Integrating the public into earthquake engineering

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ABSTRACT: Within the earthquake engineering community as it is usually defined, several kinds of professionals need to integrate their work for successful earthquake-resistant construction to result. Structural engineers, architects, mechanical and electrical engineers, building officials, and a number of specialties in the construction industry need to be coordinated. Stepping back from our earthquake engineering inner circle, we see that we are a very small field that needs to be integrated with something quite large -- the public. The amorphous and ever-present public is our client who pays for our work, the beneficiary of the earthquake engineering we conduct, and the decision maker who brings into being projects to build bridges or buildings that engineers then engineer. One of the ways to engage the public in earthquake engineering and more broadly civil engineering is via what in the United States is called informal learning: learning that takes place out of the classroom. Exhibits are an important aspect of that type of learning, and several examples are provided.

1 INTRODUCTION

1.1 Roles of the public in seismic design

The theme of this year's NZSEE Conference, Towards Integrated Seismic Design, can be interpreted in more than one way. We can interpret that theme as stating the goal of integrating the professionals who are involved in the seismic design process -- the architect, structural engineer, electrical engineer, mechanical engineer, and various other design and construction specialties, as well as the code building officials. We know those roles and who carries them out rather well, in many cases even knowing not only the general type of person, the architect for example, but also the individual architect who is involved in a specific project. The structural engineers are the professionals with the most expertise concerning earthquake engineering, whether it be related to a concrete column or a one-tonne piece of mechanical equipment, and yet they may not be involved in detail in designing or reviewing the non-structural components that are shown on the drawings of these other professionals. That kind of integration is important, but this paper deals with a different kind of integration on a larger scale: the integration of earthquake engineers with the general public. Figure 1 illustrates our little field of earthquake engineering that swims in the milieu of the much larger general public. (I say "little:" in California, the central corps of the earthquake engineers, the structural engineers, add up to less than 4,000; the population is over 38 million, or in other words, for every structural engineer, there are 10,000 members of the public.)

We know the role of the professionals in our little field, but what are the roles of your public? That broad term includes the business owner in Napier, the teenager in Dunedin, the homeowner in Auckland, the head of a government bureau in Wellington, and millions of others. What role do they play in seismic design and how can they be better integrated into that process?

First, let's not overlook the obvious fact that engineers engineer what society wants built. Members of that public are the decision makers that create the project to build an apartment building or a bank, a bridge or an airport. Engineers are given budgets for their work by the clients who pay for it. And although the public doesn't know much about all the diligence and talent that goes into the seismic design of a project, and hence they may not appreciate the work the engineer does, they are the

beneficiary of good seismic design. It is they who are protected, life and limb, and protected against excessive property loss and functional loss, by the diligent work of earthquake engineers. Thus the public plays the role of decision maker, the client who pays the money, and the beneficiary. If we can integrate the public more closely into our little field, we can both benefit.

In San Francisco in 2013, a law, the Mandatory Soft Story Retrofit Ordinance, was passed that pertains to soft story apartment buildings, a condition caused by a high-density urban environment where often most of the ground story is devoted to parking underneath the building. The owners of these buildings are being required to hire engineers to evaluate the need for seismic retrofit and proceed onward through retrofit construction from there. Predictably, the engineers, in this case represented by the Structural Engineers Association of Northern California, have been strongly in favour of this law, the rationale for which is that after a large earthquake many housing units would have to be vacated while repairs are made. This is a significant leap in the scope of building code laws beyond the goal of public safety, a leap some engineers have personal qualms about concerning how much the government should tell the private property owner what to do with their property. (While I am a member of SEAONC, I have reservations about the self-interested way in which engineers are jumping on this bandwagon. I also think that if apartment buildings are essential and have to be protected to a higher level, we should at least apply the same objective to grocery stores where people will need to get their food, bottled water, flashlight batteries, and other essentials after an earthquake. And then the list seems endless beyond there.) Nonetheless, from the standpoint of engaging the public, the San Francisco Department of Building Inspection can be complimented for its innovative work. Many meetings and an "Earthquake Retrofit Fair" have been held, the latter a type of trade show where contractors, building inspectors, and engineers can talk with apartment building owners. Subsidized-interest-rate loans are also being heavily advertised and offered to those retrofitting their buildings.

Hopkins (2009 p. 1), in his global overview of earthquake risk reduction efforts, concludes: "It is clear that reduction of earthquake risk is not a technical problem – many adequate design and retrofit solutions exist for just about every situation. Better technical solutions can and will be developed, but the main challenge is a social and political one." When we identify a problem as social and political, if we are in any country that is even moderately democratic, we are talking about the public. If we want solutions to social and political problems, we need to have the public's support.

All of us have concentric circles of interests, interests in the sense of having a stake in something and a loyalty toward it. Beyond the innermost circle of the interest we have in the earthquake safety of our own selves and our families, we next tend to look at earthquake engineering as a national cause, and thus "the public" is tantamount to "the population of my country." But increasingly we look beyond our borders to view earthquake engineering on the global scale. Those of us in the richer countries with a more highly developed earthquake engineering "infrastructure," (university programs in that field, engineering know-how among the practitioners, up-to-date building codes and enforcement thereof) have benefits we can offer to those in poorer countries where an earthquake is a disaster that causes thousands of deaths, not dozens or hundreds. Hopkins (2009) has concisely categorized the various components of both earthquake risk and efforts to control to that risk to a reasonable level. In the form of a rating system, he defines two indices to summarize risk. One is a Single Event Index calculated in terms of the losses from a given earthquake relative to national GDP and to GDP per capita. The other is a Fifty-Year Index that captures all of the credible earthquakes expected in a country over the future fifty years, again stating losses as proportions of national GDP and GDP per capita. A Vulnerability Index calculates losses for important types of construction with a 10% probability in 50 years. And his fourth index, the Capability Index, rates the amount of capability with regard to a dozen categories, such as knowledge of earthquake hazards, political commitment, standards and codes and their enforcement, and technical skills in the design and construction industries. He points out, based on a study of residential earthquake retrofitting in Istanbul, that people need to have belief in the threat of earthquake damage, trust in those who would carry out retrofits, and some help in funding the work -- in other words, public attitudes have to be on the side of increasing seismic safety, not antagonistic to it. The aim of his approach is to motivate governments to take action by keeping track of how well a country is controlling its earthquake risk -- implementing

proven techniques to increase the level of earthquake protection of the country's inventory of construction, rather than increasing the inventory of seismically dangerous construction.

It is often asserted that earthquake risk is growing on an overall absolute scale, without noting that in many places the implementation of seismic codes and practices have reduced the proportional risk and that we are on the right track. I am in favour of that proportional approach to scoring how well we are managing our risks (Reitherman 2012 p. 571).

> Almost all cities have grown over the twentieth century and continue to do so as world population and economic development have increased, and thus the amount of property and people exposed to earthquake and other risks has grown. It would not be remarkable if a typhoon or earthquake striking 24 degrees north latitude, 90 degrees east longitude today caused more damage than one occurring at those coordinates in 1900. That locale happens to be Dhaka, Bangladesh, which had a population of 90,000 in 1900, whereas a century later its population was more than10 million, an increase of more than 100 times. Even assuming constructed property increased only as much as population did, that would mean that if the overall city had a vulnerability in 1900 of experiencing an average 10% damage ratio in a given disaster, then that damage ratio would have to be reduced to one tenth of one percent to keep risk of experiencing absolute loss levels constant for the same event happening a century later. That in turn would imply that the entire vast city of 10 million people in Bangladesh in 2000 would have to be built to be more hazard resistant than even a state-of-the-art hospital or emergency operations center in Japan, California, Italy, or New Zealand today—a damage ratio of 0.1% means virtually no damage at all. It is obvious that the overall risk of absolute loss in Dhaka had to increase in the twentieth century because of the increase of exposure. Just as obvious is the fact that the realistic way to measure growth or diminishment of risk is in proportionate terms, such as losses per capita and per square meter of floor area of construction. For utilities and transportation systems, other proportionate measures are relevant, such as loss per kilometer of pipeline. Losses per currency unit, such as loss per euro or dollar or, in this case of Bangladesh, per capita, can fluctuate significantly based on financial rather than physical factors. If cities, countries, and global indices “kept score” of risk in terms of the losses that are forecast per person and per amount of construction, it would provide a simple but objective measure of risk over time.

The point of the approaches quoted above from Hopkins and Reitherman is the importance of "keeping score." Instead of creating more seismically vulnerable buildings and other construction, we seek to apply today's earthquake engineering knowledge to the task of making that inventory increasingly earthquake resistant as new construction is created and older, more deficient construction is seismically renovated or ends it useful life and is demolished. Consider the case of San Francisco, where the 1906 earthquake and fire caused such spectacular damage. When that city began a program to inventory and require retrofits of its unreinforced masonry buildings in the 1980s, it found that of 2007 such hazardous buildings, all but 123 were built after the 1906 earthquake, not before it (Holmes et al. 1990, p. 2-2). In retrospect it would have been provident had some initial measures been implemented to make brick construction more resistant after that object lesson of the great earthquake of 1906, but that needed legislation did not occur until the 1933 Long Beach Earthquake. At that point, of those 2,007 unreinforced masonry buildings that were to pose such a major social and economic burden to retrofit come the 1990s, all but 28 had already been built: the legacy of dangerous construction had already been bequeathed to future generations.

One final example of the growth of risk, and the role of the public in understanding the need for the application of earthquake engineering and supporting that cause, is provided in a remarkably precocious graphic presentation from four decades ago by Razani and Lee (1973). See Figure 2, in which they project the number of seismically hazardous buildings over future decades in terms of when an effective seismic code might be implemented. The adoption of seismic codes has been a cause led by earthquake engineers, primarily structural engineers, but the support of the public and the public's representatives in government have also been necessary.

A possibly useful resource can be cited from the field of medicine, *Engaging the Public in Critical Disaster Planning and Decision Making: Workshop Summary* (Wizemann et al. 2013). Several different techniques were tried out in different communities to engage samples of the public in discussion of alternative responses to disaster scenarios. In one method, ("Q-sort"), previously compiled opinions that extend over a wide range are concisely stated on cards. Interviewees sort the cards as per the instructions of an interviewer, such as into three piles: the statements the person agrees with, disagrees with, and a third category of cards that one neither agrees nor disagrees with. Then further sorting occurs, such as asking the person to sort the "agree" pile to prioritize the statements in terms of how much they agree with them. As the process goes on, the interviewee explains his or her rationale or feelings about the choices being made. The process is said to not only elicit what various members of a community think but also enlighten them as to the range of opinion that exists. The method comes from the field of psychology where it is used in one-on-one situations, but it has also been used in group settings.

1.2 **What does the public know about earthquake engineering?**

The pessimistic but realistic answer based on American experience is: not much. And in some cases, much of that knowledge is wrong. If at a cocktail party I say I'm an earthquake engineer the response is, "Oh, so you're a geologist?" After a newsworthy earthquake, the media will quote a seismologist, even though the big story is that the reason so many people died in a town in India or Iran is that the buildings were made of unreinforced masonry. I once sketched a little perspective view of an unreinforced masonry building, showing what was (and wasn't) inside a cutaway view of a wall, for a journalist who had covered several earthquakes. She was surprised to learn the meaning of the term she had been using in her stories, which had featured interviews with geologists. The science of faults and plate tectonics is good material for the public to learn, but after an earthquake when the photos are mostly devoted to damaged buildings and infrastructure would be a perfect time to give the public some knowledge about earthquake engineering. When earthquakes come up in conversation, people fixate on the soils factor, admittedly important, but generally not as important as building construction. I've heard people say "we're safe; we're located on a hill in San Francisco; it's bedrock," and then find out their house predates any seismic code by decades and has an unreinforced brick foundation.

Sometimes even when engineers are quoted, they are described as being scientists. The team that conducted a recent study that estimated how many older concrete buildings in Los Angeles could collapse in an earthquake was composed mostly of structural engineers, with one architect, Mary Comerio of the University of California at Berkeley. When the study was the subject of a news article, she was described this way: "Lead scientist Mary Comerio said a major quake on the Puente Hills thrust fault, which runs directly beneath downtown Los Angeles, could kill between 300 and 2,000 people in concrete structures alone, and could inflict $20 billion in damages." When Wayne Clough was selected as the head of the Smithsonian Institution, he was described in newspaper accounts as a "scientist," even though he is a civil engineer by background -- and one of our own earthquake engineers, having been a geotechnical engineering professor at Stanford University studying earthquake topics such as liquefaction. As explained later, the distinction between science and engineering is an important one. Hence, first of all we have the problem that people do not know what an earthquake engineer is. Tom Paulay once noted, "Sometimes, when I was annoyed by the ignorance of people asking what civil engineers do, I replied, "Madam, amongst many things they do, they attend to your personal needs after you pull the chain." (Paulay 2006, p. 152) The X brace has become the layperson's logo for earthquake engineering, even though buildings can have other structural systems with no X braces (or may have braces that aren't an X configuration, because such non-X braces can have some advantages in increasing the effective length of the diagonal and allowing for a controlled, ductile buckling to occur before overloading of the joint.)

At the newly built and very large California Academy of Sciences in San Francisco, an exhibition on earthquakes was mounted in 2012 and featured heavily in advertising. It consisted mostly of earth science information about plate tectonics and faults. At the end of the exhibition were two small exhibits, the engineering content. One showed what was described as a seismically vulnerable house, the other an earthquake-resistant house. The model that was supposed to show an earthquake-resistant

house featured wall framing with knee braces, short braces extending from the beam near the beam-column joint to about a metre down the height of that column. That kind of bracing has been used on a few barns to resist wind loads, but houses in Califorina use closely spaced studs, not widely spaced columns, and the bracing comes from the nailing of the plywood or oriented strand board sheathing to the studs, with appropriate hold-downs and other connection hardware. Putting a diagonal knee brace in the corners of a woodframe house may have been a scientist's idea of how to brace a house, but it was a misleading error, and one obviously caused by not consulting a structural engineer (or any carpenter). Thus one problem we have in communicating effectively with the public is what has to be called competition from our colleagues the earth scientists. The scientists need to learn to "share the playground," the engineers need to learn from the earth scientists about getting their message out to the public, and one collegial method would be to hold joint press conferences after earthquakes featuring both an engineer and a geologist or seismologist.

What earthquake myths do people believe today in our supposedly well-educated and rationally minded world? In the USA, it is common for people to think the Transamerica Pyramid building in San Francisco is mounted on teflon or is somehow isolated, making it earthquake proof. In fact (Figure 3), the building is rooted in the ground like a fencepost: three levels of basement parking garage and a 3-metre-thick reinforced concrete mat foundation are embedded in the ground. When I tell people that fact when they ask me about the "ball bearings," I may hear the counter-argument that I must be wrong, because they have heard several times that it is in fact isolated, as if hearing that assertion several times were the same thing as having what scientists call reproducible results. People often mention Frank Lloyd Wright's Imperial Hotel in Tokyo as an earthquake-proof design with a special seismic isolation foundation. Again, this is a modern myth: the building was fastened to the ground the way track shoes with spikes gets traction: short piles extended from the bottom of the spread footing under the bearing walls (Figure 4). People also commonly believe that dogs and cats or pet birds can predict earthquakes, that earthquakes are triggered by tides or the alignment of the planets, or that "they always happen here in the night" (or "morning" or "afternoon") depending on the data set of one earthquake -- the last one they felt.

Often people will say, after experiencing a very light level of shaking, that their building was not damaged "because it was designed to flex and move in an earthquake." (Engineers have yet to find a way to make a structure perfectly rigid -- where there is stress there is strain -- and all buildings flex and move in an earthquake.) They will also ask "what magnitude was that building designed for?" not realizing that a given size earthquake (magnitude) generates a wide distribution of shaking severities across a region. Actually, they usually ask "what Richter magnitude," compounding their display of ignorance. (Sorry to be a tough grader when giving marks for the American's general knowledge in this field, but again, it is based on realism.) Richter's 1935 instrumental or Local magnitude scale, popularly called the Richter Scale, is almost always not the magnitude scale on which today's earthquakes are measured. Even for us in the earthquake engineering field, unless one knows which scale (surface wave, body wave, moment, etc.**)** the seismologists used for a particular measurement, it's best to just say "magnitude." It is not very important whether the general public knows one magnitude scale from another, but it illustrates how a little knowledge, knowledge that isn't quite accurate, can get firmly lodged in the brains of the populace. That may actually good news, because it indicates that in the minds of our public we can plant some valid knowledge that will be remembered.

Popular culture has been a hindrance, not a help, in educating the populace about earthquakes. Movies and television shows accentuate reality, and in the case of earthquakes, distort reality, to create drama. Earthquakes are caused by nuclear explosions (not tectonic movement of plates that cause faults to store up strain energy). Huge crevasses open up and swallow city blocks (whereas surface fault rupture, while damaging, is less spectacular, as liquefaction usually is though it can distribute damage throughout a large area). Most of the damage in a city is depicted as skyscrapers snapped in two or fallen over like toppled trees (whereas low-rise buildings are on average more vulnerable.) See Figure 5.

We may make light of the earthquake myths of pre-scientific eras -- the huge catfish, Namazu, that causes earthquakes when it wiggles according to Japanese mythology, and likewise the huge snakes, the Nagas, in Indian tradition. Poseidon ("Earthshaker") was the cause of earthquakes to the ancient

Greeks when he tapped his trident against the ground. To the native Americans of the northwest coast of North America, a battle between a whale and a thunderbird caused earthquakes and tsunamis. But in our scientific era, the essentially skeptical attitude of science and engineering, that statements are presumed false until proven true by objectively stacking up the evidence, has not permeated everyone's thinking. The periodic survey of public knowledge of science conducted by the National Science Foundation in the USA and other organizations abroad is not reassuring either. In the latest survey, 26% of the Americans answered that the sun goes around the earth rather than vice-versa.

In the United States, the people who evaluate "informal" (out of the classroom) science education, such as occurs at science museums or exhibitions, direct exhibit designers to aim their exhibits at the fifth grade (about 10 years old) level. That may sound distressingly low, but perhaps the real level to aim at is lower. An added burden in recent years in America is the 12 million people who are in the country illegally. (People who are against this type of immigration think the 12 million figure is a problem and should preferably be reduced to zero call these people "illegal immigrants;" those who advocate that most or all of the rights of citizens should be conferred on these people call them "undocumented immigrants.") America's immigrants of this type, by whatever name, overwhelmingly come from south of the border, Mexico and other Latin American countries, and they are typically poor and poorly educated. In addition to not understanding English, their language skills in Spanish and their general educational level are not advanced: half the adults have not finished high school. In my opinion there is a low knowledge base among the populace as concerns earthquakes and earthquake engineering, even if we subtract the downward effect of immigration on the public's "grade point average."

1.3 What does the public need to know about earthquake engineering?

One of the things the public should know is what an earthquake engineer is, a definition that most often boils down to a civil engineer, specifically a structural engineer, who contends with earthquake problems. The general distinction between a scientist and an engineer is that the scientist seeks discoveries; the engineer seeks solutions to problems. The scientist can score an achievement by disproving a theory and saying more research is needed; an engineer needs to use current information to get the project built in the next year or two. The earth scientist literally studies what the earth does, including the earth, meaning the soil, up to about 30 metres beneath the building. The engineer of the geotechnical variety takes up the work through those upper 30 meters of the earth to the foundation where the structural engineer begins to take over. If young people want to go into a profession that studies how planet Earth produces earthquakes, they should major in geology; if they want to design earthquake-resistant buildings, they should major in engineering or perhaps architecture. This is basic knowledge that at least in the USA is not common knowledge. Hence one service earthquake engineering organizations can provide should be aimed at students prior to the age when they select a college and begin their studies. Around the world, it is common that a student must decide to major in civil engineering by their first or at latest second year in college (and if they went to an institution that has no civil engineering department they are of course out of luck if they then find that discipline attractive).

The public should know how sophisticated earthquake engineering is and appreciate the education and experience the engineer needs to have. There can be a common misconception that engineers apply standard "recipes," look up numbers in a table, and tinker for a little bit to come up with answers. Or people think that the engineer has a computer that does all the thinking. We come into contact with doctors from an early age and realize they are busy, important, highly educated people. People don't often meet with engineers and understand their level of expertise and how carefully they have to apply judgment. Conversely, it is common to over-rate what earthquake engineers are capable of today. The public may assume that today's state of earthquake engineering should provide earthquake-proof performance, and therefore any damage is a failure, a failure in the sense of a failure of the profession to deliver on its promise. Earthquake engineers need to avoid over-emphasizing the risk faced, using the scare tactic, and at the same time they need to explain that unless someone wants to pay much more for a building than is required by the minimums of the building code, come the infrequent severe earthquake shaking there will be damage. Some damage of the ductile type is in fact desirable and

strategically designed into various areas of the structure. In an automobile crash, at a low speed the bumper gets dented but the engine compartment is undamaged. At a higher speed the bumper and the engine are damaged but the steering column does not poke into the driver. The public needs to understand that something similar is intended for the earthquake performance of their buildings and their infrastructure.

While the general public could have a better understanding of some of the basic fundamentals of earthquake engineering, we expect the engineers to provide the earthquake engineering expertise on behalf of the public in the design of their constructions, at least the types of construction that are more essential, have more occupants, or are larger. But the engineer doesn't go into each residence and point out that next to the bed tall bookcases are placed (poised one might say, picturing what those objects will do in an earthquake). Gas-fired water heaters are usually braced, if they are at all, by either the plumber or the resident, not by a structural engineer. This is another kind of knowledge the public should have, the self-help knowledge for application in their residences and workplaces with regard to non-structural hazards.

2 ENGINEERING LITERACY

Knowledge about earthquake engineering, and civil engineering in general, can also serve broader educational goals. For several years in the USA, the acronym STEM has been used by the National Science Foundation to refer to learning about Science, Technology, Engineering, and Mathematics. This emphasis on knowledge about those fields extends to formal learning (in the classroom) and also to learning that takes place in informal settings such as museums, a zoo or aquarium, or seeing exhibits mounted next to a civil engineering work.

In the United States, a new set of educational science standards for K-12 curricula was developed in 2012, called the Next Generation Science Standards (National Research Council 2012). Related to it is the Technology and Engineering Literacy (TEL) assessment starting in 2014 as part of the National Assessment of Educational Progress. The Next Generation Science Standards, as compared to earlier science curriculum standards, move engineering up front, and it is presented as more than just applied science. There is recognition that engineering is a discipline in its own right, and while there is overlap with science, there is much that is unique, especially in the area of engineering design. The Next Generation Science Standards call for a focus on eight scientific and engineering practices. One of them (NGSS practice 6) focuses on engineering design, emphasizing the engineering thought process, not just engineering facts. Including anything called engineering in the kindergarten-through-grade 12 curriculum is a big change, and a positive one.

Engineers consider alternative designs, each design having its own advantages and disadvantages. It may seem obvious that analysing such trade-offs is part of the engineering thought process, but we should not assume that non-engineers understand that. Many people assume that from engineering formulas come the finished design, the optimal solution. They often don't realize the broader context of engineering design, such as aesthetic, economic, and social factors. An example of how an understanding of the earthquake engineering thought process can be a useful tool for efforts to increase engineering literacy in general is the engineer's choice of a structural system. The engineer has a range of potential solutions--walls, frames, braced frames, and four basic materials -- concrete, steel, masonry, timber. Relying on walls to resist earthquake forces has architectural implications. Maybe opaque walls can be conveniently located where the seismic-force-resisting ones are needed for architectural reasons, but sometimes not. The walls are stiff, which means the upper story will distort sideways only a little more than the story beneath, and that the roof will not lean over very much (will not experience much drift) in an earthquake. This is good for reducing the distortion that a non-structural component such as partitions or curtain walls are required to undergo. But there may be a trade-off because the stiff walls make the structure have a natural tendency to vibrate more rapidly than if it was braced with column-beam frames that have continuous (moment-resisting) joints. That concept of how important stiffness is, not just strength, is one that most people can understand who have never taken an engineering class, if it is presented to them clearly. And in understanding how stiffness relates to an earthquake engineering problem, they also learned something about engineering

methods in general and how engineers must contend with more than one factor at once. Thus, one of the primary ways to increase engineering literacy is to explain how engineers think rather than only explaining the technical points of their final products.

Another concept useful in the effort to increase engineering literacy is the frequency and the way a structure responds to input motion depending on the match between its natural vibration property and the earthquake motion. This is an earthquake engineering concept that in generic form has many examples in other fields. One tunes a radio to the frequency of a particular station, making the receiver sensitive to that frequency but not to others (imagine listening to a dozen stations at once). Tiny structural components of our ears vibrate in response to sound waves in such a way as to be rather insensitive to very low frequency (low note) sounds -- the sound doesn't sound very loud or clear. Humans can discern sounds at 1,000 Hz much better than they can at 40 Hz. Light vibrating at low frequencies looks red, and at even lower frequencies we can't see it at all even though the infrared radiation or light is still there. One synchronizes ones pushes of a child in a swing so that as the child is just ready to swing downward because of gravity, one's push gets added to that motion. Inverted, we have a structure which, after the ground moved one way the structure's inertia caused it to bend the other. The next instant, the ground moves in reverse direction just as the elastic energy stored up by the strained material of the structure makes it spring back in the same direction the ground motion is throwing it, and we get much larger motions. Teaching the public about the concept of frequency and dynamic response is one of the most fruitful subject areas for expanding engineering literacy, not just earthquake engineering literacy. An earthquake response spectrum could be understood by a high school physics student, for example, as an application of the basic concept of frequency. It just takes a little effort to present the material in the right way. (Thus for that educational purpose I prefer "frequency" to its inverse, "period of vibration," because "frequency" is such a common concept in physics.)

3 USING EXHIBITS TO EDUCATE THE PUBLIC ABOUT ENGINEERING

Several examples can be offered for ways to use exhibits to communicate basic ideas about earthquake engineering and civil engineering in general to the public.

3.1 The Golden Gate Bridge Permanent Outdoor Exhibition

The Consortium of Universities for Research in Earthquake Engineering teamed with the Golden Gate Bridge, Highway and Transportation District to a obtain a US $3 million National Science Foundation grant to develop a permanent outdoor exhibition at the San Francisco side of the bridge explaining its engineering and history. In the words of the general manager of the Bridge District, Denis Mulligan, "Visitors come to the bridge as sightseers, but they leave with the experience of having their curiosity piqued by innovative engineering exhibits." Figure 6 illustrates the in-progress renovation of a nineteenth century army fortification into an outdoor gallery, the centrepiece of which is a precisely fabricated scale model of the bridge made out of an especially durable grade of stainless steel (Duplex 2205), primarily designed by Professor Maria Garlock of Princeton University and a former Princeton student of hers, now a practicing engineer, Sylvester Black. Satellite exhibits around the big model and keyed to it let the visitor learn about the engineering of different aspects of the bridge.

A few examples of exhibits at the bridge will suffice to illustrate the thought process that went into designing them. The examples have been chosen for their value as teaching points about the effective design of engineering exhibits. The reader can imagine how the approach illustrated for each exhibit could be applied to a different engineering topic. The first example (Figure 7) illustrates the value in letting a visitor literally get a feel for the forces involved in a civil engineering structure. Sightseers at the bridge, who number approximately 9 million per year (i.e., the visitors who walk around and on it or ride a bike across it, not the commuters) frequently experience the breezy conditions there, and hence the question arises, how does the bridge resist the wind? One exhibit conveys the fact that as the wind speed increases, its resulting pressure greatly increases. Instead of just saying "wind pressure increases as the square of the wind speed" on a display panel, we also let the visitor literally get a feel for this phenomenon. As they push on a one-square-foot, one-tenth-square metre, plate on which is

painted a hand print to non-verbally indicate what to do, a speedometer like one you would see on an automobile dashboard registers the associated wind speed. This example illustrates the value of hands-on exhibits that allow the visitors to interact with them, to conduct their own brief experiments and see the results. It also illustrates the value of the visitor immediately seeing how to interact with the exhibit, in this case putting their hand on the plate with the handprint on it without even needing to first read the adjacent explanatory panel of text and illustrations.

Another exhibit (Figure 8) provides insights into the trade-offs engineers considered when designing the Golden Gate Bridge. When constructed in 1937, the Golden Gate Bridge had the longest span in the world, but in addition its towers were the tallest bridge towers in the world. Why so tall? Why not taller? The exhibit leads the visitor to pull on ropes to lift simulated bridge decks that all weigh the same, but the case with the shortest towers requires the most force. The tallest tower design, the one with the greatest lever arm, results in less tension and thus a smaller cable could have been used. On the other hand, there would have been the added difficulty of making even taller towers. The aesthetic aspect of a suspension bridge is also highly dependent on the proportion of the height of the towers above the deck compared with the span. Thus beyond the single technical fact about the relationship between cable sag and cable tension in a suspension structure, the broader point is made about how engineers consider multiple, often conflicting, factors in reaching a successful overall design.

The exhibit with Braille captions and with an elevation of the bridge and 3D replica of one of its towers allows a blind person to get a tactile impression of its geometry. The inclusion of the profile of the seafloor was included to explain why the engineers made the span of the bridge so very large. Moving the towers closer together would have meant founding at least one of them in deeper water. An adjacent exhibit explains what was the most difficult construction challenge in the whole undertaking, the underwater foundation construction, and one which is not visible today and thus visitors do not think of it. People tend to look at the completed engineered design as if the efficiency of that solution was the only consideration, but the construction process is often a major consideration in the selection of solutions. In the case of the Golden Gate Bridge, divers relying on air hoses in the era before scuba could only work on the seafloor during the slack water time of ebb-flood tidal transitions. Everything about the difficulty and danger increased with depth. Moving the south tower closer to the other one to the north would have meant founding it down the relatively steep underwater slope, and the tradeoff between shorter span but more difficult foundation was not worth it. In addition to the final cast bronze version of the exhibit, the figure also shows the initial sketched conception and then the intermediate step of producing a mock-up machined in plastic with Braille labels located around different parts of it. The design and its captions were refined as per the recommendations of blind people at the LightHouse for the Blind and Visually Impaired. Had my initial concept been translated directly into bronze, without the trying out of a mock-up by intended users, the result would have been much less effective.

Those of us who have had to put up with a two-decade-long process of building a US $6.4 (NZ $8 billion) portion of the San Francisco-Oakland Bay Bridge, and whose tolls and taxes have paid that sum (and slightly more than that amount to come in interest costs on the bonds) realize how bad decisions concerning the construction process can be costly. The cost of the new segment of the Bay Bridge is NZ $1.7 million per meter. More conventional designs would have cost one sixth as much and built years earlier. The new section replaces the 1936 steel truss double cantilever span -- a span that was 10% longer (427 m as compared to 385 m) than the new span. The new span did not require engineering heroics; that new span doesn't even make the list of the 200 longest bridge spans in the world. The old section the new design replaced in 2013 used one-fourth as much steel per square foot (Middlebrook and Mladjov 2014). The new self-anchored east crossing span uses more steel than the entire original Bay Bridge from end to end, including not only the section that has been replaced but the two 2,310 ft (704 m) suspension bridges that extend from the island in the middle of the Bay, Yerba Buena Island, to San Francisco. Engineering economy and sustainability somehow got overlooked. The two arms of the double-cantilever original span were built out to each other without shoring, (see Figure 10), while the self-anchored suspension bridge required shoring of all its length until completely finished, requiring large amounts of steel trusswork now sent to scrap heaps.

For the Golden Gate Bridge exhibits, CUREE designed nine tabletop displays that explain the sequence of design and construction of the bridge (Figure 11). We thought that was an important engineering insight to get across, not just how the structure stood up once all the pieces were in place. A suspension bridge, unlike a self-anchored suspension bridge, needs no shoring as it is constructed. Some people like the aesthetics of the new Bay Bridge self-anchored suspension span, but its "fan base" is tiny compared to the world-famous and world-loved Golden Gate Bridge, and even the other portion of the Bay Bridge, the suspension bridge spans with decorative patterns of lights on the suspender ropes, have stolen the limelight from the new span. The Golden Gate Bridge incorporated numerous aesthetic details that were carefully thought out, but they were inexpensive and did not burden the major task of building the bridge. Other exhibits on the Golden Gate Bridge explain how its vermillion colour was picked and how Art Deco styling is integrated into it. It stands as a wonderful example of 1930s engineering at its best, though of course later knowledge has led to retrofits with regard to wind, earthquakes, and terrorism. The whole reason for demolishing the original section of the Bay Bridge from Yerba Buena Island in the middle of the Bay to Oakland was its damage in the 1989 Loma Prieta Earthquake, and yet even its modern earthquake engineering aspects have become suspect. At what one might call the free tip of the span, except that it is anchored there to a concrete pylon, 32 of 96 large bolts designed to resist seismic shear were found to be fractured -- without an earthquake occurring.

One exhibit at the Golden Gate Bridge shows a seismic isolator as is used nearby in approach spans of the bridge. See Figure 12. From it we can learn that it is more effective to place an engineering exhibit within sight of the real thing, the real structure. Sometimes this precept is called "place-based" learning, capitalizing on being in the presence of the real thing, not just seeing a computer screen's representation of it. The experience of being there at the bridge is blended with and improves the learning experience of the exhibits.

Figure 13 shows a section of strut that was built to mimic a riveted built-up strut in the bridge and to subject it to compressive force until it buckled. This was done in recent years to calibrate analysis of the bridge's seismic behaviour. A huge hunk of bent and buckled steel gets the visitor's attention, and then their engineering literacy increases when they find out that in addition to analysis and computer-based investigations, engineers need to test physical models and compare how that real behaviour compares with how their theory predicts they will behave. Because the replacement of struts with stronger ones in earthquake retrofit work on the bridge is done with care for the historic appearance of the bridge, the exhibit also tells that "softer" side of engineering. New one-piece steel tubes replace the lattice struts built up of dozens of pieces of steel and riveted connections, but the new tubes are laser cut to have the same triangular holes as the old struts.

One more example from the Golden Gate Bridge Permanent Outdoor Exhibition involves the use of analogies. I wanted to put a "flip," a door on a display that you lift to see what's underneath, at a child's eye level, and Figure 14 shows the result. When visitors lift the cover, beneath the elevation picture of the bridge they see a matching picture of animals performing the roles of elements of the bridge. The elephants are the anchorages, and they are drawn to visibly represent how they are resisting the pull of the cables. The gorillas are drawn pushing only upward, as if holding a barbell aloft, which is what the towers do, carrying all the weight of the deck and its traffic down to the ground. In using analogies, it is important to make all aspects of the analogy accurate. The point of the exhibit is to convey the idea of a load path, something that is left bare by a bridge but is usually hidden in a building. The wording of the text again builds on the "being there" experience. It says "Look at the trusses that extend along the length of the Bridge," "See the 500 vertical lines (steel suspender ropes) across the Bridge?" and "When you look at the tops of the two towers of the Bridge...."

3.2 A shake table exhibit that gets across the idea of frequency response

For the RMS company, CUREE produced several exhibits for their corporate headquarters. One of them gets across the idea that two buildings next to each other, with the ground shaking the same underneath them, do not necessarily respond or shake the same. See Figure 14. The visitor turns a knob to change the frequency of the shaking of the ground (the platform), and two nicely crafted metal-skinned but flexible building models respond quite differently, first one tuning in and

responding more, then as the frequency is changed the other one responds more. Simultaneously one can look at the computer display of three graphs depicting the accelerations at the base and at the roofs of the two buildings, corroborating the conclusion the visitor gets from watching how intensely the buildings sway. In one minute, the visitor learns a great deal and would probably not learn the point being made as well if instead someone talked to them for a minute about dynamic response.

3.3 **Earthquake engineering exhibits for the "person on the street."**

In the month of April, 2006, for the centennial of the 1906 San Francisco Earthquake, CUREE was provided with a tent in a plaza on Market Street, the busiest street in the city, by the San Francisco Department of Building Inspection. See Figure 15. People didn't walk that block of Market Street intending to learn about earthquake engineering, but by the end of the month 40,000 passersby had gone through the tent to see its exhibits. We call the anonymous member of the public the "person on the street," but for this exhibition, the visitors were literally people walking along the street. The theme was the engineering that allows earthquake-resistant buildings and other structures to be built. Almost all science museums with exhibits on earthquakes feature only the earth science aspect of that subject, and thus there is a great need for explaining not just what the ground does but how the construction from the ground up is designed.

4. CONCLUDING REMARKS: GENERAL CAVEATS AND TRICKS OF THE TRADE FOR DESIGNING EFFECTIVE ENGINEERING EXHIBITS

A few helpful hints can be offered for designing effective earthquake engineering or civil engineering exhibits towards the aim of increasing engineering literacy. More information is found in the *Building Bridges Between Civil Engineers and Science Museums* book CUREE produced for the National Science Foundation (Reitherman et al. 2008).

- Engineered construction -- a building, dam, bridge, tunnel, aqueduct -- can be the main exhibit, and one that is free in terms of exploiting it for its educational value. Tie the educational content of exhibits to that particular civil engineering construction.
- For place-based learning, practical aspects of the site are foremost. The place has to have pedestrian access, not present any safety or security concerns, and have a good view of the construction.
- Public works agencies that operate bridges, water systems, and other infrastructure can be enticed into the business of providing exhibits for the public. The CUREE project for the Golden Gate Bridge included a conference titled Public Works for Public Learning (CUREE 2012) and an online course in the American Public Works Association continuing education program (American Public Works Association 2013).
- Passersby and sightseers can become engaged with well-designed exhibits, even though the exhibits were not their destination.
- Without "dumbing down" the content, work the text and the images over and over until they present the information as clearly and simply as possible. There is nothing wrong with introducing engineering terminology, but it needs to be prefaced with less technical wording.
- Accessibility includes not only wheelchair access but consideration of those who are blind or visually impaired. More than one language may need to be provided, depending on the visitor base. Informal learning venues, such as exhibitions, usually have a mixture of ages.
- Text should be large (approximately 24 pt is usually recommended) and have high contrast with the background (usually black type on white or light background). Limit the use of all caps type to major headings and avoid the use of italics. Lines of text should not be longer than about 50 characters. More details are provided in Smithsonian Accessibility Program (no date). An exhibition containing only panels with text and images is likely to be less interesting than one that also contains objects (what the museum curator calls artefacts) and hands-on exhibits.

- Outdoor exhibits within sight of the bridge or other construction can be exhilarating, but the elements can take their toll. Exhibits made of hot-dipped galvanized steel, or stainless steel of 316L or more corrosion-resistant grades are advisable. And the most demanding environmental factor is the human one in the form of intentional vandalism and theft in outdoor areas that are by their nature not as well supervised as an interior space in a museum. Unintended damage or safety problems can also occur because of visitor misbehaviour, such as climbing on exhibits.
- Sharp edges and anything that can cause a bump on the head must be prevented.
- Electricity can be difficult to arrange in outdoor settings, introduces a hazard, and should be used only if non-electrical exhibits can't do the job.
- Visitors don't usually spend more than a fraction of a minute or a few minutes with an exhibit, and many will sample a few exhibits but not all of them. Informal education isn't like classroom education where the teacher expects all the pupils to pay attention to the lesson for a full hour. A brief educational experience is still a valuable one.
- Don't think of a set of exhibits as chapters in a book, because visitors may interact with them in different sequences, or skip some exhibits. Also don't be afraid to repeat some things in different ways on different exhibits, for even the visitor who sees all of the exhibits will have their insights reinforced.
- Photo opportunities don't necessarily distract from the learning. People who take snapshots of their friends and family standing by an exhibit are going to provide free advertising when they circulate those snapshots with others, as is electronically commonplace today.
- Get independent opinions on early drafts of a design, preferably mock-ups in three-dimensions (such as made out of cardboard or plywood). Evaluate what the visitors think of the exhibits in mock-up and in their final form: how long do they spend with the exhibit, did they find it entertaining, did they learn the key point of the exhibit?
- For earthquake engineering exhibits, concentrate on the engineering, for almost every science museum and science curriculum in the schools will concentrate on the earth science aspects of earthquakes. Plate tectonics is fascinating, but it doesn't tell an engineering story.
- Exhibits should be fun, not just educational.

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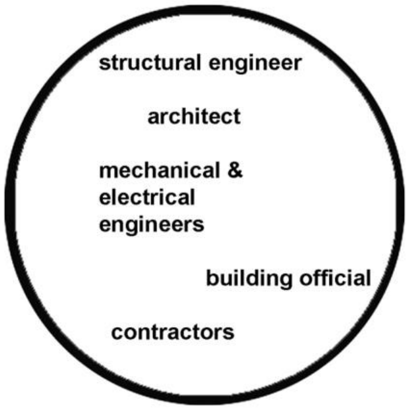
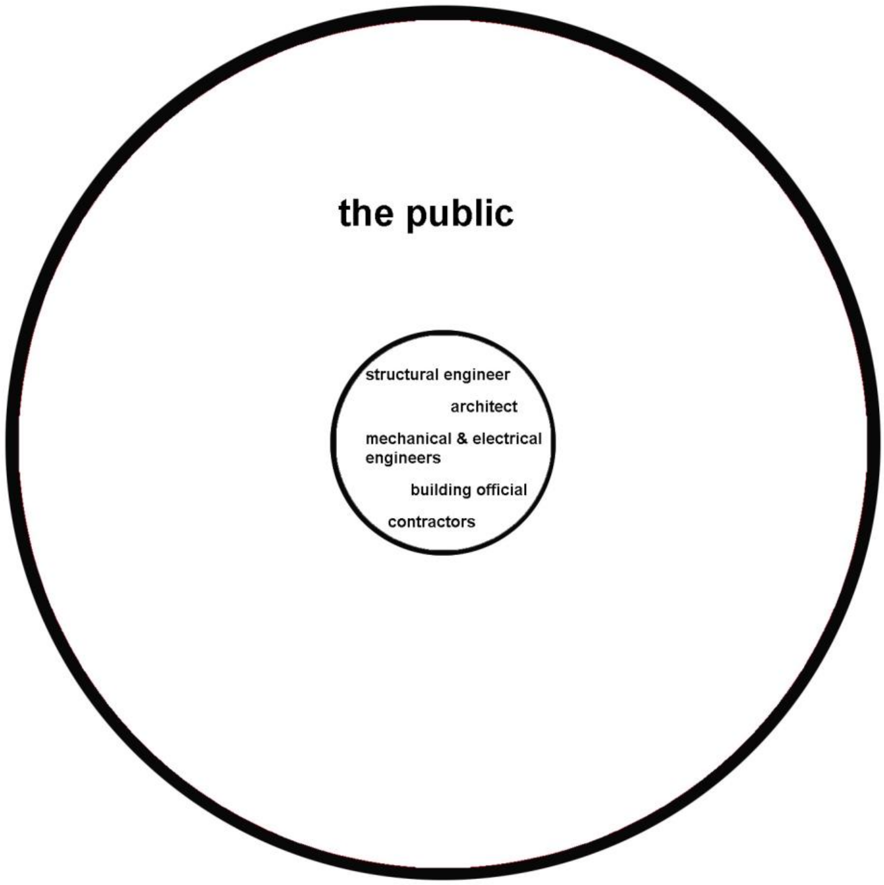


the earthquake engineering community as we often see it



the earthquake engineering community as it really is

Figure 1. Our Little Earthquake Engineering Field vis-a-vis the Public

CONDITION OF SHIRAZ BUILDINGS IN YEAR 1984 (1363) AND THE CODE EFFECT

Year of Adopting Seismic Code		1951 (1330)	1961 (1340)	1971 (1350)	1981 (1360)
Built According To Seismic Code	No. Buildings % Total	82400 %94	73600 %84	59000 %67	20000 %23
Built Before Code Adoption	No. Buildings % Total	5600 %6	14400 %16	29000 %33	68000 %77

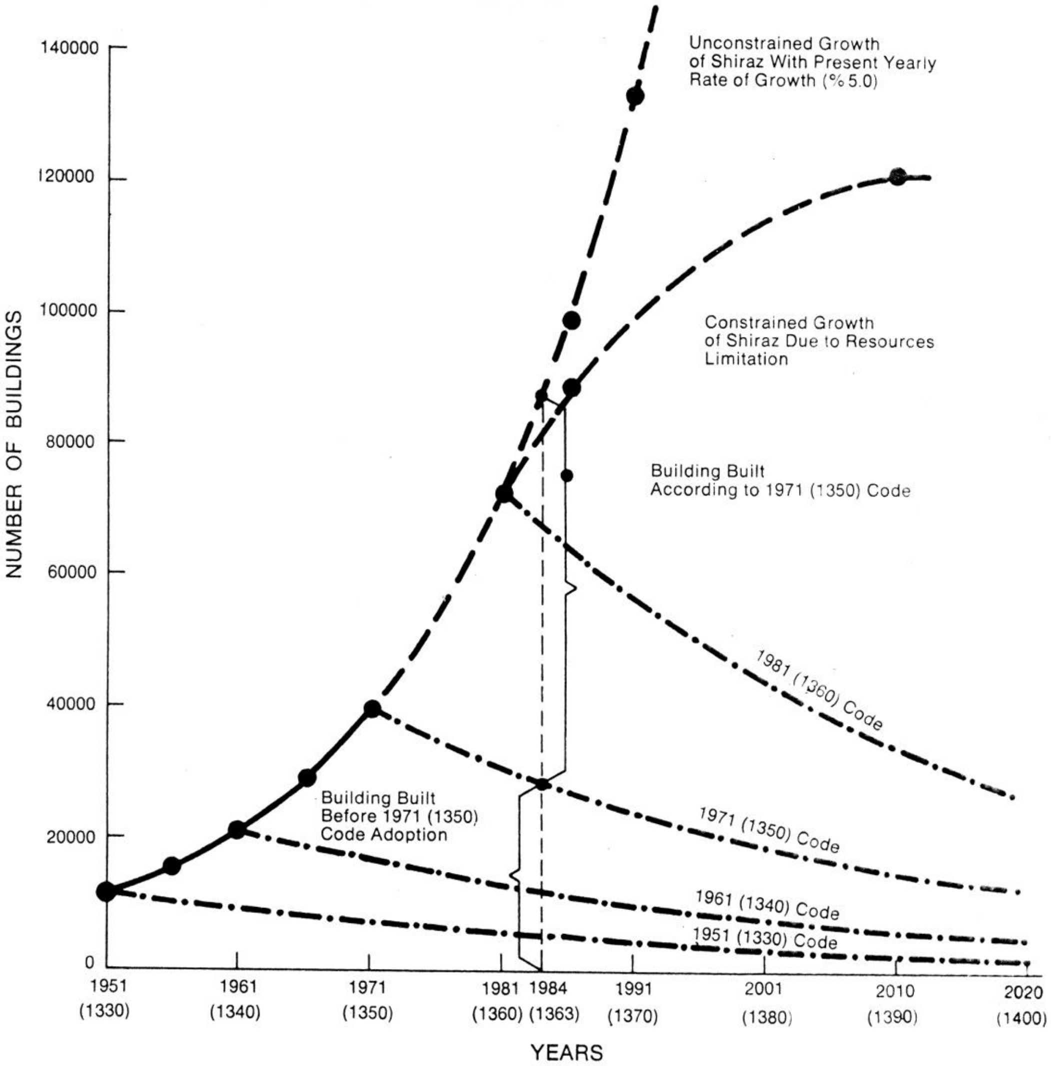


Figure 2. Projection of the Growth in Vulnerability Without the Adoption of a Seismic Code (Razini and Lee 1973)

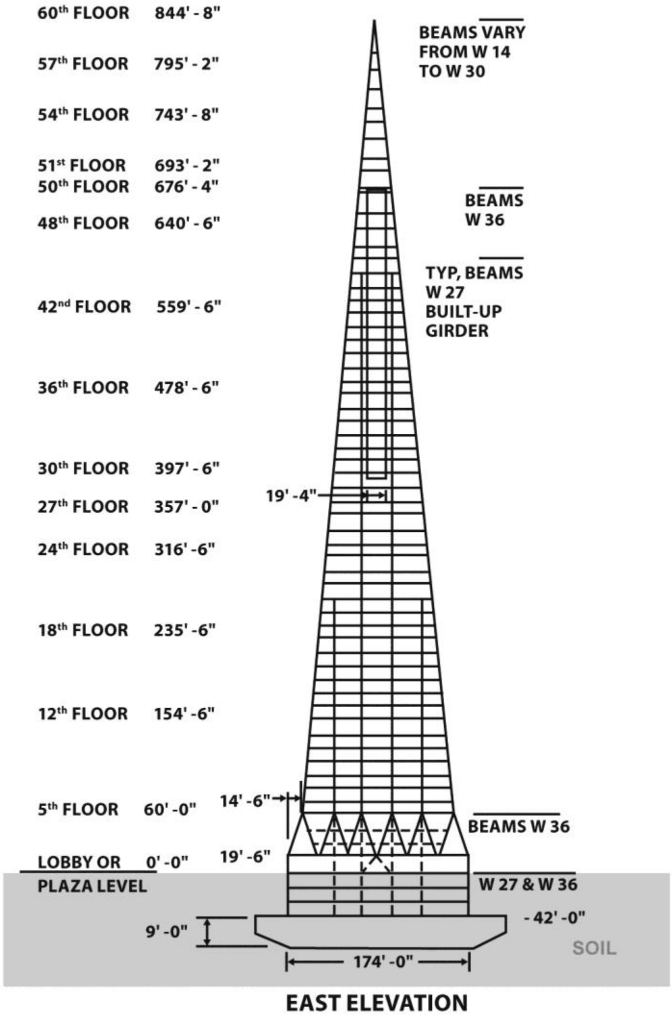


Figure 3. Pyramid Building in San Francisco (Stephen et al. 1974)

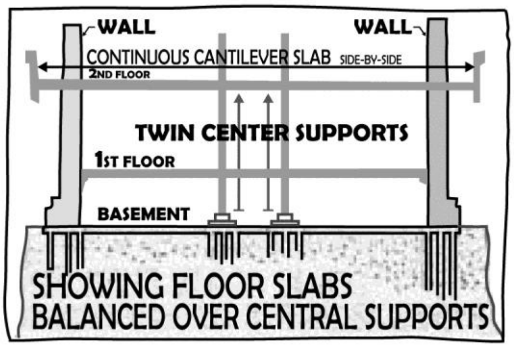
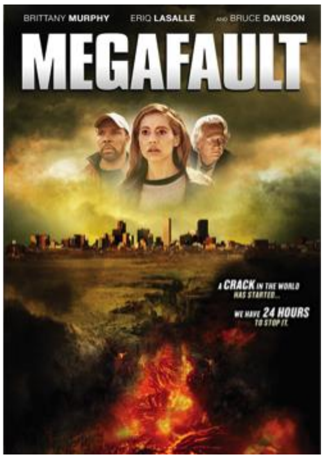


Figure 4. Cross-section of the original Imperial Hotel in Tokyo



Global Asylum, Inc.

TomCat Films, LLC

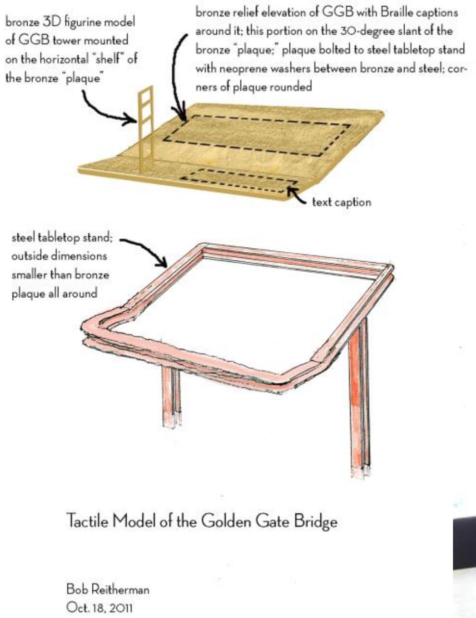
Universal Studios Licensing, LLC

Figure 5. Earthquakes as We Learn About Them from the Movies

Figure 6. Golden Gate Bridge Permanent Outdoor Exhibition

Figure 7. Golden Gate Bridge Wind Pressure Exhibit

Figure 8. Golden Gate Bridge Exhibit Relating Tower Height to Cable Tension (The Exploratorium)



initial concept

mock-up at the LightHouse for the Blind and Visually Impaired

completed exhibit in cast bronze

Figure 9. Golden Gate Bridge Tactile Exhibit with Braille

Figure 10. Original Double Cantilever Section of the Bay Bridge, Under Construction (California Department of Transportation)

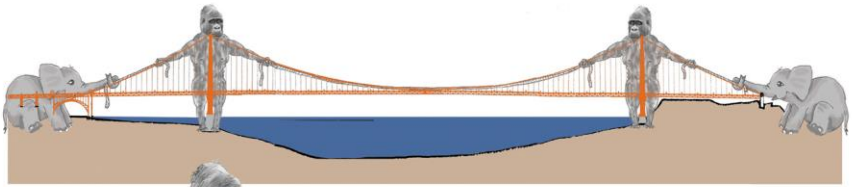
Figure 11. Golden Gate Bridge Construction Sequence Display

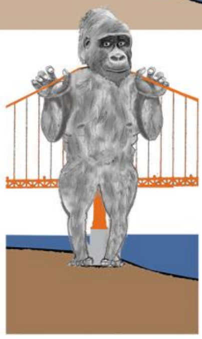
Figure 12. Golden Gate Bridge Seismic Isolator Exhibit

Figure 13. Golden Gate Bridge Strut Exhibit (structural specimen and photograph of test apparatus courtesy of Prof. Hassan Astaneh-Asl, U.C. Berkeley)

load path explanation in text and photos **low-height "flip" reveals animal analogy**

first version of animal analogy





refined version of animal analogy

Figure 14. Golden Gate Bridge Exhibit Explaining How it Spans Across the Golden Gate Strait

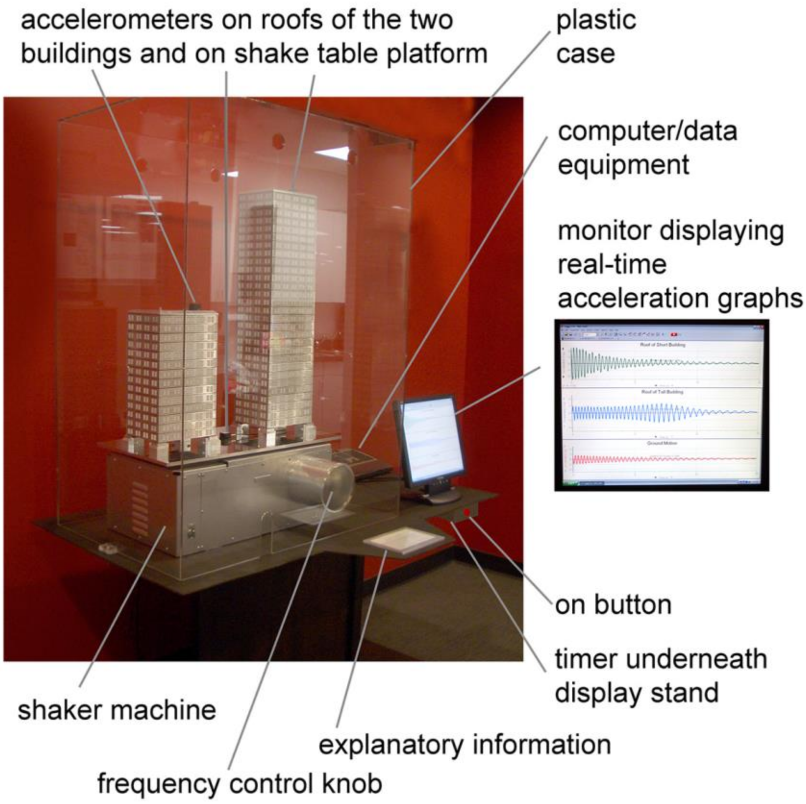


Figure 15. Variable Frequency Shake Table, RMS, Inc.

Figure 16. Earthquake Engineering for the "Person on the Street"