Wellington building inventory: rapid earthquake response framework

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ABSTRACT

This paper is focused on the design and implementation of a functional tool to evaluate and communicate the seismic risk to increase resilience and reduce human and economic loss. Wellington has been selected as the case study for this research due to the existence of a robust database of buildings within the central business district. In the first phase of this research, a high-level near real-time seismic impact framework is designed to identify the response of buildings to an earthquake. This scenario and planning framework showcases the consequences on the Wellington building inventory caused by an earthquake by comparing accelerations recorded at GNS strong motion stations in the city to building design accelerations. The outputs of the framework facilitate the different stakeholders, *i.e.*, building owners and decision-makers, to provide a rough estimation of the severity of building-level seismic impacts. This research presents the first phase of a larger research programme focused on: (1) quantifying the direct repair costs associated with region-wide earthquake damage to buildings with common structural and non-structural vulnerabilities in terms of expected annual monetary loss and disruption and (2) identifying evidence-driven retrofit priorities by systematically removing vulnerabilities from the building stock, and re-evaluating the repair and downtime costs across the region.

Keywords: Seismic risk analysis, Risk communication, Risk mitigation, Wellington building inventory, Near-real time earthquake response framework.

1 INTRODUCTION

This paper outlines the development of a framework that relates earthquake ground shaking information to estimated demand on the buildings within the framework. The primary outcome of the research is thus to provide rapid situational awareness to decision makers following any earthquake, indicating likely damage to any given building. The framework generates interactive regional maps that display the evaluated seismic risk for each building. The framework is the first phase of research that ultimately aims to provide two outcomes: understanding of the disruption, life, and monetary loss for future modelled scenarios and, understanding and prioritising the best value retrofit options to improve resilience.

Wellington has been selected as the case study of this research due to (1) the large monetary losses and disruption caused by the recent earthquakes which have highlighted the need for improved approaches to manage and mitigate the financial risk for future, potentially more damaging, events and (2) due to the existence of a comprehensive database of buildings within the Central Business District (CBD). The 14 November 2016 Kaikoura earthquake is the most recent major earthquake that affected Wellington and had a moment-magnitude (M_w) of 7.8 (Potter *et al*. 2015). Whilst the epicentre of the earthquake was in Kaikoura, which is more than 200 kilometres away, the closest extent of fault rupture was 50 km South of Wellington, causing widespread damage to buildings across Wellington (Bradley, Wotherspoon, and Kaiser 2017). Immediately following the earthquake about 10% of the city's office space was closed for assessment, which resulted in relocation of thousands of workers from their offices (Harris 2016). Nearly 20 buildings in Wellington have been demolished or remained vacant, and 10 additional buildings which were initially closed for detailed assessment, re-opened upon the completion of inspections. Most of the damaged buildings were in the CBD of the city and were moment-resisting reinforced concrete frames with 6 to 15 floors that were constructed after 1980 (Kestrel Group 2017).

Risk analysis and identification of vulnerabilities across a city or region's building are dependent on comprehensive information about them. The efforts to provide a multi-disciplinary database of the Wellington Building Inventory have been carried out in a collaboration between QuakeCoRE and Wellington City Council (WCC) and have produced an effective and usable multi-disciplinary building inventory spatial database for Wellington CBD (Puranam *et al*. 2019). This database consists of several different databases for Wellington CBD, including Building Seismic Assessment, Hollowcore Floors, Targeted Damage Evaluation, 1935-1975 RC Buildings, CityScope, Earthquake Prone Buildings, and WCC Heritage, which have been combined in a master database and evaluated by a comprehensive site survey. Figure 1 shows a snapshot of Wellington CBD building inventory. Additionally, the database is enriched by the building drawing database which consists of building drawings and consents for a large number of buildings in the wider database. The readable access to the structural drawing of buildings facilitates the extraction of building structural properties and forms the foundation for further investigations in this research. This paper focuses on medium to high rise concrete buildings located at the Wellington CBD as the case study.

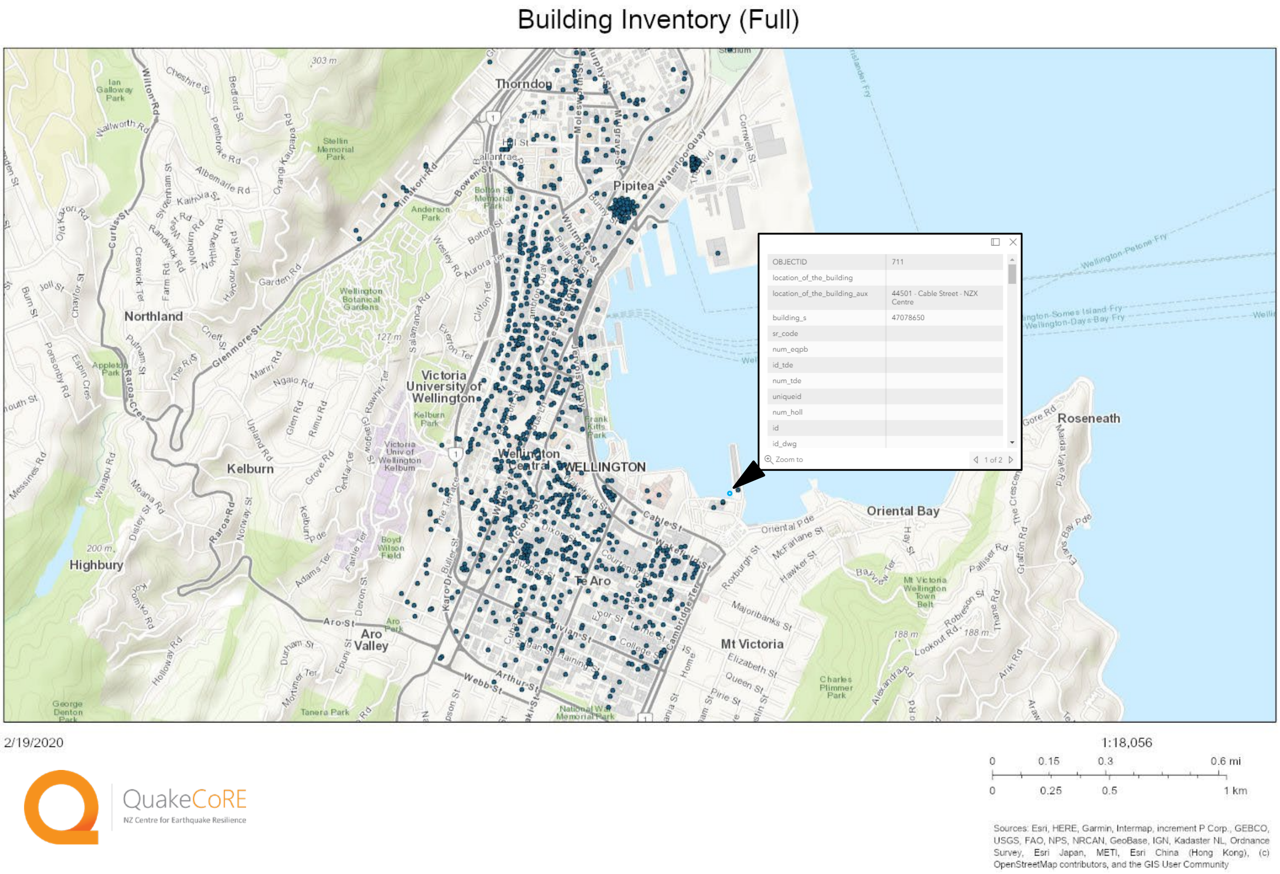

Figure 1: A snapshot of Wellington CBD building inventory (Puranam et al. 2019).

The overarching objectives of this larger research programme are twofold: (1) quantifying the direct repair costs associated with region-wide earthquake damage to buildings with common structural and non-structural vulnerabilities in terms of annual monetary loss and disruption and (2) identifying evidence-driven retrofit priorities by systematically removing vulnerabilities from the building stock, and re-evaluating the repair and downtime costs across the region. To begin to address these objectives, a high-level near real-time seismic impact framework is designed to identify the response of buildings to an earthquake and provide a scenario and planning tool which is the focus of this paper. This framework, which is explained in detail in the following sections, showcases high-level consequences on the Wellington building inventory caused by an earthquake by comparing spectral accelerations recorded at GNS strong motion stations in Wellington to individual building design accelerations. The outputs of the framework provide a rough estimation of the severity of building-level seismic impacts to the different stakeholders, *i.e.*, building owners and decision-makers. The following sections will discuss the Wellington building inventory and high-level near real-time seismic impact framework as well as the next steps in the larger research programme.

2 WELLINGTON BUILDING INVENTORY DATABASE

The Wellington Building Inventory Database is the basis of this research and, as stated previously, one of the primary reasons for selecting Wellington as the case study. This database comprises of a combination of 11 different databases which have been verified by a comprehensive site survey. This paper focuses on the medium to high-rise concrete buildings, which have five or more storeys above ground. Furthermore, this research only focuses on the buildings for which structural drawings are available in the building drawings database. Currently, the number of buildings in the building drawing database with five or more storeys is ~270, with additional drawings added regularly. The most important buildings parameters in this research are the geographic location, number of storeys, above ground height, year of design and construction, lateral load bearing system, flooring system, presence of vertical/horizontal irregularity, use category, and footprint area, all of which are available in the building inventory.

2.1 Estimating building design accelerations

Several important parameters required to estimate the design spectral accelerations for each building were not included in the original Wellington Building Inventory Database, namely the site subsoil class and structural period. This research utilises the available site subsoil class maps for central Wellington presented by Kaiser *et al*. (2019) to identify the buildings' soil types based on the geographic location. Figure 2 shows the Wellington CBD including the boundaries of different site subsoil classes according to NZS 1170.5 (2004), where soil type B is for Rock, C is for shallow soil, and D is for deep or soft soil.

The building period is essential for the evaluation of earthquake design action. Consequently, this research employs the analytical approach proposed in the Commentary of NZS1170.5 to estimate the approximate period of the building based on the height (NZS 1170.5 Supp1:2004 2004). Adding site subsoil class and building period to the database, the design acceleration of each building is calculated in accordance with NZS 1170.5 (2004) and added to the database for use in the framework.

Figure 2: Site subsoil classes for central Wellington adopted from Kaiser et al. (2019).

2.2 Strong motion stations

The other important parameter which is not available in the original Wellington Building Inventory Database is the building site periods, which are used to link strong motion stations to individual buildings as discussed in the next section. Since the Wellington CBD has very dense site period contours, the change in site periods of buildings over very short distances can be extreme. Hence, the geotechnical characteristics of buildings are more related to building site periods rather than the geographic location. For this reason, the initial contours map of Wellington CBD site periods was adopted from Kaiser *et al*. (2019) with the low amplitude natural period contours for the Wellington CBD shown in Figure 3. The black contours in Figure 3 are over 0.2-second intervals which were represented by Kaiser *et al*. (2019). However, four colour contours for periods of 0.7, 0.9, 1.1, and 1.5 seconds have been added to the original contours map based on the opinion of experts in the field. These contours are required to determine the corresponding site periods of strong motion stations more precisely.

Figure 3: Central Wellington low amplitude natural period contours; black contours are in 0.2-second intervals, reported by Kaiser et al. (2019); corresponding site periods of colour contours are determined in the legend.

3 NEAR REAL-TIME EARTHQUAKE RESPONSE FRAMEWORK

A near real-time framework was designed to showcase the consequences of earthquakes to the buildings of interest in the Wellington database. In this initial high-level analysis, the design acceleration is compared to the measured acceleration which can highlight when the design threshold may have been exceeded and the building should be inspected for damage. To this end, each building is connected to a strong motion station to identify the occurred hazard information after the occurrence of an earthquake. The New Zealand Strong Motion Database contains a comprehensive compilation of high-quality source and site metadata for large New Zealand earthquakes, rupture models of past large earthquakes, and strong motion recordings with component-specific processing (Van Houtte *et al*. 2017; Kaiser *et al*. 2017). GeoNet provides various levels of processed data for many strong motion stations across New Zealand, including corrected acceleration, velocity, and displacement time histories. To connect the buildings to individual strong motion stations, this research utilises site periods as the matching index rather than the geographic location due to the rapidly changing site conditions, as described previously. This means that each building is linked to the station with the nearest site period which is not necessarily the nearest station. A complete map of central Wellington site periods has been created to draw the boundaries of each strong motion station and link the buildings to these stations, which is shown in Figure 4.

Figure 4: Central Wellington strong motion station boundaries.

The first version of the near real-time framework was designed as an offline web page platform that displays the percentage of measured acceleration after the occurrence of an earthquake to the earthquake design acceleration. The demonstration version of the framework is shown in Figure 5, which was created for the Foxton 5.8 M_w earthquake that occurred on 24 May 2020, 19:53:33 UTC. The selected buildings of the central Wellington database are shaded according to a colour scale that represents the ratio of measured earthquake acceleration to the Ultimate Limit State (ULS) design acceleration. This framework generates the response spectra from acceleration data recorded at the strong motion stations and compares the design spectral acceleration, A_{design} at the fundamental period of the building, T_1, to the recorded spectral acceleration at T_1, dubbed $A_{measured}$. The map is designed interactively which enables the user to click on each building and view the building name and the corresponding demand ratio, $A_{measured}/A_{design}$. The map also includes the locations of Wellington strong motion stations and allows the user to access information about each station including the name and site subclass. As shown in Figure 5, the map displays a set of spectra for each strong motion station, including design ULS and Serviceability Limit State (SLS) spectral acceleration spectra for the corresponding soil type, as well as the spectra for both components of acceleration measured at the station for the earthquake, which is Foxton earthquake in the case shown in Figure 5. It should be noted that in the current version of the framework, the design accelerations for all the buildings are calculated based on NZS 1170.5 (2004). However, an ongoing area of this research is working to identify the corresponding seismic design code of the buildings based on the year the buildings were designed.

Figure 5: Snapshot of near real-time earthquake response framework.

4 CONCLUSION

This paper puts forward the design and implementation of a near real-time earthquake response framework. The framework aims at communicating the seismic risk to decision-makers through evaluating the ratio of measured acceleration caused by an earthquake to buildings design acceleration at the nearest possible time after of an earthquake. Wellington CBD has been selected as the case study of this framework due to large monetary losses and disruption caused by the recent earthquakes and the existence of a comprehensive database for building inventories. The first version of this framework generates an overview of the measured acceleration of buildings after the occurrence of an earthquake which indicates the severity of building damage.

The next step of this research is to identify the broad vulnerability archetypes of buildings in Wellington and select candidate buildings as representative of each vulnerability archetype. This selection will be performed using an unsupervised machine learning method. These candidate buildings will be modelled using a set of detailed structural macro models to assess the seismic risk by evaluating the expected monetary loss. Also, the candidate buildings are going to be instrumented using the system identification process to extract the dynamic properties from vibration data. The final step of this research is to remove the vulnerabilities of candidate buildings using different retrofit strategies and re-evaluate the seismic response of these buildings to see the effect of the vulnerabilities on economic and human loss and use these metrics to develop a retrofit prioritisation framework for Wellington buildings.

This research envisions to tie into a broader research project conducted by Resilience to Nature Challenges (RNC2) built environment workstream with a focus on vertical infrastructure. The fundamental objective of vertical infrastructure research is to identify effective means of reducing the damage and disruption of vertical infrastructures caused by future earthquakes, focusing on two main research areas: (1) quantifying and mitigating the risk, in terms of monetary losses, associated with different design solutions and building technologies, and (2) supporting the development of design and assessment standards for New Zealand buildings to enable enhanced performance objectives to be achieved in practice. This research will be integrated with the other workstreams of RNC2 through the integrated Wellington scenario which utilises

Wellington City and a major Hirukangi subduction zone as a case study to provide a deep appreciation of the vulnerability and impacts of Wellington in significant detail.

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