Appropriate Seismic Regulations for Urban Structures

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Summary

Urban areas subjected to significant earthquake shaking require appropriate regulations and guidelines for seismic resistant construction. While seismic design codes and criteria are similar worldwide, every country and urban area has specific limitations on certain construction types and systems. There is a need for universal criteria, however there must be suitable caution in adopting new approaches not yet proven in actual earthquake exposures.

Bridges have been the subject of major changes in design criteria in recent years, hopefully to prevent the all too frequent collapse of critical spans. Underground structures and tunnels have received little attention recently and appropriate criteria is needed built on a consensus base. New buildings are perhaps the most regulated of structures, although new performance based designs are pushing the bounds for acceptance. These new designs need careful and thorough study to ensure acceptable performance. Existing buildings and bridges are perhaps our greatest urban hazard in strong earthquakes, and appropriate mitigation strategies and criteria are needed to gradually reduce these hazards.

1. Introduction

Our planet earth is an active planet with its geologic plates still floating and adjusting towards a possible equilibrium. Along these plate boundaries that ring the Pacific Ocean, transverse the south of Europe and into Asia and elsewhere lie many of the worlds major population centers and large cities. Many of these locations are frequented by earthquakes, some every 50 years or so, some every few hundred years and some less frequently. While the desire for worldwide building regulations or codes is a worthy cause, it is really unpractical, partially due to the different levels of seismicity in the various population centers, not to mention extreme wind and hurricane exposures and other climatic variations. In addition, local traditions of construction practice and zoning somewhat preclude such universal regulations.

Thus it is necessary for each country or each major urban center to develop its own appropriate building regulations and codes to properly protect its citizens from loss of life and control of damage when there infrequent earthquakes occur. It is also appropriate, in the author’s opinion, that each urban area study and recognize its own seismic exposure (or extreme wind – tornado – hurricane exposure) and establish its own standards for building performance and life safety protection of its population.

The issue of new buildings and bridges is relatively simple. Our engineering knowledge is now quite complete that we can easily draft codes and regulations for appropriate safety and performance, recognizing that codes can never be completely up to date with new concepts of construction. Dealing with the existing building and bridge inventory is a much larger and more difficult problem, as we know many of those structures are very vulnerable to seismic events. This issue takes considerable community study debate to reach a consensus of how the potential hazard can be reduced and how the cost to abate will be funded and justified. Finally, one component of urban construction often ignored for seismic performance is the underground structure. As we build more of these structures and we observe their damage in earthquakes, we realize these buried structures can move with the ground and all of our urban communities lack appropriate guidelines for these structures.

In the following sections, each of these components of the urban infrastructure and development will be discussed and opportunities to enhance the safety of our communities will be explored. The goal is for each urban area to set their appropriate level of safety and enforce their regulations to provide life safety protection for their citizens.

2. Bridges

In an earthquake bridges are potentially very vulnerable to damage or collapse. We have seen many bridges collapse in recent earthquakes. Bridges are often high above the water or land resulting in tall columns and long spans between columns or abutments. Bridges are seldom subjected to strong earth shaking but often subjected to thermal extremes requiring expansion and contraction joints for normal use. These movement joints often make sound earthquake resistance difficult.

Let’s consider the experience in California. There was the great San Francisco earthquake of 1906 but there were no bridges in San Francisco at that time. There were significant earthquakes in Santa Barbara in 1925 and Long Beach in 1933 but again no major bridges to be shaken. In the 1950s and 1960s many new bridges were built for the interstate highway system with no consideration of ductility or sound earthquake resistance. The 1971 San Fernando earthquake caused several of these new bridges to collapse which started a change in bridge design criteria in California. More bridges collapsed in the 1989 Loma Prieta and 1994 Northridge earthquakes. Today, California has a policy that all bridges are essential structures and should be operational after an earthquake. Considerable laboratory research has led to ways to make bridges ductile and earthquake resistant. New bridges are very substantial with robust details. Billions of dollars have been spent seismically strengthening existing bridges. A very expensive experience and time will judge its effectiveness.

Short span bridges have special requirements for abutments, bearings and provisions for thermal movements. Any intermediate columns need be ductily detailed. Piles need ductile confinement as pile failures have been documented beneath large concrete abutments. Restrainers are essential to prevent large movements of the bridge deck in seismic events.

Long span bridges have similar needs plus the complication of tall columns in many bridges. Whereas in building frame systems we try to protect the columns and force the inelastic response into the beams or horizontal members, this is not possible for most bridges. Thus we need highly confined ductile columns that can absorb considerable energy without loss of strength and function. The other factor affecting long span bridges is the out of phase effects of the supports. Seismic ground motion is like waves passing through the ground beneath the bridge. Most structures are relatively small in plan so the ground beneath the structure is all going the same way at each instant of time during the earthquakes ground shaking. But long span bridges can have out of phase ground motion at their supports which further tends to shorten or elongate the bridge. Modern, long span bridges in seismic regions include this effect in their design criteria.

A related problem exists when the earthquake fault passes beneath the bridge and permanently offsets. The Akashi Kaikyo suspension bridge in Kobe Japan was under construction in 1995 when the fault offset about ½ meter between the main columns. There was no damage and deck panels were simply changed in fabrication to accommodate the new length of the bridge. This would have been somewhat more complicated had the bridge been completed. An elevated concrete motorway bridge in Turkey did not fare as well in 1999 when fault offsets caused considerable distress.

Bridges are important structures and essential for evacuations, relief and reconstruction after major earthquakes. New, stringent design criteria is essential in seismically active regions so these critical bridges can be operational after brief inspections and possibility minor repairs.

3. Buildings

New buildings are probably the structures that are most up to date with seismic state of the art and state of the knowledge in areas subject to strong seismic shaking. Building Codes tend to be updated more frequently than other building regulations and affect the larger number of structures. After significant earthquakes often anywhere in the world affecting modern construction, we often see changes in Building Codes trying to prevent the type of failure most recently observed.

Let's briefly observe the Building Code history in San Francisco. There was no formal building code in San Francisco in 1906 and the local engineers, after studying all the effects on structures, concluded that a building properly designed for a 30 pound per square foot wind load would survive an earthquake similar to San Francisco 1906. They had an understanding of what "properly designed" mean, generally for multistory buildings a riveted steel frame with infill brick masonry or concrete walls. As the years past, many newer engineers and designers were not so clear what "properly designed" meant and many other designs began to appear. In the middle of the twentieth century building codes began to be formalized and much of this historic data was incorporated into the code, such as dual systems to reflect the taller 1906 building that did well. After subsequent earthquakes, as the concept of ductility became well understood, requirements for ductile performance were mandated and enhanced. Studies of strong motion records led to higher design forces. More and more code writing committees, some wanting to place their "stamp" on the code, has resulted in code changes perhaps too frequent. But today in San Francisco, any building honestly designed to the current code will not collapse and probably be repairable after the worst future event. Many other seismically vulnerable cities have a similar history.

Simply having good building codes does not guarantee that new buildings are seismically sound. In some cities, such as Istanbul and nearby cities in Turkey, there is a very up-to-date modern seismic code but few buildings are in compliance. Engineers and/or contractors routinely ignore many seismic provisions in the interest of providing the least expensive building for their client. Regulation of the code is not enforced on most projects so more and more seismically vulnerable buildings are constructed. It should be noted that many major projects in Turkey do get well constructed with code compliance. The author has also observed that in some seismically vulnerable areas of Latin America that many new buildings are not designed nor constructed with complete load paths and other sound seismic resistant design details. The author attributes this to a lack of training and understanding by many practicing engineers. In Italy, where 2000+ years of recorded history documents damaging earthquakes in some cities only every 500 ± years, engineers have questioned the need to design all buildings, with an expected lifetime of 50 to 100 years, for earthquakes they may never be exposed to based on this historical record. An interesting proposition.

Building codes tend to focus on the most commonly built structures, such as low and mid rise buildings. A group of structural engineers designing very tall building in the seismically active west coast of the United States have been proposing advanced analysis and/or "performance based design" to circumvent certain prescriptive code requirements, provide more economical structures and provide what they sincerely believe are very sound seismic resistant designs. San Francisco has just adopted guidelines for such structures and Los Angeles is also in this process. These buildings are typically 40+ stories in height and are subject to extensive peer reviews by a panel of experienced engineers. While these structures most likely have satisfied designs, the peer review process is not uniform and we are testing our lack of experience of similar structures in actual strong earthquake exposure.

4. Existing Buildings and Bridges

Existing buildings and bridges represent our greatest potential hazard in earthquake prone cities. Except for very new structures, older buildings and bridges were constructed under older versions of codes or guidelines that often did not require ductile details or systems of proven earthquake resistance. These structures are all "legal" since they complied with codes and regulations at the time of their construction and building regulations are seldom retroactive.

Our recent earthquake history has clearly shown us the vulnerability of these existing buildings and bridges. In the US, the 1971 San Fernando, 1989 Loma Prieta and 1994 Northridge earthquakes demonstrated that many poor configurations and "non-ductile" details lead to collapse or severe damage. In Japan, the 1995 Kobe earthquake revealed a surprising lack of seismic resistance in many structures except those in strict compliance with the most recent Japanese code. Recent Turkish earthquakes also show the vulnerability of non-ductile concrete structures and soft first stories in buildings. The 1988 Armenia earthquake revealed similar deficiencies in Soviet construction practices. Recent earthquakes in Central and South America have shown similar problems with the exception being the 1985 Chilean earthquake where concrete buildings with very extensive shear wall systems essentially had enough brute strength to survive the earthquake with minor damage. Thus, we see that earthquakes from 1970 to the 1990s worldwide have clearly exposed the vulnerability of our existing building and bridge stock to severe ground shaking.

Several of these earthquakes have also demonstrated the vulnerability of structures directly over active fault traces. Bridges crossing active fault traces in Turkey and Taiwan, a dam in Taiwan and buildings in several countries have performed poorly when built directly over active faults. Our geologic knowledge has now advanced to a level where these active fault traces can be identified and new construction prohibited in the fault zone. However, this leaves the issue of existing structures built on these active faults.

What can be done about these vulnerable existing structures? There are a few knowledgeable building owners who study their buildings and upgrade vulnerable ones. But they are the exception, not the rule. In most cases it takes government intervention with programs to identify and study selected types of structures and eventually require them to be seismically strengthened or demolished. In California, there was first a program in the 1970s to evaluate and strengthen cantilever parapets above the roof which was a relatively low cost requirement. There were also programs requiring all public schools and hospitals to meet seismic standards. These are costing billions of dollars to achieve compliance.

Another program identified all unreinforced masonry buildings and most local jurisdictions have required abatement or demolition. Thousands of bridges have been strengthened at a cost of billions of dollars. Studies are currently underway looking at the scope of the problem with soft first story buildings and older non-ductile concrete buildings. All of these programs are expensive and require support from the public. They do increase safety in future earthquakes, but the cost to owners and government bodies is considerable.

The existing building and bridge dilemma is one that every community or locale in seismic regions must address. Each community must set their own program. The cost of retrofit can be considerable but lives will be saved. There are many ways local government can encourage retrofits by offering incentives such as tax breaks and waivers of various fees. These are tough issues to address and solve. They take considerable study, education of all the stakeholders and a consensus that life safety in earthquake prone regions is worth the investment.

5. Underground Structures

Underground structures and tunnels have received little attention with respect to seismic response. This is because the typical underground structure is the basement structure of typical buildings. These basements retain earth around their perimeter with substantial reinforced concrete basement walls around their perimeter which provide a very rigid below-grade lateral force resisting system. Earthquake experience of these basement structures has generally been good with very little reported damage. It is not uncommon after an earthquake to see a 1 to 2 centimetre gap in the soil against the basement wall at the soil surface indicating that the soil has been subject to horizontal movement against the rigid base building structure.

Let's consider what really goes on in a significant earthquake. The ground moves, both horizontally and vertically from the movements that radiate out from the fault offset that has caused the earthquake. The ground motions, especially horizontal movements, tend to shake the base rock as a unit with the base rock vibrating back and forth, the magnitude depending on the proximity and nature of the fault offset. When rock is at the surface, this rock movement is what our structure is subjected to and these movements can be relatively small, leading to the observation that structures built on rock tend to have less damage and smaller shaking response than similar structures built on soft soils.

When alluvial or softer soils overlie the baserock, as is typical in many of our cities and building sites, the ground motion of the baserock is amplified with increased shaking or lateral movement in the upper layers of the soil deposit. The magnitude of the horizontal soil displacement is a function of the rock motion and the stiffness of the soil layers. The softer the soil, the more horizontal displacement or amplification. The ultimate example is the old lakebed beneath Mexico City which amplifies like a larger bowl of jello when shaken. For the typical building basement with basement walls forming a rigid box in the ground, these movements are typically small resulting in no damage or minor cracking at critical sections which is usually not detected as the cracks close after the ground shaking has stopped.

But let us consider other kinds of underground structures which do not have the "rigid box" basement properties. Consider an underground transit subway station which may be 300 meters long with heavy side walls but end walls with large openings for the trains to pass. This results in a weak structure for soil movements perpendicular to the tracks as lateral movements must be resisted by frame action of the walls, basemat and roof slab. The structure starts to resist these soil movements, but since there are no cross walls to keep the structure rigid, the structure tends to move with the soil and rack laterally like a parallelogram. A transit substation in Kobe, Japan, failed in the 1995 Kobe earthquake. The station, located in the soft clays near to the bay, racked laterally with concrete spalling at the top and bottom of the side walls of the station. The lateral displacement were sufficient to cause complete failure of the nominally tied, non-ductile concrete columns between the tracks in the center of the station. The result was a major depression in the street above as these central columns collapsed.

The author was a consultant to the design team for the Los Angeles metro rail project in the 1980s and 1990s. After the 1994 Northridge earthquake there was concern about stations in Hollywood quite close to an active fault. A three dimensional soil model predicted about 12.5 centimetres (5 inches) of horizontal offset over the height of the station. When the station was added to the soil model, the racking reduced to about 10 centimetres (4 inches). Confinement ties were added in the walls of the concrete subway station at locations of potential plastic hinging.

Another example of such lateral racking or distortion occurred to an underground double box water culvert that racked in the 1971 San Fernando earthquake. This section of culvert that failed was located in an area of fill soils. A section nearby built in cut in native soils experienced no racking. Again, the softer or less dense, fill soils moved more laterally allowing the racking to occur to the transversely weak box culvert. While this box culvert did not collapse, it was ineffective to transport drinking water in this condition.

Many engineers knowledgeable in seismic design dismiss or ignore such earthquake pressures or buried structures due to the good performance of building basement structures which are very rigid in all directions. But the effect on laterally weak linear structures in softer soils is real and needs to be addressed as our urban infrastructure becomes more complex. We need an engineering consensus so suitable criteria can be adopted in our codes and regulations.

6. Conclusion

Due to significant variations in seismic exposure and other climatic differences, local building regulations and requirements are essential and inevitable so each community can determine and control an acceptable level of safety for its occupants. National and international codes are an essential guideline for local adoption, but each community must refine such codes to their particular situation and vulnerabilities.

Building Codes for acceptable seismic exposure are the most mature of our regulations, but new materials and constriction concepts continue to challenge our knowledge and experience base. A wealth of new research on seismic bridge vulnerability has given us the technical tools to design and build seismically safe bridges and updated bridge codes are being refined. Our existing building and bridge inventory represents our greatest hazard in future earthquakes and thoughtful community programs are needed for education and mitigation with incentives to allow such programs to be effective. Developers of large underground structures and buried subway systems need to carefully study the potential performance of these buried facilities and incorporate design features consistent with the soil conditions and our knowledge, which unfortunately lacks consensus at this time.