URBAN EARTHQUAKES
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Although I have met many Californians who are terrified of earthquakes, there have actually been relatively few fatalities in the past 75 years. We have relatively strict building codes in the United States and this has undoubtedly saved numerous lives. However, what is the vision for our future? Will we have manageable earthquakes or will we have some true catastrophes?

One extremely optimistic view is from a book by Robert Hill entitled "Southern California Geology and Los Angeles Earthquakes" published by the Southern California Academy of Sciences in 1928. The following quote is from the book cover. "This book completely refutes the prediction of Professor Bailey Willis that Los Angeles is about to be destroyed by earthquakes. It proves that this area is not only free from the probability of severe seismic disturbances, but has the least to fear from *Acts of God* of any city under the American flag."

Given the occurrences of the 1933 Long Beach earthquake, the 1971 San Fernando earthquake, and the 1994 Northridge earthquake, this claim looks pretty silly. Yet, we did make it through these earthquakes and Los Angeles is still standing. In the aftermath of the Northridge earthquake, we have not seen a massive overhaul of our building codes. Are we doing most of the right things, or will future earthquakes send us back to the drawing board to completely rethink things?

What earthquakes are in our future? What if we were simply to replay historic events but with modern populations? We are certain to replay the 1906 San Francisco earthquake. Or what about the 1700 Cascadia earthquake (Satake *et al.*, 1995)? Was it really a magnitude 9 plus? What about three large earthquakes in the New Madrid region in 1811 and 1812? What about the 1952 Kern County earthquake? Could an earthquake like this occur beneath Los Angeles? Many tens of millions now live in areas that were sparsely populated when they were last visited by large historic earthquakes.

Do we know about what will really happen when a large earthquake strikes one of our urban areas? There are currently about 30 strong motion records taken at distances less than 5 km from earthquakes larger than M 6.5, and they confirm numerous eyewitness reports that near-source shaking can be very violent. Peak ground acceleration of 80% g and peak ground velocity of 100 cm/sec are *median* values for these 30 records (Heaton *et al.*, 1995). These values are considerably larger than is anticipated in our existing building codes.

Although building codes are our first line of defense against earthquakes, I must confess that I don't feel comfortable talking about them because I don't know very much about them. Unfortunately, I suspect that most seismologists are in the same situation. However, after working with my engineering colleagues, one thing has been made clear to me. That is, building codes are not based on an understanding of ground motions and the corresponding response of buildings. Rather they are largely empirically based. Following damaging earthquakes, engineers study the performance of various designs and modify the code if certain designs are found to perform poorly. While this is a very practical approach, it may not predict the performance of structures in very large earthquakes, since the largest earthquake in a modern urban environment is the M 6.7 Northridge earthquake in the US, and now the M 6.9 Kobe earthquake in Japan.

Even in the M 6.7 Northridge earthquake, there were disturbing indications of poor performance of modern structures. Most steel-frame buildings located within 10 km of the rupture surface have shown serious signs of distress (Bertero *et al.*, 1994). That is, cracks have been discovered in the joints. These cracks were a great surprise. Yet the steel frame buildings by and large were not located in the region of maximum long-period shaking. The maximum ground velocities of over 120 cm/sec were in the northern part of the San Fernando valley and especially in the Santa Susanna mountains where there were very few steel frame buildings (Heaton and Wald, 1994). In fact, a ground velocity of 175 cm/sec was recorded in this region. The maximum velocities in regions of steel frame buildings were probably less than 50 cm/sec. Of course, the dense downtown part of Los Angeles only experienced velocities in the range of 30 cm/sec. I suspect that we were quite fortunate that the Northridge earthquake fault was dipping to the south. We can only guess what might have happened if the same earthquake had directed its 1-second energy towards downtown Los Angeles on a north-dipping fault.

I suspect that high velocities from rupture directivity are part of the reason that the Kobe earthquake was so devastating. That is, a large concentration of buildings was subjected to relatively high ground velocities (Wald, 1995). There are undoubtedly many other factors contributing to the Kobe disaster. To be sure, the style of traditional Japanese wood-frame house construction is clearly inferior to that in the US. Nevertheless, in a country known for its attention to detail, many modern buildings were destroyed by a M 6.9 earthquake.

As disturbing as the Northridge and Kobe earthquakes are, they still do not answer the question of what might happen in a much larger urban earthquake. I recently visited a trench opened by Charlie Rubin in a scarp along the base of the San Gabriel mountains about 2 km north of where I live and work. It showed several Holocene offsets of about 2 to 3 meters. I couldn't help but wonder what kind of ground shaking happened in these prehistoric earthquakes. How would our buildings survive in this shaking?

I was reading about Oldham's description of the 1897 Indian earthquake. Of course little definite is known, except that very violent shaking occurred over a region of about 250 km by 150 km. Richter's (1958) book says that, "not merely did eyewitnesses report seeing pebbles bouncing on the ground 'like peas on a drumhead,' but numerous instances were observed, photographed, and figured in detail, of posts shot out of their holes and of boulders lifted out of the ground without cutting the edges of their former seats." What happened here? Could it happen again? Could it happen anywhere?

At present, we have only two near-source ground motion records from earthquakes larger than M 7. The Lucerne record taken in the middle of the Mojave desert from the M 7.2 Landers earthquake (Iwan and Chen, 1994) and the Tabas record from the 1978 M 7.4 Tabas earthquake (Shoja-Taheri and Anderson, 1988). Both of these are impressive records, the peak velocities are 155 cm/sec and 125 cm/sec, respectively. The peak ground-motion displacement in the Lucerne record is over 2 meters and it is probably comparable in the Tabas record. While these are very impressive records, it is unlikely that they represent the strongest shaking that occurred in either of these earthquakes. Furthermore, these are not particularly large earthquakes when compared with others in our past. In 1857, the slip on the San Andreas may have been about 10 meters in the Carrizo plain (Sieh, 1978; Grant and Donnellan, 1994), or in 1906 it may have been about 7 meters north of San Francisco (Thatcher, 1975). Ground motions were large enough to snap trees near their base in both of these great California earthquakes (see Wood, 1955, for the 1857 earthquake; see Lawson *et al.*, 1908, for the 1906 earthquake). How do you snap a tree?

While we may not have a very clear idea of what can happen in close to a very large earthquake, we can come to some tentative conclusions. The ground accelerations would be expected to be at least as large as for smaller earthquakes, but they are likely to last longer and to occur over a larger region. Since we already have seen that the median peak acceleration from the near-source region of smaller earthquakes is about 80% g, we should not be surprised by violent shaking in future large earthquakes.

The most important difference between a smaller and larger earthquake is that the larger earthquake will have much larger slips than the smaller one. This means that the peak ground-motion displacements can be much larger than has been seen in the past. I am not aware of any modern city that has experienced a ground-motion displacement approaching a meter—perhaps Tangshan, China, did in 1976, but they had very poor construction (a large percentage of the population was killed). San Francisco may have had large long-period motions in 1906, but the indications are that the epicenter was in the city (Boore, 1977) and thus the city may have been spared from a severe displacement pulse caused by directivity. Even so, the damage from the San Francisco earthquake was severe. The 1923 Kanto earthquake beneath Tokyo probably also produced large ground-motion displacements in a city, but again it is hard to learn the appropriate lessons from this earthquake, except that it devastated the largest city in Japan. What will happen when these earthquakes repeat?

If the average slip on a fault beneath a city is several meters, then we can expect to see ground-motion displacements of meters. Furthermore, these ground-motion displacements will probably happen relatively quickly; remember that the expected velocities probably exceed 1 m/sec. In the 1983 Borah Peak earthquake, eye witnesses reported that a 1.5 m scarp formed in about a second (Wallace, R.E., 1984). Similarly short times were reported for the surface faulting from the Luzon, Philippines, earthquake in 1990 (Yomogida and Nakata, 1994).

These large ground-motion displacements could be especially important for flexible structures, such as moment resisting frame buildings and base isolated buildings. However, there is virtually no past experience with flexible structures that have experienced very large ground-motion displacements. As it turns out, the strain (or drift) in a building due to a wave traveling in the building is approximately the ground velocity divided by the wave velocity in the building (for example, see Hall *et al.*, 1995). Since the waves can interfere with each other due to reflections, and because buildings are nonlinear for large motions, the maximum strain in real buildings could be even larger.

Recent modeling of the response of moment resisting frame buildings to near-source ground motions indicates that drifts in excess of 5% could easily develop in the lower floors (Hall *et al.*, 1995). This is would apply for both steel and concrete frame buildings. Although it seems pretty clear that buildings would be heavily damaged by these large strains, it is unknown if they would collapse. It is clear that they will be taken far into the inelastic range of deformation. If the frame is not ductile, as is the case for most concrete frame buildings built before the mid 1970's and perhaps welded steel frame buildings, there is an even greater concern that the buildings would collapse. Furthermore, these large ground motions have the capacity to overwhelm the displacement limits for existing base-isolated buildings. In fact, ground motions already recorded in the Northridge earthquake are large enough to cause violent impacts of existing base-isolated buildings with their concrete retaining walls (Hall *et al.*, 1995).

So let's recap the situation. The recent experiences of the Northridge earthquake and the Kobe earthquake have already shown us that urban earthquakes can be very damaging and very dangerous. Furthermore, we can anticipate that even larger urban earthquakes are certainly lurking somewhere in our future. We have no direct experience with such earthquakes, but we can anticipate large ground motions having the capability to strain buildings far more than has been seen in the past. These earthquakes also have the potential for completely disrupting our transportation systems, water and power delivery, sewage removal, and many other aspects of our lifelines. Furthermore, in a very large earthquake, this could happen over a very broad geographic region.

Frankly, when I think of these things, it frightens me. Perhaps the one bright spot in this picture is that large earthquakes are rare and our lives are short, so there is still a pretty good chance that we'll already be dead by the time that a very large earthquake visits one of our major cities. Although it seems that counting on the brevity of our life spans is the basis for much of our public policy making, this is clearly shortsighted and could backfire in a few tens of seconds.

So what should be done about the problem of urban earthquakes? Given the tens of millions of people at risk and the prospect of a trillion-dollar catastrophe, it would seem logical that we should invest heavily in understanding how to protect ourselves. Yet we see an earthquake community that is struggling. I won't go into the details here—you know the situation. Furthermore, if the funding problem seems bad to earth scientists, in some ways it is even worse for earthquake engineering. Critical testing has not been done and attempts at mathematical models have been relatively modest.

Given the extreme cost of retrofitting buildings, it seems totally illogical to continue constructing buildings whose response to future earthquakes is unknown. While I suspect that it is feasible to economically construct buildings that would survive very strong shaking, I doubt that we have a clear idea of exactly how to do it. Only through research by both seismologists and engineers can we gain the necessary knowledge to best design buildings to survive such earthquakes.

I think that much of the problem is that the general populace has no knowledge of the issues that I have raised. Furthermore, they are not being told. Consider the problem of the hundreds of steel-frame buildings with welds that were cracked by the Northridge earthquake. As nearly as I can tell, the occupants of most of these buildings have not been told of the problems. The owners of the buildings could suffer catastrophic financial loss if occupants are told that the safety of their buildings is uncertain. Practicing engineers are paid by building owners and it is difficult for them to publicly discuss their concerns about these buildings. Seismologists don't say much about the situation because they know so little about buildings. Although there are many interests to protect, who protects the interests of the occupants?

As many of you know, I have expressed similar concerns about the potential dangers from large ground motions before (e.g. Heaton, 1991). Frankly, some earthquake professionals have scolded me for expressing these views. They argue that, while recent earthquakes showed that there are some problems, particularly with older buildings, they also showed that modern buildings have the capacity to withstand the strongest shaking anticipated. These people have also told me that to voice my concerns publicly is irresponsible. Why focus on an improbable doomsday scenario that scares the public and could have a negative economic impact? While I'll concede that doing our science in a public arena is less than satisfying, I think that it is the best way to focus the necessary attention to understand and mitigate our vulnerability to future disasters. How can we expect to obtain the resources to solve these problems if we don't acknowledge that there is a problem? If we do not clearly and openly discuss these critical issues, then there are many compelling reasons for people to assume that the *status quo* is adequate. Unfortunately, learning that the *status quo* is inadequate could come at a very high price.

I feel that we have been evading key issues about the potential impact of large earthquakes on cities. The social and economic pressures associated with these issues are so intense that many earthquake researchers avoid direct discussions of our ability to predict the consequences of large urban earthquakes. As serious as earthquakes like Northridge and Kobe were, I suspect that they will not receive much attention in future history books. These pages are reserved for the much larger earthquakes that will inevitably strike heavily urbanized areas. I feel very frustrated knowing that we have been given warning signs of things that may go very wrong in the future, but we lack the necessary knowledge to take the steps to protect ourselves. If most of the public knew how much could be done, but that isn't being done, I think that they would be frustrated too.

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