Seismic structural monitoring in Wellington using advanced seismological techniques

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ABSTRACT

Sklodowska et al. (2021) employed advanced seismological techniques usually applied to Earth studies to the Te Puni building (instrumented as part of the GeoNet building instrumentation programme) for the 2009-2017 time-period. Focusing on two techniques (Interferometry and transfer function), we were able to track transient changes in the building dynamic response from various levels of earthquake loading, and over time despite the absence of structural damage. Learning from this project, we apply the above techniques to buildings from the GeoNet building instrumentation programme with different service functionalities and construction typologies.

MBIE Stout street is an interesting example of a robust 1920s concrete encased structural steel moment frame structure with an elevated importance level (IL3) based on its government department tenancy. We selected a total of over 3,000 earthquakes as part of this study. Results show a clear decrease in the fundamental frequency of the structure in a step change trend related to the 2016 Kaikoura earthquake. We will discuss the interpretation of these results and interest in expanding this research to other parts of the building.

Wellington Regional Hospital, a modern base-isolated structure, is also an ideal candidate showcasing a damage avoidance system designed to a high importance level (IL4). We selected a total of 903 earthquakes as part of the analysis of this structure. Preliminary results show a clear decrease in the fundamental frequency of the structure in a step change trend, occurring following the 2013 Cook Strait sequence and the 2016 Kaikoura earthquake. This analysis is specifically related to one direction of the building and more detailed analysis is currently being progressed.

1 INTRODUCTION

Seismic Structural Health Monitoring (S2HM, Limongelli et al. 2019) makes rapid and objective structural damage assessment faster and more precise. It is based on the analysis of both the short and long term acquisition of seismic data from sensors deployed strategically in a building. Sklowdowska et al. (2021) employed advanced seismological techniques usually applied to Earth studies to the Te Puni building (instrumented as part of the GeoNet building instrumentation programme) for the 2009–2017 time period. Focusing on two techniques (Interferometry and Transfer Function), they tracked transient changes in the building dynamic response from various levels of earthquake loading over time, despite the absence of structural damage.

This paper presents an overview of the Sklodowska et al. (2021) study for two Wellington buildings (Figure 1), with different building typologies and instrumented by the GeoNet Building Monitoring Programme (Uma et al., 2011).

MBIE Stout Street
1920s two-way structural steel moment frame structure encased in reinforced concrete and of government level importance (IL3).

Wellington Regional Hospital
modern base-isolated structure showcasing a damage avoidance system and a high importance level (IL4) designed for post disaster functionality.

Figure 1: Two Wellington buildings with different construction typologies and part of the GeoNet Building Instrumentation Programme chosen for the S2HM analysis.

2 STOUT STREET BUILDING

MBIE Stout Street is an interesting example of a robust 1920s concrete encased structural steel moment frame structure with an elevated importance level (IL3) based on its government department tenancy. The building instrumentation consists of 16 seismic sensors spread across the 8 levels plus basement of the building (Chandramohan et al., 2017). Eight of these sensors are conveniently arranged in a vertical array configuration along the central part of the building. As part of an initial analysis to detect potential structural changes from past earthquakes we have exclusively focused on the sensor vertical array. Future work will include data analysis from the other sensors in order to provide a more detailed 3D response of the structure.

Instrumentation of the building started in 2014. We selected a total of over 3,000 earthquakes from 2014 to 2021. The data appears a lot more scattered than for other seismic arrays and the results from 2018-2019 in particular present spurious higher amplitude values. There is also a gap in the recorded data between 2017 and 2019. We performed a preliminary analysis of the fundamental frequency of the structure to review if any change could be detected over time.

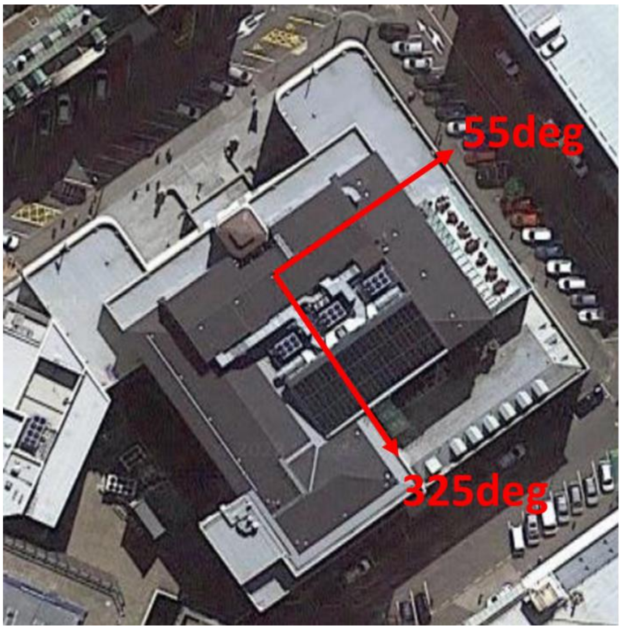

Figure 2: Plan view of the Stout Street Building showing the principle component directions (Source: Google Maps)

Figure 3 presents computed fundamental frequencies as a function of time (ie days prior to and post the 2016 M7.8 Kaikoura earthquake). Initial frequencies in the 325 degree direction and the 55 degree direction are similar at about 1.9Hz (0.53sec). This is consistent with the symmetrical shape of the Stout Street building. Early results show a clear decrease in the fundamental frequency of the structure in a step change trend with regard to "before" and "after" the Kaikoura earthquake. Changes are estimated to be also about 15%. It's worth noting that this analysis is only presenting changes related to one location of the instruments in the building. It is also noted that the there is a small degree of recovery in stiffness the first few days following the Kaikoura event plateauing to a new normal over time.

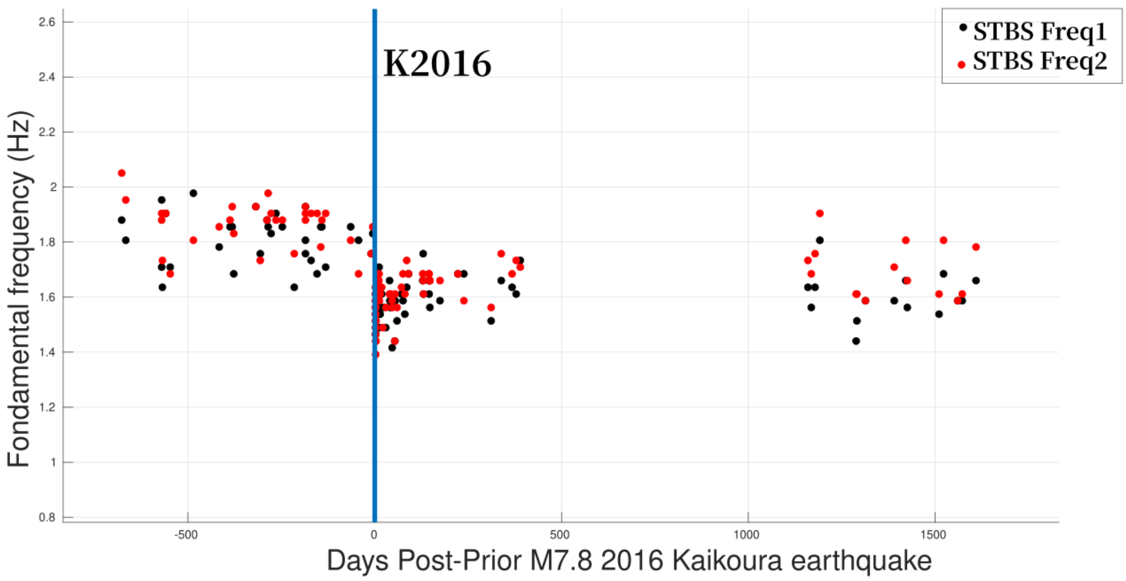

Figure 3: Measurement of the fundamental frequency in the 325 degree direction (Freq1 in black) and the 55 degree direction (Freq2 in red) of the Stout Street building (STBS) against days before and after the 2016 Kaikoura earthquake (day 0) marked by the blue line.

Focusing on the vertical array of sensors we were able to perform a deconvolution of the signals based on the signal recorded at the top and identify the floors that have changed the most (Picozzi et al. 2011; Nakata et al. 2013). We also stacked the results according to two time periods: prior to Kaikoura and post Kaikoura. Figure 4 shows the shapes of the interferograms for specific floors (basement, ground level, 1, 3, 5, 6, 7 and 8) and one specific direction (325 degrees). These interferograms represent a snapshot of the building response to a seismic pulse travelling from the bottom floor, reflected at the very top of the building and travelling back down. The interferogram of a simple structure, comparable to a homogenous block with little attenuation, will show a pulse travelling with constant propagation velocity and amplitude. However, variations in the building properties will affect the pulse amplitudes, "spurious floors" will create reflected pulses, and softening of the structure at a later time will be expressed by delays in the pulse travelling times. There is a wealth of information contained in figure 4 for the two time periods, however three principle features are noted: the overall signal shapes remain the same for both periods from levels 6 to 8 (shown by green dashed line), indicating no significant structural change. There is a clear time delay between level 5 and level 6 post Kaikoura (as shown by offset measured between red and black dashed lines) indicating that the observed changes in fundamental frequencies are concentrated between these floors. We also observe no extra time delay below level 5 (shown by constant offset between the red and black dashed lines). This change could be attributed to minor cracking of the concrete encasement encompassing the structural steel frames, and/or a softening of non-structural elements and partitions. Some damage or softening to the non-structural elements is particularly likely given that the periods recorded remain higher than that obtained from 3D analysis models of the building which do not account for the initial stiffening effects of non-structural elements. This is a preliminary analysis that needs to be investigated further with the inclusion of other available sensor data.

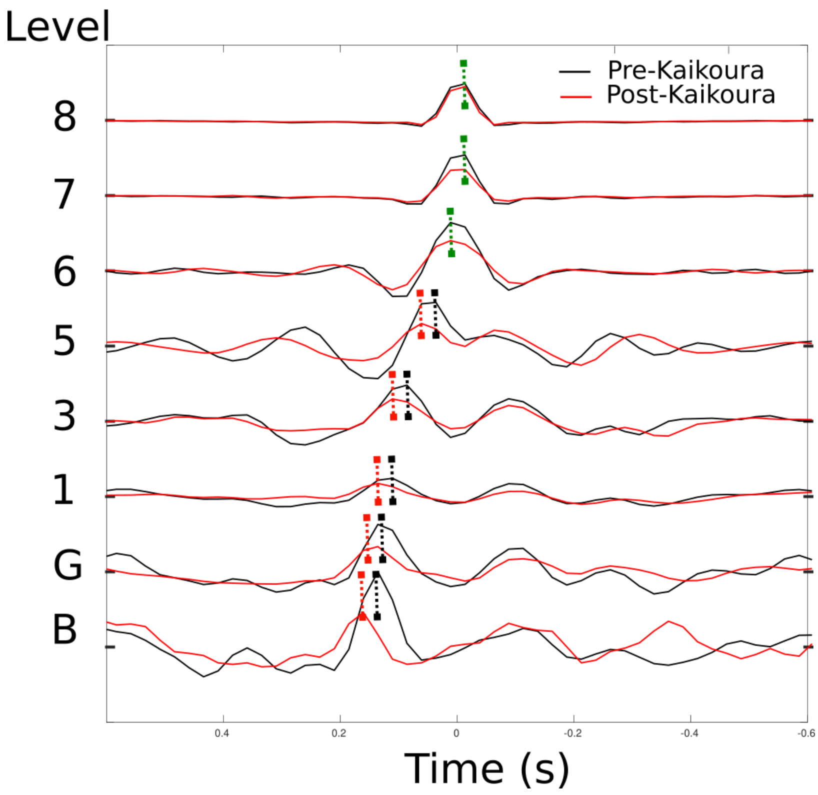

Figure 4: Stacked deconvolved traces from periods pre (black) and post (red) Kaikoura earthquake for the 325 degree direction at each instrumented level (from bottom to top trace: basement, ground level, 1, 3, 5, 6, 7 and 8) in the building derived from acceleration time-history. Dashed black and red lines mark locations of peak pulses (travelling upward) for each level and pre-Kaikoura, post-Kaikoura time periods respectively. Green dashed lines show zero time delay between red and black pulses (floors 6 to 8); black and red dashed lines show a 0.02s time delay between the red and black pulse (between floors 5 and 6), then this delay stays constant for the floors below level 5.

3 WELLINGTON REGIONAL HOSPITAL BUILDING

Wellington Regional Hospital, a modern base-isolated structure, showcases a damage avoidance system designed to a high importance level (IL4) for post disaster functionality. The building instrumentation consists of 16 seismic sensors spread across the 7 levels of the building (Uma et al., 2011). Seven of these sensors are conveniently arranged in a vertical array configuration, spanning across the 7 floors, located to the southernmost end of the building. As part of an initial analysis to detect potential structural changes from past earthquakes we are exclusively focusing on the vertical array sensors for this study. Future work will include data analysis from the 9 other sensors in order to provide a more detailed 3D response of the structure.

Figure 5: Plan view of the Wellington Hospital Building showing the principle component directions (Source: Google Maps)

Instrumentation of the building started in 2009. We selected a total of 903 earthquakes from 2009 to 2021. We performed a preliminary analysis of the fundamental frequencies of the structure in the main component directions of the building (45 and 135 degrees), to verify if any change could be detected over time. Figure 6 presents computed fundamental frequencies as a function of time (ie days prior to and post the M7.8 Kaikoura earthquake). The initial frequency in the transverse direction (45 degree) is about 2.0Hz (0.5sec) compared to 1.7Hz (0.59 sec) for the longitudinal direction. These differences in fundamental frequencies are not unexpected given the pronounced asymmetry of the structure.

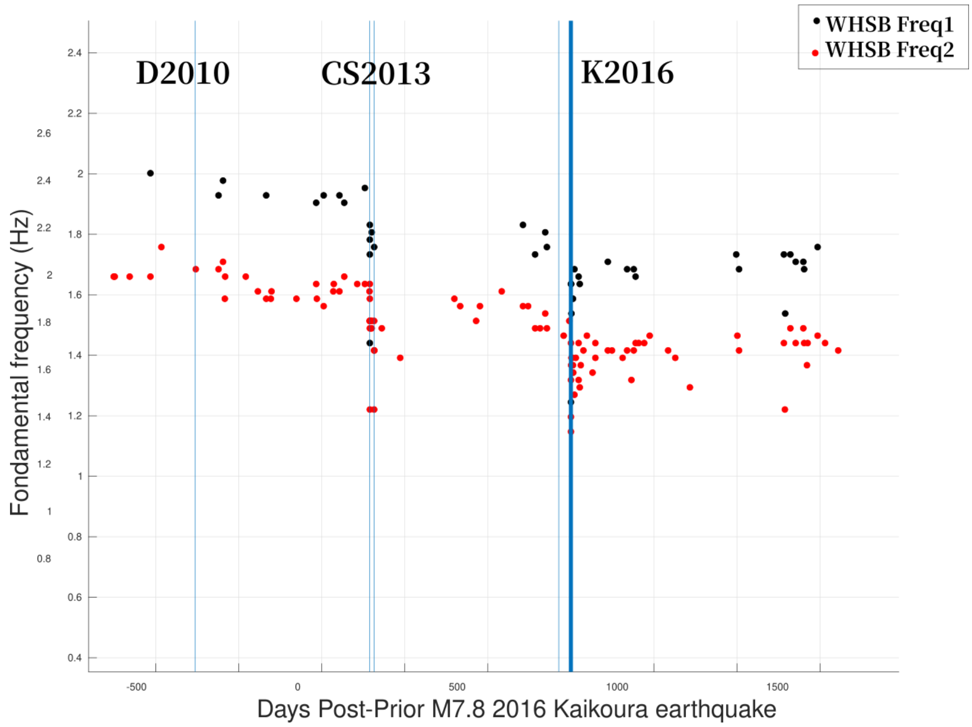

Figure 6: Measurement of the fundamental frequency of WHSB (Wellington Hospital) in the 45 degree direction (freq1 in black) and 135 degree direction (freq2 in red) against days before and after the 2016 Kaikoura earthquake (Day 0). The figure also shows significant recent earthquake timeline (blue lines): M7.1 Darfield 2010 (D2010), Cook Strait Sequence (CS2013) and the M7.8 Kaikoura earthquake (K2016)

Early results show a clear decrease in the fundamental frequency of the structure, for both directions, in a step change trend. The step changes occur following the 2013 Cook Strait sequence and the 2016 M7.8 Kaikoura earthquake. Changes are estimated to be about 10%. It's worth noting that this analysis is only presenting changes related to one particular location of the instruments in the building and that more detailed analysis is currently being done.

As for the previous buildings, we focused on the vertical array of sensors to perform a deconvolution of the signals based on the signal recorded at the top and identify the floors that have changed the most (Picozzi et al. 2011; Nakata et al. 2013). Here we have stacked the results according to three time periods: prior to Cook Strait 2013, prior to Kaikoura and post Kaikoura. Figure 7 shows the shapes of the interferograms for specific floors (levels A, C, D, E, F and G) and one specific direction (45 degrees). Attention is focused on two principle observations: both the Cook Strait sequence and Kaikoura earthquake impacted the structure, and the majority of the observed change appears to have occurred between levels C and D. The change in fundamental frequency as noted in Figure 6 is therefore attributed in principle to the concentrated impact observed between level C and level D.

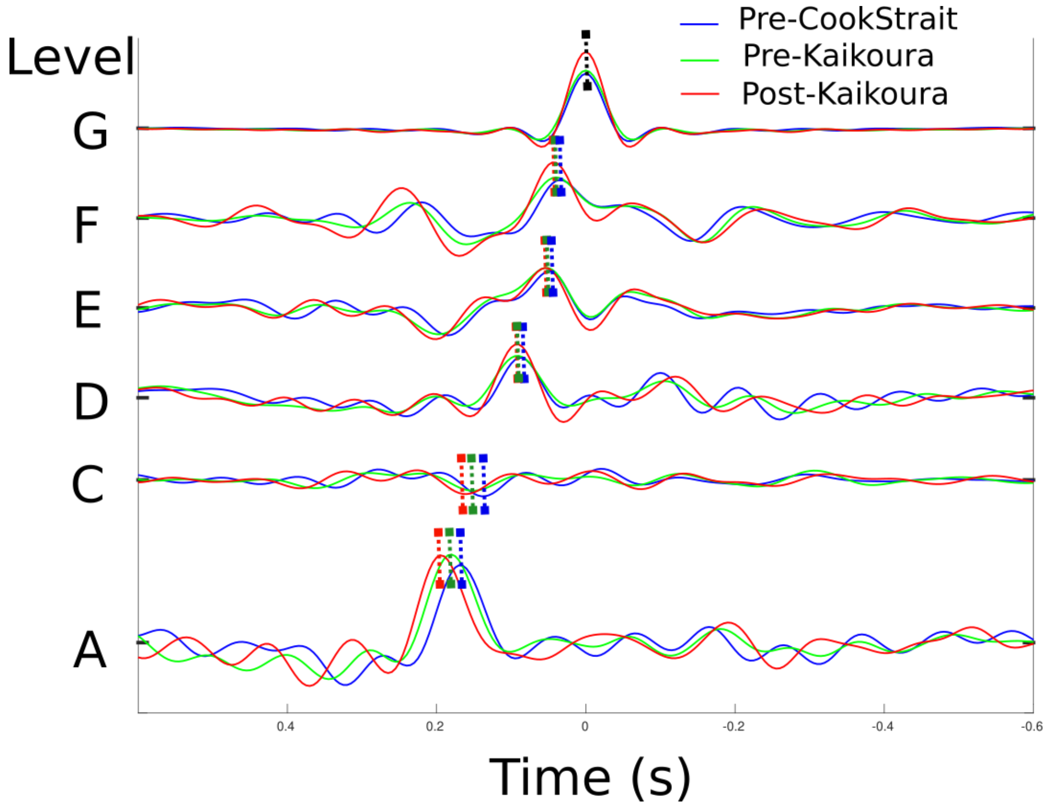

Figure 7: Stacked deconvolved traces from periods pre-Cook Strait sequence (blue), pre (green) and post (red) Kaikoura earthquake for the 45 degree direction at each instrumented level (from bottom to top trace: A, C, D, E, F and G) in the building derived from acceleration time-history. Blue, green and red dashed lines mark peak pulses (travelling upward) for various floors and pre-Cook Strait, pre-Kaikoura and post-Kaikoura time periods respectively. There are only very small pulse offset changes between these time periods for floors D to G and floors A to C. However there is a 0.03 s total offset between floors C and D following both Cook Strait and Kaikoura earthquake sequences.

4 SUMMARY

Thanks to the GeoNet Building Instrumentation Programme, we were able to detect and locate structural changes for buildings with different construction typologies using S2HM: Te Puni, a relatively light weight steel frame structure with damage avoidance systems, Stout Street, a heritage structure with heavy structural steel frames with a robust reinforced concrete encasement and partitions, and the Wellington Regional Hospital, a modern base-isolated structure. As summarised in Figure 8 our analysis shows a consistent increase of the fundamental periods of the structures in a step-change manner. With advanced analysis the source of the changes can also be localised within the structure. The absolute amplitude of that step change is building dependent.

Recent data acquired a few years following the Kaikoura earthquake indicate that the structures have recovered some of that period shift but also settled to a new plateau level.

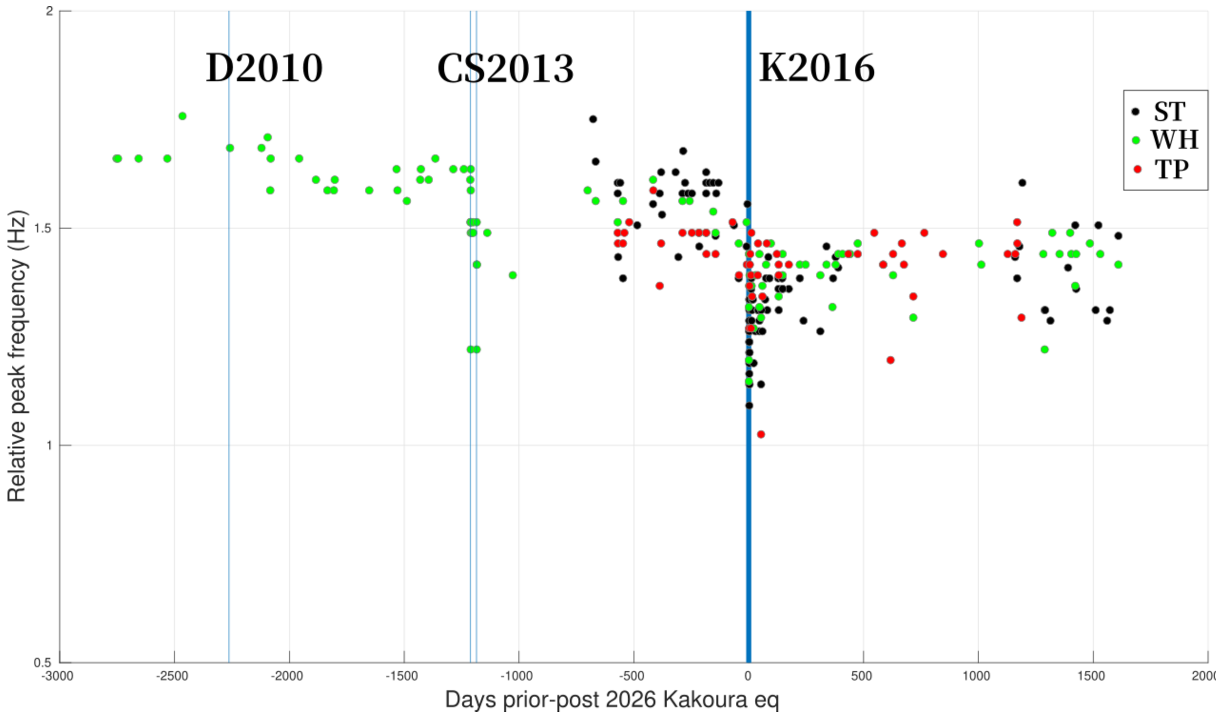

Figure 8: Comparison of the (relative) fundamental frequency of Stout Street (ST) , Wellington Hospital (WH) and Te Puni (TP) buildings against days before and after the 2016 Kaikoura earthquake (Day 0). The figure also shows significant recent earthquake timeline (blue lines): M7.1 Darfield 2010 (D2010), Cook Strait Sequence (CS2013) and the M7.8 Kaikoura earthquake (K2016)

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