only along earthquake belts, but in certain countries that experience a much higher risk than others (Fig 5).

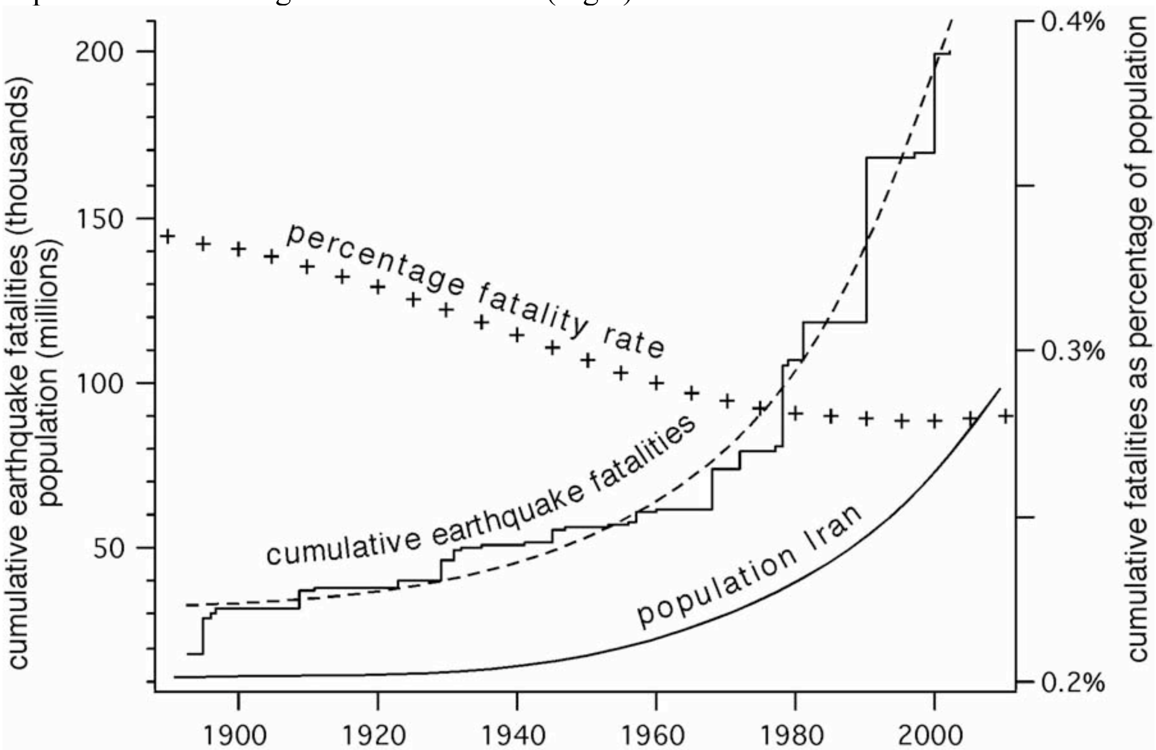

Figure 6. Earthquake fatalities in Iran, despite their erratic timing and variable deathtoll have almost exactly kept pace with Iran's increasing population. The population curve presented here is a least-squares power law fit to data compiled by Klein-Goldewijk and Battjes (1997). The percentage fatality curve is derived from the ratio of the power law fit to earthquake fatalities (dashed line) to the population curve.

The half–dozen countries that have experienced multiple fatal earthquakes are also the countries with largest cumulative fatality loss from earthquakes. These regions fare worst, both in a five-century view of fatalities, and in the most recent century. An inescapable conclusion is that each of these countries has much to gain from rigorous application of earthquake resistant construction (Tucker, 2004). The statistics of Iranian earthquakes, for example, demonstrates that the fatality rate tracks the instantaneous population quite closely (Fig. 6). While there has been a fall in the percentage of the population killed by earthquakes, the fall consists of a statistically insignificant decline from 0.33% in 1900 to 0.28% in 2000. The existence of earthquake codes have had little or no effect in a century of earthquakes in Iran, an observation voiced by Berberian (1999). The people of Iran live with an astonishingly high seismic risk, despite an earthquake construction code, and high national awareness of the recurrence of earthquakes. Unless construction practices change, one Iranian in 3000 can expect to die during an earthquake.

The data from Iran indicate the weakness associated with the analysis of global earthquake fatality data. Global averages mask the vulnerability of certain nations.

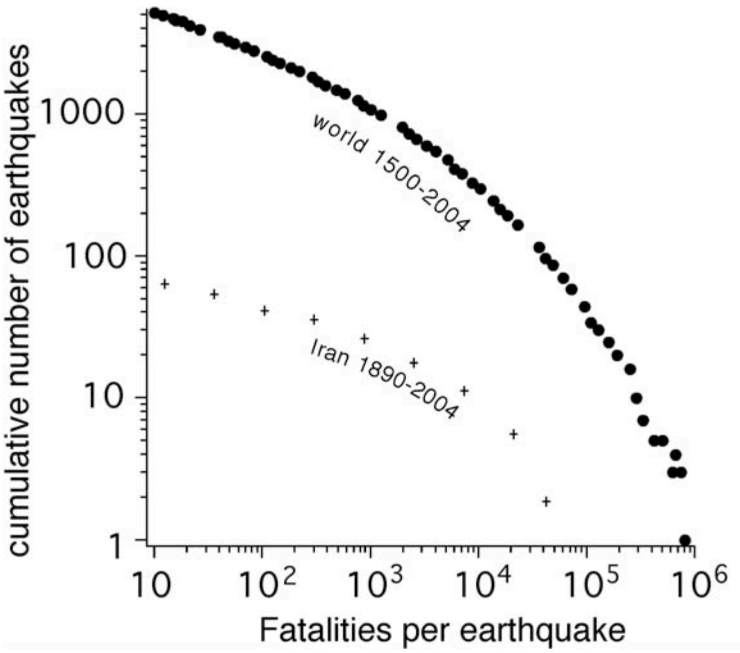

Figure 7 The number of earthquakes that cause a given number of fatalities shows a curved relationship in the past five centuries. The curve may be interpreted in two ways: that an extreme event results in a million fatalities every 500 years with an average population of approximately 2 billion people, or that with a 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. The data from Iran shown in Fig.6 are shown for illustrative purposes.

The forecast of extreme earthquakes has the largest uncertainty in the "all-event" curve of Figure 3 . One approach that provides insight into their future probability is to examine the ratio of the number of moderately fatal earthquakes to larger ones in a search for a fractal relationship that may be used to extrapolate to rare infrequent events. Nishenko and Barton (1995) normalized global fatality data to global populations using linear fits, however, the fractal nature of the data is not well characterized by a single straight line. Century-long data reveal a curve, rather than a linear relationship (Figure 7), but since the resulting curves have similar shape, independent of which century is considered, they offer predictive capability (Bilham, 1995). The reason for the curve is not known. One possibility is that the data are incomplete for rare events but this is unlikely to result in the smooth observed curve. Philip England investigated the possible influence on the data, of areas of intensity VIII shaking anticipated from the range of earthquake depths and magnitudes in the global seismicity catalog, but the results though suggestive, were inconclusive (personal communication, 2000). If we accept a fractal origin to the global fatality data presented in Figure 7, the five-century or IXX-century curves all point to an extreme event occurring roughly once each century.

The size of this extreme event in any given century has varied from 100,000 to more than 500,000 (XVIth century China). The data on which these curves are based apply to a changing demographic population, both in terms of number of people and their geographic distribution. Specifically, earthquake damage prior to the 20th century was primarily aimed at a rural population of fewer than 2 billion people living in relatively small cities. The current population is 6 billion and almost half live in cities. In 1950 there were only two megacities in the world, but now there are more than thirty. A large earthquake has yet to occur beneath one of these new megacities. Tokyo's regional population in 2030 years is predicted to exceed 70 million, a target of unprecedented size, but one where earthquake resistant construction is mandatory. More than a dozen less-prepared cities in the developing nations lie above earthquake zones, and the former villages from which they recently grew have a history of damaging earthquakes.

Because of the world's fourfold increased population, and the concentration of a significant fraction of this population in poorly constructed cities, future extreme events may potentially far exceed in severity those that occurred in the past. Although such large events (>1 million fatalites) are unprecedented, they were never before possible because urban agglomeratons have never before grown to current sizes. In the Tangshan earthquake of 1976 at least 35% of the population perished. A 35% fatality count is unusually high, but were it associated with a city of 3 million it would result in a million fatalities. The world has recently constructed more than 100 cities of this size, and more than half of these lie in earthquake zones in the developing nations where recent earthquakes have demonstrated that earthquake resistant construction may be unevenly applied.

CONCLUSIONS

Despite an increase in the number of fatalities from earthquakes each year, the 1950-2004 four-fold expansion of urban society has resulted in a paradoxical three-fold reduction in individual risk from earthquakes. This result is counterintuitive to most seismologists, because it suggests that our new urban society inhabits a safer world.

The paradox is partly attributable to the short exposure time of the world's greatly increased population to earthquakes, as suggested by an analysis of 20th century Iran, where fatal earthquakes have occurred regularly during the period of population expansion, and partly to the influence of infrequent extreme events, for which the historical record provides few precedents.

Recent earthquakes in the developing nations have resulted in huge loss of life, either because no earthquake resistance exists or because an existing building code has not rigorously been implemented. Many of the new urban dwellers live in regions where poverty is accompanied by low cost construction, notoriously vulnerable to earthquake damage. Many of the cities that are now doubling in size lie in countries with a disastrous record of previous earthquake fatalities.

A grim conclusion then, is that the reduction in risk to the urban population of the world is a misleading indicator of true seismic risk. To support this conclusion one must ignore the current indications of global fatality rates, and appeal instead to the potential infrequent occurrence of large earthquakes close to urban agglomerations. Numerous lethal earthquakes with 5- and 6-figure fatality counts have occurred historically in China, Japan, Iran, Italy and in Turkey. Half of the worst hit countries are in diffuse earthquake zones, rather than in clear-cut plate boundaries. Cities in India, Indonesia, Bangladesh, Pakistan, the Caribbean, Central and Western America are prime targets for future large earthquakes. Urban agglomerations in these countries are now larger and more numerous, and rare, infrequent earthquakes that hitherto have claimed more than 100,000 lives, may in future years result in more than a million fatalities per event. Although such disasters have no precedent in earth's history, urban agglomerations have never before presented opportunities for fatality counts of such magnitude.

Acknowledgments

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