



**Investigation into the performance of
Statistics House in the 14 November 2016
Kaikōura Earthquake**

March 2017



Executive Summary

Statistics House is a six storey reinforced concrete office building with a lightweight roof structure, built in the CentrePort Harbour Quays business park in 2005. As a result of the M_w 7.8 Kaikōura earthquake on 14 November 2016, the building suffered the partial collapse of two floors.

The way a building responds in an earthquake is a result of a combination of factors, including the magnitude and distance from the epicentre of the earthquake, the size and design of the building, and the ground conditions at the site. In the case of Statistics House, these factors all combined to amplify the building response and cause the partial floor collapse.

The Chief Executive of MBIE commissioned an independent expert investigation into the performance of Statistics House in this earthquake in order to understand implications for the building regulatory system. This includes the Building Code, guidance published under the Building Act, and any other functions of the Chief Executive under the Building Act.

This report presents the conclusions and recommendations of this investigation. The investigation was not intended to consider the future use or reparability of the Statistics House building, nor to carry out a full review of the design and construction for compliance with the Building Code.

■ Key conclusions

The Panel's overall conclusion is that the partial floor collapses of Statistics House were caused by a combination of:

- a highly flexible ductile frame with two bays of frame per precast floor span, which effectively doubled the impact of beam elongation due to plastic hinging; and
- shortening of the precast double-tee flooring units as the ends spalled during the earthquake; and
- amplification of ground shaking, primarily due to basin-edge effects in the Thorndon basin area; and
- the duration of the earthquake.

The combination of these effects was not anticipated by the New Zealand design Standards recognised in the Building Code at the time of the design of Statistics House.

The Panel's view is that the primary cause of the partial floor collapse was beam elongation in the transverse moment resisting frames that provide the building's seismic resistance. This was exacerbated by the multiple bay frame arrangement in the east-west direction. This, combined with a sliding floor at one end, forced most of the effects of beam elongation to accumulate at one end of the frame, resulting in the loss of support to three precast concrete floor units on the first and second floors.

The moment resisting frames performed as expected, and were not in danger of collapse.

■ Secondary conclusions

The site conditions were investigated and the geotechnical advice provided was generally in accordance with the standard of practice for this type of building at the time. The site subsoil classification was appropriate.

The building was designed for the maximum level of ductility allowed under the New Zealand Building Code Verification Method¹. This means it would dissipate seismic energy mostly in hinging of the beams that are part of the moment resisting frames that provide the building's seismic resistance. It also means that this hinging would have started at a relatively low level of seismic demand. This is an important feature of the NZ Building Code, which permits controlled damage provided that life safety is maintained.

Results from analysis and modelling undertaken for the Panel suggest that there is a shortfall in capacity of the transverse frames. This may have had an exacerbating effect that contributed to the partial floor collapse, but is not the primary cause.

Statistics House was otherwise generally designed and constructed in accordance with the New Zealand Building Code at the time. While there were a number of design features that do not appear to conform to the design Standards at the time, it is the Panel's view that these were not relevant to the partial collapse.

A seismic review of Statistics House had taken place following the 2011 Christchurch earthquake in response to the Canterbury Earthquake Royal Commission. The seating of floor units at the four corners of the building were identified as a critical element. Retrofitting was underway at the time of the Kaikōura earthquake. Work had been completed on floor 4, which performed as expected with no loss of floor support observed.

The 14 November 2016 earthquake generated demands close to or above Building Code design levels, especially for medium rise buildings in the Wellington region. These are typically 8-15 storeys, but can be as low as 5 storeys for buildings with highly flexible frames, a feature of the design of Statistics House.

Performance of reclaimed land at this site does not appear to be a significant contributing factor to the observed building damage, with no evidence of differential settlement or foundation movement that would have contributed to the partial collapse.

The duration of the earthquake may have been a contributing factor. Multiple cycles of movement are implicitly included in the Building Code, but the impact of duration may be underestimated for systems with degrading stiffness. This would typically include highly ductile moment frame structures, such as incorporated in the design of Statistics House.

¹ Following Verification Method B1/VM1 is a means of demonstrating compliance with the New Zealand Building Code. The New Zealand Building Code is a performance based system. Verification Methods and Acceptable Solutions are published providing one way to comply with the performance requirements of the Code. Other ways of demonstrating Code compliance are possible.

■ Recommendations by the Panel

Recommendation 1: Investigation of existing buildings in the Wellington region with a similar design that may have been damaged by the Kaikōura earthquake

Existing buildings in the Wellington region (not just the Wellington City CBD) that have a similar design to Statistics House (buildings with precast floor systems and frames that may be affected by beam elongation) should be investigated as soon as possible to determine if precast floor seating problems exist as a result of the Kaikōura earthquake.

Building owners, tenants, consenting authorities and engineers should be provided with guidance to aid with the assessment of damage in existing buildings. This should build on the process begun by the Wellington City Council in December 2016 following the Panel's interim findings.

Recommendation 2: Notify the industry about issues with existing buildings with precast floor systems and frames that may be affected by beam elongation

MBIE, working with IPENZ and its technical societies, should immediately notify the engineering sector of issues relating to the use of precast floor systems in existing buildings that may be affected by beam elongation. This may occur in any region of New Zealand because a large earthquake is likely to create similar or greater demand on buildings. Particular aspects that need attention include:

- the impact of beam elongation on precast floor systems, particularly in conjunction with multi-bay frames
- the need to maintain composite connection of the precast flooring to the in situ topping
- the need to review the precast floor support details

MBIE, working with IPENZ and its technical societies, should consider developing a longer term plan for how to implement this recommendation. This could include disseminating guidance on how to assess existing buildings and providing guidance on standard methods of improvement, if required.

Recommendation 3: Access technical expertise to consider the implications for this type of design for new buildings

MBIE should access specialist expertise in order to:

- consider whether further controls should be placed on the design of new flexible buildings on sites which may be affected by significant ground motion amplification in regions of higher seismic hazard
- develop recommendations for amendments to Concrete Structures standard (NZS3101) to address the matters highlighted in recommendation 2 that would be applicable for the design of future buildings
- clarify the provisions of the Earthquake Actions Standard (NZS1170.5) for the application of P-delta effects in the design of new buildings

Recommendation 4: Review and undertake research into the provisions in the Earthquake Actions standard to ensure they reflect current knowledge of earthquake engineering practise

A review of the provisions in the Earthquake Actions standard (NZS1170.5) should be undertaken. MBIE should access specialist expertise to undertake the research to support this review. The research should focus on:

- the amplification of earthquake ground shaking due to basin-edge effects. Detailed geological and geophysical data should be incorporated into ground motion modelling. A focus on Wellington should be a priority for such research and the research should be extended to other urban centres as appropriate.
- the impact of duration of shaking, particularly for ductile building designs. The potential for large earthquakes to affect Wellington and other metropolitan centres may require duration to be more explicitly incorporated in the New Zealand Building Code system.

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Introduction

Statistics House was designed and constructed in 2004/2005 to provide office accommodation in the CentrePort Harbour Quays business park (Figure 1). As a result of the M_w 7.8 Kaikōura earthquake (00:03 14 November 2016) the building suffered a partial collapse of two floors. The earthquake shaking led to beam elongation, which resulted in dilation of the perimeter moment resisting frames. This reduced the support for the precast double tee flooring units, three of which fell at the northwest corner of the building, at floors 1 and 2.

The building was assessed as “entry prohibited” on the morning of 15 November 2016 and has been unoccupied since.

The Ministry of Business, Innovation and Employment (MBIE) commissioned an independent expert investigation into the performance of Statistics House in this earthquake, in order to understand the implications for the building regulatory system. The Terms of Reference for this investigation is included in Appendix A. This report takes into account the following:

- relevant documentation from the design and construction of Statistics House
- site visits, including internal inspection of the collapsed floor areas to the extent safely accessible
- analysis by the Panel and other technical experts, including:
 - assessment of the seismological and geotechnical data
 - detailed structural analyses
- interviews conducted with relevant technical experts and parties to the design and construction of Statistics House, and of nearby buildings (which did not experience similar failures)
- review of inspection reports from the 2013 Seddon earthquake and the subsequent review and modification of the building (underway at the time of the Kaikōura earthquake).

This report provides findings about the causes of the floor collapse and recommendations for further action. The investigation was not intended to consider the future use or reparability of the Statistics House building, nor to carry out a full review of the design and construction for compliance with the New Zealand Building Code.



Figure 1: Statistics House

Investigation Methodology

This section outlines the methodology and procedures adopted for the investigation. This includes the establishment of an expert Panel, interviews with relevant parties, the physical inspections that were conducted and the information collected.

■ Expert Panel appointed by MBIE

The Panel was appointed by MBIE for their expertise in the design and construction of buildings and the impact of earthquakes. Brief biographies of the Panel are included in Appendix B. The Panel consisted of:

- Dr Helen Anderson (Chair)
- John Hare
- Rick Wentz

Other external experts were consulted to provide additional advice on technical aspects of the investigation.

The Panel has drafted this report with the support of MBIE officials. The Panel was supported by MBIE's Deputy Chief Engineer and a Policy Director from the Building System Performance branch. The report has been independently reviewed by the MBIE Chief Engineer and Dr Hugh Cowan, a geoscientist with expertise in the topic area of engineering investigations.

No conflicts of interest with the building owner, designers, building contractors, or geotechnical engineers were identified.

■ Inspections

Members of the Panel visited the CentrePort Business Park and the Statistics House building to:

- Undertake an internal and external inspection to observe damage of Statistics House
- Undertake external inspections of the adjacent similar style office buildings (the BNZ Harbour Quays and Customhouse)
- Review general land damage in the CentrePort facility

■ Information collected

Documentation

The following documents and reports were obtained for the investigation:

- Wellington City Council building consent documentation supporting various building consent applications
- Additional information provided by the structural engineering consultants including retrofit details and inspection reports for the 2013 earthquakes and the November 2016 earthquake
- Geotechnical reports for the Statistics House site and for adjacent sites.

Interviews conducted

The following interviews were conducted:

- GNS Science representatives
- Wellington City Council building control officials
- Representatives of the original design and construction team for Statistics House including the structural engineer, geotechnical engineer and the main contractor
- Structural engineering designers representing the consultancies involved in the design of the adjacent BNZ Harbour Quays and Customhouse buildings
- Dr Brendon Bradley from the University of Canterbury to provide engineering seismology advice
- Structural engineers engaged as independent advisors by Statistics New Zealand.

■ Investigation procedures

The following supporting procedures were performed to assist with understanding the performance of Statistics House:

- A review of the ground motion records from nearby instrumented sites. The comparability of these sites has been tested through instrumentation installed in Statistics House by GNS Science after the earthquake to capture aftershock data and measure the specific response of Statistics House.
- The University of Auckland carried out ambient surface wave testing to determine the site period of the Statistics House site. This testing was also carried out at the BNZ and Customhouse sites, as well as at other locations in central Wellington.
- Structural analyses – this involved developing computer models to simulate the buildings earthquake response. This included linear dynamic and time history analysis in order to validate original design assumptions.
- Undertaking an internal and a high resolution external survey to accurately determine the building's residual deformations and displacements resulting from the earthquake.

Limitations

This investigation has not commissioned or undertaken:

- geotechnical site investigation
- invasive sampling or testing of building materials
- review of the original design for full Building Code compliance
- interviews with the architects who designed the building.

The Panel considers that such additional investigations would not materially affect the conclusions of this report, based on modelling and site inspections.

Design and Construction of Statistics House

Statistics House was designed and constructed in 2004 and 2005 and opened on 7 December 2005. It is located in the CentrePort Harbour Quays business park in Wellington. This section outlines key features of the building design and construction process and the ground conditions. It also notes recent work carried out in the building to address recommendations from the Canterbury Earthquakes Royal Commission.

■ Building description and key features

Statistics House is a six storey rectangular building with a footprint area of approximately 58m x 32m (Figures 2, 3 and 4, which also show the extent of damage). The lower levels are of reinforced concrete construction and the top storey is a lightweight steel structure that contains plant and storage space.

The gravity system for the typical floors includes three bays of the proprietary double tee precast concrete floor system (Figure 5). The double tee flooring units have an in-situ concrete topping over the floor unit and the double tee units span between reinforced concrete floor beams that run north-south. The reinforced concrete beams are supported by reinforced concrete columns, which in turn are supported on the building's foundations.

The lateral load resisting system for the building is primarily provided by perimeter reinforced concrete moment resisting frames on each side of the building. The longitudinal frames on the east and west elevations also provide gravity support to the floor. The transverse frames on the north and south elevations do not support significant floor areas. Shear walls adjacent to the central lifts provide some additional lateral resistance in the longitudinal direction.

The building has a piled foundation with four bored belled corner piles. The remaining 56 piles are driven cast in-situ piles.



Figure 2: Architectural long section

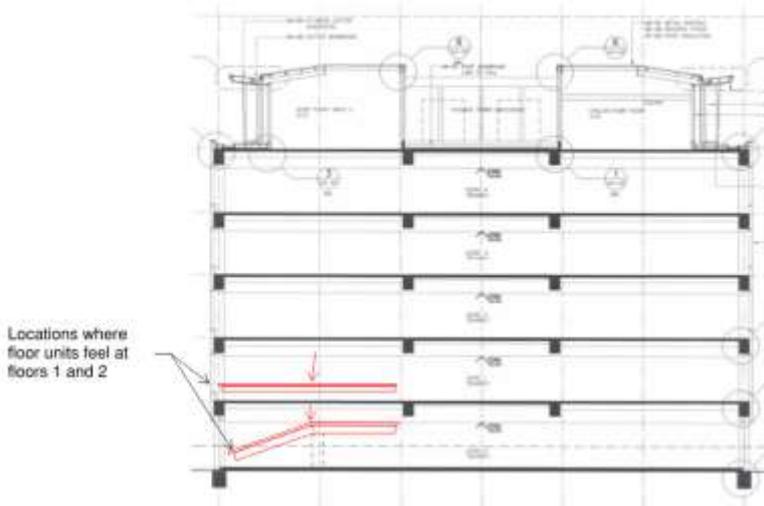


Figure 3: Architectural cross section

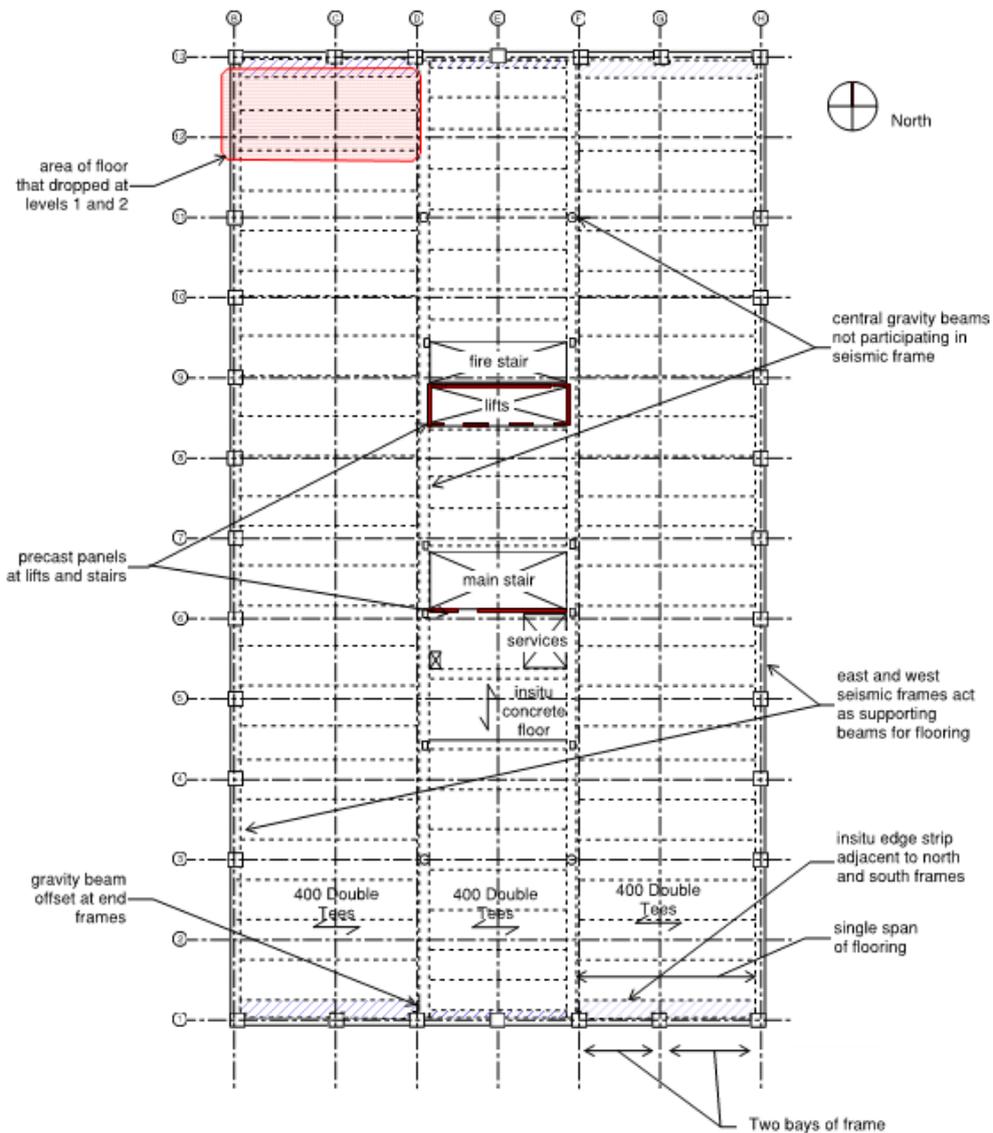


Figure 4: Typical floor plan (structure only)

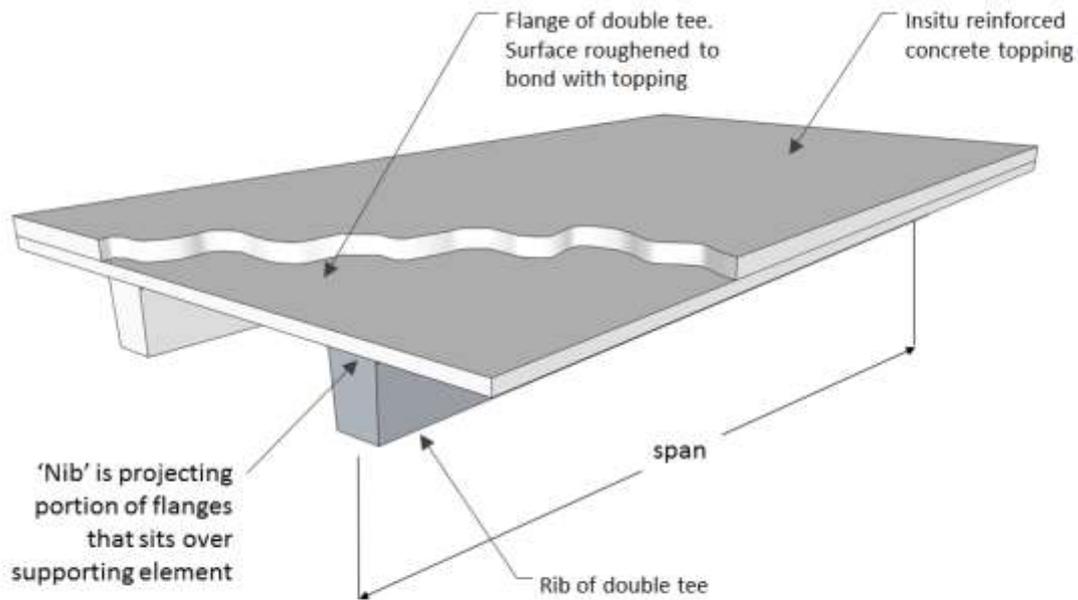


Figure 5: Double tee precast floor unit

■ Ground Conditions

The land on which the building is located is reported to have been filled (i.e. “reclaimed”) between 1893 and 1901. The site is located approximately 75 metres from the mass concrete seawall which marks the edge of this reclamation.

The 2004 geotechnical investigation of this site indicates in the order of 3-4m of dumped fill (predominantly sand with some gravels) overlying 4.5-6.0m of natural sand and silt “beach” deposits. Underneath these there is natural colluvium (gravel, sand and silt mixtures).

Liquefaction of the soils above the natural colluvium was reported as being possible for this site. This influenced the choice of the foundation system for the building.

Site Subsoil Class

The site subsoil class is used in the NZ loadings standard in the calculation of earthquake structural design actions. It influences the design spectral accelerations by incorporating site-specific geological and geotechnical properties to estimate the dynamic stiffness and period of the site. In the current loading standard (1170.5), there are five site subsoil classes (A through E, A corresponding to stiffest subsurface profile and E to softest subsurface profile). A and B represent rock sites, C corresponds to a shallow soil site, and D and E correspond to deep and soft/very soft soil sites, respectively.

Based on the available data, the site subsoil class for the Statistics House site is assessed to be category (C) – flexible or deep soil under NZS4203:1992 and class D – deep or soft soil under NZS1170.5. This is similar to much of central Wellington (Appendix C map that shows distribution of different site subsoil classifications in Wellington).

■ Regulatory framework

Wellington City Council records show that there was a staged consent process for the original design, as follows:

- Stage 1: Foundations and in-ground services, issued 15 June 2004
- Stage 2: Structural frame, issued 29 July 2004
- Stage 3: Building envelope and base building fit-out, issued 14 March 2005.

The Code Compliance Certificate was issued on completion, and is dated 11 November 2005.

A separate *Producer Statement – PS1 – Design* was signed by the engineer for each of the three stages of the Building Consent process. Each referenced clause B1 of the Building Regulations 1992 and stated that the design had been prepared in accordance with the verification methods of the approved documents. No further detail was provided on the means of compliance.

A review of the structural calculations confirms that the structural design was undertaken using the provisions of the following primary structural design standards relevant at the time:

- NZS4203:1992 – Loadings Standard (now updated to NZS1170.5 – Earthquake Actions Standard)
- NZS3101:1995 – Concrete Structures Standard (now updated to NZS3101:2006 – Concrete Structures Standard)
- NZS3404:1997 – Steel Structures Standard (still current with subsequent amendments)

A Building Consent was issued on 17 August 2016 for seismic strengthening alterations. The work relating to this consent was in progress at the time of the 14 November earthquake (see next section).

■ 2013 earthquake damage and repairs and subsequent retrofit

Statistics House incurred minor damage (mostly non-structural) in the M_w 6.5 Seddon earthquake of 21 July 2013 and M_w 6.6 Grassmere earthquake of 16 August 2013. The building owner asked the structural engineers responsible for the building design to review the building for damage, and requested a review of the building against the recommendations of the Canterbury Earthquake Royal Commission (CERC) reports (released in November 2012).

On 22 October 2013 the engineers reported that they had not observed damage of the primary structure. A number of minor repairs or further inspections were required for secondary elements. The panel understands that the building capacity was assessed at this time, using the methodology of the New Zealand Society for Earthquake Engineering (NZSEE) Guidelines. The panel has not assessed this capacity, noting that the design process for new buildings is not the same as the assessment of existing buildings.

The engineers' recommendations based on the CERC were submitted to CentrePort on 14 October 2013. In the recommendations the seating of the floor units at the four corners of the building was identified as a critical element². Retrofitting, by installing catch brackets in these locations, was recommended, along with some supplementary tying across key areas of the concrete slab to control

² The panel infers that the identification of this element as critical refers to its importance for structural performance and is not inferred as implying imminent failure.

cracking of the floor system. The recommended floor support details were designed with the Building Consent for this work approved. The installation of the catch brackets and diaphragm ties were completed on level 4 and partially completed on level 3 at the time of the Kaikōura earthquakes (Figure 6).



Figure 6: A typical catch bracket retrofitted in 2016

2016 Kaikōura Earthquake and Damage to Statistics House

November 14 Earthquake

The 14 November earthquake ($M_w 7.8$) was a complex multi-fault rupture. Its epicentre was over 200 km from Wellington, and the closest point of rupture was approximately 60 km from the city. More than 120 seconds of ground shaking was recorded. The strong motion duration, defined here as the Significant Duration (D_{S595}), of the earthquake ranged between approximately 25 and 30 seconds across central Wellington.

Because of the long distance from the point of rupture to Wellington (source-to-site distance) the short period shaking was largely filtered out. Figure 7 shows the mean response spectra derived from the records of strong motion stations located on soil within the Thorndon Basin and a nearby rock site (POTS) for the 14 November earthquake. All of the soil sites exhibit appreciable amplifications across a wide range of vibration periods. The ground motion intensities relative to both the standard for design (NZS4203) cited in the Building Code Verification Method and to the current cited standard (NZS1170.5) spectra for a deep soil site, are largest over the range of approximately $T=0.6-2.5$ sec. This dominant longer period motion affected mainly buildings with a natural period of 1.0-2.0 sec (typically 8-15 storeys, but as low as 5 storeys for buildings with highly flexible frames).

The phenomenon of concentrated damage in areas at significant distance from an epicentre on deep soil deposits has been seen in 1985 in Mexico City, San Francisco (Loma Prieta) in 1989 and Kathmandu in 2015.

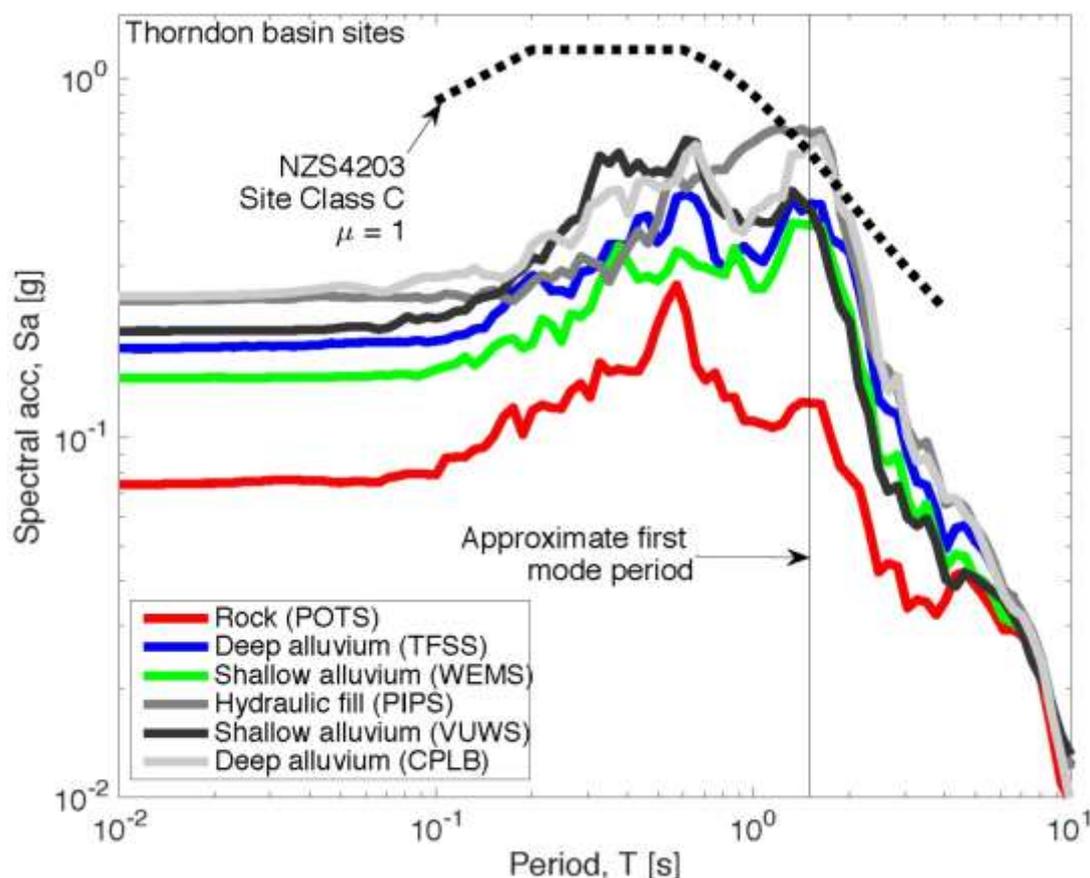


Figure 7: Geometric mean response spectra at strong motion stations located in Thorndon Basin relative to strong motion station on rock, for $S_p=1$

■ Damage to Statistics House

This section sets out the damage to Statistics House following the 14 November 2016 earthquake.

The moment resisting frames provided seismic resistance as expected, and were not in danger of collapse. There was significant building deformation and structural damage, summarised as follows:

- The north and south end frame beams have elongated and there is permanent frame dilation at both ends of the buildings (Figure 14 is an illustration of the process of beam elongation and frame dilation). There is a maximum permanent displacement of approximately 100mm at the column at the north east corner of the second floor (Figure 8). The residual frame dilation of the north frame was approximately 150mm at the second floor and 100mm at the first floor. These displacements were estimated based on a high resolution survey of the building.
- Precast floor units have lost their support at both the first and second floor at the northwest corner of the building, due to the beam elongation and shortening of the precast flooring units. Two units at the first floor and one unit of the second floor have dropped onto the furniture below them (Figures 9 and 10). In both cases, the in-situ concrete floor topping has remained in place and the unit that fell from the second floor onto the first floor has been held up at that level. Because the frame has returned to a near vertical position (excluding the dilation effects), it is not possible to estimate how near the building was to losing further flooring units.
- There has been significant and widespread cracking to the floors from beam hinging and elongation, with the effects apparent at all levels and in both directions. The most extreme floor cracking is at the first floor and at the sliding floor supports in the end bays of the longitudinal frames.
- There is widespread damage to secondary and non-structural building elements and contents.
- Liquefaction-induced ground settlement relative to the pile-supported building perimeter in the order of 50 to 100mm was observed (Figure 11). An estimated 50 to 75mm settlement of the internal ground floor slab was observed. There is also buckling of the footpath pavers near the northeast and northwest corners of the building; possibly indicative of displacement of the large-diameter corner piles in the north-south direction (Figure 12).
- The tops of the piles and pile caps/ground beams have not been accessible to inspect. However, no evidence of differential settlement or foundation movement that would have contributed to the partial collapse was observed. The high resolution external survey of the building confirms the Panel's view there is no significant differential settlement of the building.

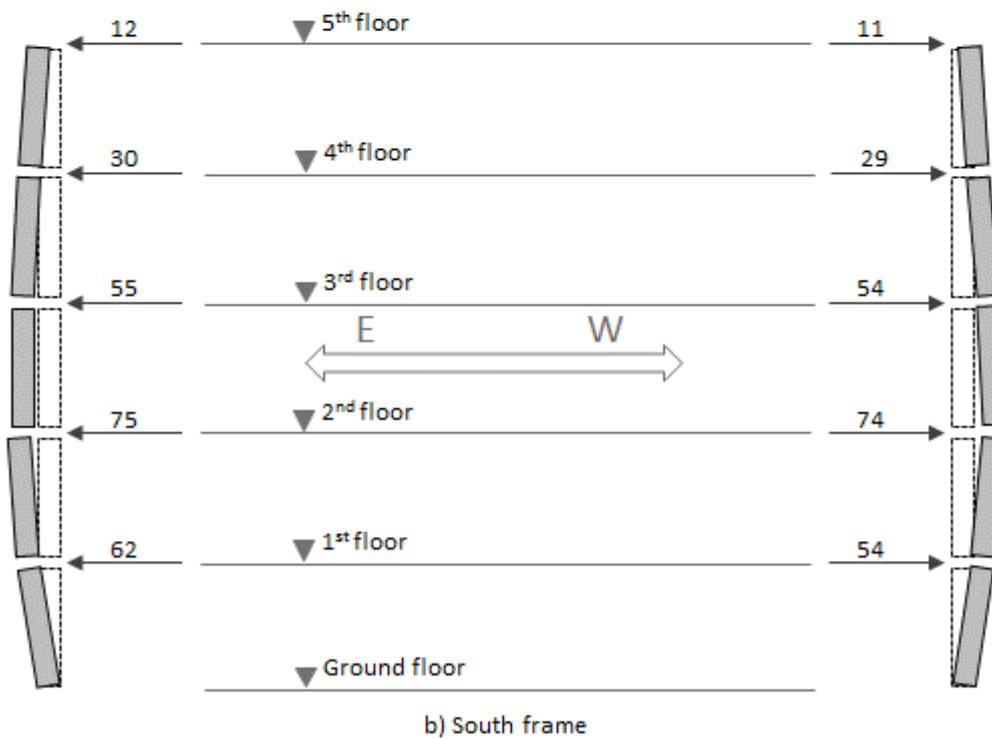
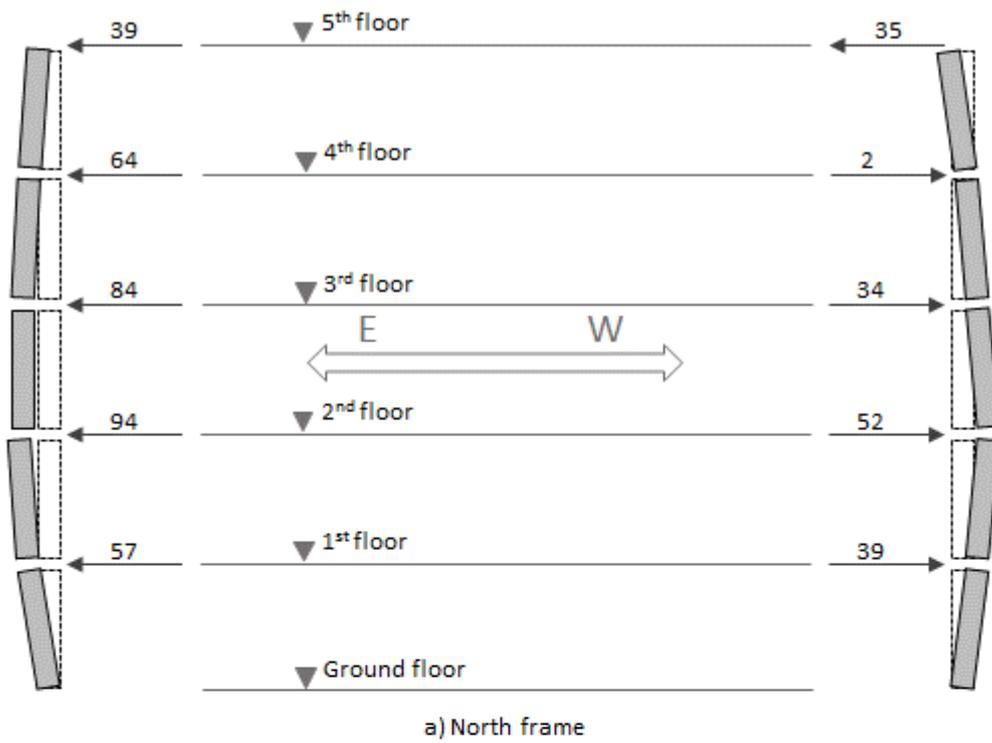


Figure 8: Corner column residual displacements (mm) in the transverse direction (from external survey)

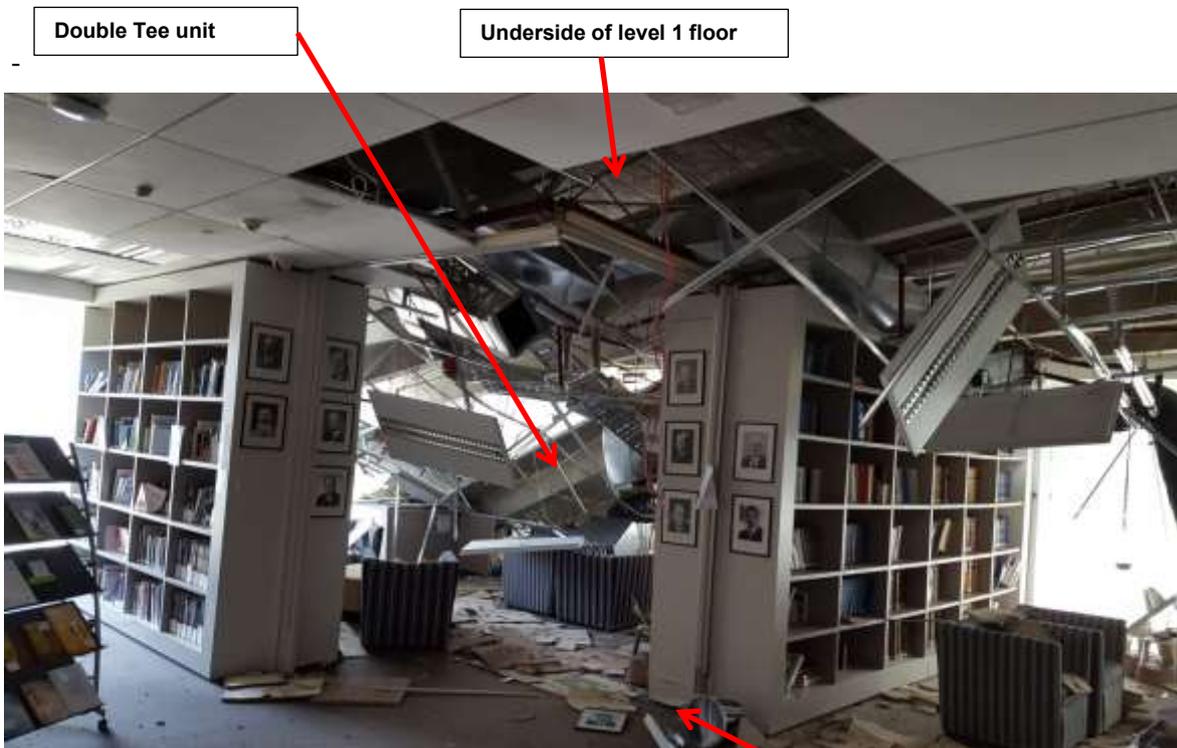


Underside of level 2 floor

Double Tee unit previously at level 2 floor

Level 1 floor

Figure 9: Fallen Double Tee unit at the first floor level



Double Tee unit

Underside of level 1 floor

Ground floor level

Figure 10: Fallen Double Tee units (in background, across the shelving) at ground floor level.



Figure 11: Ground surface settlement adjacent to the perimeter of Statistics House



Figure 12: Compression of pavers adjacent to NW corner of Statistics House

Review and Analysis: the performance of Statistics House

This section considers the extent to which a range of factors contributed to the partial collapse of some of the precast floor units in Statistics House. It also compares the performance of Statistics House with nearby buildings, which did not experience similar failure in the same earthquake.

■ Design and construction process

The site subsurface conditions were investigated and the geotechnical advice provided appears to have been in accordance with standard of practice for that time.

To support this investigation, structural analysis and modelling was undertaken for the Panel. Results of a conventional design review suggest that there is a shortfall in capacity of the transverse frames. The calculated displacements appear to have exceeded the deflection limits set in the loadings standard in place at the time that could be used for determining compliance with the Building Code (by up to 50%). In addition, the modelling undertaken for the Panel suggests that the overall strength of these frames was less than the requirement in the standard at the time (about 75% capacity³).

The analysis and modelling process used for the panel incorporated a methodology from the non-mandatory commentary to the loadings standard of the day (relating to the application of P-delta effects). The Panel understands that this methodology would have been considered to have been best practice at the time, but was not adopted in the design of this building. In the Panel's opinion, the shortfall in the frame capacity may have had an exacerbating effect that contributed to the partial floor collapse, but is not the primary cause.

In the course of investigation, the Panel has identified a number of other details that appear not to conform with the New Zealand Standard in place at the time. It is the Panel's view that these are not relevant to the partial collapse of some floors in the building. Statistics House was otherwise generally designed and constructed in accordance with the Building Code system in place at the time.

To better model the likely behaviour of the building during the earthquake a non-linear time history analysis was also undertaken. This used ground motions from the Kaikōura earthquake, recorded at the nearby Thorndon Fire Station and BNZ Building sites (refer to Ground conditions: site response and site amplification). The modelling undertaken for the Panel suggests that the building is likely to have deflected more than would have been expected for a building that conformed with the design standard. The overall performance of the building would otherwise have been generally satisfactory.

The Panel has seen no evidence to suggest that contracting relationships were other than professional and positive. All relevant parties have provided access to records and key personnel to support the investigation process.

³ Note that this is not a calculation of %NBS capacity, which would be calculated in accordance with the New Zealand Society for Earthquake Engineering Guidelines for the seismic assessment of existing buildings, not the design standards.

■ Ground conditions: site response and site amplification

The ground motions at nearby Thorndon Basin deep soil sites are considered likely to represent the range of ground motions experienced at the Statistics House site during the Kaikōura earthquake. This is based on their generally similar soil profiles and geology, source-to-site distance, and close distance (<2km) to Statistics House.

Figure 13 shows that amplification of longer period ground motions, particularly between 0.6 and 2.0 seconds, occurred at the two Thorndon Basin strong motion stations located nearest to the Statistics House site (and others in the Wellington region, refer Figure 7). This amplification has been observed at both stiffer and softer soil sites (NZS1170.5 site subsoil classes C and D) and basin-edge effects have been identified as a potentially significant factor. Neither the previous loadings standard NZS4203 nor the current earthquake actions standard NZS1170.5 require basin-edge effects to be considered.

It is also likely that amplification of ground motions occurred on sites in the Wellington region containing thick deposits of soft soils, including those associated with reclaimed land. Such amplification is not believed to have been significant at the Statistics House site.

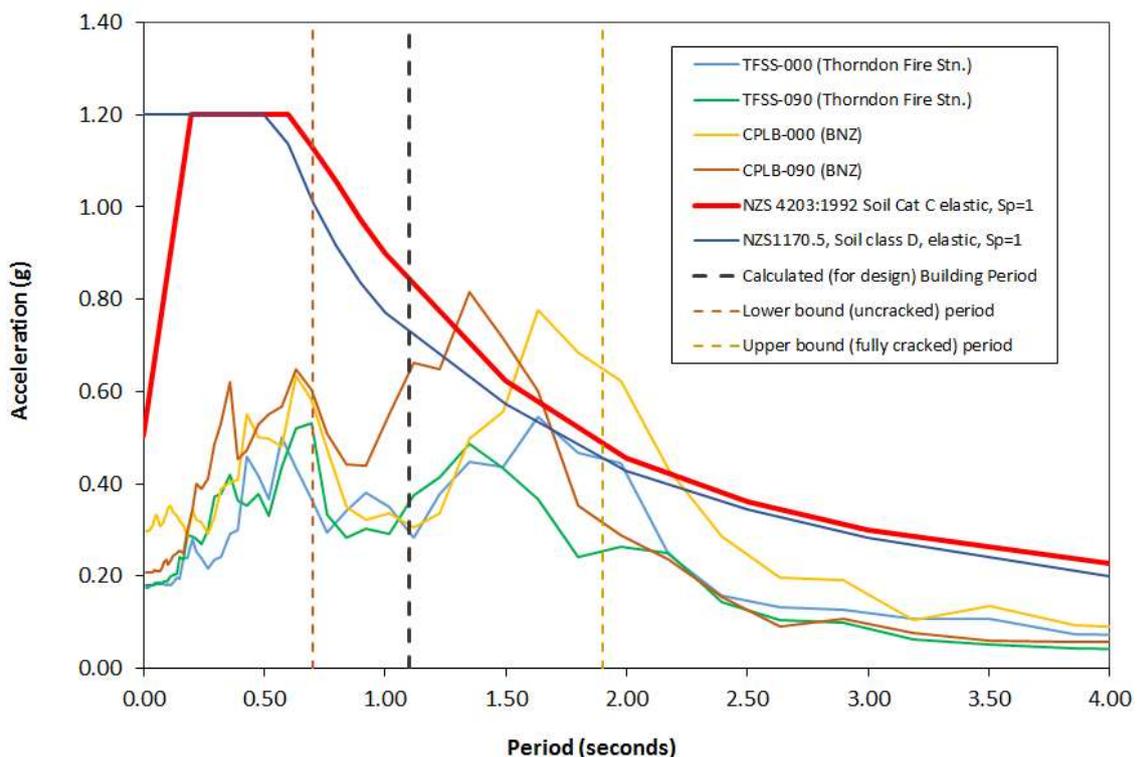


Figure 13: 5% damped acceleration response spectra at Thorndon Fire Station and BNZ Building strong motion stations

The vertical dotted lines in Figure 13 represent the estimated period shift of the building as it softened and the response increased.

■ Earthquake duration

The duration of the earthquake (seismic energy release lasting ~ 120sec or Significant Duration (D_{s595}) of 20 to 30 seconds) may have been a contributing factor in the performance of this building, but to what extent is unclear. Multiple cycles of movement are implicitly included in the design Standard (notionally based on a M7.5 earthquake and the associated duration), but the impact of duration may be underestimated for structural systems with degrading stiffness. This would typically include highly ductile moment frame structures, such as Statistics House.

■ Precast flooring: interaction with the building structure

This section considers how key features of the building design contributed to the partial collapse of the precast concrete floor units.

Beam elongation

As reinforced concrete beams develop plastic hinges due to repeated earthquake shaking cycles, they lengthen through:

- cracks opening as the longitudinal reinforcement in the beam yields, which is only partially recoverable in cycles of reversing loads
- geometric lengthening, as the contact points in compression between one end of the beam and the other are on the diagonal of the beam.

The combination of these two effects is the beam elongation and is illustrated in Figure 14. This leads to frame dilation, meaning that the frame grows in length. Some of this lengthening is not recoverable, even though the building may self-centre to a degree under the cyclic loading (as happened with Statistics House). Beam elongation forces the columns apart at each end of the beam. This then pulls apart any orthogonal beams supported by those columns. If the elongating beam is running parallel to the adjacent floor, it leads to the potential for loss of support to the floor.

Beam elongation effects were not widely known at the time of the design of Statistics House. While a paper had been published on this topic in 1993, the first publication in the current research stream appeared in 2004. The majority of papers on the topic post-date the design of Statistics House. A selection of research papers is provided in Appendix D.

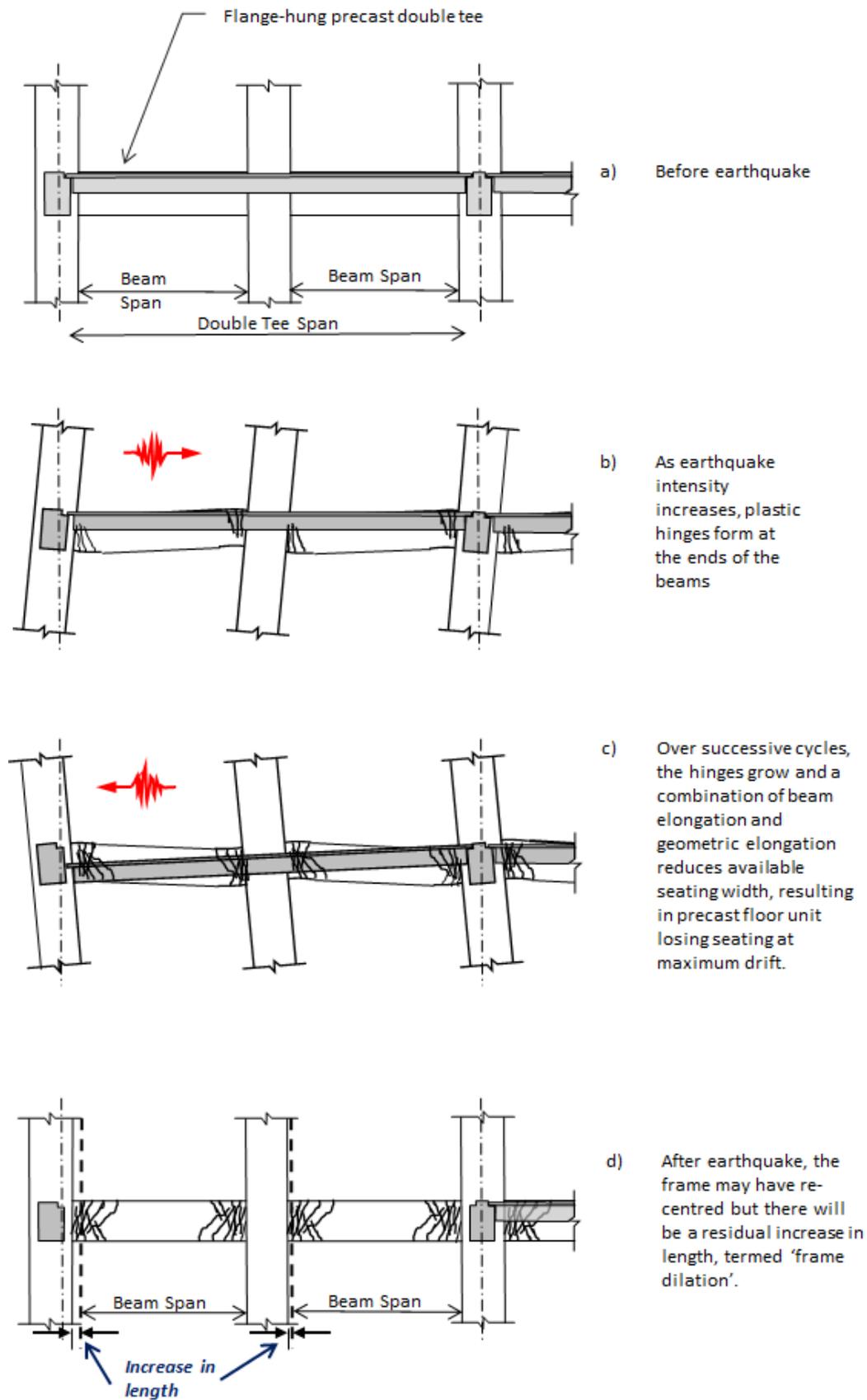


Figure 14: Illustration of beam elongation and frame dilation

The aggregating effect of the multiple-bay frames in a ductile design

In order to stiffen perimeter frames but still achieve large column-free interior spaces, some designers add intermediate columns to the perimeter frames and span the floor past those columns onto more widely spaced gravity supports. Statistics House incorporated this design and had two frame bays for every bay of flooring (Figure 15). This means in Statistics House there were four units of beam elongation per floor bay, rather than two (because beam elongation occurs at each end of each beam).

The support conditions at each end of the outer bay varied considerably. The inner end (grid F in Figure 15) had a conventional seating with the topping cast continuously over the supporting beams, whereas the supports at the outer edge (grid H in Figure 15) had a sliding support to prevent the floor constraining the elongation. The effect of this is that the majority of the elongation was concentrated at the outer supports. In Statistics House, there was about 3-4 times the elongation at those outer supports than there would have been with a single frame bay and equal end fixity.

The estimated maximum reduction of seating for the precast flooring units (based on the frame dilation and the multiple-bay frame effect) is approximately 60mm at the second floor.

Beam elongation of multiple bay frames is not explicitly addressed in the provisions of the current NZS3101 concrete structure standard.

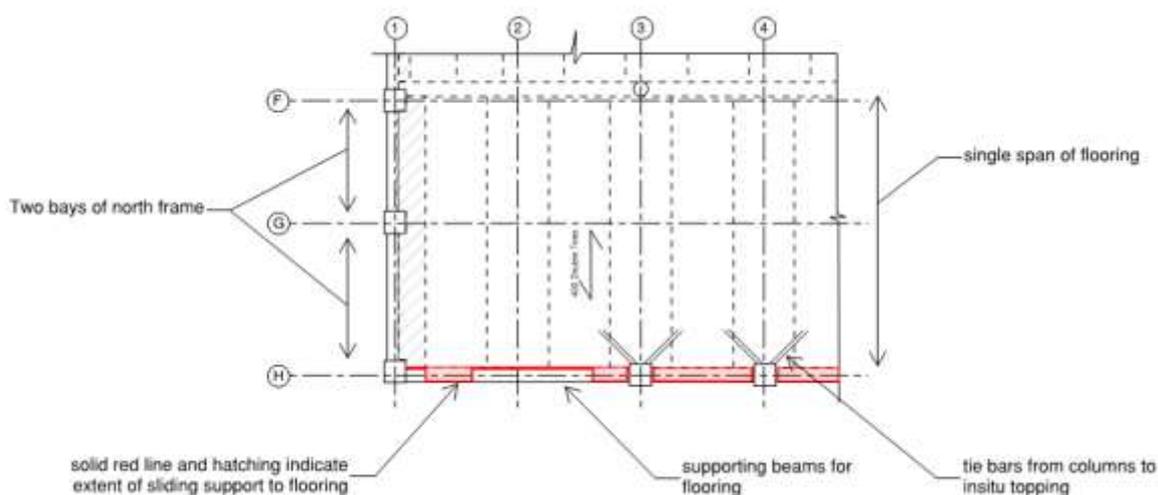


Figure 15: Part floor plan of northwest corner of typical floor showing two bays of beams per floor span

The lack of mechanical connection from the precast flooring and the in-situ topping slab

Precast flooring systems generally rely on roughening of the precast surface (during manufacture) to form a composite bond with the reinforced concrete topping which is cast on site. The Concrete Structures Standard requires mechanical anchors (generally reinforcing steel) to bond the two when seismic shears exceed a certain limit, but this requirement was most likely not triggered in this case. A more robust connection of the precast units to the topping, combined with a ductile anchorage across the supporting beams, may have provided a supplementary load path.

At both level 1 and level 2, the topping remained in place after the floor units fell and there was a relatively clean separation at the precast to insitu concrete interface. The precast units generally showed good levels of surface roughness from manufacturing. While it is possible that the level 1 units may have failed in part due to the impact and/or extra load from the unit that collapsed from level 2, the precise sequence of failure is unknown.

The support system for the precast floor units

The double tee precast concrete floor units in Statistics House are directly supported on concrete beams with seating specified on design drawings as 75mm maximum and 50mm minimum. This was clarified on pre-cast concrete shop drawings as 75mm typical with no less than 50mm after placement. The seating required to conform with the design standard at the time was 60mm.

The double tee unit has a loop hanger (commonly referred to as a pigtail): a pair of plain round bars looped at each rib and embedded back into the ribs, with a short length of 20mm round reinforcing bar inserted through the loop bars (Figure 16). The loop bars project from the double tee precast units and are cast into the concrete topping, although without a positive connection.

The failures consistently showed the outer edge of the nib breaking off, generally at the end of the loop bar, and in some locations, a small amount of spalling to the supporting beam ledges. This had the effect of shortening the floor units at the same time as the beams were elongating. This failure sequence is illustrated in Figure 17. The length of seating actually achieved during construction would have had no effect on this form of failure, as it is determined by the geometry of the loop bars, not the nib length.

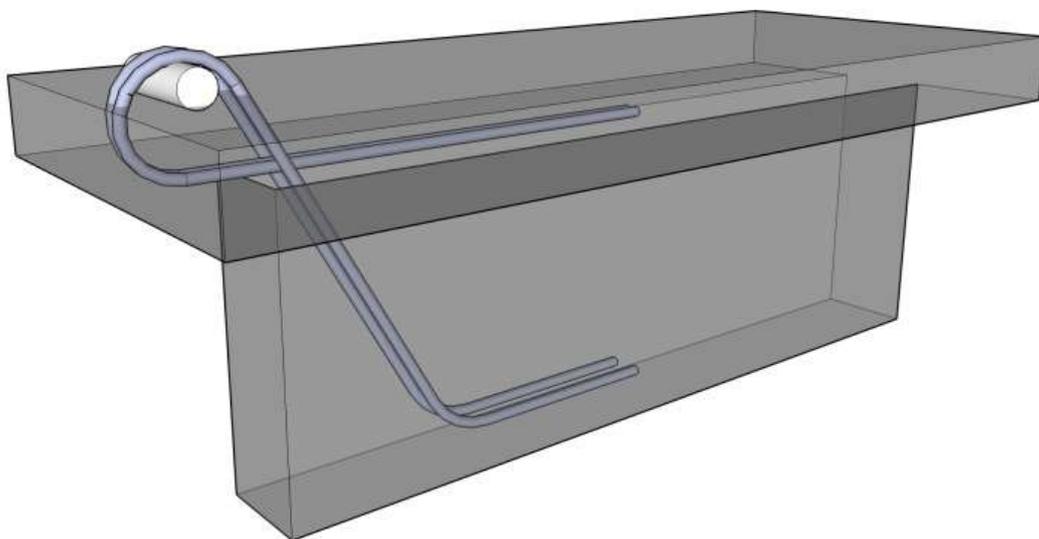


Figure 16: Loop bar hanger in precast double tee unit

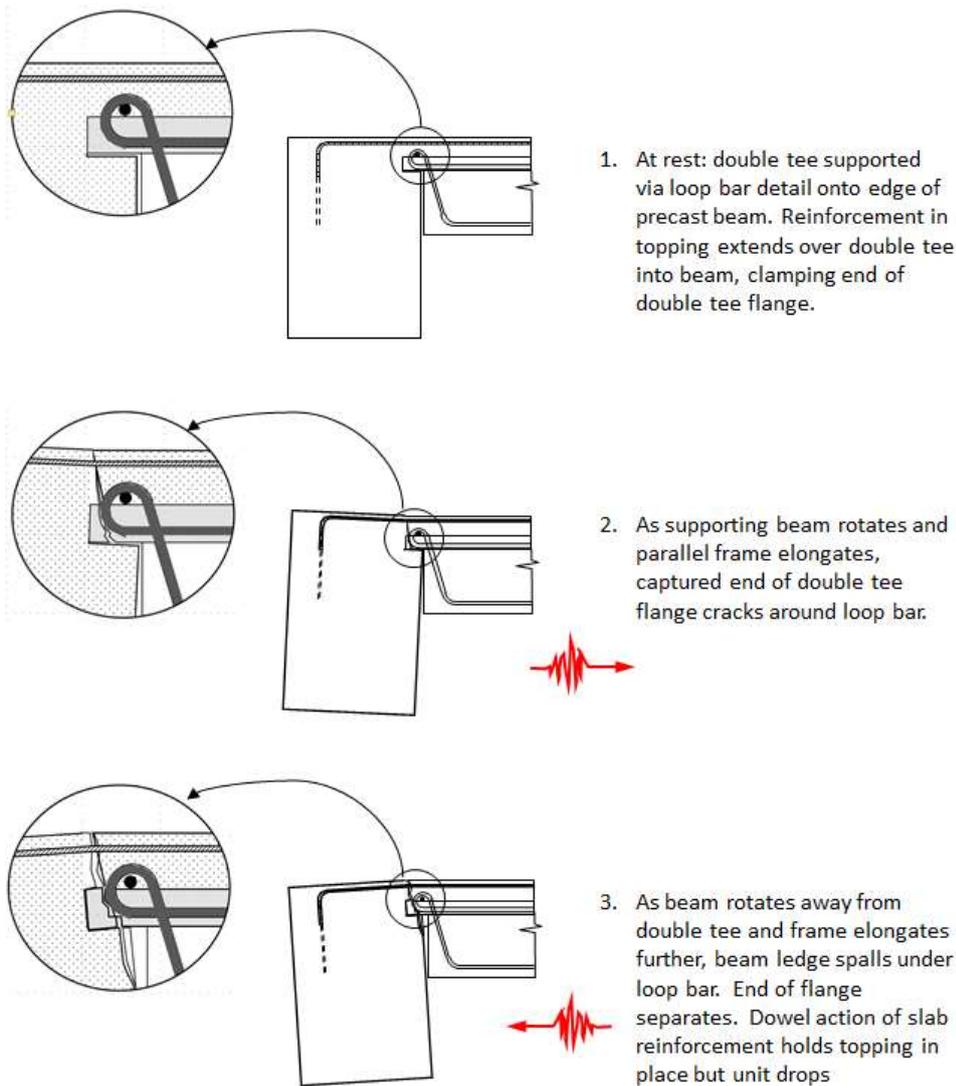


Figure 17: Failure sequence of double tee nib

Frame ductility and flexibility

The building was designed for the maximum level of ductility allowed under the design standard in place at the time ($\mu = 6$). This means it would dissipate seismic energy mostly in hinging of the beams that are part of the moment resisting frames that provide the building's seismic resistance, and that this hinging would have started at a relatively low level of seismic demand. This is an important feature of the design philosophy of the New Zealand Building Code, which permits controlled damage provided that life safety is maintained.

Modelling undertaken for the Panel suggests that the flexibility of the frame was greater than it should have been, due to the apparent underestimation of the seismic demand, discussed previously. The effect of this increased flexibility is important but not critical. The more critical factor in the beam elongation was the number of cycles of inelastic demand, which would not have been sensitive to the capacity of the frame.

■ Comparison with performance of nearby buildings

The investigation also considered the earthquake performance of two nearby and similar style office buildings, designed and built not long after Statistics House was completed: the BNZ Harbour Quays and Customhouse. To understand the performance of these buildings in comparison with Statistics House, the Panel interviewed the structural engineers involved in the original design and who are still engaged to undertake ongoing inspections of these buildings. The Panel did not undertake investigation or design review of these buildings.

Customhouse building

Customhouse is a six storey building that was designed and built 2009/2010, located on broadly similar ground conditions to Statistics House and has a pile foundation system. The lateral resistance for Customhouse is provided by coupled shear walls, a different structural system to the ductile moment resisting frames used in Statistics House. The floor system is primarily double tee flooring similar to that used in Statistics House. The gravity frame supporting beams would not have been expected to yield under earthquake loads, and so significant beam elongation would not be expected.

Based on discussion with the engineers, the building experienced multiple inelastic cycles during the Kaikōura earthquake, with expected damage observed in the plastic hinge zones designed to dissipate seismic energy, and the remainder of the structure indicating insignificant damage.

BNZ Building

The BNZ Harbour Quays was designed and built in 2008/2009 and comprises three separate buildings that are connected by two atria. The lateral resistance system of the buildings is ductile perimeter moment resisting frames similar to that of Statistics House.

The ground conditions at the BNZ site are broadly similar to those at the Statistics House site. However, given the site's closer location to the waterfront, liquefaction-induced lateral spreading was identified as a significant risk. To mitigate lateral spread risk ground improvement work was undertaken. According to the site geotechnical report, this consisted of a 20m-wide stone column buttress extending from underneath the southern portion of the building footprint to a seawall located along the waterfront. The building is reportedly supported on a grid of bored and belled piles that extend into non-liquefiable soils. The foundation system is reported to be considerably stiffer than the foundation system supporting Statistics House.

The floor system in the BNZ buildings incorporates proprietary hollow core precast floor units with an in-situ concrete topping over. To address emerging industry concerns over the connection of hollow core flooring to supporting beams, the hollow core units in this building featured a more resilient end connection detail. This end anchorage detail may have acted to spread the effect of beam elongation, and the hollow core end supports maintained their integrity by not shortening during the earthquake. The precast floor units in the BNZ buildings were also orientated at approximately ninety degrees to the orientation of the precast floor units in Statistics House and this may have resulted in reduced seismic actions (and therefore reduced beam elongation potential) parallel to the flooring span in the BNZ buildings compared to Statistics House.

The BNZ buildings reportedly suffered extensive contents and non-structural damage in the 2013 earthquakes. This resulted in an extensive retrofit of the installation of the non-structural elements of the building. The BNZ buildings were part of the Wellington City Council targeted building assessment programme that required detailed structural inspections after the 14 November 2016 earthquake. The results of these inspections were not available to the Panel at the time the report was issued.

Conclusions and recommendations

■ Overall Panel conclusion

The Panel's overall conclusion is that the partial floor collapses of Statistics House were caused by a combination of:

- a highly flexible ductile frame with two bays of frame per precast floor span, which effectively doubled the impact of beam elongation due to plastic hinging; and
- shortening of the precast double-tee flooring units as the ends spalled during the earthquake; and
- amplification of ground shaking, primarily due to basin-edge effects in the Thorndon basin area; and
- the duration of the earthquake.

The combination of these effects was not anticipated by the New Zealand Building Code system at the time of the design of Statistics House.

The overall conclusion reflects the Panel's view that the primary cause of the localised floor collapse is the effect of beam elongation in the multiple bay frame, with a sliding floor at one end only. This forced most of the effects of beam elongation to accumulate at one end of the frame, resulting in loss of support to three precast concrete floor units on the first and second floors.

Precast floor units on other floors which had been recently retrofitted did not lose support.

■ Recommendations by the Panel

Recommendation 1: Investigation of existing buildings in the Wellington region with a similar design that may have been damaged by the Kaikōura earthquake

Existing buildings in the Wellington region (not just the Wellington City CBD) that have a similar design to Statistics House (buildings with precast floor systems and frames that may be affected by beam elongation) should be investigated as soon as possible to determine if precast floor seating problems exist as a result of the Kaikōura earthquake.

Building owners, tenants, consenting authorities and engineers should be provided with guidance to aid with the assessment of damage in existing buildings. This should build on the process begun by the Wellington City Council in December 2016 following the Panel's interim findings.

Recommendation 2: Notify the industry about issues with existing buildings with precast floor systems and frames that may be affected by beam elongation

MBIE, working with IPENZ and its technical societies, should immediately notify the engineering sector of issues relating to the use of precast floor systems in existing buildings that may be affected by beam elongation. This may occur in any region of New Zealand because a large earthquake is likely to create similar or greater demand on buildings. Particular aspects that need attention include:

- the impact of beam elongation on precast floor systems, particularly in conjunction with multi-bay frames
- the need to maintain composite connection of the precast flooring to the in situ topping
- the need to review the precast floor support details

MBIE, working with IPENZ and its technical societies, should consider developing a longer term plan for how to implement this recommendation. This could include disseminating guidance on how to assess existing buildings and providing guidance on standard methods of improvement, if required.

Recommendation 3: Access technical expertise to consider the implications for this type of design for new buildings

MBIE should access specialist expertise in order to:

- consider whether further controls should be placed on the design of new flexible buildings on sites which may be affected by significant ground motion amplification in regions of higher seismic hazard
- develop recommendations for amendments to Concrete Structures standard (NZS3101) to address the matters highlighted in recommendation 2 that would be applicable for the design of future buildings
- clarify the provisions of the Earthquake Actions Standard (NZS1170.5) for the application of P-delta effects in the design of new buildings

Recommendation 4: Review and undertake research into the provisions in the Earthquake Actions standard to ensure they reflect current knowledge of earthquake engineering practise

A review of the provisions in the Earthquake Actions standard (NZS1170.5) should be undertaken. MBIE should access specialist expertise to undertake the research to support this review. The research should focus on:

- the amplification of earthquake ground shaking due to basin-edge effects. Detailed geological and geophysical data should be incorporated into ground motion modelling. A focus on Wellington should be a priority for such research and the research should be extended to other urban centres as appropriate
- the impact of duration of shaking, particularly for ductile building designs. The potential for large earthquakes to affect Wellington and other metropolitan centres may require duration to be more explicitly incorporated in the New Zealand Building Code system.

Appendix A Terms of Reference for the Investigation

PERFORMANCE OF STATISTICS HOUSE IN 14 NOVEMBER 2016 EARTHQUAKE

Technical Investigation of Design, Construction and Land influences on the performance of Statistics House in the Kaikoura earthquake on 14 November 2016

Terms of Reference

The Chief Executive, as provided for in s169 of the Building Act 2004, is undertaking this investigation to establish factors which may affect the building code, guidance published by the Chief Executive under s175 of the Act, and other duties of the Chief Executive as defined in s11 of the Act.

The magnitude 7.8 Kaikoura earthquake on 14 November 2016 caused significant damage to buildings elsewhere in New Zealand, and specifically caused the partial collapse of an intermediate floor in Statistics House, in the Wellington Port business park.

As New Zealand's construction regulator, the Ministry of Business, Innovation and Employment (MBIE) wishes to understand the factors which led to the partial collapse, in order to ensure that the regulatory system is effectively delivering safe buildings.

Matters for investigation

The purpose of this technical investigation into the performance of Statistics House is to establish and report on:

- the original design and construction of the building;
- the impact of any alterations to the building; and
- how the building performed in the 14 November 2016 Kaikoura earthquake.

The investigation will take into consideration:

- the regulatory settings in force at the time the building was designed and built, including design and engineering standards and guidance;
- local knowledge of specific design and construction requirements (including land conditions) for the area; and
- any changes over time to knowledge in these areas.

In addition to Statistics House, for context the investigation may also consider other multi-storey commercial buildings where the life-safety performance of the building in the 14 November and subsequent seismic events may have been less than expected by MBIE.

Where practically possible, it will be useful to compare the performance of Statistics House with newer buildings nearby which have performed as expected in the 14 November event. This will determine any obvious impacts of changing engineering and construction knowledge and practice.

Matters outside the scope of this investigation

The investigation and report is to establish, where possible, the cause(s) of the observed partial building collapse at Statistics House, in order to enable MBIE to (if necessary) amend its regulations or powers to act. It is not intended to address any issues of culpability or liability arising from the collapse. These matters are outside the scope of the investigation.

We will work with CentrePort, Wellington City Council and others as necessary to:

1. Access the property, to be able to collect information, take photos and if necessary samples. We may need to move items to achieve this, and we may need to discuss whether items have been moved by others.
2. Access people, to discuss with key staff and advisors (and on-site building maintenance/facilities staff) the design, construction and any alterations made to the building.
3. Use information to form our conclusions. For the avoidance of doubt we will share all of our findings and reports with CentrePort/Statistics New Zealand/Ministry of Transport, and the designers and contractors involved. MBIE will otherwise keep all information confidential, unless legally required to disclose the information (i.e., by a Court or the Ombudsman).

We will provide:

A brief written report on the specific features (under the scope above) of the buildings investigated.

Expert Panel

The Ministry will appoint a panel as soon as practically possible to oversee the investigation, including an independent chairperson. The Chair will have access to the support and resources required to deliver the review.

The panel members will have a background of experience at a very senior level of the range of matters relating to the planning, design, approval and construction of buildings.

Specifically, the panel will include recognised expertise in seismology, structural and geotechnical engineering.

The first task of the panel once appointed will be to advise on a timeline for the investigation.

Note: *Having convened this panel, the Ministry may use it as a source of advice in instances where other buildings (as yet unknown) may not have performed as expected in the 14 November earthquake and aftershocks.*

Timing

Timing will ultimately be set by the expert panel, however the Ministry's expectation is that this investigation will proceed at pace. Specifically, a final report is sought by the end of February 2017, with initial findings available for discussion with the key stakeholders by mid-December 2016.

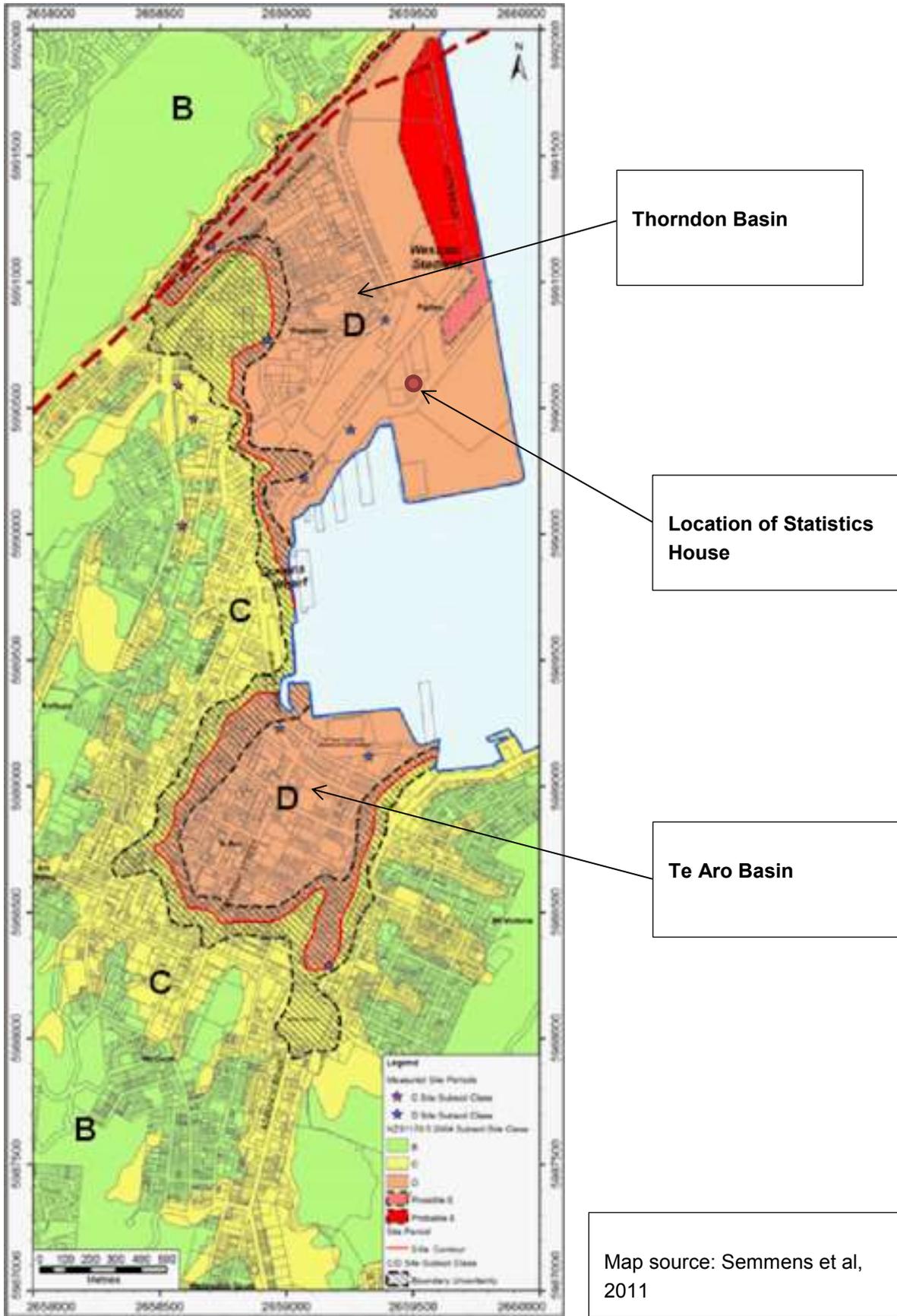
Cost

MBIE will meet costs associated with the investigation described above.

Appendix B Biographies of Panel Members

<p>Dr Helen Anderson</p>	<p>Dr Helen Anderson QSO is Chair of BRANZ and she was a member of the Inquiry into Christchurch CBD building collapse. She has a PhD in seismology from Cambridge University.</p> <p>Helen is a professional director and a Chartered Fellow of the Institute of Directors. She was a former Chief Executive of the Ministry of Research, Science and Technology.</p>
<p>John Hare</p>	<p>John Hare is a consulting structural engineer and is the Chief Executive Officer of Holmes Group Limited. He has a Bachelor of Civil Engineering with Honours from the University of Canterbury and is a Chartered Professional Engineer.</p> <p>John has practised in both New Zealand and California and is a former President of the Structural Engineering Society of New Zealand.</p>
<p>Rick Wentz</p>	<p>Rick Wentz is a consulting geotechnical earthquake engineer and is the Director of Wentz-Pacific Limited. He has a Bachelor of Civil Engineering from California State University – San Luis Obispo and a Master in Civil Engineering (geotechnical emphasis) from the University of California at Berkeley.</p> <p>Rick practises in both New Zealand and California and is a Chartered Professional Engineer in New Zealand, and a registered Civil Engineer and registered Geotechnical Engineer in California.</p>

Appendix C Wellington site subsoil classification Map



Appendix D Selected Bibliography

Soil Classification

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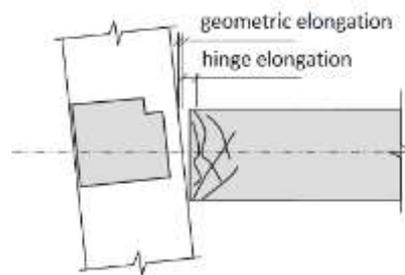
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Appendix E Glossary of Selected Terms

Basin-edge effects The development, within or near the edges of an alluvial basin, of stronger ground shaking (e.g., amplification) and longer durations of shaking than would be conventionally predicted when considering only vertically propagating shear waves due to the multiple reflections of seismic waves. Ground motion amplification (and associated damage to structures) due to basin-edge effects was clearly demonstrated during the 1995 Kobe, Japan earthquake.

Beam elongation Beam elongation occurs when the elastic capacity of the beam is exceeded, that is, the reinforcement in the beam begins to yield and deform inelastically (permanently). There are two components of elongation. Hinge elongation occurs as large cracks form and although the steel may compress on the return cycle, the cracking and movement of the concrete prevents it returning to exactly the same length. Geometric elongation is the additional elongation that occurs due to the rotation of the frame columns relative to the centreline of the beam.



Belled Piles Belled piles are piles which have had the material at the tip of the pile undercut to a greater diameter in order to create a larger bearing area than would be obtained with the shaft diameter only.

Diaphragm A horizontal system (typically a floor or roof) which acts to transmit lateral forces to the lateral force resisting elements.

Double Tee Precast pre-stressed floor units used in the construction of floors (see figure 5).

Ductility The ability of a structure to sustain its load carrying capacity and dissipate energy when it is subjected to cyclic inelastic displacements during an earthquake.

Frame Dilation Frame dilation is the overall increase in length of a full frame due to the cumulative effects of beam elongation over multiple bays.

Hollow-core Precast pre-stressed floor units used in the construction of floors.

Moment Frame or Moment Resisting Frame (MRF)	A structural frame (comprising beams and columns) that resists lateral load by bending in the major elements.
Natural Period	The time (in seconds) it takes for a structure to complete an oscillation cycle.
P-delta effect	Refers to the structural actions induced as a consequence of the gravity loads being displaced laterally due to the action of lateral forces.
Response Spectrum	A spectrum used for design and analysis of a structure.
Shear Wall	A wall that is used to resist lateral forces induced by earthquake actions
Strong Ground Motion	Earthquake shaking of sufficient strength to affect people and their environment.
Strong Motion Duration	The time interval during the earthquake over which the strong ground motion occurs. This is sometimes expressed as the time over which 5% and 95% of the total Arias Intensity accumulates, usually expressed in seconds. This is referred to as the Significant Duration (D_{s595}).
	Arias Intensity is a measure of the strength or intensity of an earthquake ground motion.
Yield capacity	The yield capacity of a reinforced concrete element such as a beam is reached when the reinforcing steel in the element starts to deform permanently (generally, to stretch).

For a fuller bibliography of terms and background on seismicity, soils and the seismic design of buildings refer to [Volume 1 of the Final Report of the Canterbury Earthquakes Royal Commission](#)