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Societal and observational problems in earthquake risk assessments and their delivery to those most at risk

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ABSTRACT

Losses from earthquakes continue to rise despite increasingly sophisticated methods to estimate seismic risk throughout the world. This article discusses five specific reasons why this should be. Loss of life is most pronounced in the developing nations where three factors – poverty, corruption and ignorance – conspire to reduce the effective application of seismic resistant codes. A fourth reason is that in many developing nations the application of seismic resistant construction is inadvertently restricted to wealthy, or civil segments of the community, and is either unobtainable or irrelevant to the most vulnerable segment of the public — the owner/occupiers of substandard dwellings. A fifth flaw in current seismic hazard studies is that sophisticated methodologies to evaluate risk are inappropriate in regions where strain rates are low, and where historical data are short compared to the return time of damaging earthquakes. The scientific community has remained largely unaware of the importance of these impediments to the development and application of appropriate seismic resistant code, and is ill-equipped to address them.

1. Introduction

Despite more than a century of earthquake resistant engineering (Milne, 1891; Tobriner, 2006) and the development of increasingly sophisticated methods to estimate future risks from earthquakes, the past decade has been the most fatal ever if we ignore the 1556 Shanxi earthquake (Fig. 1). Since 2000 AD the world has lost 630,000 people. The cumulative cost of recent earthquakes has exceeded $300 billion, largely due to reconstruction costs in the industrial nations (Fig. 2). The disasters of the past decade may in fact foreshadow yet greater disasters should one or more of the world's megacities suffer a direct hit, similar to those that occurred in Port au Prince, Haiti, or Christchurch NZ.

Several articles have pursued the problems of seismic risks faced by the world's rising populations, concentrated, as they are, largely in cities whose populations have doubled every few decades in the past century (Bilham, 1988, 1995, 2009; Holzer and Savage, in press; Nichols and Beavers, 2008; Nishenko and Barton, 1996). In general these articles note that deaths and costs will continue to rise in the next century, but that extreme events will occur in the large cities of the developing nations, setting new records in terms of death tolls for single earthquakes and costs associated with reconstruction. An unprecedented death-toll exceeding 1 million is now possible in a single earthquake, should it occur near one of the world's megacities (Bilham, 2009).

At the root of the problem faced by the world's cities is that the population now targeted by earthquakes has increased by an order of magnitude in the recurrence interval of a single earthquake at a typical plate boundary. The former villages and towns that earthquakes have visited in the past are now cities and megacities, and the building stock of many of the world's megacities now include fragile buildings, assembled without adequate earthquake resistance.

A recent study by England and Jackson (2011) notes that the largest death toll from earthquakes results not so much from $M>8$ earthquakes, but from relatively modest earthquakes with magnitudes in the range of $7<Mw<7.5$, and specifically from earthquakes in plate interiors. The larger $(M>8)$ plate boundary earthquakes in recent years have been expensive but have not resulted in significant loss of life if we exclude the effects of tsunami.

2. Corruption, ignorance and poverty

The building booms of the past four decades have caused the world's cities to increase their stock of buildings often without consideration of earthquake resistance. In many cases the number of buildings has been increased by an order of magnitude. Inevitably many of these buildings, especially in the developing nations, have used inferior materials and methods of assembly and a large number of these buildings are vulnerable to collapse in future earthquakes. It is only after an earthquake that we are likely to learn how poorly they were assembled. The absence of earthquake resistance in these buildings is attributable to several factors, but its prevalence is disappointing given that earthquake resistant construction methods have

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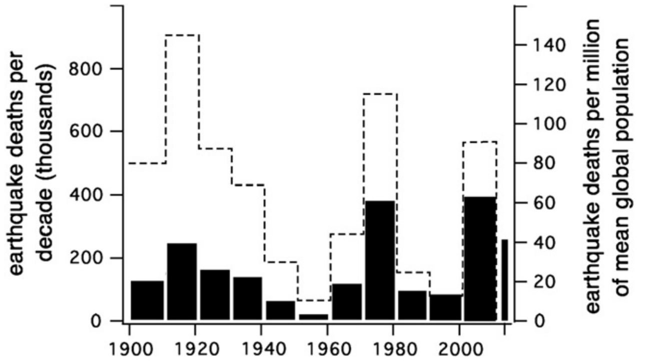

Fig. 1. Deaths per decade from earthquakes since 1900. The dashed line (right axis) is the decadal average normalized to mean global population for that decade.

been adopted by most governments, and implemented by engineers for more than a century.

One startling measure of our failure to prevent deaths from earthquakes is our ability to forecast the death toll anticipated from an earthquake within 30 min of its occurrence, long before news is available from the epicenter. Both the USGS (Wald et al., 2008) and WAPPMER (Wyss et al., 2006) have refined methods to incorporate the magnitude, depth and societal setting of an earthquake, and from these to estimate an empirically determined death-toll and injury-count using building fragility estimates of settlements in the epicentral region. The calculations can be undertaken in within 30 min of an earthquake occurring anywhere in the world, and typically they are accurate to within an order of magnitude of the true death toll.

That instant death toll estimates are routine is an admission that earthquake resistance is incomplete and is unavailable for most people especially in the developing nations. Why is this? 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: *corruption* in the building industry, an absence of earthquake *education*, and the prevalence of *poverty* in earthquake zones. These three factors often act together, such that their effects cannot easily be separated one from another.

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).

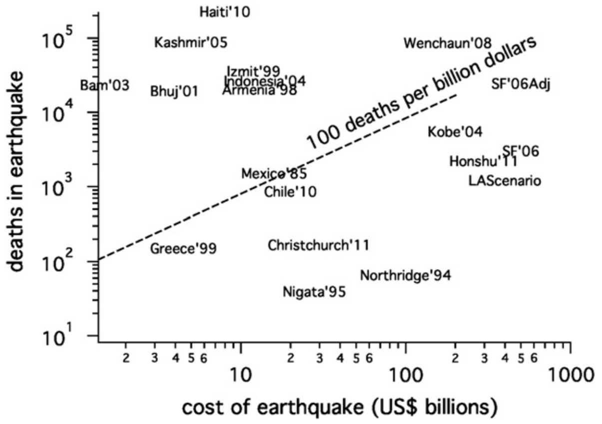

Fig. 2. The reconstruction cost of recent earthquakes is compared to the number of people killed in these earthquakes. The dashed line has a slope of 100 deaths per billion dollars and acts as a divide between countries with low per capita income from those that are wealthy.

Poverty is both responsible for people constructing buildings from inappropriate 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, regions prone to flooding and landslides etc.

Ignorance about the 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 the absence of education is ultimately responsible for weaknesses at several levels of society. Children are not told how to mix concrete in school, these children in adulthood 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 importance of adhering to construction guidelines.

A simple correlation between corruption and *per-capita* income is evident in Fig. 3. Corruption is quantified by the *Transparency International* Corruption Index (see Ambraseys and Bilham, 2011 for the methods adopted). A large Corruption Index value means the country is considered less corrupt (10 means no corruption) and a small index value implies a more corrupt society. The existence of the approximately inverse relationship between income and the level of corruption is presumably linked to the availability and enforcement of regulations in wealthy countries, and if so, one might suspect that wealthy countries are less prone to earthquake disasters because earthquake resistant regulations are always applied. To some extent this is true, but this is clearly not the whole story. In Fig. 3 some countries (below the dashed least-squares regression line) are more corrupt that they should be given their income (e.g. Italy, Greece and Russia). The numerical placement of a country below or above the regression line defines an "expectation index", which can be interpreted as a measure of integrity, or national behavior.

If this "expectation index" is now plotted against national income, with the number of deaths from earthquakes in those countries as a third axis we find that 90% of all earthquake deaths in the past few decades have occurred in poor countries that are more corrupt than expected (Fig. 4). Using this metric, the PRC with an expectation index of +1 (= less corrupt than expected) is one of the few countries where corruption does not appear to contribute specifically to a large death toll. Whether or not corruption is considered the cause of the large number of deaths from earthquakes in the developing nations, an inescapable conclusion is that most deaths from earthquakes occur in countries that are poor.

3. A bias in the application of earthquake resistance

Thus far I have reviewed the possible contribution of three societal conditions to earthquake disasters: corruption, poverty and education. I now introduce a fourth parameter that amounts to a disconnection between earthquake engineering community and society. The ideas developed in this section are summarized schematically in Fig. 5. There exist few outlets for the application of the results of most state funded

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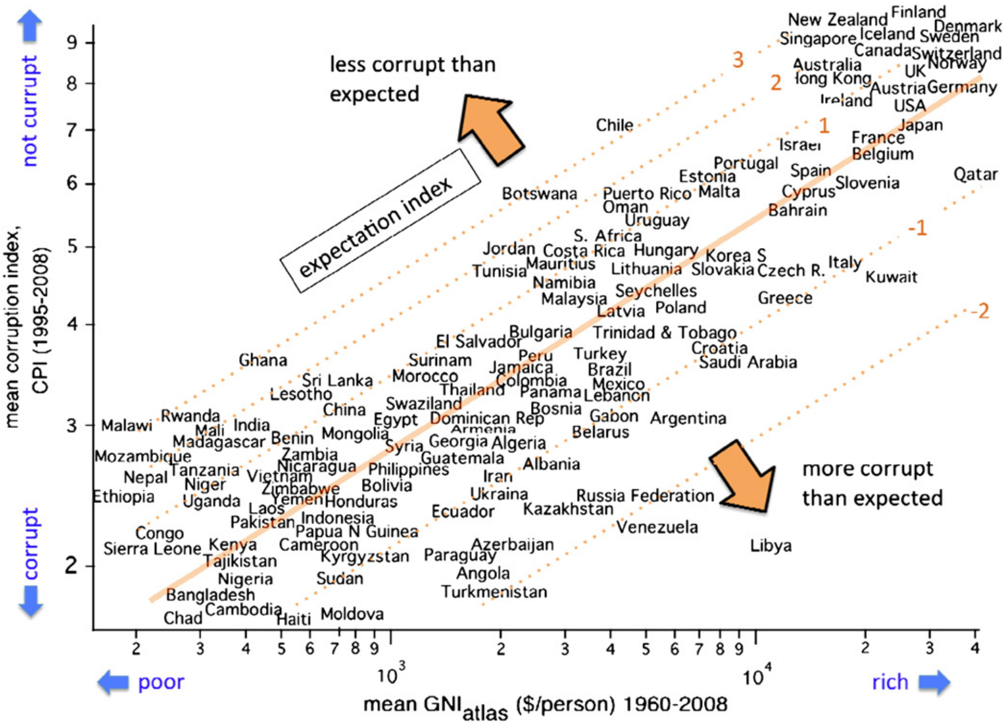

Fig. 3. Corruption and per capita income in a country are closely linked (from Ambraseys and Bilham, 2011), yet those countries below the regression line are more corrupt than they should be given their per capita income. We characterize the departure of each country from this mean expectation as an expectation index. A Corruption Index of 10 means that no corruption is perceived in that country. An expectation index of +2 signifies (e.g. Chile) that it is two corruption units less corrupt than that expected from its per capita income.

earthquake research findings to those most in need of protection from earthquake shaking. This is particularly a problem in the developing nations.

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 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 is converted into

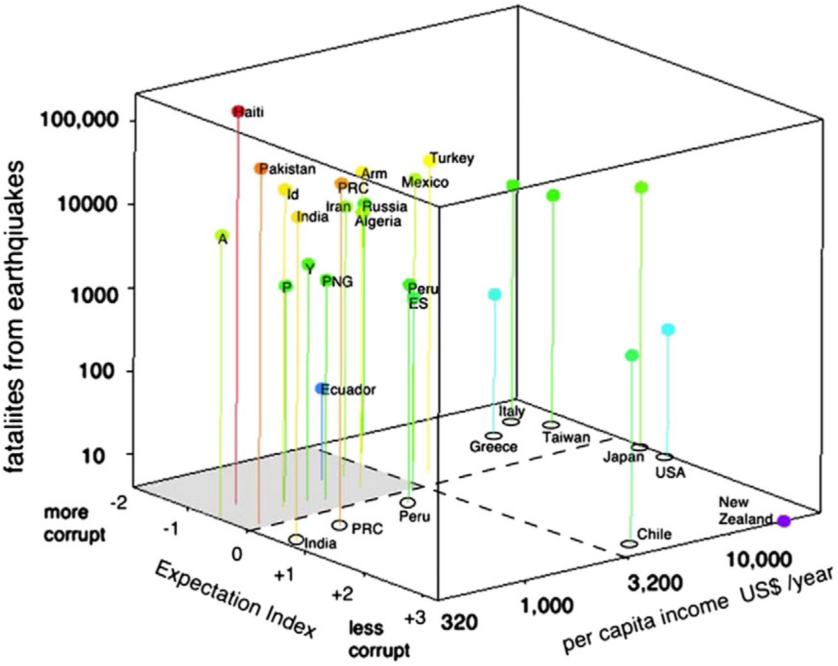

Fig. 4. Ninety per cent of all deaths from earthquakes occur in low income countries (<$3200/yr) and/or where corruption is worse than expected from per capita incomes (gray area on left hand side of the plot) A = Afghanistan, Y = Yemen, P = Philippines, PNG = Papua New Guinea, ES = El Salvador, Id = Indonesia, Arm = Armenia (after Ambraseys and Bilham, 2011).

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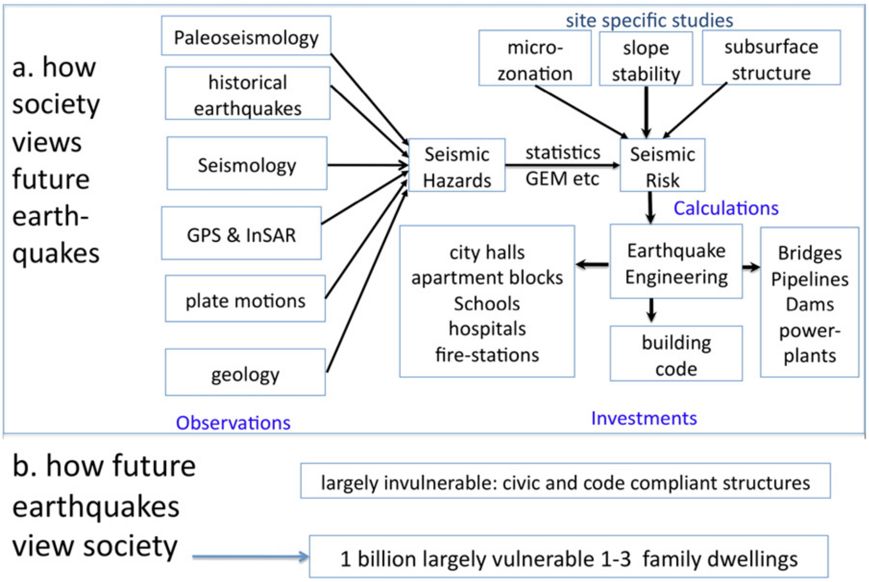

Fig. 5. A comparison between (a) Mitigation strategies — the box encapsulates the cerebral response of the earthquake community to understanding and mitigating the effects of earthquakes and (b) Disaster scenarios — how earthquakes view society. Mitigation efforts successfully protect community investments, 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.

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.

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 communities. 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.

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. In such cases 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 Fig. 5 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 (Fig. 6).

4. Earthquakes in unexpected places

We review above, four perceived impediments within the structure of society that take a hand individually or together in suppressing the best intentions of seismology and earthquake engineering to reduce losses in earthquakes. We now examine the thumb on this hand of disaster — the possibility that crucial input to seismic hazard analysis is simply missing in a region. If a large earthquake has occurred in a region but is missing in the historical record, seismic risk estimates will inevitably be too low.

Two recent earthquakes illustrate this problem. In 1993 the Mw = 6.1 Latur/Killari earthquake in central India caused the collapse of 30,000 houses resulting in 7900 deaths. Prior to the earthquake the region was considered as one of low seismic hazard (Kayal, 2001; Seeber et al., 1996) although Rajendran et al. (1996) present evidence that this is not the first time that the Latur Fault has slipped. In 2010 and 2011 Christchurch, New Zealand, was damaged by Mw = 7 and Mw = 6.3 earthquakes respectively that occurred in a region hitherto recognized as one of low seismic hazard. In each of these examples, earthquakes occurred on shallow faults that had not been recognized as potential sources for damaging earthquakes. In each region the observed strain rate was low. In each case the seismic history of the region did not extend reliably beyond two centuries, although there were indications of potential hazards in the Christchurch region from moderate earthquakes in the previous century (Elder et al., 1991).

A similar situation could have existed in the New Madrid region of North America. Had there been no damaging earthquakes in 1811 and 1812 it is very doubtful that the New Madrid region would be suspected as capable of Mw ≈ 7 earthquakes. The geodetically observed strain rate is low, and there is no significant topography associated with the region. As a result of these earthquakes paleoseismic investigations were

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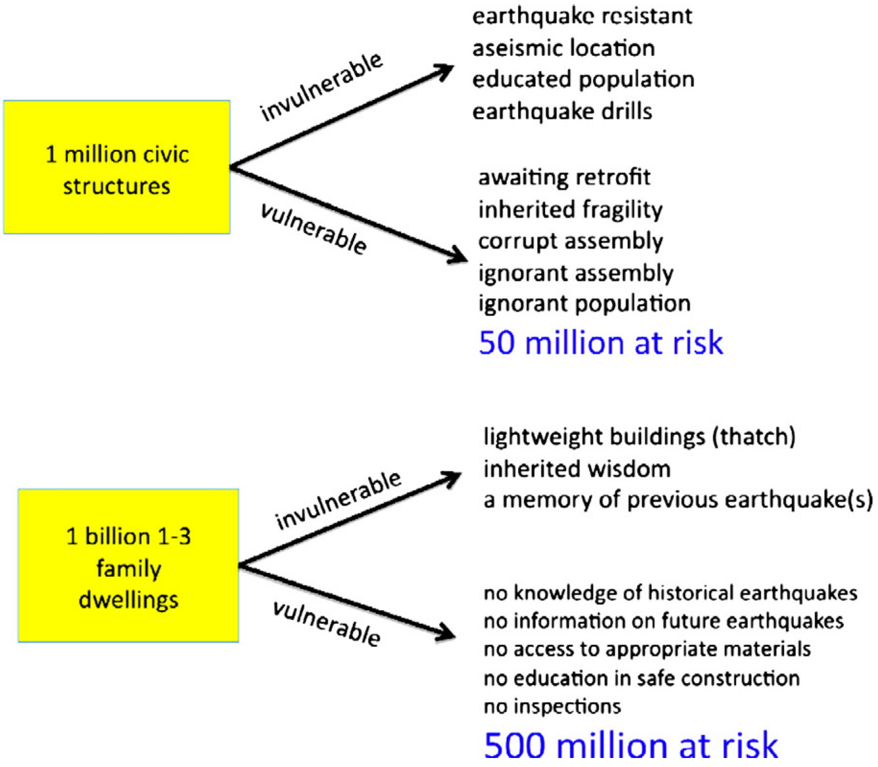

Fig. 6. The influence of earthquake engineering on building safety is effective only where earthquake resistant codes are applied throughout society. In a few societal settings earthquake resistant engineering sometimes prevails despite the absence of codes and their enforcement. It is estimated that ten times more people worldwide live outside the protection of code enforcement, than within its safety net.

focused in the region and have revealed a recurrence interval of the order of 500 years (Tuttle et al., 2002).

The Wenchaun 2008 Mw = 7.9 earthquake falls into this same category (Burchfiel et al., 2008). Although numerous capable faults exist along the eastern edge of the Tibetan Plateau their recurrence rate is of the order of 3000 years, longer than the written historical record. Again in this region the strain rate observed geodetically prior to the earthquake was remarkably low.

It is almost certain that other regions have the potential for “unexpected” earthquakes. At plate boundaries where most earthquakes occur, the displacement inputs to the earthquake cycle are clearly understood from the motions of the plates. In mid-plate settings the stressing rates necessary to repeatedly drive earthquakes are far less clear. For example, for the Indian subcontinent the mean geodetic strain rate is observed to be one third of a nanostrain per year (Apel et al., 2006; Banerjee et al., 2008). This low strain rate suggest that the time to raise a region from a condition of post-seismic strain relaxation to failure conditions (10^{-4} strain) would be of the order of 300,000 years (Bilham and Gaur, 2011). In India the historical record of earthquakes is not much more than 200 years for most of the subcontinent (Martin and Szeliga, 2010).

The special conditions in India that single it out from most other mid-continent settings are that India is being flexed and buckled by its collision with the southern edge of the Tibetan Plateau (Vita-Finzi, 2004). These flexural stresses are not reflected in horizontal shortening observed by surface geodesy, but have raised stresses throughout the Indian Plate to high levels such that relatively minor perturbations can trigger local earthquakes.

In hindsight it is easy to recognize locations where unexpected earthquakes should have been anticipated. Can we proactively identify future disasters? Colorado is an example of a region in North America that is considered unlikely to sustain a Mw = 8 earthquake (because none have occurred), yet there are many resemblances between Colorado and the Wenchaun region. Consider the following: each region is associated with a step in topography, marked by steep topographic gradients associated with range-front faulting (Burchfiel et al., 1995; McCalpin, 1986; Widmann et al., 1988). The geodetic convergence rate across the Longmenshan Fault prior to the Wenchaun earthquake was −1–2 mm/yr (Chen et al., 2000), whereas the divergence rate across the Front Range of Colorado is currently +0.5 ± 0.4 mm/yr (Berglund et al., 2012). The patterns of seismicity prior to the Wenchaun earthquake and in the Colorado region are shown in Fig. 7.

The current geodetic strain rate in Colorado is rather imperfectly known but is calculated by Berglund et al. (2012) to be approximately 1 nanostrain/yr, which if uniformly applied would require an elapsed time of 100,000 years to attain failure strain conditions of 10^{-4} strain throughout the region. Were this strain rate focussed on specific structures, however, the time to reach failure could be locally reduced by more than an order of magnitude. Several faults with lengths capable of sustaining a Mw = 7.5 rupture have been mapped in Colorado (Widmann et al., 1988; Wong, 1986). Extrapolations of the Gutenberg–Richter relation from historical and instrumental seismicity in Colorado (Charlie et al., 2002) suggest that M = 7.5 earthquakes could recur at intervals of 1 kyr–4 kyr (Fig. 8), and M = 8 earthquakes at <9 kyr intervals (Fig. 8). Hence the seismic and geodetic estimates for recurrence intervals are approximately consistent. The concept of a Mw = 8 earthquake is unreasonable only in that there are no faults long enough to sustain such a large earthquake. In the case of Wenchaun, however, the earthquake ruptured several contiguous fault segments. A similar multiple rupture surely cannot be excluded from the Colorado Front Range.

5. Flexural stresses and the absence geodetically observable strain rates

In the absence of a long history of earthquakes, one recourse to estimating earthquake productivity and hazard potential is to examine

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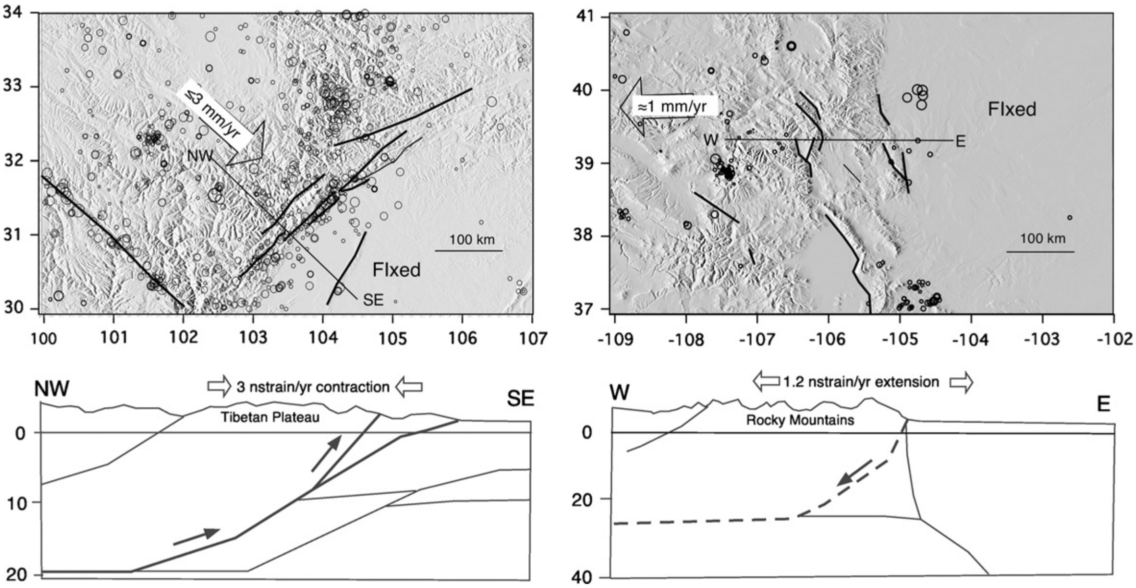

Fig. 7. Seismicity 1965–2007 (IRIS catalogs), topography and geodetic rates for the Wenchaun earthquake region (left, Chen et al., 2000) and Colorado Plateau regions (right Berglund et al., 2012). Schematic cross-sections and faults adapted from Hubbard et al. (2008), Widmann et al. (1998) and Karlstrom and the CD-ROM Working Group (2002). Prior to the 2008 earthquake, local authorities in the Wenchaun region were largely indifferent to the seismic potential of faults along the Front Range. The same is currently true of the faults of Colorado.

the strain rate in a region. Geodetic methods permit the strain rate in region to be monitored, the assumption being that the rate of strain is an indication of the renewal time for earthquake rupture conditions. This information when combined with the existence of mapped geological faults can be used to assess the maximum credible earthquake in a region, and its return time, as we have done in a preceding section.

The existence of flexural stress, however, can cause considerable epicentral strain in the absence of horizontal strain (Fig. 9). In India, for example, the plate and subcontinent are deformed by buckling from in-plane stresses of collision, and from flexural forces caused by the depression of the northern edge of the Indian Plate beneath the southern edge of the Tibetan Plateau (Watts, 2001). The subcontinent as a result is depressed 4–6 km in the north, rises to a few hundreds of meters in an outer rise represented by the Central Indian Plateau, and is then depressed in an outer moat at the latitudes of Mumbai to Hyderabad (Bilham et al., 2003; Watts, 2001). Vita-Finzi (2004) identifies slightly different bands of seismically deformation parallel to the Himalaya. Whatever its form one can think of the resulting deformation field in India as a standing wave with a wavelength of many hundreds of km — locked in space, through which the subcontinent streams (Fig. 9). Thus a surface rock in southern India heading north as a result of plate motion would pass through the undulations of this wave, encountering first near-surface compression in southern India, followed by extension when it reaches the Central Indian Plateau, followed by compression as it descends beneath the Himalaya.

Rocks at seismogenic depths below the neutral flexural axis in the continent experience the opposite effects — extensional strain beneath the outer moat and compressional stress below the Central Indian Plateau. Earthquakes in this deep compressional setting do not result in surface faulting, because their ruptures terminate as they approach the reduced stresses near the flexural neutral axis. This appears to lie 9–20 km from the Earth's surface judging from aftershock sequences to the Latur-1993, Jabalpur-1997 and Bhuj-2001 earthquakes (Kayal, 2001).

Although strain rates throughout a flexed continent vary too slowly to monitor with current techniques, large spatial gradients in strain exist that amount to several bars per km in the direction of plate motion, and numerous faults must be assumed to be on the brink of failure (Bilham et al., 2003) . The concept of a recurrence interval must also be revised in such a setting because unlike at plate boundaries where displacement inputs are uniform, faults in a flexural setting experience limited slip budgets, often less than tens of meters throughout their active life. The simple elastic model depicted in Fig. 9 is rendered more complex than shown when realistic rheologies are incorporated (e.g. Burov and Watts, 2006).

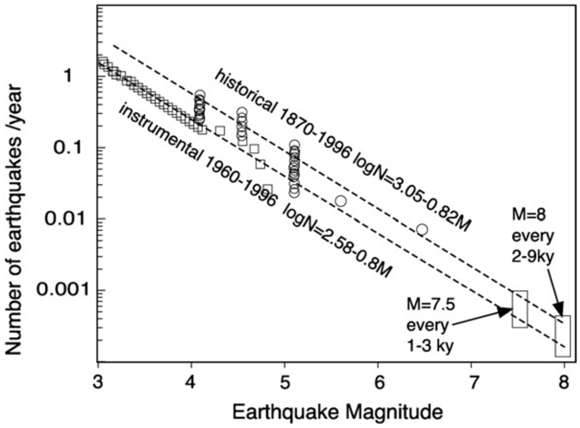

Fig. 8. b-value extrapolations for M = 7.5 (from Charlie et al., 2002) for Colorado. There are no known faults capable of sustaining Mw = 8 ruptures, however, such an earthquake could occur if, as in the Wenchaun region, contiguous fault segments ruptured simultaneously.

6. Discussion and conclusions

In this article I highlight issues that effectively thwart the efforts of seismologists and earthquake engineers to improve the resilience of large segments of the world's peoples currently at risk from earthquakes. The first three of these issues – corruption, ignorance and poverty – are social conditions that are often considered outside the realm of science and engineering. Yet if they are ignored the efforts of earthquake engineering can be diluted, or in many cases negated.

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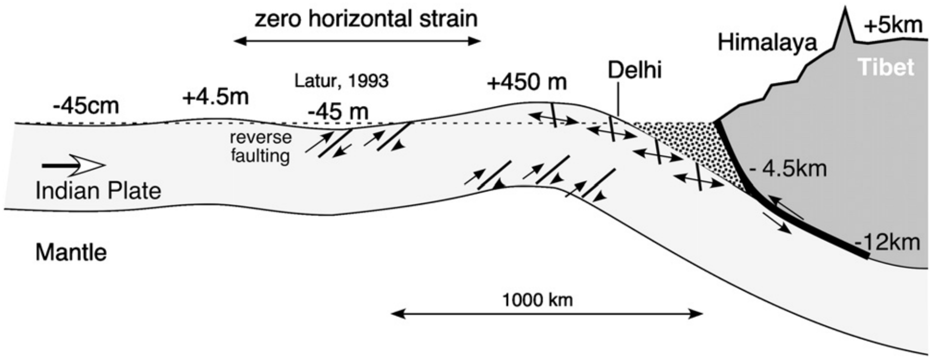

Fig. 9. The flexural wave caused by the collision of India with southern Tibet is “fixed in space” and as the rocks of India stream through this wave they are stressed toward failure conditions that may be tensile or compressional depending on their position above or below a neutral axis. In a flexural setting such as India, geodetic measurements of horizontal strain are incapable of contributing to seismic hazard analysis, and thrust faults at depth are not amenable to traditional paleoseismic studies.

A fourth issue, results from the way that earthquake engineering and preparedness is preferentially focused by government agencies and insurance companies on civic infrastructure and industrial investments in the developed nations. Clearly this focus has resulted in few deaths in the industrial nations. However, the sophistication of risk analysis in urban settings in the wealthy countries contrasts strongly with the absence of simple guidelines to the poorest communities in the developing nations. Large numbers of deaths from earthquakes that have occurred in recent years have occurred in owner-constructed buildings or in rented accommodation constructed by unsupervised contractors. Here there is considerable room for outreach and education by the science community, although without doubt very little can be done to rebuild numerous weak structures that have been hastily constructed in the past few decades. The inherent weaknesses of structures that will collapse in future earthquakes are often the result of poor assembly rather than poor quality materials.

Finally, I address an issue that no amount of statistical manipulation can overcome, the appropriate characterization of seismic risk where earthquakes are infrequent, where strain rates are low, and where the historical record is short. In the absence of adequate historical observations a statistical view of future seismicity is subject to large uncertainties. Several approaches can be adopted by the seismic community to overcome shortcomings in historical data, but these inevitably invoke certain assumptions. Thus in the absence of a historical record, a recent history of instrumental earthquakes can be assembled to construct a Gutenberg–Richter curve that can be extrapolated to obtain a probabilistic estimate of the recurrence rate of larger earthquakes. The assumption in this procedure, however, is that both the a-value and the b-value of this relationship remain constant. However, it is quite probable that in certain settings, the seismic productivity in a region (the a-value), may vary slowly, or rapidly, with time.

A second assumption that is commonly invoked is that seismic productivity is proportional to observed strain rates, now easily measured using geodetic techniques. In a flexural setting, such as in India, or in the vicinity of retreating ice sheets, it is quite possible for large stresses to exist and to evolve, with no significant change in horizontal strain. Adding further difficulties to the study of earthquake hazards in flexural environments, the faults that slip in concave-down flexural settings seldom reach above the neutral axis, terminating at depths of many km that are inaccessible to traditional paleoseismic investigations.

From the above discussion, I conclude that seismic hazards can be quantified and cast into refined seismic risk calculations where sufficient data exist to make these meaningful, however, it is clear that this cannot be undertaken uniformly on Earth. Many parts of the world have incomplete fault maps, and incomplete earthquake histories. Furthermore, seismic risk calculations and guidelines appear as yet to have had little impact in the cities and villages of the developing world where large numbers of earthquake fatalities continue to occur.

Acknowledgments

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