An Analysis and Comparison of the Response Spectra Records from the 4 September, 2010 Darfield Earthquake and the 22 February, 2011 Port Hills Earthquake to Building Code NZS1170.5 using SPECTRA Software

by

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1. ABSTRACT

The Christchurch area is characterized by its soft soil and fertile flood plains and most recently by its frequent earthquakes, two of which, the Darfield and Port Hills events, devastated the central city and surrounding areas. On and after 4 September, 2010 and 22 February, 2011, groups of civil engineers assessed damaged areas and collected vital aftermath data to be analysed. This data was analyzed using SPECTRA software and compared to NZS1170.5, the New Zealand Standards for structural design actions, specifically for earthquake actions. Problem areas were characterized by the spectral acceleration exceeding building codes developed using the equation $C(T) = C_h(T)ZR$ and the associated building heights using the equation $T1 = 1.25k_t hn^{0.75}$. Sixteen sites during the September event and 10 sites during the February event exceeded standard design codes. Increasing the hazard factor, Z, for both Darfield and Christchurch, as well as designing for earthquakes more likely to occur over a 1000 year time frame or 2500 year time frame will increase the cost of designing and building but will also decrease the likelihood of these buildings being irreversibly damaged during earthquakes, thus saving repair costs.

2. INTRODUCTION:

On 22 February, 2011, a 6.3 Richter magnitude and 3-12 km deep earthquake struck Christchurch at 12:51. Just 171 days after the 7.1 Richter magnitude and 10 km deep quake on 4 September, 2010, deemed the Darfield Earthquake, the Christchurch quake killed at least 181 victims, though the toll is unlikely to rise much higher (ONE, 2011). As painful as it may be to cope with so many lost lives, engineers are more focused on how Christchurch has survived two large earthquakes in less than six months and not completely crumbled to the ground. Engineers are researching how sites respond to earthquakes, how buildings respond, and how codes should be written or amended for future earthquakes.

It is vital to understand how and why the earth responds as it does to tremors so engineers can build and design homes, high rises, schools, hospitals, bridges, levees, etc. resistive enough and strong enough to withstand such powerful forces. Engineers analysing and comparing both the Darfield and Christchurch earthquake are using earthquake acceleration records to produce response spectra, from which structural performance can be predicted. Through these predictions and comparisons, building codes can be assessed and re-evaluated as needed.

3. BACKGROUND:

Christchurch is situated near the center of the east coast of the South Island of New Zealand in the South Pacific Ocean located between the Indo-Australian and Pacific Plate (Figure 1). The city was established on the coast of the Canterbury Plains adjacent to an extinct volcanic complex that formed Banks Peninsula The site of Christchurch was mostly swamp, beach dune sand, and estuaries and lagoons, which were drained. It is bounded on the east by the estuaries of the Avon and Heathcote Rivers and to the north by the Waimakariri River (Brown et al.).

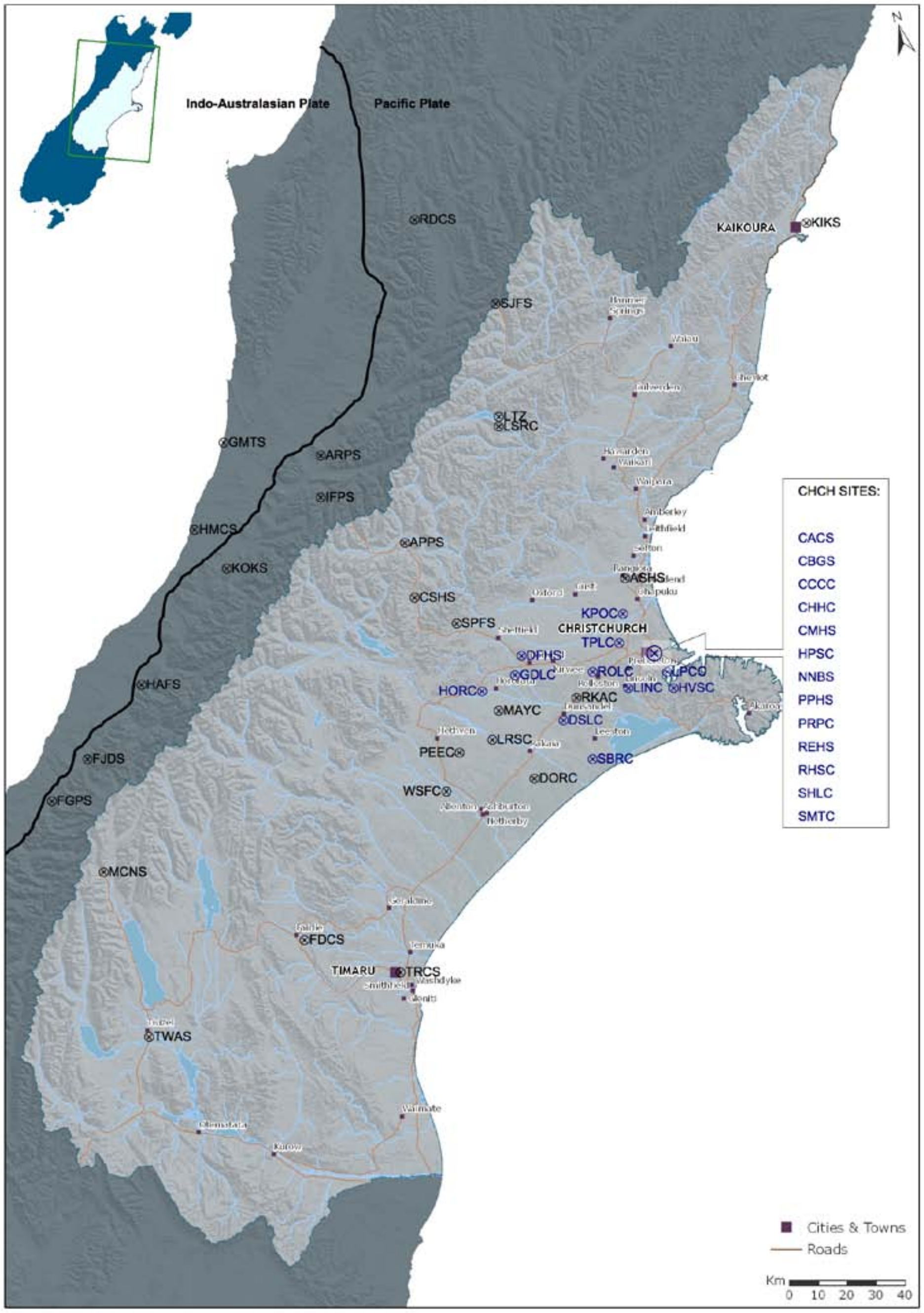
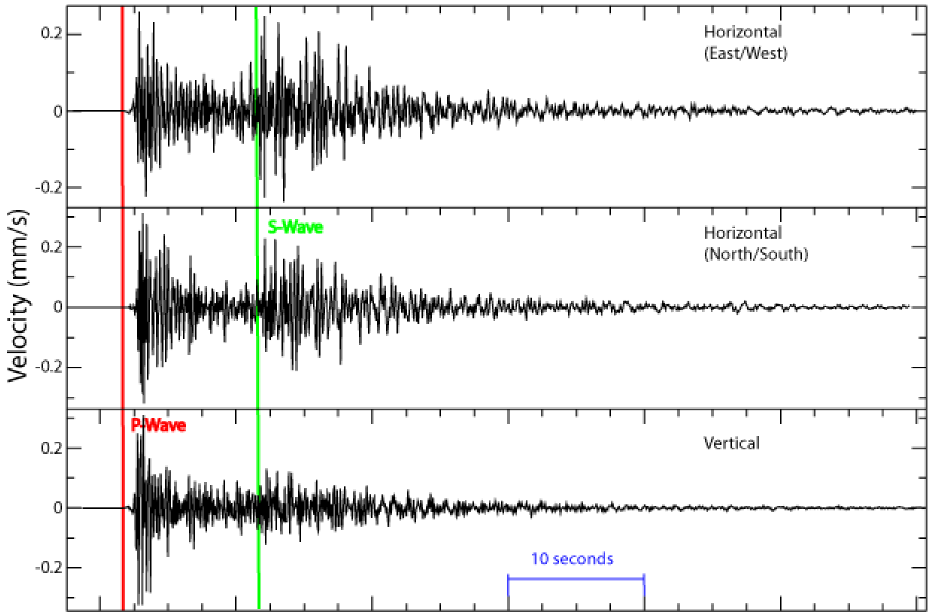


Figure 1. Map of 57 recording sites across the South Island, as well as the plate boundary (bold line).

Earthquakes are caused by ruptures below the surface of the ground, which create seismic waves that spread outwards through the ground from the focus of the earthquake. The shaking that people experience on the surface result from the three basic types of elastic waves that occur: P, S, and surface waves (Bolt, 2004).

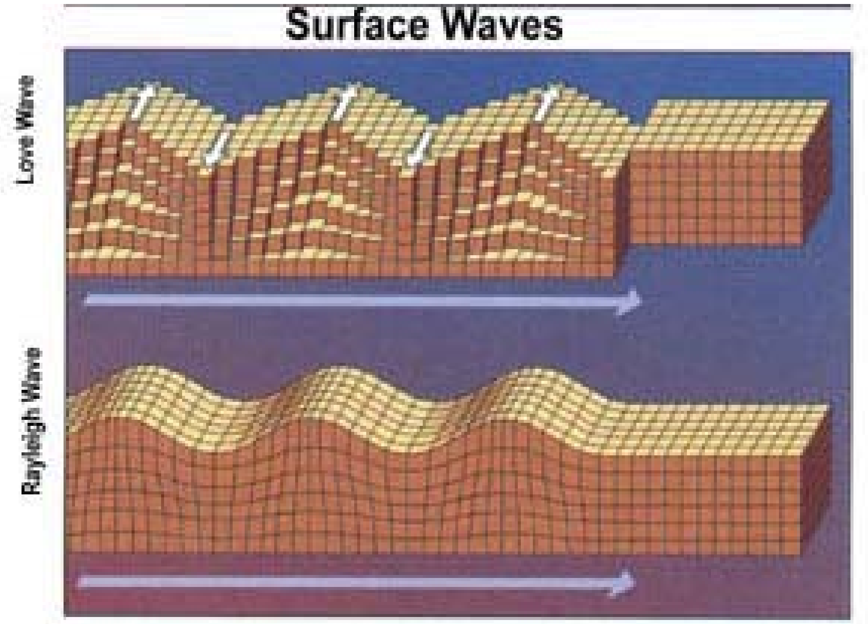
P and S waves (Figure 2), or primary and secondary, waves are defined as body waves simply because they occur within the body of the rock through which they travel. Primary waves are the faster of the two and function much the same as sound waves, alternately pushing and pulling on the rock as they move through it. P waves are able to travel through both solid and liquid material and can often be heard when they reach the surface, thus the rumbling of which many people speak before and during earthquakes. S waves, the slower of the two, shear the rock, traveling sideways through it at a right angle. Secondary waves are unique in that they cannot propagate through liquids and therefore only function in the solid parts of the Earth.



http://en.wikipedia.org/wiki/File:Seismogram.gif

Figure 2. P & S waves as detected by a seismograph. P waves travel through solid and liquid materials horizontally, S waves travel through solid materials at right angles.

The third type of seismic waves is defined as surface waves (Figure 3), which travel more slowly than the body waves. Surface waves are restricted to the ground surface, which means that as the depth below the surface increases, wave motion decreases. They can be broken up into two different types: Love waves and Rayleigh waves, each named after the English mathematicians who first described them. Love waves travel in much the same way as S waves, perpendicular to the direction of the wave but with no vertical displacement. The horizontal displacement caused by these waves is usually what causes the most damage to structure foundations. Rayleigh waves travel in a rolling fashion, much like an ocean wave, and cause both vertical and horizontal displacement.



http://en.wikipedia.org/wiki/File:Pswaves.jpg

Figure 3. Surface waves as they travel through material. The material is displaced either vertically or horizontally, as illustrated.

The ground and every building have a natural frequency at which they vibrate. When waves pass through the ground, they travel at a frequency that can match those of buildings. When this occurs, the vibration of the building will be more and more amplified, which will cause it to fail earlier. Different storied buildings will each have unique natural frequencies, or spectral accelerations, and the code provides spectral acceleration graphs that limit different scenarios (Figure 4).

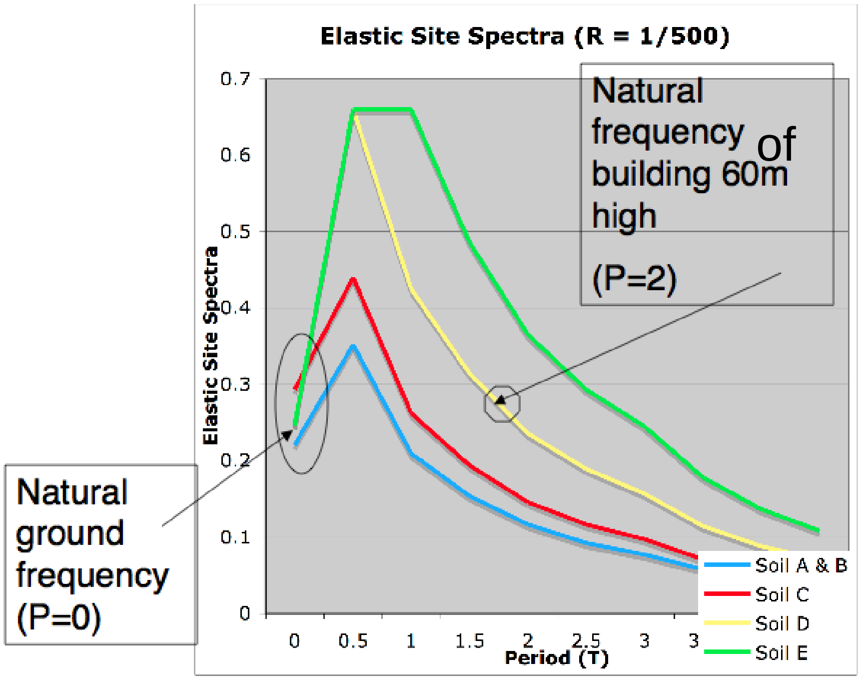


Figure 4. Example of spectral accelerations of the ground (P=0) and buildings for different soil classes. Building heights (for example 60m at said period and soil class) are found using the equation $T1 = 1.25k_t hn^{0.75}$

There are three factors that influence the amount of damage cause by the seismic waves that occur during an earthquake: geology, soil conditions, and topography. Christchurch and the Canterbury region lie on the Pacific Plate. It is believed that the recent earthquake activity in the Canterbury area was due to fractures within fragments of the plate atop which the region lies. The soil conditions in the Canterbury plains may also have been a large factor for the recent earthquakes. Canterbury is a floodplain, which means it contains soft, fertile soil in most regions. An abundance of rivers and aquifers lace the area as well.

The size of an earthquake can be characterized by its magnitude and intensity. The moment magnitude scale (M_W) is the device commonly used today to measure the magnitude of an earthquake. The magnitude assigned to an earthquake is found using a mathematical equation: magnitude = rigidity of the Earth * average amount of slip on the fault * size of the area that slipped (Bolt, 2004). An earthquake can also be characterized by its felt intensity, which is measured by the Modified Mercalli Intensity (MMI) scale, a subjective study of the damage done during the quake and people's reactions to it. It is rated from 1 to 12 on a scale depending on peoples' descriptions (Hikuroa). A third measure of earthquake size is peak ground acceleration (PGA), which is a measure of the earthquake acceleration on the ground. Peak horizontal acceleration (PHA) is the most common ground acceleration measured and is often used to set building codes. But sometimes, as with the Christchurch earthquake, the vertical acceleration is greater (Bolt, 2004).

New Zealand building codes are set by the New Zealand Standards, a set of guides outlining the principles and parameters for all types of engineering in New Zealand. NZS1170.5 is the New Zealand Standards for design actions specific to earthquake design actions. Section 3 of the earthquake design actions sets site hazard spectra for all regions of New Zealand. For comparison of spectral acceleration data collected the elastic site hazard spectrum for horizontal loading, C(T), for a given return period is used. The equation used to calculate the spectrum for any given area is:

$$C(T) = C_h(T)ZRN(T,D)$$

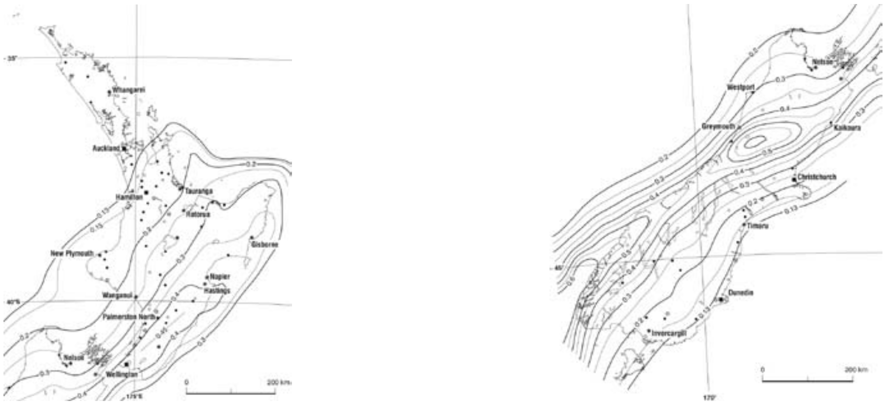
where:

- the spectral shape factor, $C_h(T)$,
- the hazard factor, Z,
- the return period factor (probability an earthquake will occur annually), R, and
- the near-fault factor, N(T,D,)

are all determined from different clauses laid out in the code (King, 2004). The spectral shape factor, $C_h(T)$, is determined by the subsoil class of the area of study. There are four areas: strong rock and rock (class A and B), shallow soil (class C), deep or soft soil (class D), and very soft soil (class E). Christchurch and the surrounding Canterbury region generally falls into class D or deep or soft soil, although there are some areas closer to the mountainous regions that will fall into classes A and B, strong rock and rock. Class D regions are usually defined as areas where low-amplitude natural period is greater than 0.6 s, areas with depths of soils exceeding 100m, or areas underlain by less than 10m of soils with an undrained shear-strength less than 12.5 kPa.

Hazard factors have been determined for all locations within New Zealand, according to Figures 5 and 6. Best practice across New Zealand is to design buildings assuming an earthquake disaster once every 500 years (R 1/500). For the purposes of this research the near-fault factor, N(T,D), was ignored specifically to simplify analysis of results.

The geology, tectonic setting, and active seismicity of the Canterbury region forecast that future large earthquakes could occur. Planning and design based on the two previous big earthquakes in Christchurch are essential to the future of New Zealand's earthquake preparedness.



Figures 5 and 6. Hazard factors, Z, for the North and South Islands, respectively (King et al, 2004).

Additionally, NZS1170.5 provided another equation, $T1 = 1.25k_t hn^{0.75}$, where $k_t = 0.075$ for moment-resisting concrete frames. The equation is solved for h using the periods, T, for which the spectral acceleration exceeds the code.

The data contains multiple acceleration, velocity, and displacement records. However, only the horizontal acceleration versus time data is required for SPECTRA, a software program that outputs a response spectrum, among other spectra.

SPECTRA uses multiple parameters, such as duration, period, and damping to transform the text document data into graphs and new data points. The duration was site specific, as the P and S waves affected each site differently and the shaking lasted for various periods of time (though the majority varied only by a few seconds or even milliseconds). The period and damping were the same for every data set, with 500 natural periods and 5% damping.

Once all the data was entered, SPECTRA computed various graphs and data sets, the most important for this research being the response spectrum. A response spectrum plots the peak or steady-state response (displacement, velocity, or acceleration) of a series of oscillators of varying natural frequency (Newmark). The data set of spectral acceleration versus period and response spectra are useful tools to analyze how buildings will react to certain movements, and see where the natural frequency of the structure will align with the response spectra frequencies.

4. METHODS:

Acceleration data was entered into SPECTRA, which produced a set of period versus spectral acceleration data points. The data points were then entered into a text document, which was then entered into SPECTRA. Since SPECTRA produces a data point for every 0.02 periods, data was taken every 0.5 period from 0 – 4.5 periods to simplify analyses.

The acceleration spectra developed through SPECTRA were then compared to those governed by the equation $C(T) = C_h(T)ZR$ written out under code NZS1170.5. The code spectra were developed from soil type factor ($C_h(T)$), a site hazard factor (Z), and a return factor (R). All the site values were taken from the code. This equation was then graphed in EXCEL, along with the SPECTRA data points from periods 0 – 4.5. The SPECTRA data was graphed as a smooth curve since it was not an equation but rather points, so they were good approximations of the entire data set.

For any response spectra that exceed the code, the equation $T1 = 1.25k_t h\mathrm{n}^{0.75}$ was applied to the periods that exceed the code to determine the heights of buildings most affected.

5. RESULTS:

Using the equations set out in NZS1170.5, $C(T) = C_h(T)ZR$ and $T1 = 1.25k_t h\mathrm{n}^{0.75}$, and using site specific parameters where possible, site response spectra were graphed with code response spectra for different probablities of earthquakes occuring.

5.1 SEPTEMBER 2010 RESULTS:

5.1.i R 1/500

There was a total of 57 sites examined and for 16 sites,

CACS	DFHS	HVSC	PPHS
CCCC	**GDLC**	KPOC	ROLC
CHHC	HORC	**LINC**	SHLC
CMHS	HPSC	NNBS	TPLC

at some point during the first 4.5 periods, the acceleration buildings experienced exceed the baseline set down by the code. At the bolded sites, every design would have exceeded building codes. Buildings were designed to this standard (R 1/500), yet most at most sites the natural frequenices at which they shook greatly exceeded the code (Figures 7 & 8). Most of the building designs that would have exceeded the code were above between 60-90m or over 110m high.

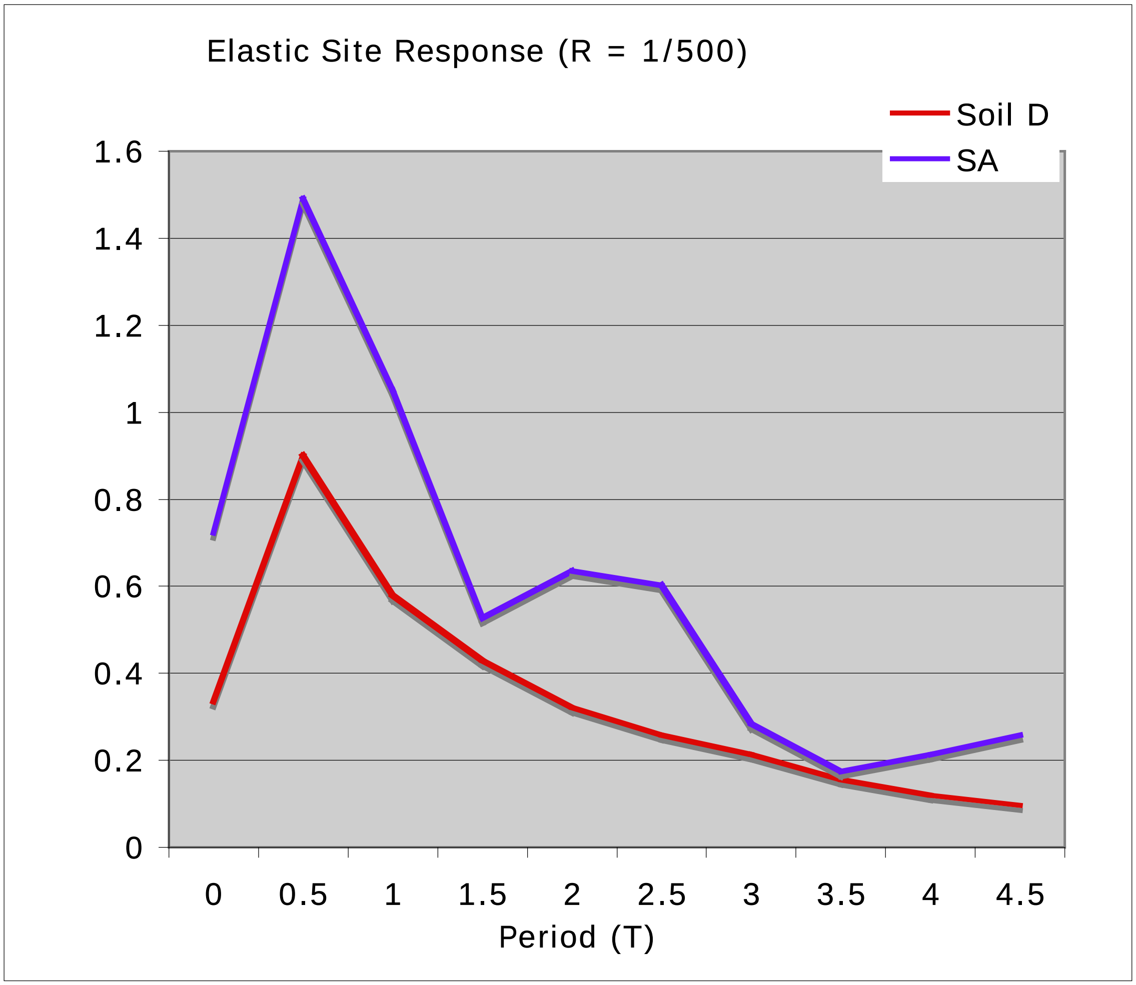


Figure 7. Buildings designed of all heights at Greendale, GDLC, exceeded the building code since the spectral acceleration is above the code at every period.

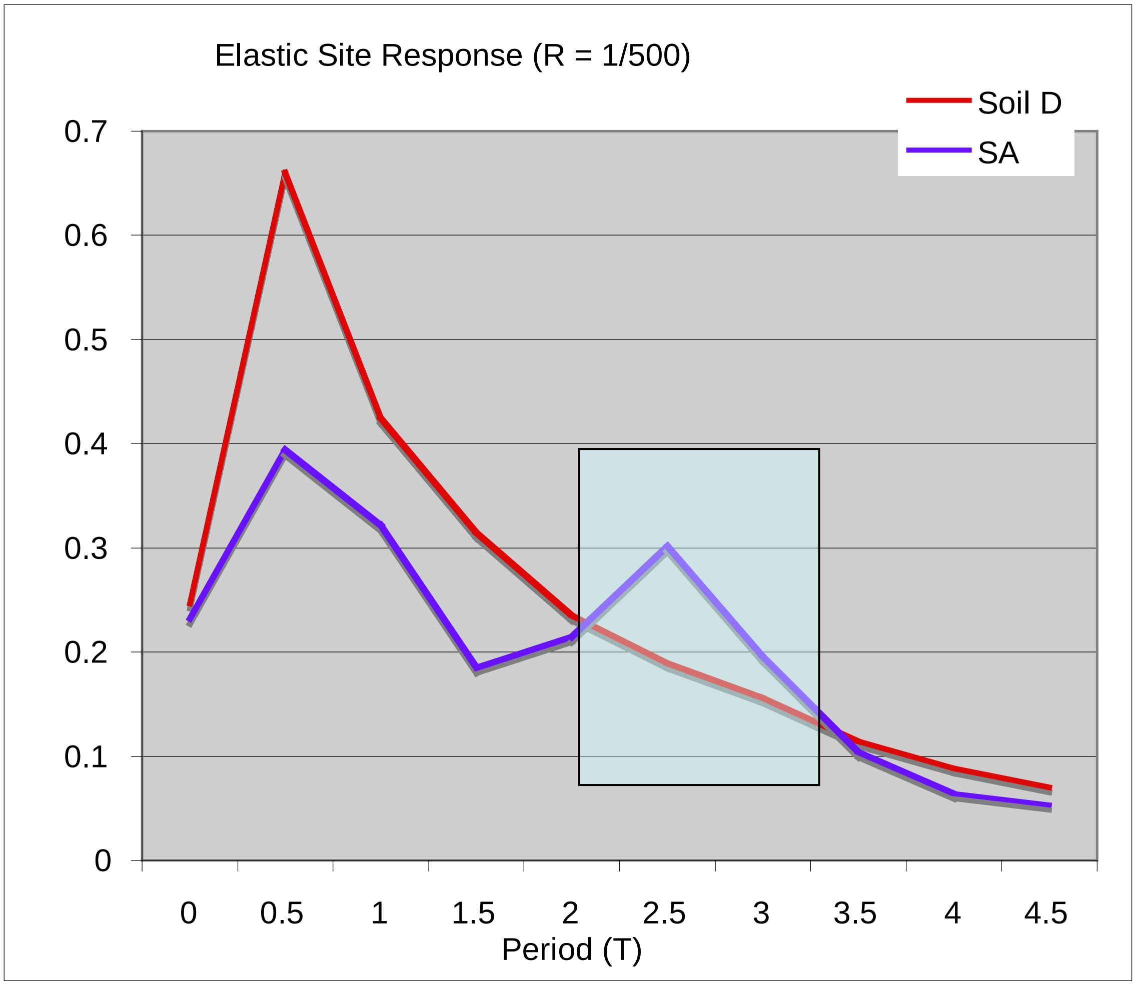


Figure 8. Near Christchurch Cathedral College (CCCC), buildings designed in the shaded region (60m-102m [calculated using $T1 = 1.25k_t hn^{0.75}$]) exceeded the code and would likely have experienced structural damage such as shear cracks or worse. Buildings of other heights (below the red line) should have been fine.

5.1.ii R 1/1000

If buildings had been designed for larger earthquakes that occur once every 1000 years, 12 sites would have exceeded building codes, those being:

CCCC	HORC	GDLC	PPHS
CHHC	HPSC	KPOC	ROLC
DFHS	HVSC	LINC	TPLC

Had buildings been designed to this standard, not as many would have exceeded the code (Figures 9 & 10).

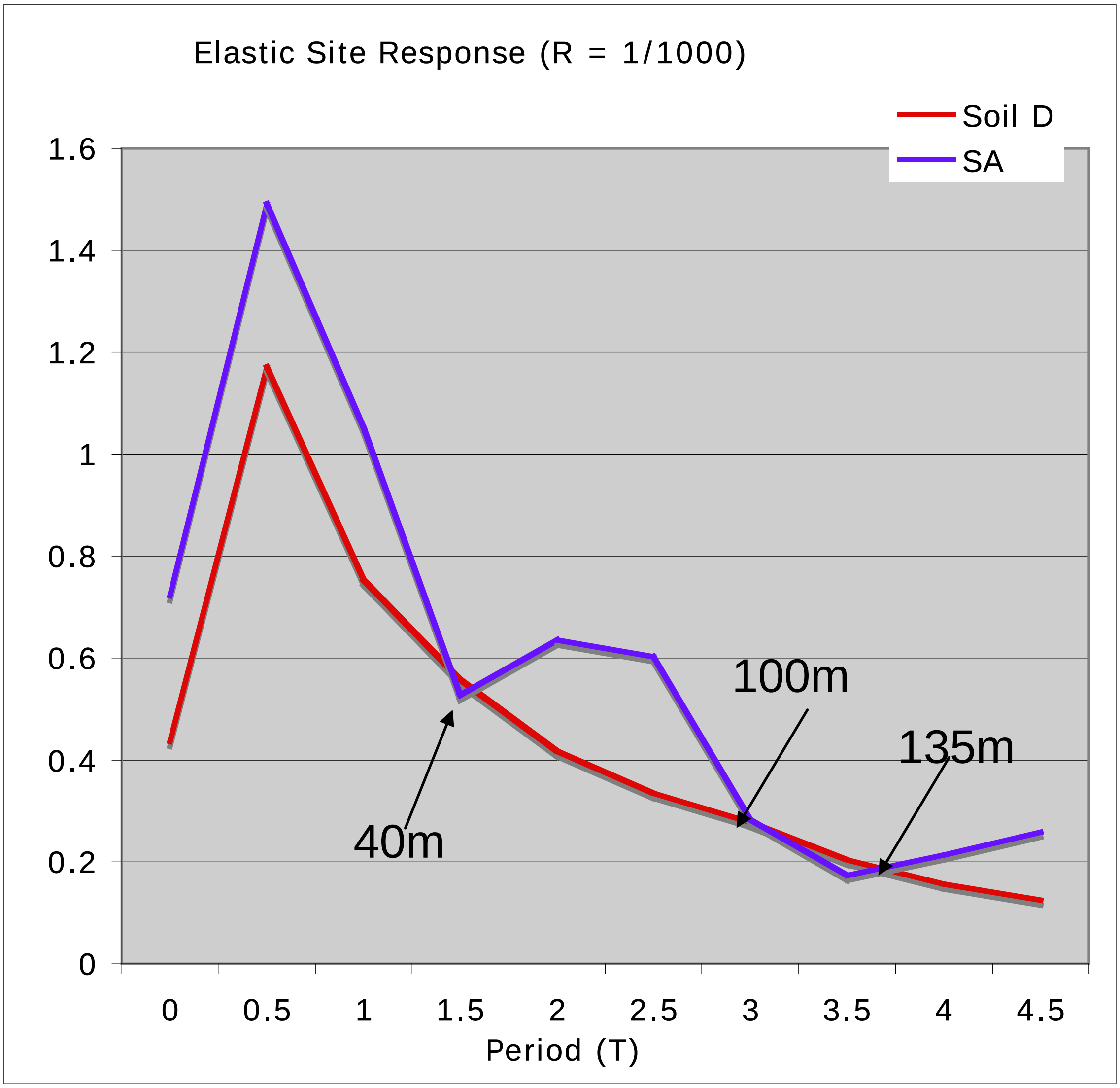


Figure 9. Even designing buildings to a stricter standard, buildings of almost every height (except around 40m, 100m, and 135m) would have exceeded the code at the GDLC .

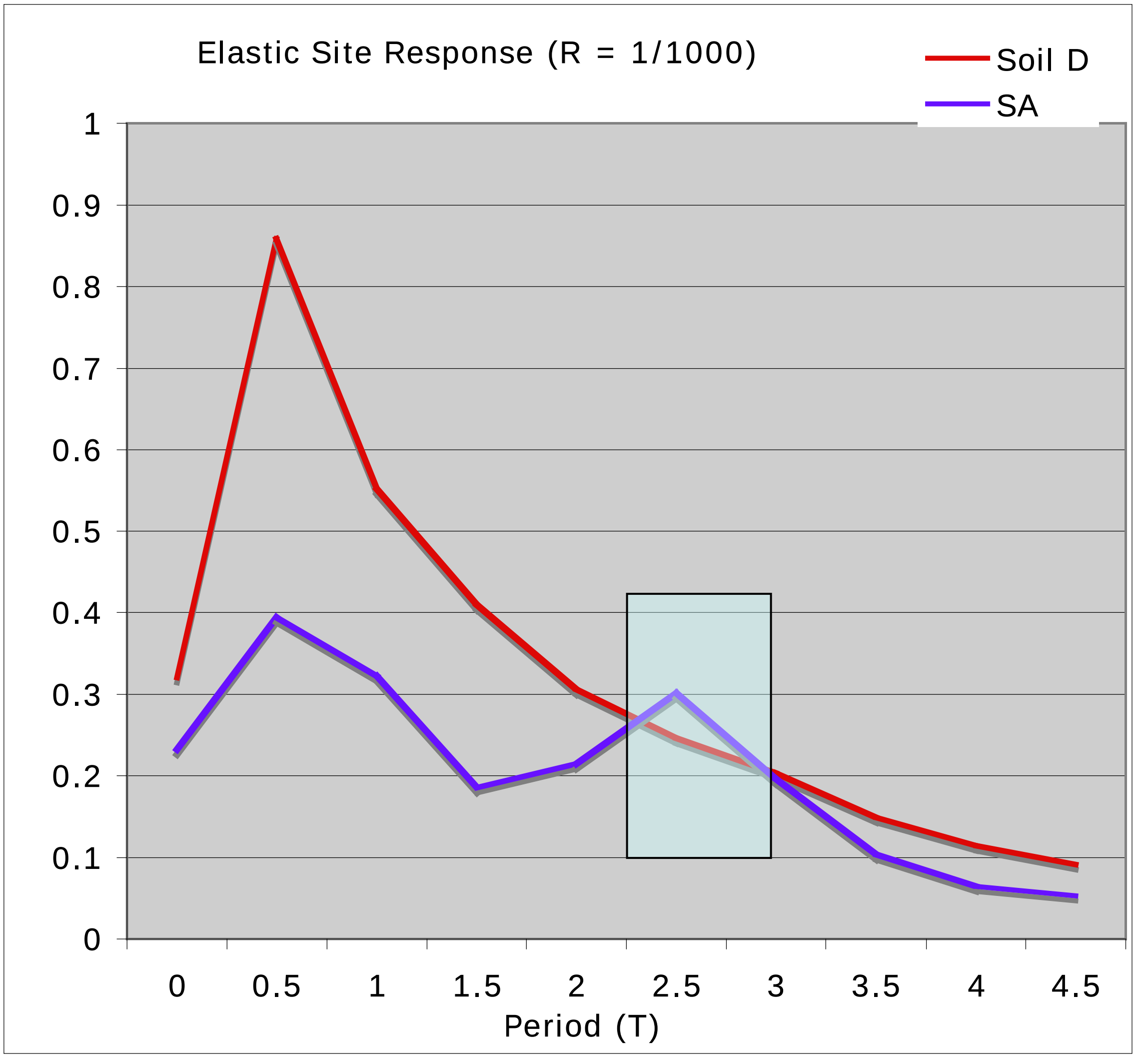


Figure 10.Buildings designed 60-80m high at CCCC would have exceeded building codes.

5.1.iii R 1/2500

If the return period were yet again increased, this time to the probablity of an earthquake occuring1/2500 years, the following six sites would have still exceeded the building code, though not as greatly:

CHHC	GDLC	HPSC	LINC	ROLC	TPLC

Most of these sites were near the Darfield epicenter or the Christchurch CBD , where taller buildings would have been more likely to fail (Figures 11 & 12).

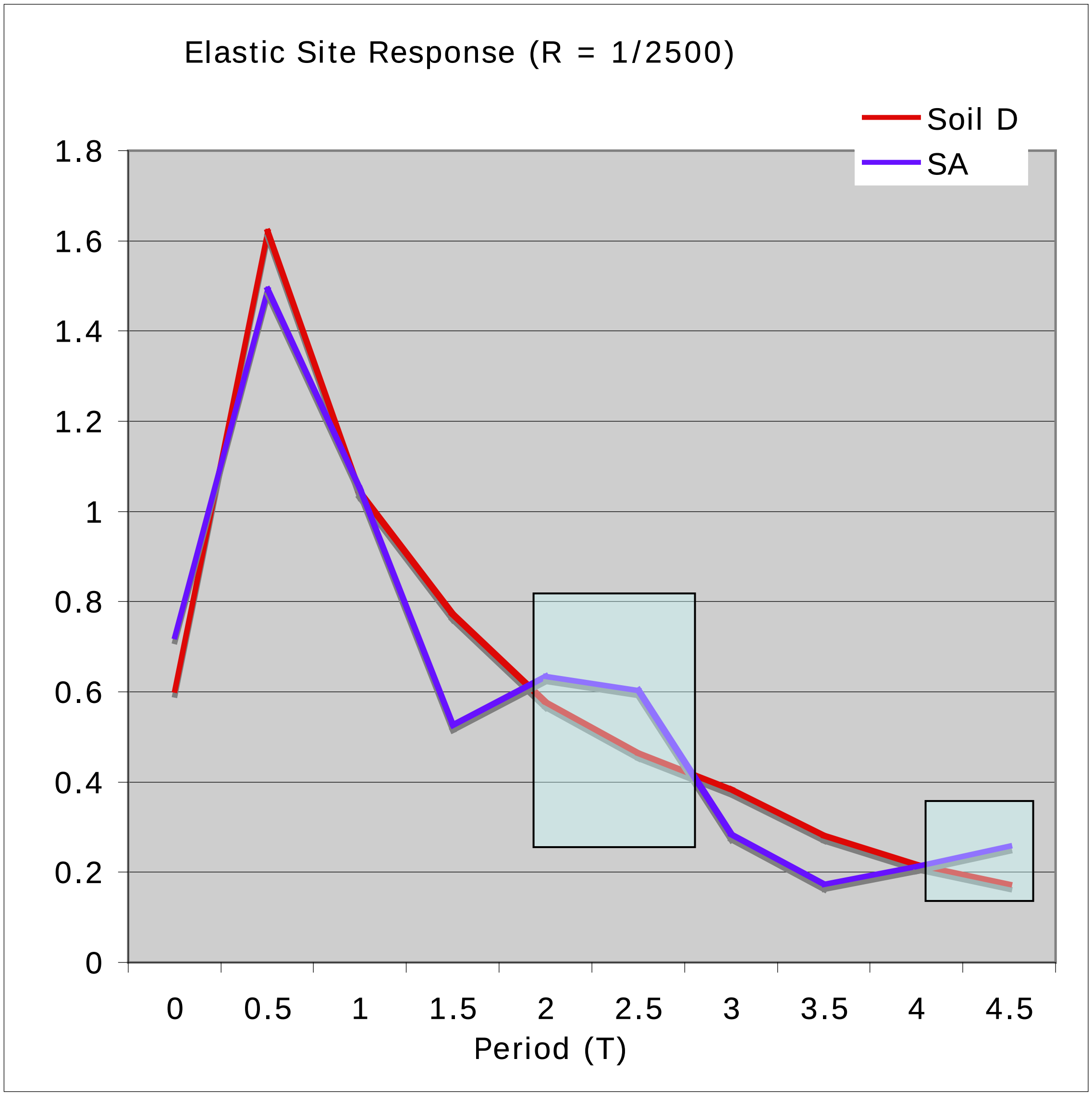


Figure 11. At site GDLC, buildings designed 60-90m high or higher than 135m would have exceeded building codes.

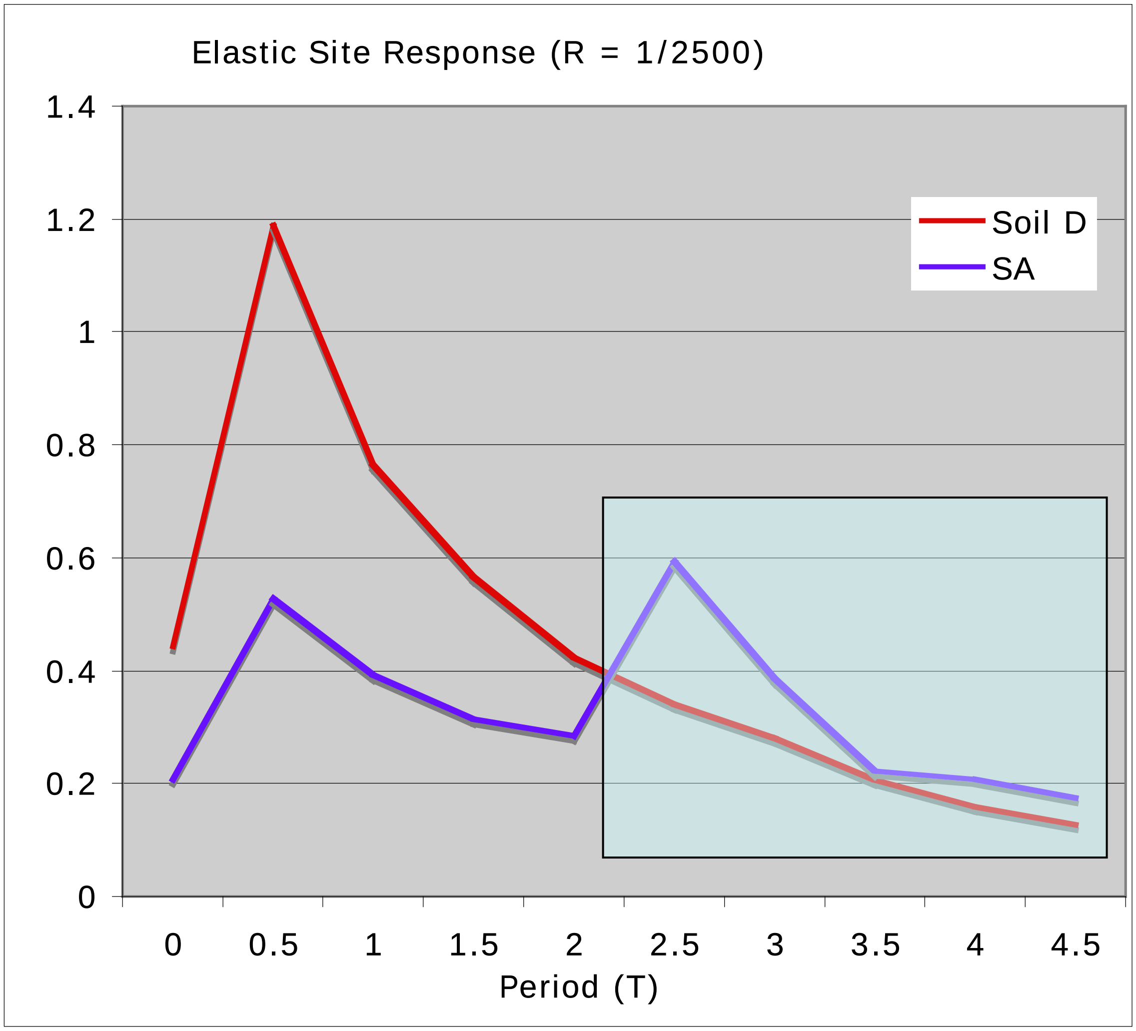


Figure 12. At site CHHC, the Christchurch Hospital, buildings designed higher than 60m would have exceeded the building code.

5.2 FEBRUARY 2011 RESULTS:

Sites around the September 2010 epicenter, Darfield, and the Christchurch area were analyzed, as sites farther away from these two locations were unaffected in the previous earthquake.

5.2.i R 1/500

Buildings designed to the normal standard of an earthquake occuring once every 500 years would have failed at the following ten sites:

CHHC	HPSC	KPOC	LPCC	**PRPC**
CMHS	HVSC	LINC	**NNBS**	**REHS**

All building designs would have exceeded codes at the bolded locations above. The severity of exceedence shown is comparable to the September earthquake (Figures 13 , 14 & 15).

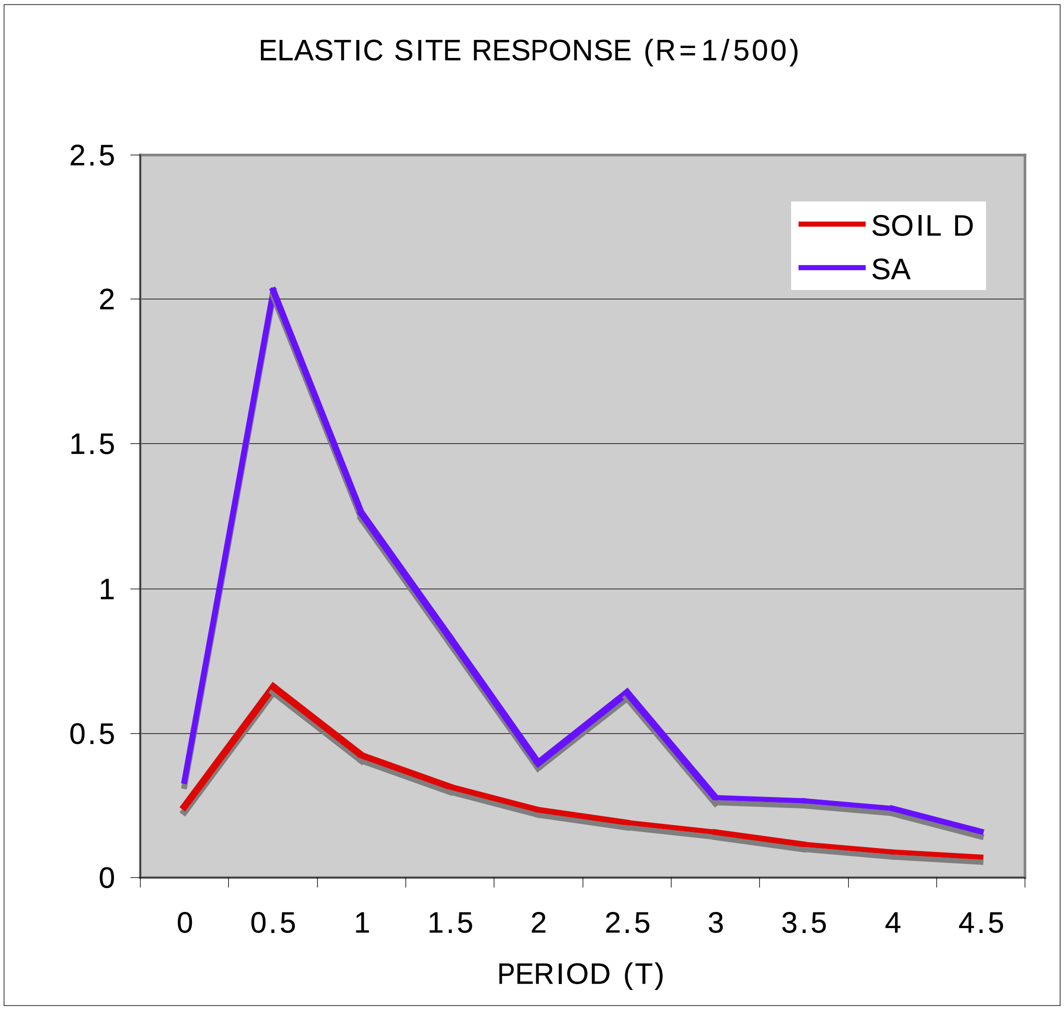


Figure 13. All buildings designed near site CHHC would have exceeded the basic building codes.

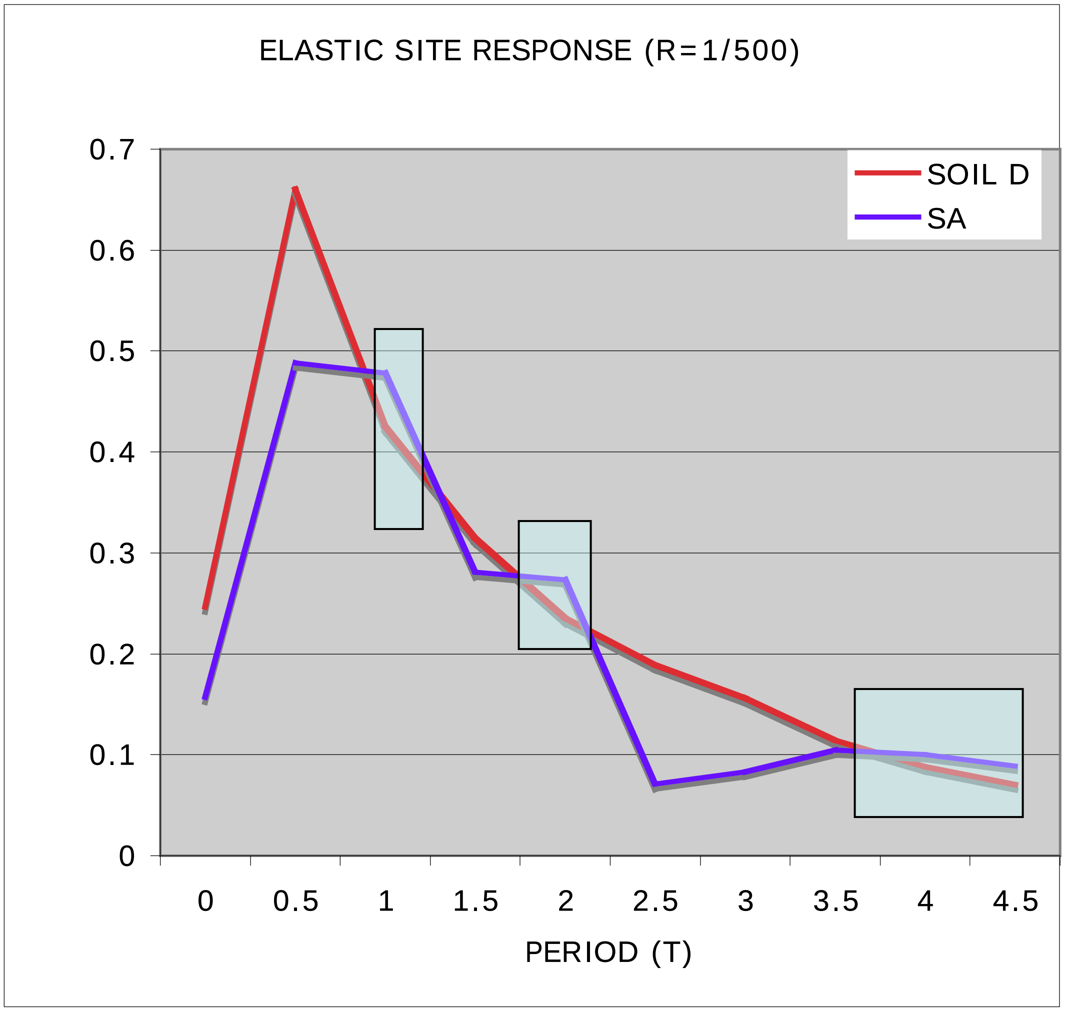


Figure 14. Buildings at site LINC, near Lincoln, designed to be16-24m high, 40-48m high, or higher than 137m would have exceeded building codes, though minimally.

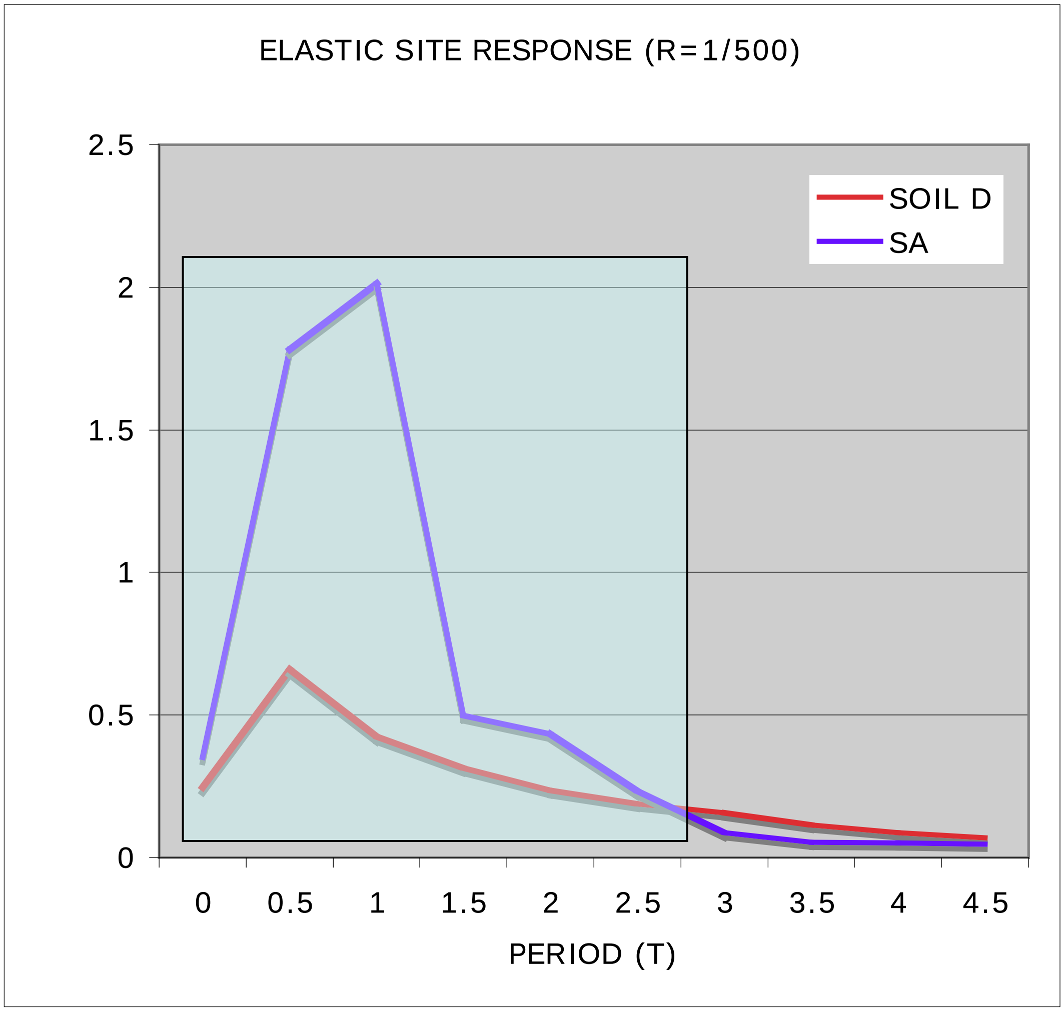


Figure 15. In comparison to LINC, buildings designed under 80m near site CMHS, Christchurch Cashmere High School, would have exceed building codes greatly.

5.2.ii R 1/1000

With stricter building codes, the buildings designed at the following nine sites would have exceeded codes:

CHHC	HPSC	KPOC	**NNBS**	**REHS**
CMHS	HVSC	LPCC	**PRPC**	

All buildings designed at the bolded aforementioned locations would have exceeded building codes. Most of the much shorter or much taller buildings would have been more likely to fail at the other sites (Figures 16, 17 & 18).

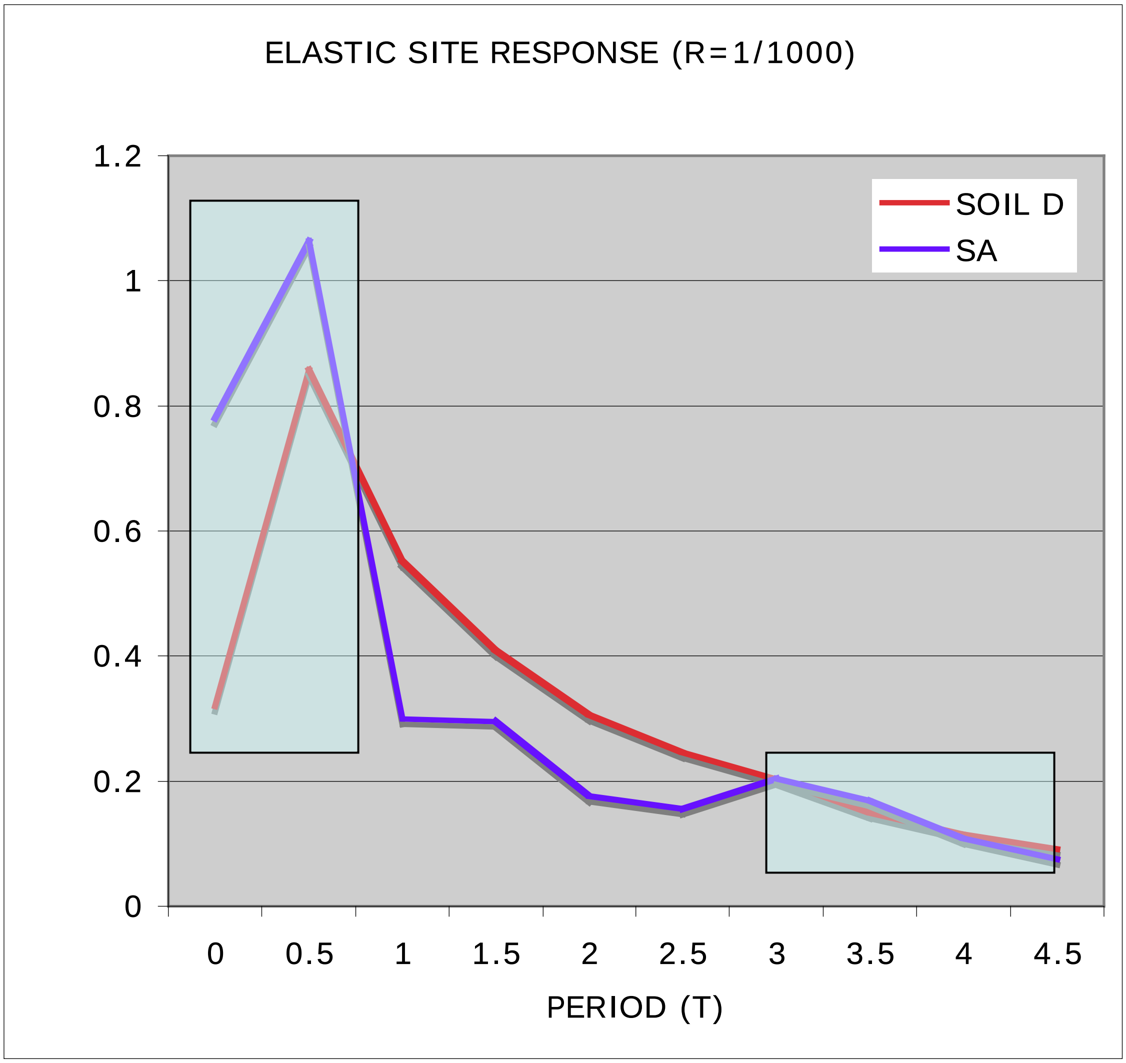


Figure 16. At site LPCC, in Lyttleton, very tall or very short building designs would have exceeded (for the most part) the code, those being unider 9.5m or over 119m tall.

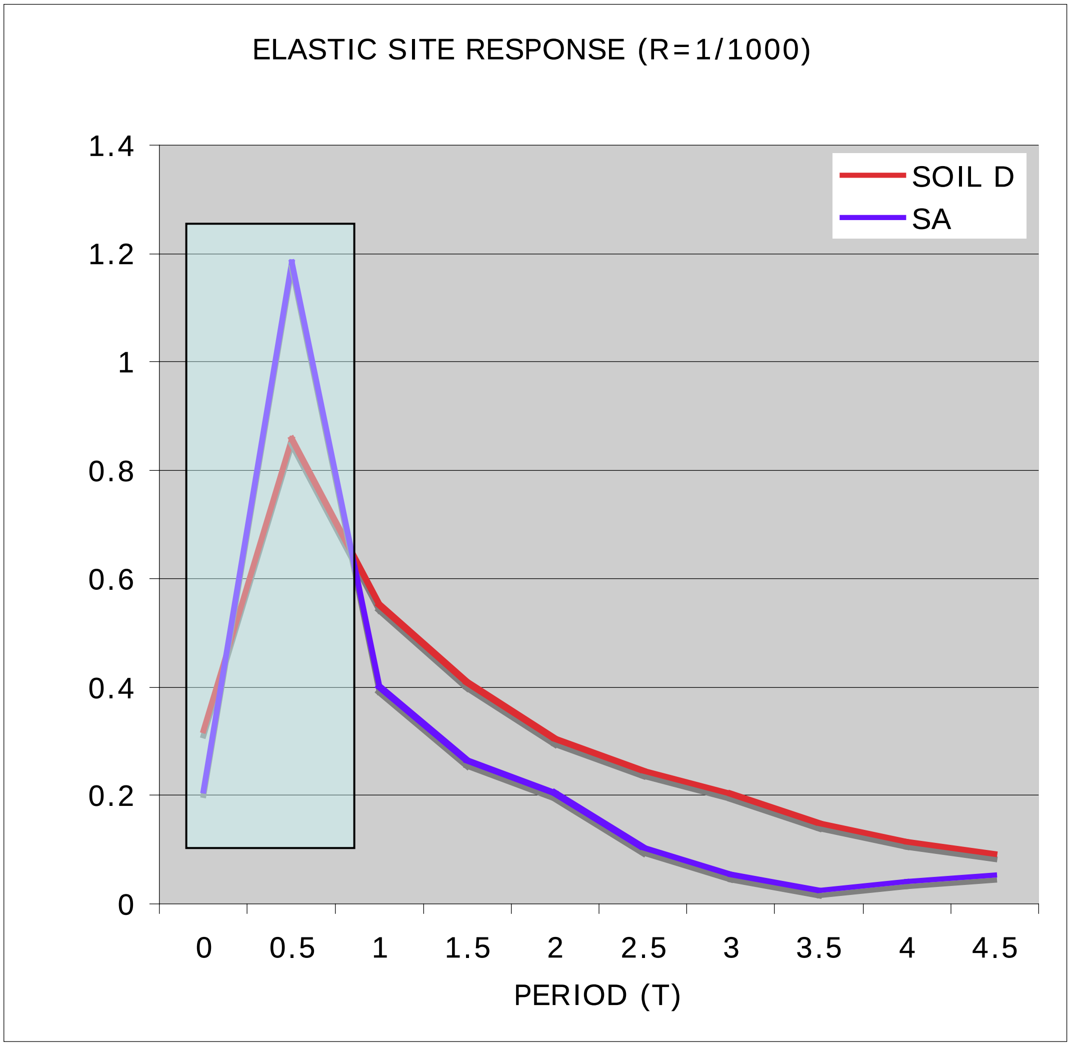


Figure 17. Buildings designed to be under 16m tall at KPOC would have exceeded the code.

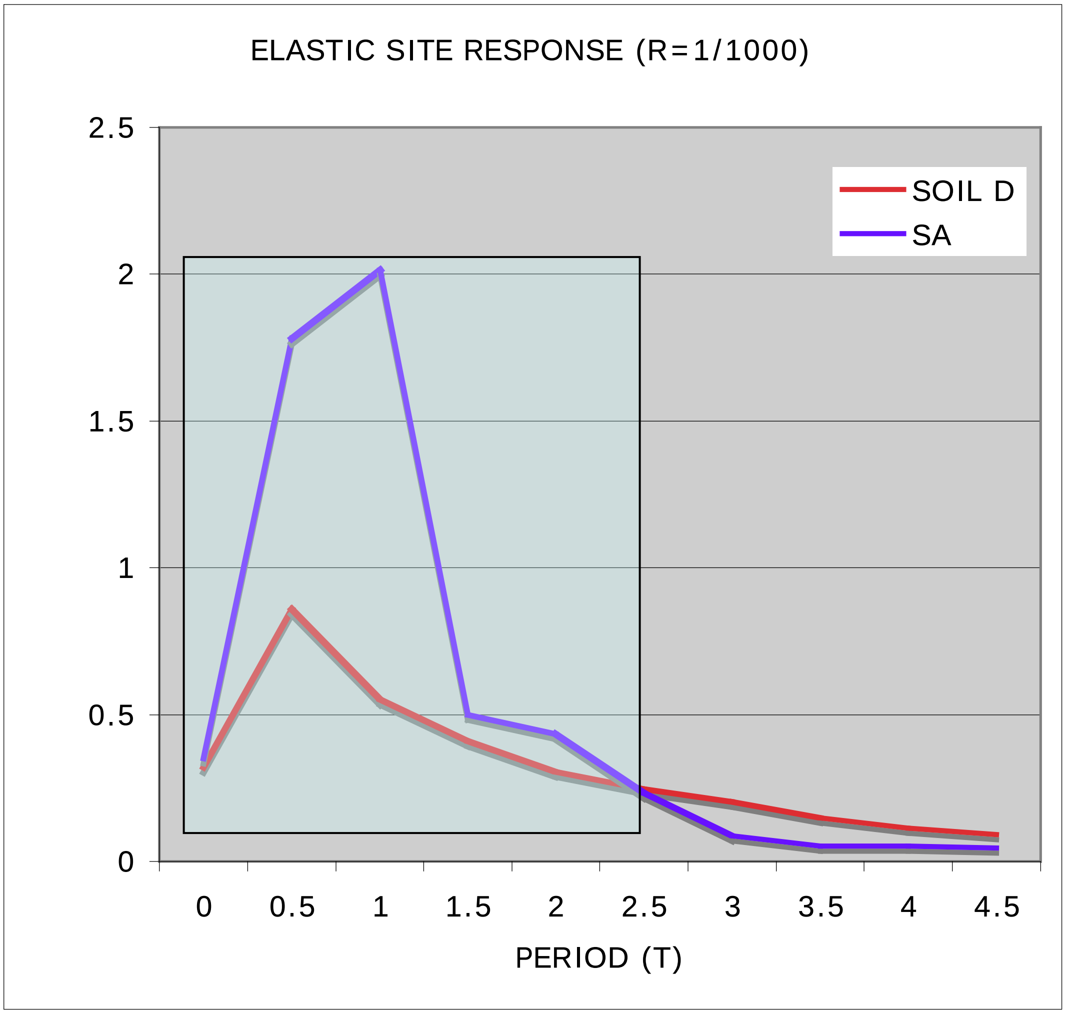


Figure 18. Buildings designed near CMHS to be under 70m tall would have exceeded the code.

5.2.iii R 1/2500

Had buildings been designed for an earthquake event that occurs once every 2500 years, buildings at the following six sites would have still exceeded codes:

CHHC	CMHS	LPCC	**NNBS**	PRPC	REHS

All building designs at the bolded sites above would have exceeded the code. Most buildings would have been relatively unaffected, but still there would have been issues (Figures 19, 20, 21). At site LPCC, only buildings under 4m tall would have exceeded codes.

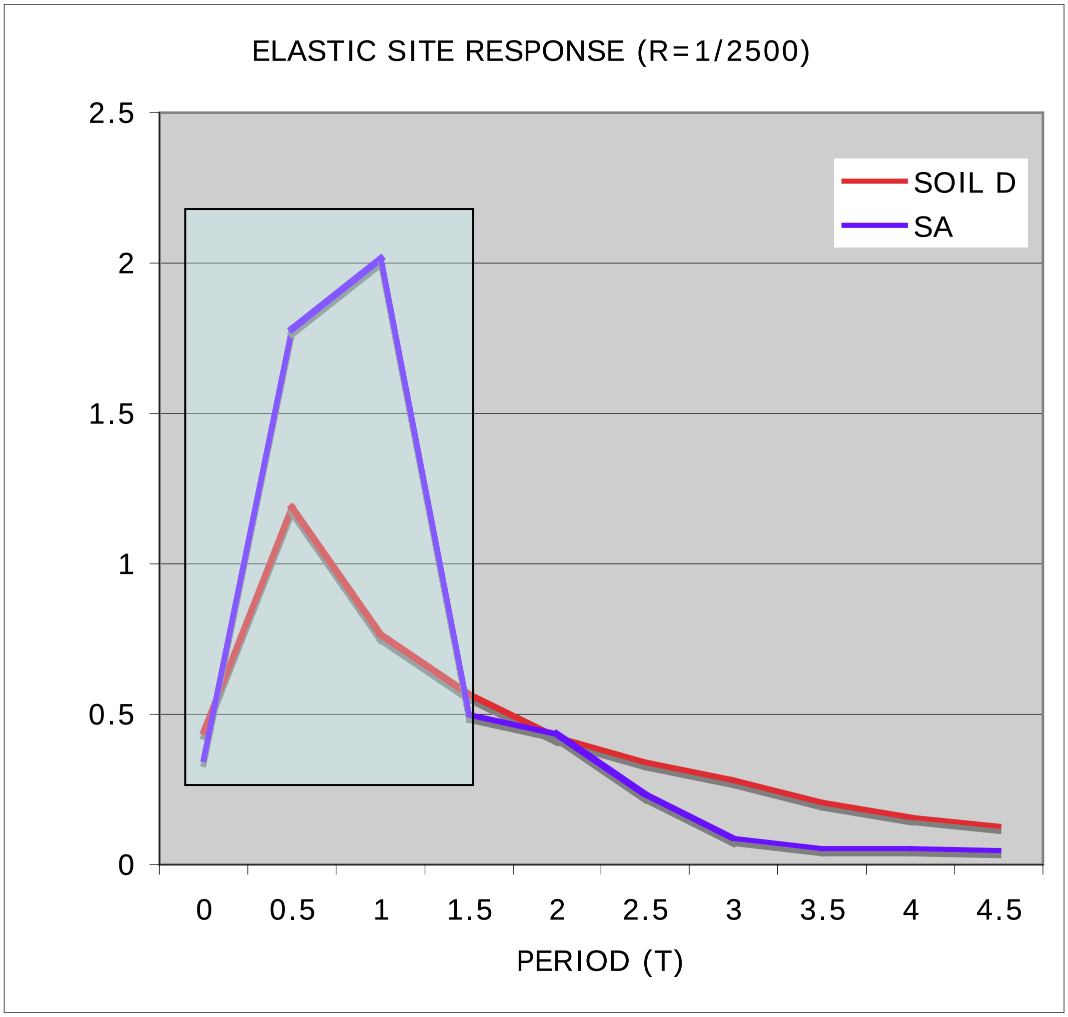


Figure 19. Buildings designed to be under 32m near CMHS would have exceeded code standards.

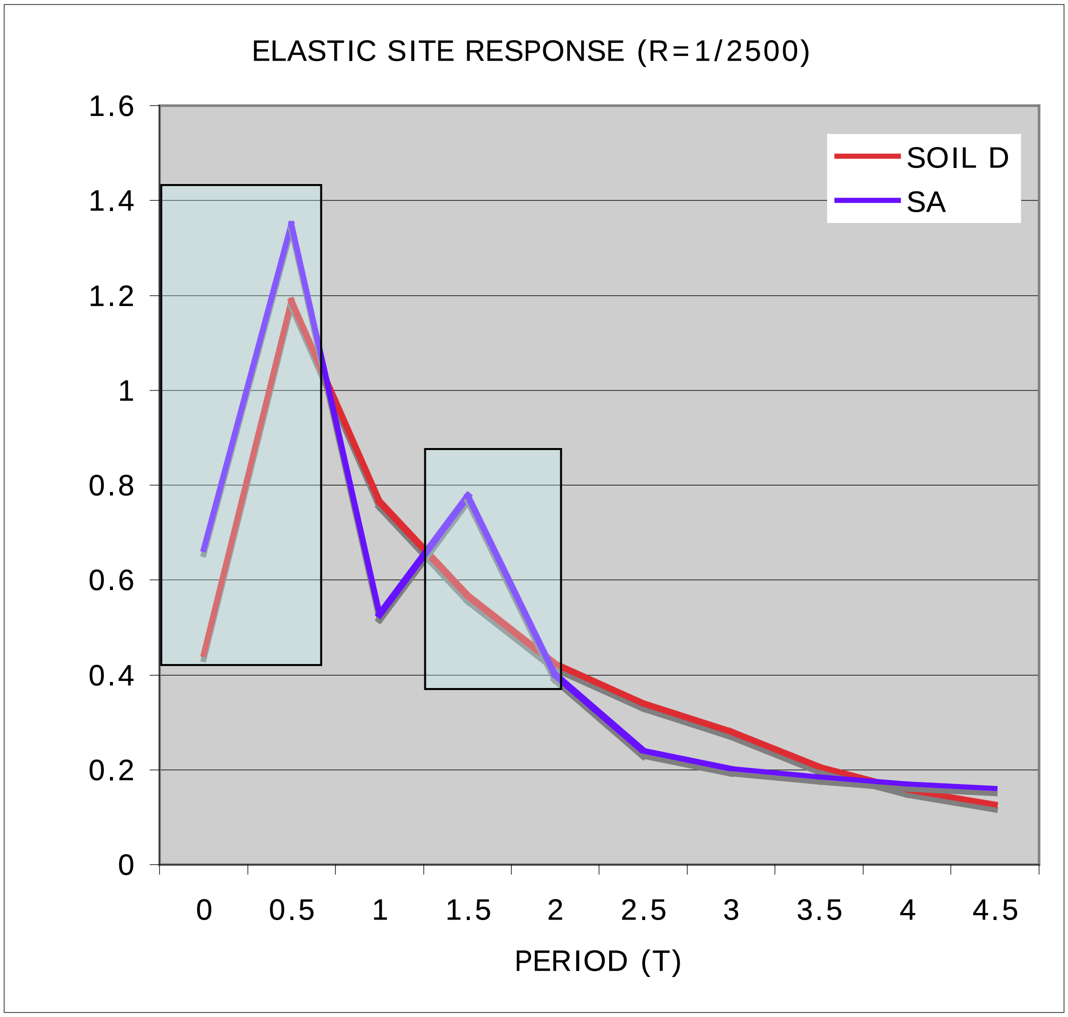


Figure 20. At site PRPC, buildings designed to be under 9.5m or between 23-50m tall would have exceeded building codes.

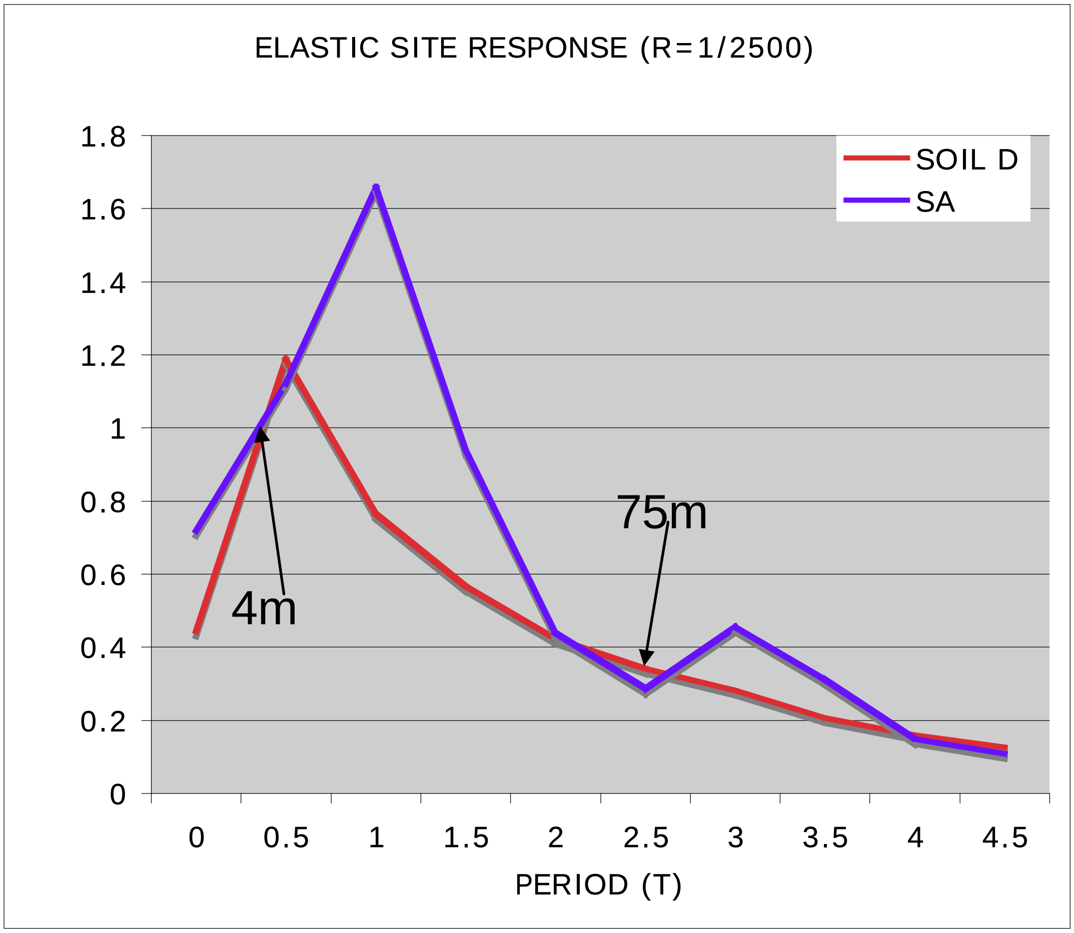


Figure 21. At site REHS, all building designs, expect those under 4m and around 75m tall, would have still exceeded building codes.

6. DISCUSSION:

6.1 Comparisons:

During the Darfield earthquake on 4 September, 2010, a number of building designs would have still exceeded building codes. Buildings did not necessarily fail to meet standards (not many buildings are more than a few stories tall in Darfield), but had there been more buildings in the danger zones they most likely would have failed. Likewise, not many buildings are 100m tall in Christchurch, but even the tallest buildings in the CBD did sustain damage, as did the older ones. Those, especially, were not designed for an earthquake event 1/500 years, so they were even more likely to fail.

During the 22 February, 2011 event, many of the buildings in the CBD failed because they were already structurally weakened. There were not nearly as many sites that exceeded codes (ten in February compared to 16 in September), yet more sites in the February event exceeded codes for every building design height and the damage sustained was irreversible. Many buildings, after the two events, need to be demolished and billions of dollars are being invested to repair Christchurch, a feat that may take years or decades.

6.2 Varying Return Factor R:

As return factors, or probability of occurance, are decreased, the code generated accelerations increase and building codes are less strict. Current building codes across New Zealand use the probablity of 1/500, producing a realtively lenient standard compared to larger return periods. With regards to future code amendments, designing buildings to withstand a large earthquake that might occur 1/1000 years or even 1/2500 years would be more suitable. Even though this would cost more money (precisely the reason most standards are only for 1/500 year events), it would not cost anywhere near the amount of economic damage Christchurch sustained after both events. Had building codes been stricter, a majority of the newer buildings may not have sustained as much damage.

6.3 Varying Hazard Factor Z:

Hazard factors are assigned specfically to a region and therefore the code limits will vary from site to site. Christchurch and Darfield have relatively low Z factors, but in light of recent events should be assigned higher hazard factors since they now are in a dangerous area. Changing Z is the best way to fortify the code site to site.

6.4 Building Codes:

Many of the buildings that failed in Christchurch were older buildings or tall buildings. The older buildings, of course, were not built to today’s standards and were the first to fail, and the taller buildings were significantly damaged after the 4 September, 2010 earthquake as well and therefore were more likely to fail during subsequent events. Stricter building codes will lessen the chance that so many buildings fail.

Though it is improbable that the code can be changed to withstand such violent ground acceleration that each even brought about, perhaps it can be altered to allow buildings, such as those in the Christchurch area, to withstand the continued shaking after the initial shock. The best way to alter or improve the code is to assign a new hazard factor to areas such as Christchurch and Darfield that, prior to 2010, had never experienced such large and damaging earthquakes, and to design for larger events likely to occur over a longer period of time (increasing R). With a higher hazard factor and strict adherence to building codes, it is possible that in the future buildings and structures in the Canterbury region will be more resistant to high magnitude and shallow earthquakes.

7. CONCLUSION:

The overarching goal of this research project was to examine the earthquake response spectra of the Darfield and Porthills events in September and February. The response spectra were used to generate accelerograms for 57 sites covering the Canterbury region from the east to west coasts. These accelerograms were compared to building parameters set by the NZS1170.5 and thus determined if the code was still suitable for the earthquake events that the Canterbury region had and can expect to experience. The results showed that building designs at sites close to the epicenters did exceed the limits, though not all to the same degree. It can be surmised that much of the ground acceleration felt in these areas was heightened by the region’s soft subsoil. The firmness of the ground determines the felt intensity of the earthquake on the surface, which is therefore going to determine how conservative building codes will be in certain areas.

Currently, buildings are designed to withstand an earthquake that occurs once every 500 years. However, in light of recent events, it is evident that many buildings did not fare well during these earthquakes – ones that occurred once every six months.To ensure that no building in a region exceeds the allowable acceleration set by the code, a new hazard factor should be assigned to regions that have already experienced devasting earthquakes or were near epicenters. Additionally, buildings can be designed for a return period of 1/1000 or even 1/2500 years, which encompasses the likelihood of there being a disasterous earthquake within that period of time. Though this would increase the cost of designing and building, in the event of an earthquake occuring within the return period, the aftermath may not be as severe. Less buildings may be damaged and therefore less money would need to be spent repairing buildings. The money spent today on increasing building standards would be insignificant compared to the amount of money that would be spent rebuilding had codes not been as strict.

8. **REFERENCES**:

A. King et. al. (2004).Structural Design Actions Part 5: Earthquake actions – New Zealand NZS1170.5

Bolt, Bruce A. Earthquakes. 5th ed. New York: W.H. Freeman and Company, 2004.

L. J. Brown et al. “Geology of Christchurch, New Zealand” *Environmental & Engineering Geoscience*; November 1995; v. 1; no. 4; p. 427-488

Newmark, N. M., and Hall, W. J. 1982. “Earthquake Spectra and Design,” Engineering Monographs on Earthquake Criteria, Structural Design, and Strong Motion Records, Vol 3, Earthquake Engineering Research Institute, Oakland, CA.

ONE News Staff. “Joint inquest scheduled for unidentified quake victims”. ONE News. May 04, 2011

The Shaky Isles: Earthquakes. Dr. Dan Hikuroa

Project Sheet: New Zealand National Seismic Hazard Model http://www.naturalhazards.co.nz/projectsheet/projectsheet.pdf?projectId=11