Seismic isolation in North and South America

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ABSTRACT

Seismic base isolation is one of the most popular and effective means of seismic hazard mitigation. The main principles of seismic isolation are to decouple the structure from the ground and to absorb the earthquake energy. This paper summarizes the use and development of seismic isolation in the Americas. Although the seismic risk is high in both North and South America, the implementation of protective systems is quite different. Countries like Chile, Peru, Colombia, and Mexico are highly interested in using protective systems such as seismic isolation to keep their buildings and bridges functional after an earthquake and to improve community resilience. Compared to Latin American countries, the interest in using base isolation in USA and Canada for buildings and bridges is low. This might be attributed to the recent significant earthquakes that occurred in Latin America and how the damage caused by these seismic events affected the countries' economies and raised seismic awareness among the general public. However, in USA, the last significant damaging earthquake was Northridge in 1994. The differences also come from: how each market views better performance; cultural differences; people's perception and tolerance for risk; first cost considerations and whether the building is being built for an owner-occupier or to be sold after construction; and finally the public awareness of seismic provisions that allow for the buildings to be damaged but not collapse. This paper also presents a wide range of traditional seismic isolation applications in addition to new products developed to protect non-structural components such as mission critical equipment, supercomputers, and high value items.

1 INTRODUCTION

The concept of seismic isolation began in the 1970's in New Zealand (Skinner et al. 1993). Seismic base isolation is used to decouple the structure from the ground and to absorb earthquake energy, thereby reducing the energy transferred to the structure. Since seismic isolation is very effective in protecting structures against earthquakes, it was implemented in many earthquake-prone countries. The first base isolated building was completed in Japan in 1983 (Pan et al. 2005). From 1983 to 1995 the use of seismic isolation in Japan increased slowly. After the Kobe earthquake occurred in January of 1995 there was a sudden and significant increase in seismic isolation applications in Japan.

Many countries in Latin America took the same path as Japan. Countries like Chile, Peru, and Colombia showed higher interest in implementing seismic base isolation after being struck by a destructive earthquake. Life and property losses increased engineers', owners' and the public's awareness of the risks from a seismic event and drove the population to want higher-performance and more resilient structures.

In the United States, requirements for seismically isolated structures were first used in a code as an appendix to the 1991 Uniform Building Code (ICBO 1991). Many buildings and bridges were isolated in the 1990s. Since 2000, there has been less use of base isolation. More recently there has been growing use of non-structural isolation.

The main goal of this paper is to show the differences in implementation of seismic base isolation throughout North and South America.

2 LATIN AMERICA

This section shows the seismic hazard in Latin America and how the recent destructive earthquakes led to a significant increase in the use of seismic isolation. Some applications in Chile, Peru, Colombia, and Mexico are also presented.

2.1 Seismic hazard and significant earthquakes

Latin America is located across the Earth's largest ocean-continent subduction system. Along the South American margin, the Nazca plate subducts beneath the South American plate where many earthquakes with magnitude $M_w > 7.5$ have occurred (Fig. 1).

Figure 01: Recent Significant Earthquakes in North and South America

The 2010 magnitude 8.8 Maule, earthquake that occurred off the coast near central Chile was the turning point in seismic awareness in Chile. The fault ruptured over an area approximately 500 km long by 100 km wide. The shaking durations of this event were from two to three minutes. There were 130 hospitals affected by the earthquake which accounts for 71% of all public hospitals in Chile. Four hospitals became uninhabitable, twelve had more than 75% loss of function, and 62% needed repairs or replacement (EERI 2010). Since this earthquake, the interest in seismically isolating structures in Chile has significantly increased. In 2014 and 2015, two earthquakes of magnitude > 8.0 occurred in Chile and were further reminders of the seismic hazard.

Peru also was shaken by two recent significant earthquakes that struck the central and southern coast. The M_w 8.4 Atico (Arequipa) earthquake occurred in 2001 and the M_w 8.0 Pisco Earthquake occurred in 2007. Seismic risk awareness is high in Peru. In 2014 the government mandated the use of seismic isolation in all hospitals to ensure that they remain functional after a seismic event.

Similarly, many other countries in South and Central America showed more interest in using seismic isolation to improve the structure resiliency after having a major earthquake (e.g. Ecuador in 2016, Costa Rica in 2012, and Colombia in 2004)

Mexico is considered one of the world's most seismologically active regions where the Cocos plate subducts beneath the North American plate. Mexico has a long history of destructive earthquakes (e.g. M_w 8.1 in 1985, M_w 7.2 in 2010, M_w 8.1 in 2017, and M_w 7.1 in 2017). Since major earthquakes are occurring frequently in Mexico, there is an increased interest in adding seismic protective systems such as dampers and seismic isolators to their buildings and bridges.

2.2 Seismic isolation applications in Latin America

The adoption and use of base isolation in South and Central America is "traditional" in the sense that it follows what typically occurred in other countries around the world. The implementation of seismic isolation is generally driven by professionals or academia promoting the technology, a desire by the public to use it, and almost always a large damaging earthquake to show the need for structures to perform beyond code-minimum requirements. All of these factors are present in many countries in South and Central America. Furthermore, the many frequent earthquakes have caused public officials and private citizens to want better performing structures that will not be damaged in earthquakes.

2.2.1 Chile

The increasing use of seismic isolation in Chile is a classic example of this pattern and mirrors what happened in Japan after the Kobe Earthquake in 1995. There were several seismic isolation projects including two large hospitals, bridges and residential buildings prior to the Magnitude 8.8 Maule earthquake in 2010. However, after that devastating earthquake, the isolation of hospitals became recommended for all new hospitals in the country. This decision was driven by the fact that several hospitals were destroyed by the Maule earthquake and that hospitals are an essential facility that need to be operational after a major earthquake. The economic losses in health facilities exceeded 3 billion US dollars. In the case of bridges, it has been mandatory to evaluate the use of seismic protection technologies since 2010. The cities of Talca, Curico and Cauquenes, among many others, saw their hospitals collapse; a XIX century stone arched bridge over the Rio Claro was destroyed and many conventionally designed bridges suffered damage.

Since the Maule earthquake, the hospital in the city of Talca and the Rio Claro Bridge were both rebuilt using seismic isolation and two new buildings at the University of Talca were seismically isolated.

Figure 02: Destroyed Rio Claro Bridge, Chile

Figure 03: Base isolated replacement Rio Claro Bridge, Chile

Approximately 300 bridges in Chile were damaged by the Maule earthquake (Buckle et al. 2010). This resulted in a review of the seismic codes of structures and a shift to more base isolation being used. In addition to having superior performance during a seismic event, seismic isolation on bridges also reduces foundation and substructure member sizes due to the reduction in design forces.

Figures 04 and 05: Two new buildings at the Catholic University of Maule in Talca, Chile

Subsequent to the initial rebuilding after the 2010 earthquake, other types of buildings such as condominiums, data centers, high tech laboratories and office buildings were also seismically isolated.

An engineer in Chile tells the story that he has been in his 8th level apartment during large earthquakes and that you “get thrown to the floor and shaken 500 mm backwards and forwards for several minutes before you can get up again.”

Figure 06: Nunoa Condominiums, Chile

Figure 07: Claro Data Center, Chile

Experiences like this drove the demand for better performance of condominiums during seismic events. As a result, buildings such as the Nunoa Condominiums were seismically isolated.

The Claro Data Center near Santiago was designed to meet the TIER 4 standard of the Uptime Institute. This specifies a maximum downtime of 8 minutes in an entire year. The decision to isolate the building was made to cater to businesses and banks that cannot afford downtime of their data servers.

Figure 08: The UTEC Building in Lima, Peru won the 2016 RIBA (Royal Institue of British Architects) International Prize

Figure 09: Corredor Honda-Manizales Bridge, Colombia

Seismic isolation is now a well-established technology in Chile and it is used widely.

2.2.2 Peru

Likewise, Peru has also increased the number of seismically isolated structures in recent years. Hospitals and public buildings such as Moquegua City Hall and UTEC University, were built with a seismic isolation system. More recently, bridges are also being seismically isolated.

The Peruvian government mandated in 2014 that public hospitals be seismically isolated. The stock of public hospitals is very old with many hospitals over 50 years old. Thus, many of these are being replaced with new buildings.

2.2.3 Colombia

Colombia is another country were seismic isolation of structures has increased in recent years. One of the first hospitals to be isolated in Colombia was based on a commercial decision. The hospital owner had a conventionally designed hospital in Cali that was extensively damaged in the 2004 Earthquake. The repair of the building, which had just been completed, took 3 years and meant it wasn't generating income during that time. Subsequently they have chosen to isolate all of their new hospitals in high seismic zones. Other healthcare providers have also followed suit. University buildings, and condominiums are often isolated in Colombia.

Bridge engineers in Colombia have used seismic isolation to achieve some elegant structural forms as seen in the Corredor Honda-Manizales Bridge shown in Figure 10.

2.2.4 Mexico

Mexico has several isolated bridges and buildings. Seismic isolation technology is used regularly but not as widely as in other Latin American countries. Mexico has regular large earthquakes, however, in places such as Mexico City, dampers are the preferred solution. This is due to the frequency range associated with the main energy content of soft soil sites, which generally matches the frequency range of isolated systems reducing their effectiveness. (Filiatrault 1990)

One of the leading designers in Mexico; Constructora Cautín, has success at base isolating bridges by showing clients the cost savings between an isolated and conventional design. As an example, the cost savings on the Distribuidor Vial Lopez

Figure 10: Distribuidor Vial Lopez Mateos-Lazaro Cardenas, Mexicali, Mexico

Mateos-Lazaro Cardenas bridge in Mexicali were 50% for the substructure and foundation.

Table 1 shows a comparison between isolated and conventional design for the bridge in Mexicali. Reduction in structural members between the two designs is presented.

Moreover, the bridge performed flawlessly in the Magnitude 7.2 earthquake in 2010 (Nunez 2011).

Table 1: Distributor Vial Mexicali Bridge Isolation resulted in cost savings of 50% for the substructure and foundations along with damage free performance

	Isolated	**Conventional**
Period	1.83 sec	0.75 sec
Column size	4 – 120 cm diameter	4- 150 cm diameter
Column reinforcing	285 cm^2	810 cm^2
Concrete volume ratio	1.00	1.56
Steel volume ratio	1.00	2.85
Pile cap size	6.4 x 6.4 x 1.5 m	12 x 12 x 1.5 m
Pile cap concrete	61 m^3	216 m^3
Pile cap reinforcing	10,100 kg	35,900 kg
Concrete volume ratio	1.00	3.54
Steel volume ratio	1.00	3.55

Figure 12: Construction of the first base isolated bridge in Nicaragua

2.2.5 Other Latin American countries

Other countries in Latin America, including Costa Rica, Ecuador, Nicaragua, Panama, Haiti, Guatemala, and Puerto Rico, have one or two projects and are currently looking to implement more seismic isolation in their infrastructure.

Lead rubber bearings for the first seismically isolated bridge in Nicaragua. Projects such as these in countries that have only recently begun to implement the technology require good design support and help with the approval process as many of the players are not familiar with the design and implementation of seismic isolation.

3 USA AND CANADA

This section shows the seismic hazard in USA and Canada and how the implementation of seismic isolation is different than Latin America. Applications for seismic isolation in USA and Canada is also presented.

3.1 Seismic hazard and significant earthquakes

The United States is one of the countries where destructive earthquakes could occur from either subduction zones or crustal faults. The Cascadia subduction zone (CSZ) lies off the Pacific Northwest coast of North America, and it stretches from northern California to southern British Columbia, with a total length of about 1000 km. In this zone, the Gorda, Juan de Fuca, and the Explorer oceanic plates are being thrust below the continental North America plate (Fig. 13). Studies have shown that the CSZ has experienced up to magnitude 9.0 earthquakes, with the most recent having occurred in 1700 AD (Atwater et al. 2005). Earthquakes of magnitude 7–8 can occur across crustal faults such as San Andreas and Hayward faults. Figure 14 shows the seismic hazard in the United States, and based on historic

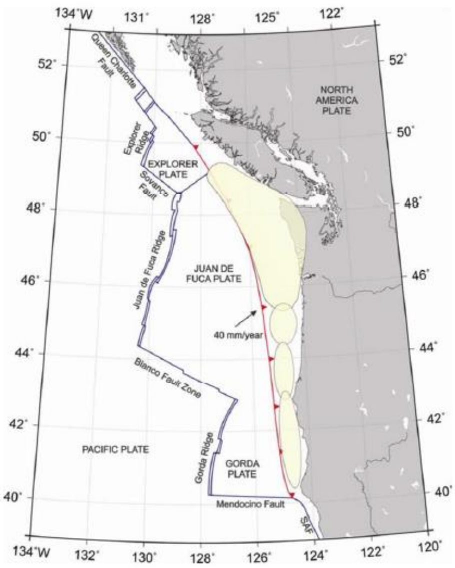

Figure 13: Tectonics of the Cascadia subduction zone (modified by Rajendran, 2013 after Nelson et al., 1996)

trends, the regions that are most at risk are the West Coast, the Intermountain West, and several known active regions in the central and eastern US, including near New Madrid, Missouri, and Charleston, South Carolina.

Some of the major earthquakes that occurred in the US are the 1971 San Fernando earthquake, the 1989 Loma Prieta earthquake, and the 1994 Northridge earthquake.

Many parts of Canada are also considered seismically active especially in the west along the Cascadia subduction zone (Fig. 15).

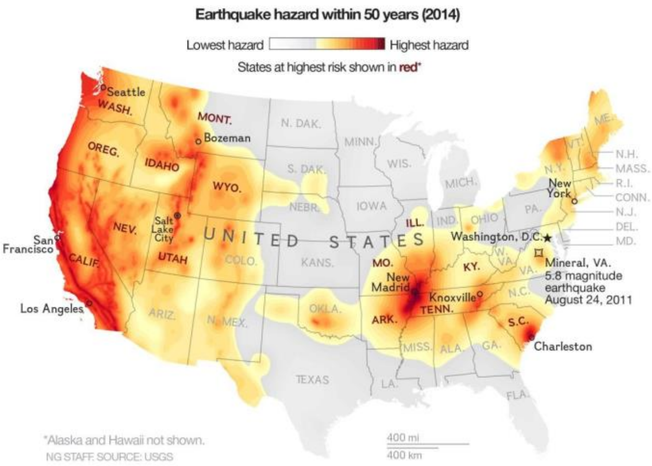

Figure 14: Seismic hazard in the United States (USGS)

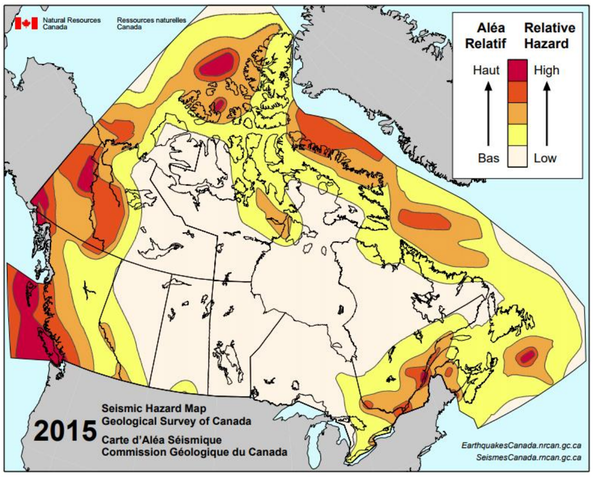

Figure 15: Seismic hazard in Canada (Geological Survey of Canada)

3.2 Seismic isolation applications in Canada

Bridges in Canada have been base isolated for more than 20 years. Similar to in Mexico, isolation is used regularly but in a limited number of applications.

The most recent Canadian National Building Code from 2015 included provisions for seismic isolation and damping. As a result of the new Code, the Lord Strathcona Elementary school in Vancouver was the first base isolated building in Canada. It was retrofitted with 30 lead rubber bearings and 18 sliding bearings.

There is good awareness and understanding of the seismic hazard amongst decision makers including public sector managers and the engineering community. However, an absence of damaging earthquakes in recent history has meant that the general public has not called for better performing structures.

An electric utility in Canada is an interesting study. They understand their seismic risk very well and have identified acceptable levels of performance for their dam structures at maximum considered earthquake (MCE) and design basis earthquake (DBE) levels. At MCE levels key equipment must function so that water levels can be drawn down in a controlled and safe manner. For DBE level earthquakes some repairable damage is acceptable along with a few days of downtime whereby electricity generation may be interrupted.

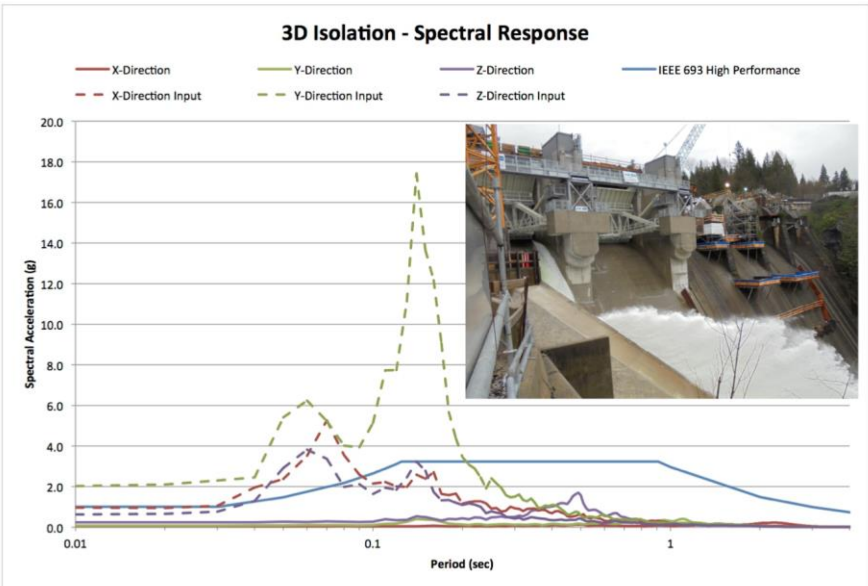

Figure 16: A Comparison of Spectral Accelerations above and below a 3D isolation system for equipment on a Canadian dam.

Dynamic Isolation Systems developed 2D and 3D isolation systems for key equipment and extensively shake table tested the systems to confirm their function. The IEEE693 High Performance standard was used as a benchmark of performance. Each piece of equipment was tested to the IEEE693 HP spectrum which involves shake table testing over the range of specified frequencies and accelerations. The purpose of the isolation was to reduce the accelerations and demand on the equipment to be below the IEEE693 HP spectrum. As can be seen in Figure 16, the accelerations on equipment at the top of the dam were 17g horizontally and 4g vertically; well above the IEEE693 HP curve shown in blue. Once the equipment was isolated the accelerations were reduced to levels well within their capacity. The equipment is located in the small buildings on top of the butresses.

The isolation of non-structural components is a good engineering approach when the structure is difficult or impractical to isolate.

3.3 Seismic isolation applications in the United States

Bridges continue to be isolated in USA with more than 5 projects per year. They include a mixture retrofits and new projects including one for the California High Speed Rail. There are pockets of awareness of base isolation throughout USA, with many engineers still not being familiar enough with the technology to use it. However, engineers are generally very receptive to base isolation when it is presented to them. There has been a recent surge in bridge funding and it is expected to help grow the use of seismic isolation of bridges.

The building sector in the US is not using seismic isolation as often as in the past. Currently, there are less than 5 building projects a year. One of the reasons for less implementation of seismic isolation, is that most buildings are now being built by developers, where the focus is to meet the code with the lowest cost.

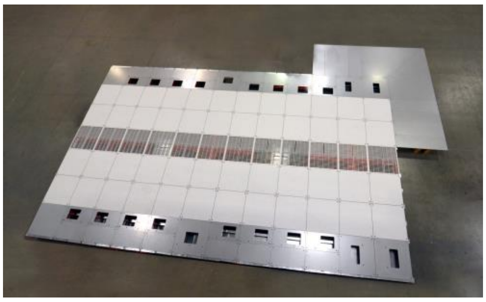

Figure 17: An isolated platform to protect servers that process data from a RADAR array.

Another factor is that the last significant earthquake was Northridge in 1994. The fact that there has not been another major earthquake since then, is probably the key factor as to why the general public is relatively more tolerant to the seismic risks when compared to many Latin American countries.

An interesting development in recent years is the strong demand for the Isolation of Non-Structural components such as Equipment, Supercomputers, Servers and Modular Data Centers. Most of these were driven by the end user to give excellent seismic performance.

Figure 18: A 1200mm tall isolated floor system that protects two Super Computers.

DIS' Non-Structural Isolation systems use springs with stiffness's in the 0.5-25 kN/m (3-150 lb/in) range. This is 20 to 40 times softer than Isolation Bearings used in buildings and bridges.

The Lawrence Berkeley Computational Research and Theory facility shown in Figure 18 has a 1500 m^2 isolated floor that protects 2 supercomputers from earthquake damage. The computers are the Department of Energy's center of operations and also serve 6000 researchers around the world.

The Isolated Platform shown in Figure 17 was chosen by a US Defence contractor to protect servers that process mission critical RADAR data. When shake table tested, servers in good quality seismically rated racks typically stop functioning at about 0.75g have structural failures at around 1g.

Figure 19: Isolated Platforms in the SLC PSB server room

The Salt Lake City Public Safety Building shown in Figure 20 is a state of the art building designed for a 2500 year return period earthquake. It is a moment frame structure with viscous dampers. However the floor accelerations at the servers would have damaged them so they were base isolated. The isolation platforms reduce the accelerations by a factor of 3 and ensure that the servers will continue to function.

Figure 20: The Salt Lake City Public Safety Buiilding (SLC PSB)

A current project in design is using an isolated floor system to isolate new servers being installed in an existing medium rise building. By isolating the servers the seismic lateral loads will stay below the existing capacity of the building and avoid a seismic upgrade of the superstructure. These types of applications will become more common as newer computers are heavier and older buildings often have limited lateral strength.

4 CONCLUDING REMARKS

Although the seismic risk is high in both North and South America, the implementation of seismic base isolation is quite different. The recent frequent large earthquakes that occurred in Latin American countries pushed them to protect their structures using seismic isolation. Life and property losses increased engineers', owners', and the public awareness of the risks from an earthquake and drove the population to want higher-performance and more resilient structures. In USA and Canada, there is a good awareness of the seismic hazard amongst decision makers and the engineering community. However, the absence of damaging earthquakes in recent history has meant that the general public has not called for better performing structures and this lead to a lower number of isolated structures. The engineers in USA and Canada are more interested in protecting high-value non-structural components such as equipment, supercomputers and servers. Therefore, the concluding questions are: Do the decision makers, engineers and general public in USA and Canada need a significant earthquake to occur in order to implement seismic isolation? Do they want to take the same path as other countries where a damaging earthquake should occur first in order to call for a better performing resilient structure?

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REFERENCES

Atwater, B.F., et al. 2005. *The orphan tsunami of 1700: Japanese clues to a parent earthquake in North America*, US Geological Survey Professional Paper 1707, University of Washington Press, Seattle, WA.

Bilek, S.L. 2010. *Seismicity along the South American subduction zone: review of large earthquakes, tsunamis, and subduction zone complexity*, Tectonophysics, Vol 495, 2–14.

Buckle, I., Hube, M., Chen, G., Yen, W. & Arias, J. 2012. Structural Performance of Bridges in the Offshore Maule Earthquake of 27 February 2010, *Earthquake Spectra*, Vol 28(S1, June 2012), S533-S552.

EERI. 2010. *The Mw 8.8 Chile Earthquake of February 27, 2010*, EERI Special Earthquake Report, 10.

Filiatrault, A., Cherry, S. & Byrne, P.M. 1990. The Influence of Mexico City Soils on the Seismic Performance of Friction Damped and Base Isolated Structures, Earthquake Spectra, Vol 6(2, May 1990), 335-352.

International Conference of Building Officials (ICBO). 1991. *Earthquake regulations for 570 seismic isolated structures*, Chapter 23 of Uniform Building Code, Whittier, CA.

Métois, M., Socquet, A. & Vigny, C. 2012. Interseismic coupling, segmentation and mechanical behavior of the central Chile subduction zone, *J. Geophys. Res.*, Vol 117, B03406.

Nelson, A.R., Kelsey, H.M. & Witter, R.C. 2006. Great earthquakes of variable magnitude at the Cascadia subduction zone, *Quaternary Res.*, Vol 65, 354–365.

Pan, P., Zamfirescu, D., Nakashima, M., Nakayasu, N. & Kashiwa, H. 2005. Base-isolation design practice in Japan: Introduction to the post-Kobe approach, *Journal of Earthquake Engineering*, Vol 9(1), 147–171.

Rajendran, K. 2013. On the recurrence of great subduction zone earthquakes, *Current Science*, Vol 104(7), 880-892.

Skinner, R.I., Robinson, W.H. & McVerry, G.H. 1993. *An Introduction to Seismic Isolation*, Wiley, England.