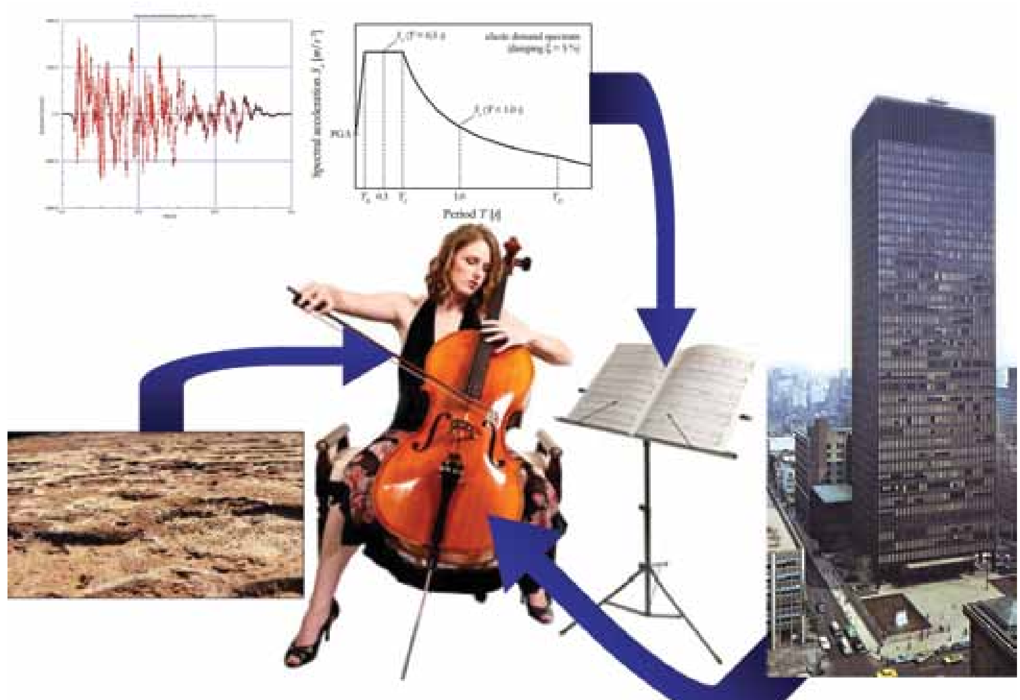

Figure 1. Analogy: The ground exerts seismic forces upon a building following particular spectral acceleration, not unlike a musician playing an instrument according to a given score.

Understanding Seismic Design through a Musical Analogy

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Seismologists, earthquake engineers and seismic code experts understand the science of earth that moves and the structures built on it, but many of the concepts involved may be too abstract for architects, builders and the public. This article offers an analogy to help explain seismic design and presents three different construction techniques used in Chile, Japan and the United States that counter an earthquake's effects.

Earthquake ⇔ Music

The ground exerts seismic forces upon a building following a particular spectral acceleration, like a musician playing an instrument according to a given score. In both cases, there are several elements that determine how energy is transferred, and describe how it is felt.

Earthquake ↔ Music
Soil ↔ Musician
Seismic Spectrum ↔ Score
Building ↔ Instrument
Building's Response ↔ Sound
Building's Occupants ↔ Audience
Event's Social Context ↔ Concert Hall

Soil ⇔ Musician

The musician engages her instrument just as the ground engages a building's foundation (*Figure 1*). She plays her instrument based on a score composed of a variety of musical pitches (frequencies), dynamics (loudness), tempo (velocity/acceleration) and time (length of the piece). In the same way, ground-waves "play" a building with varying frequency content, magnitude, acceleration and shaking duration. Both instrument and building either absorb or resonate the energies received based on their structure.

Different musicians play an instrument differently – musicians have different temperaments, hold their instruments differently and play with greater or lesser force. Different soils similarly "play" upon structures in varying ways.

Solid rock provides a strong foundation for a building. This dense medium also carries seismic energy at high speeds and over great distances. For example, granite, with densities generally ranging between 2.5 – 2.7 grams per cubic centimeters (g/cm^3) or 155-170 pounds per cubic foot (lbs/ft^3), carries compressive-dilating P-waves at up to 6,000 meters per second (m/s) or 19,700 feet per second (ft/s), and shearing S-waves at up to 3,300 m/s (10,800 ft/s) (*Bourbié 1987*). These speeds are a function of the material's elastic properties: the incompressibility modulus (k) and the rigidity modulus (μ).

Figure 2. Liquefaction damage to New Zealand highways during the 2011 Christchurch Earthquake. Courtesy of NZ Raw, 2011.

Figure 3. Soil liquefaction at Cherrapunji cemetery, 1897.

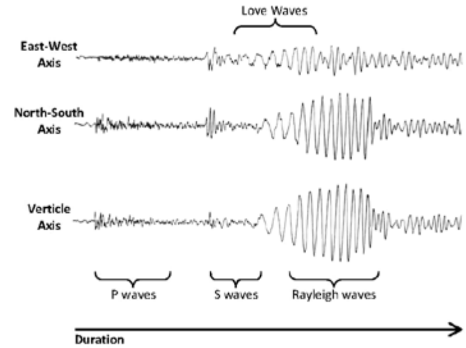

Figure 4. A "composition" of waves over time. Represented (from top) on east-west, north-south, up-down axes. Courtesy of Ota Kulhanek, 1990.

Sand, on the other hand, being far less dense at approximately 1.5 g/cm^3 (95 lbs/ft^3) and having lower elastic moduli, may carry the P and S waves at only 400 and 100 m/s (1,300 and 300 ft/s) respectively. This medium will therefore quickly dissipate an earthquake's momentum; but, at low densities and high water saturation, it is susceptible to "liquefaction" or displacement from beneath the building whereby, under certain vibrations, sandy soils act as a liquid (*Figure 2*). A first-hand account of the 1897 earthquake in Assam, India by Captain A. A. Howell illustrates this phenomenon:

> *Several posts have sunk from a few inches to a foot deeper into the earth, causing the floor to buckle and the roof to sag. Many, too, are out of the perpendicular. At the point each post enters the ground, a cup-shaped depression, from one to six inches in depth and diameter, has been worn round it as though the post had been given a circular movement… Many houses sank into the ground bodily, the roof alone being visible… Several villages were, and still are, partly submerged (Oldham, 1899) (Figure 3).*

Clay and ***silt*** act like a bowl of jelly, reverberating the seismic waves received from deeper and more rigid strata. The softer soil amplifies the shaking by a factor of four or more, depending on the wave frequency and the thickness of the layer of alluvium (*Bolt, 1993*). Subsequently, within the softer material, seismic energy may get trapped by reflection and refraction of these waves. This effect is similar to the trapping of sound waves in a concert hall where the sound energy echoes back and forth from the walls. In such cases, the phase of each component wave is critical, since when waves are in phase, the energy is compounded.

Seismic Spectrum ⇔ Score

A musical composition is defined by the loudness, pitch and tempo of its note, and can be represented graphically as a score. A specific earthquake can also be represented graphically – seismologists do this with seismograms, while engineers use spectral acceleration models.

An earthquake is defined by its magnitude (loudness or energy it releases), frequency content (pitch), and acceleration (tempo). The waves of ground motion develop and change over distance as a result of geological properties and elasticities of the component soil materials, as well as the waves' reflection and refraction. These waves reach the earth's surface in different locations, at different times, then join together to produce a "composition" of P waves, S waves, Love waves, and Rayleigh waves that can be transcribed by seismographs (*Figure 4*).

Because P waves travel fastest of the four wave types, they arrive at a location prior

Types of Seismic Waves

All elastic bodies, including geological media, carry two types of waves outward from the source of an impact – in this case, the epicenter of an earthquake. We identify these as primary (P waves) and secondary (S waves). P waves resonate through compression and dilation of (pushes and pulls within) the medium, the same way that sound waves travel through the air. Soils, unlike gasses or liquids, also transmit S waves that twist and shear the medium. These waves move the particles of the material transversely (either vertically or horizontally) to the direction of the wave's propagation. These motions are more similar to the behavior of light waves. P waves always travel faster than S waves.

When P and S waves reach the earth's surface, or planar boundaries between geological strata, additional types of surface waves are generated. These waves behave comparably to sound that travels along the surface of a dome's interior. Love waves are one type of S wave whereby surface particles shear only along the horizontal plane, perpendicular to the direction of propagation. Another type of surface wave is called Rayleigh, which causes surface particles to move forward, up, backward and down, in the direction of propagation, similar to ripples in a pond (*Figure 5*).

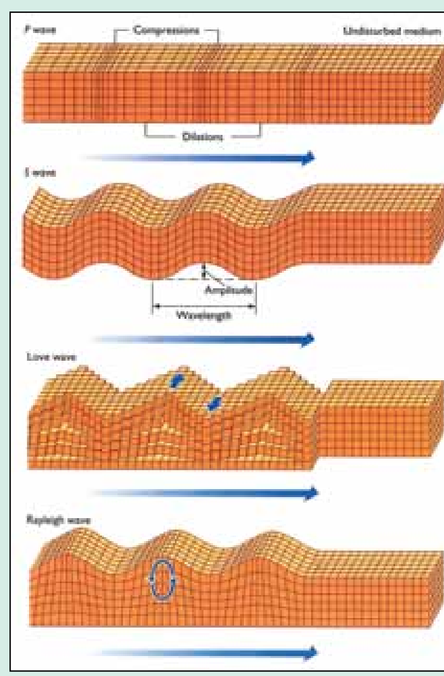

Figure 5.

to surface waves, which tend to be more destructive. P waves thus serve as a kind of early-warning system in advance of subsequent, more severe shaking. This resembles the traditional structure of a classical symphonic score – four movements, where the first, a fast-tempo Sonata Allegro, foretells what is to come.

Building ⇔ Instrument

A musical instrument and a building both resonate, but while a musical instrument is designed to resonate music, a building is engineered to do the opposite – to stifle reverberation. The seismic engineer employs mathematical techniques to understand a structure's "harmonics" with ground movements. Every building has its own natural frequency that depends on different factors, including its height and the lengths of structural members that comprise its frame. A xylophone's resonators (the tube-like parts) each reverberate to their natural frequency, according to their length and stiffness in a similar way.

A building's ***Seismic Response*** is the equivalent of an instrument's signature sound. Some types of music naturally sound better on certain types of instruments. In the 1985 Mexico City Earthquake, the oscillation of the deep-soil lake bed caused significant damage to mid-rise concrete buildings having natural frequencies similar to the soil, whereas both stiffer and more flexible buildings were damaged less (*Stone, 1987*).

Apart from resonance, a musical instrument's quality can be measured by three attributes: tonal range, ease by which pitches are carried through its body, and toughness, known as the modulus of resilience (U_r), which describes a material's ability to absorb energy. These three attributes are also the focus of three different approaches engineers take to mitigate the impacts of an earthquake. The seismic engineer's goal is to ensure that the "instrument" can resist an aggressive "player."

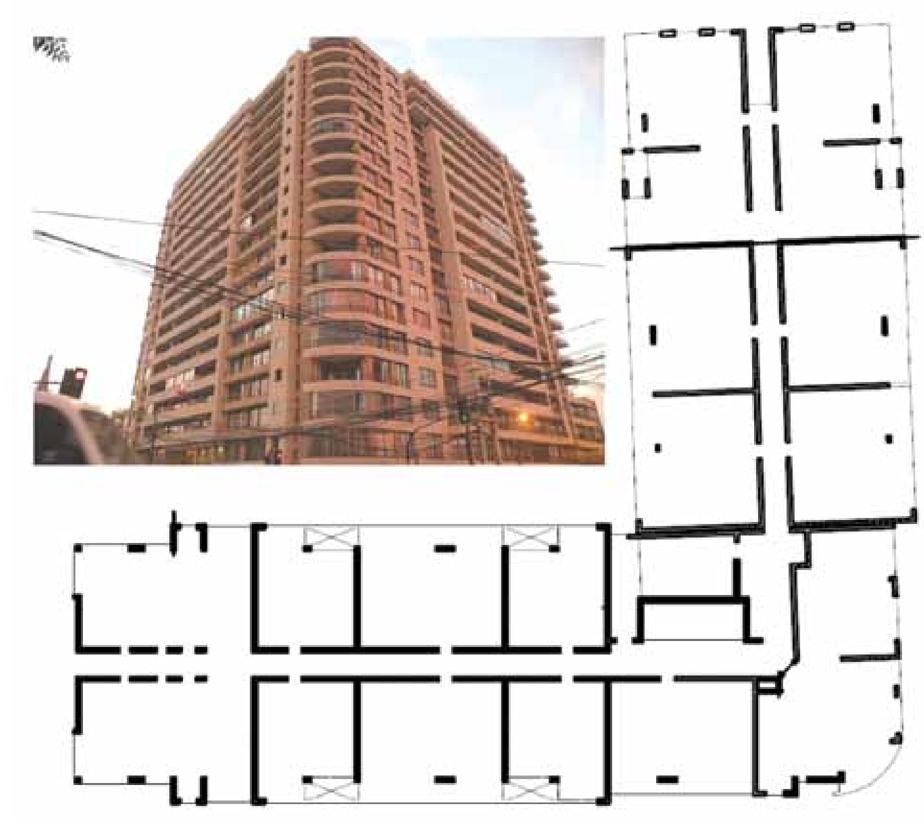

Figure 6. Concrete construction in Talca, Chile. Courtesy of GMS.

Three Design Approaches

Chilean seismic design practice focuses on strength with the goal of immediate re-occupancy. Buildings in Chile are designed with redundant shear walls so as to survive the quake. It is common for buildings in these seismic regions to have walls comprise 2% of the floor area (compared to only 0.5% in the US) (*Figure 6*). Masonry and concrete are brittle materials, yet have a high capacity to carry compression stresses. With proper reinforcement, they also possess the required tensile strength. For concrete and masonry structures, the shear strength must exceed the flexural strength to ensure that inelastic shear deformations do not occur because such deterioration of stiffness and strength could lead to failure (*Paulay, 1992*).

This strategy, however, significantly constrains architectural design and induces non-structural damage (of fixtures, egress, utilities) as the building moves rigidly with the movement of the earth; the building's contents get severely shaken. In music, maracas have very strong, rigid shells. When shaken, the shell remains intact, but its internal pellets (contents within the maraca) are severely agitated.

Alternative seismic design approaches contend that excessive strength is not essential, or even necessarily desirable, focusing less on "resistance" of large seismic forces, and more on the "evasion" of them.

Japanese seismic design practice effectively attempts to construct an "unplayable instrument" by disassociating the structure from the earth's movements using base isolators.

Seismic isolation is a passive structural vibration control technology that lengthens a building's fundamental period of vibration in order to dissipate, disperse and absorb dynamic loads. Base isolators are composed of structural elements that collectively decouple a superstructure from its substructure that rests on shaking ground (*Figure 7, page 18*). These must provide both flexibility at the base of the structure in the horizontal direction and damping elements to restrict the amplitude. Additional flexibility, however, results in large relative displacement across the flexible mount. These displacements are controlled by introducing additional absorption at the isolation level. Mechanical energy dissipaters are used to provide rigidity under low lateral loads, such as wind, by virtue of their high initial elastic stiffness (*Islam, 2011*). Many different types of isolator constructions exist, including elastomeric bearings, sliding bearings, springs, rollers and sleeved piles. One drawback of this approach is its high development cost.

Figure 7. Building seismic base isolators. Courtesy of Wiki: Marshelec.

In our musical analogy, a flautist may exhale as hard as she likes, but the flute will not play a note if it is detached from her lips.

The ***United States*** looks to energy dissipation through plastic deformations of the structure as a more cost-effective approach toward minimizing loss of life due to collapse during an earthquake. Buildings are designed to remain intact enough to allow for safe egress, while at the same time fail at pre-determined weakened frame locations and allow for possible remediation.

Electrical musical instruments are similarly designed with fuses that will blow if overloaded rather than electrocute the player.

In steel structures, frames are proportioned and beam sections are locally weakened in such a way that the required plastic deformation of the frame may be accommodated through the development of plastic hinges at desired locations within the girder spans. Beam-column connections are designed to force development of the plastic hinge away from the column face. When a sufficient number of plastic hinges develop, the entire frame can deform laterally in a plastic manner (*Figure 8*). This behavior significantly dissipates energy (FEMA-350). In wood-framed buildings, the energy dissipation is almost entirely due to nail bending.

The downside of this strategy is that, after a seismic event, the building is substantially damaged and the cost of repairing buckled or yielded structural members and connections may be on par with the cost of demolishing and replacing the structure.

Similarly, a cello is designed so that during fierce play, the strings (which are easy to replace) will dissipate energy by breaking, rather than failure of the instrument.

To put this damage into perspective, engineers forecast probabilities of failure during a Maximum Considered Earthquake (MCE). Under these conditions, there is a 10% chance of collapse and 45% chance of damage to a building. Therefore, 45% of the time, the building is expected to remain functional. The probability of a seismic event occurring in excess of the MCE is only 2% in 50 years (*FEMA P-695*). However, "it really is the probability of structural failure with resultant casualties that is of concern, and the geographical distribution of that probability is not necessarily the same as the distribution of the probability of exceeding some ground motion," (ATC 3-06).

The ASCE 7 seismic design provisions have therefore been amended to instead account for "risk-targeted" ground motion (MCE$_R$), representing (i) a 1% in 50-year probability of collapse, and (ii) a 10% risk of collapse given MCE$_R$ occurring at a particular site. "The 1% in 50-year collapse risk objective is the result of integrating the hazard function (which is different for each site) and the derivative of the hypothetical collapse fragility defined by the 10% conditional probability" (*NIST, 2012*).

Building's Occupants ⇔ Audience / Event's Social Context ⇔ Concert Hall

Different audience members may have different interpretations of the music, resulting in varying subsequent critiques of the same performance. The "intensity" of an earthquake, a qualitative concept, depends on its perceptibility (i.e. where and how the earthquake is felt), and its destructivity (i.e. what damage ensues). The Modified Mercalli Earthquake Intensity Scale is used in this regard to classify seismic activity into twelve classes ranging from "(1) Not felt except by a very few under especially favorable circumstances," to "(12) Damage total; waves seen on the ground" (*Krynine, 1957*). The occupants of a building

Figure 8. Local weakening of the beam section at the desired location for plastic hinge formation. Courtesy of GMS.

feel a seismic event and interpret it within the context of society the way that music is "felt" as an audience perceives it within a concert hall.

Such dichotomies in social context and public perception of earthquakes date back to the Enlightenment era. In his 1756 Poem on Natural Law, the philosopher Voltaire laments the devastation caused by the Lisbon earthquake of 1755, using the disaster as a vehicle to attack an erstwhile optimism (that by divine provenance, "whatever is, is right") (*Dynes 105*). In response, Rousseau contends that disaster is a social construction, defined by existing cultural norms and that whether an event is considered a disaster depends on who is affected:

> *You might have wished … that the quake had occurred in the middle of a wilderness rather than in Lisbon … but we do not speak of them, because they do not cause any harm to the Gentlemen of the cities, the only men of whom we take account. Should it be … that nature ought to be subjected to our laws, and that in order to interdict an earthquake, we have only to build a city there? (Masters, 1992)*

Figure 9. Post-earthquake conflagration in San Francisco, 1906.

In the same correspondence, Rousseau suggests that we, ourselves, are the causes of our own problems.

> *Without departing from your subject of Lisbon, admit, for example, that nature did not construct twenty thousand houses of six to seven stories there, and that if the inhabitants of this great city had been more equally spread out and more lightly lodged, the damage would have been much less and perhaps of no account.*

Rousseau's discussion was perhaps the first attempt to conceptualize what is now known as "vulnerability." From the Age of Enlightenment onward, modern disasters are usually considered primarily technological failures.

Conclusion

In a symphony, there are many different instruments involved, some more critical than others depending on the musical piece. For example, a composition might involve a trumpet solo, without which, the performance would seem empty and incomplete.

Each city, like a symphony, is different and each has its different components (like instruments), some more exposed than others (like solos within a composition). Neither city nor orchestration functions as a sum of independent components, but rather as a complex, integrated system consisting of interdependent parts.

Individual buildings within an area are different; they are constructed differently and serve functions of varying importance to the city. Engineers focus on building performance in particular, but it is important to recognize that the buildings are only one part of a much larger system. While a building may be engineered as earthquake-resistant, society may incorrectly assume the structure is "earthquake-proof," which it is not given the probabilities of damage described above. Therefore, in addition to life-safety, to account for economic and functional consequences of a seismic event, a conceptual framework is being developed by the Applied Technology Council that defines two new hypothetical levels of earthquake intensity: risk-based functional level (FLE_R) and risk-based service level (SLE_R) ground motions (*Kircher, ATC-84*).

Life-safety, operational down-time (when the building cannot be used) and repair costs (to allow reoccupancy), though not always quantifiable, are at the forefront of an engineer's priorities during the design of a building. However, structural damage is not the only effect of an earthquake. The wake of an earthquake may carry with it tsunamis, fires, and risks to security, transportation, sanitation and, in some areas, nuclear hazards. It has been estimated that structural failure resulted in only 3-5% of the 3,000+ deaths and $350M damage caused by San Francisco's 1906 earthquake (*Tobriner, 2006*). A conflagration followed, lasting about three days, and destroying 2,831 acres. The property damage was estimated to be at least four-fifths of the property value of the city. Actual collapses during the earthquake were mainly confined to flimsy, framed structures (*Reed, 1906*). In fact, a report by the National Board of Fire Underwriters from the year prior to the earthquake recognized the hazard:

> *In view of the exceptionally large areas, great heights, numerous unprotected openings, highly combustible nature of the buildings, almost total lack of sprinklers... and comparatively narrow streets, the potential hazard is severe... In fact, San Francisco has violated all underwriting traditions and precedent by not burning up (NBFU, 1905) (Figure 9).*■

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