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Damage assessment of structures based on monitoring data

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ABSTRACT: Damage assessment of structures after extreme events such as earthquakes is an essential and critical task for owners, users, authorities and the community. Accurate and quick damage assessment of structures can effectively reduce economic losses and speed up the reconstruction of the affected earthquake region. Visual inspection is currently the most common damage assessment technique. However, this technique is subjective, time consuming, dangerous for inspectors and not reliable for complex and large structures. Following this approach, structure owners need to wait in line for their structures to be visually inspected and tagged by city officials or evaluated by an engineer in order to assess the status of their structure. This process may take days, weeks or even months if there are a large number of buildings requiring inspections and evaluations. Given these shortcomings in visual inspection, a significant amount of research has been carried out over the past several years to determine the feasibility of vibration based damage assessment of instrumented structures and establish a coherent and consistent set of techniques and methodologies of real-time damage detection and performance evaluation. In this paper, new computational tools for damage identification and long-term dynamic monitoring, developed in the MATLAB environment, are described. The toolkits provide functions for automated dynamic parameters and response amplitude monitoring. The potential of these toolkits is illustrated using data collected by a continuous dynamic monitoring system installed on a concrete bridge in Wellington, New Zealand.

1 INTRODUCTION

Several civil engineering structures including bridges, buildings and tunnels continue to be used despite aging and the associated risk of damage accumulation. Therefore, monitoring the structural integrity of these structures is becoming increasingly important from both economic and life-safety viewpoints. Civil engineers in charge of safety and maintenance of these structures are aware of the limitations of their current common practice of condition assessment based on visual inspections (Beskhyroun et al 2012). Routine condition assessment is carried out on structures on two-to-five year intervals. The consequence could be sudden collapse between inspection intervals and unbearable costs on governments and owners for replacement and retrofit tightened up by shrinking budgets. The expressed intention of the bridge owners globally is to reduce the number of bridges rated deficient within a short time through the application of sophisticated methods based on actual measurements (Bornn et al 2010, Brownjohn et al 2011).

Moreover, damage assessment of structures after extreme events such as earthquakes is an essential and critical task for owners, users, authorities and the community. Accurate and quick damage assessment of structures can effectively reduce economic losses and speed up the reconstruction of the affected earthquake region. Utilisation of a sensor network system integrated within the structure itself can greatly enhance the inspection process through rapid in-situ data collection and processing. However, these sensor networks typically produce large and complex sets of data that become difficult to process using on-hand database management tools or traditional data processing applications. The challenges include capture, storage, search, sharing, transfer, analysis and visualisation. The main objective of this research is to design and develop an automated damage identification system for continuous health monitoring of civil engineering structures. In this automated system, a cluster of computers will perform different steps of the damage detection process, including control of equipment and hardware, data collection, data analysis and generation of evaluation reports and

triggering an alarm signal in the case of damage detection. This system can be an essential tool not only for damage detection and SHM of structures but also to manage data of several monitored structures.

In this paper, new computational tools for damage identification and long-term dynamic monitoring, developed in the MATLAB environment, are described. The toolkits provide functions for automated dynamic parameters and response amplitudes monitoring. The potential of these toolkits is illustrated using data collected by a continuous dynamic monitoring system installed on a concrete bridge in Wellington, New Zealand.

2 LONG-TERM DYNAMIC MONITORING

2.1 Vibration behaviour

Civil engineering structures have a unique vibrational behaviour which maybe addressed as a 'vibrational signature'. This 'vibrational signature' is typical for a structure and can be obtained by appropriate measurements and used for the evaluation of the condition and performance of the structure and detection of damage after respective assessment.

Structure ambient vibration induced by wind, traffic, tremors and operational use can be recorded periodically at user specified intervals, continuously, or based on pre-trigger settings. Dynamic characteristics of structures and key response parameters such as peak acceleration, root mean square of response and many others are extracted from the recorded raw data and then interpreted to evaluate the structure's 'vibrational signature'.

2.2 Potential Impact

Ambient vibration based evaluation of structures is selected in this study for bridge condition assessment under the premise that it can be used practically without any impairment of the traffic flow. One of the main goals of the developed system is to provide a monitoring system that makes it possible to reduce the employment of bulky inspection equipment by well-aimed specification of suspected damage zones, therefore minimising the disturbance to the traffic flow during inspection works. The proposed system can be implemented independent of the type and construction of the structure, and the type of construction materials.

By measuring the actual vibration characteristics, the 'vibrational signature' is obtained and is not subject to the circumstances of the personnel carrying out the test. Therefore, the condition assessment of the monitored structure can be determined by a systematic analytical evaluation.

2.3 Automated monitoring system

Utilisation of a sensor network system integrated within the structure can greatly enhance the inspection process through rapid in-situ data collection and processing (Ou et al 2010, Zhang 2009 et al, Yang et al 2015). However, these sensor networks typically produce such large and complex sets of data that it becomes difficult to process using on-hand database management tools or traditional data processing applications (Chris 2010, Li et al 2015). The challenges include capture, storage, search, sharing, transfer, analysis and visualisation. The main objective of this research is to design and develop new computational tools for structural modal identification and long-term dynamic monitoring. The toolkit is developed in MATLAB environment as it permits the easy development of graphical interfaces and provides powerful tools for automated data processing; a characteristics that is essential in the context of continuous monitoring. The developed system consists of two independent toolkits: the modal parameters identification toolkit (MPIT) (Fig. 1a), which is used for structural dynamic identification (Beskhyroun 2011), and the automated data analysis toolkit (ADAT) (Fig. 1b), which is used for data management and processing of large data sets. The MPIT is mainly used for identification of dynamic characteristics such as natural frequencies, mode shapes and damping ratios (Döhler et al 2012, Chobra 1995). In this toolbox, frequency domain based and time domain based system identification techniques are implemented. System identification techniques also include output only as well as input-output methods. The intention is to provide a user friendly toolbox for estimating modal parameters, make a comparison of several system identification techniques, and

compare modal parameters from different tests.

The ADAT is used for automated dynamic monitoring, excluding any user interaction. This toolkit can divide and process large data sets automatically. Available tools in this toolkit include functions for communications with servers, data downloads, changing the format of the raw data, dividing continuous data to user specified intervals, running data analysis and saving the results. The toolkit also provides functions for data visualisation and comparison.

Firstly, peak and root mean square (RMS) accelerations are detected automatically, enabling the statistical treatment of the response time series. Secondly, a succession of power spectral density (PSD) lines is produced to form a spectrogram of hourly distribution of frequency components. Then, an automated modal parameters identification procedure is implemented to extract dynamic characteristics from successive hourly data sets.

The potential of the developed system is illustrated using data collected from the Thorndon Overbridge by a continuous dynamic monitoring system for 1 year.

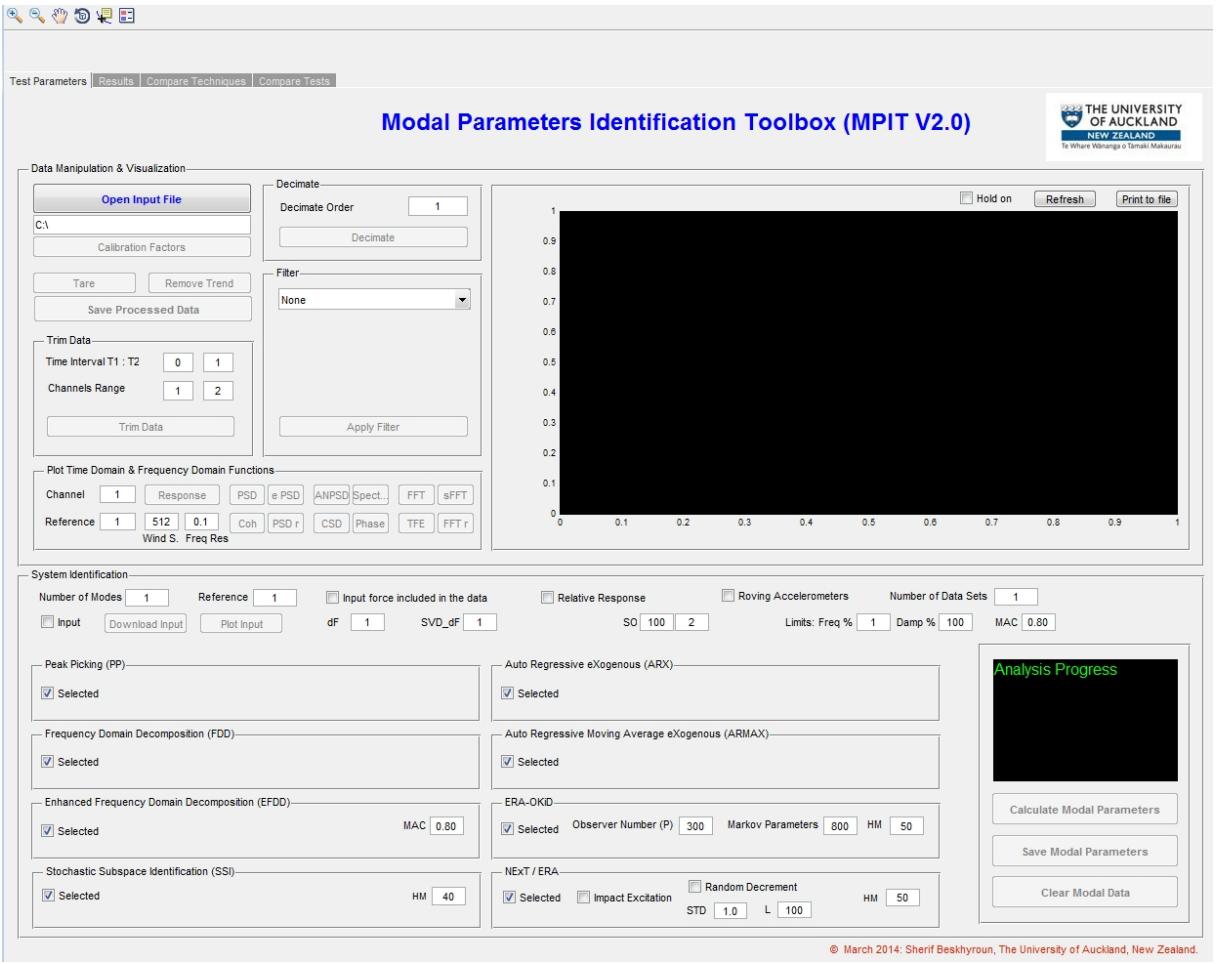

Figure 1a: Modal parameters identification toolkit (MPIT)

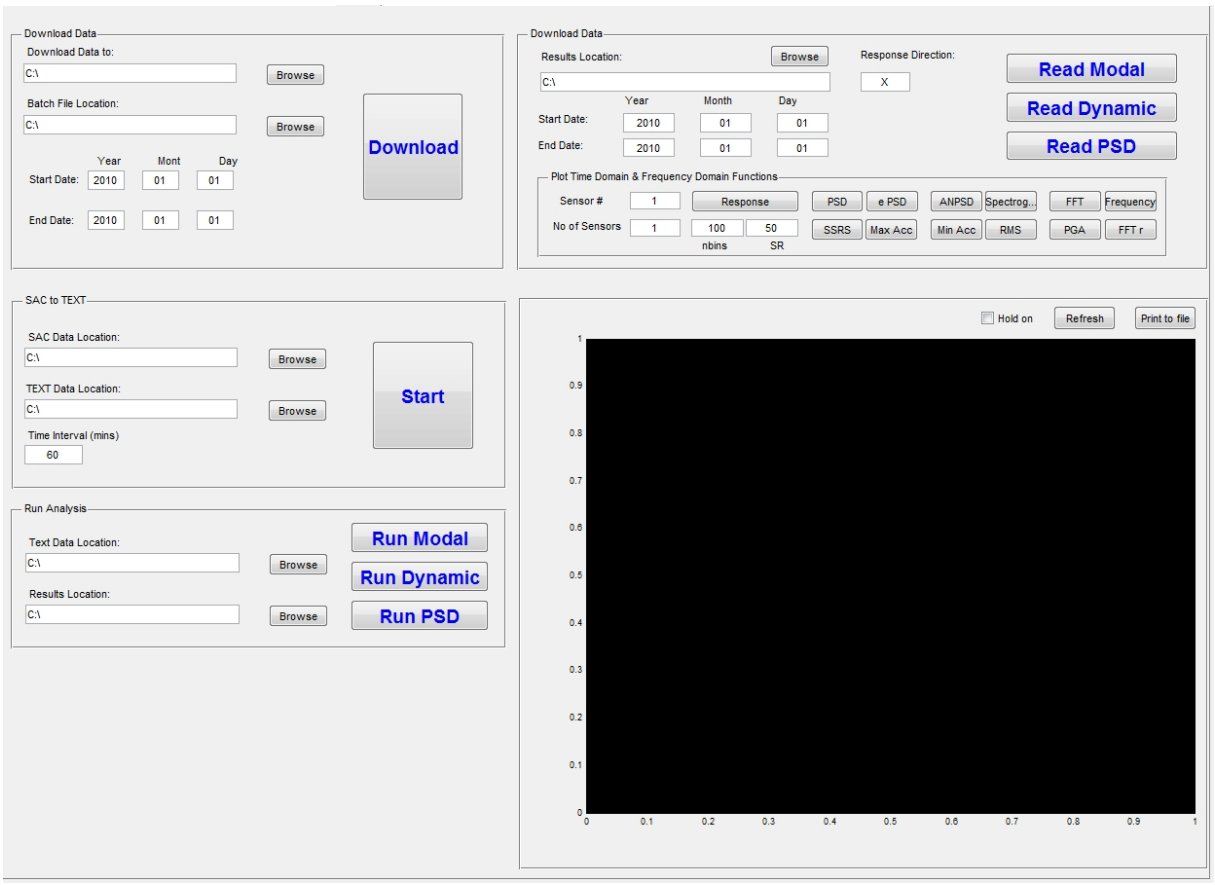

Figure 1b: Automated data analysis toolkit (ADAT)

3 THORNDON OVERBRIDGE

3.1 Structure

The Thorndon Overbridge is a twin 1.3 km long elevated concrete bridge located on the shore of the Wellington Harbour in New Zealand (Wood 2014). The bridge is located in area of high seismicity as the dominant earthquake source in New Zealand, the Wellington Fault, passes under the bridge. It was constructed in 1972. The superstructure consists of simply supported precast concrete I girders spanning between pier caps. Two superstructure expansion joints per span which can rotate in plan are provided to enable the piers to respond independently to seismic forces in the transverse direction. The southbound and northbound are 11.5 m wide and carry 3 x 3.5 m traffic lanes in addition to 0.5 m shoulders.

Due to the importance of the bridge and the high seismicity of the bridge location, it has recently been instrumented with strong motion accelerometers as part of the GeoNet Structures Instrumentation Programme (www.geonet.org.nz/). The GeoNet Instrumentation project aims to install multiple seismic instruments in several representative commercial and residential buildings and bridges in areas of high seismic hazard throughout New Zealand to gain insight into the earthquake performance of typical structures.

3.2 Instrument locations and events during recording period

The bridge was instrumented with 16 tri-axial accelerometers in North and South bounds. In each bound, seven accelerometers were located on the superstructure on two adjacent piers and two adjacent spans and one accelerometer at the ground level. The accelerometer zones in the two bounds were approximately 400 m apart. The accelerometer locations in Zone I are summarised in Table 1 and shown in Figure 2.

The instruments recorded both the 21 July 2013 Cook Strait and the 16 August 2013 Lake Grassmere earthquakes. The M6.5 Cook Strait earthquake was centred around 20 kilometres east of the town of Seddon in Marlborough. The earthquake struck at 5:09:30 pm on 21 July 2013 (05:09 UTC) at a depth of 17 km, according to GeoNet. The quake caused moderate damage in the wider Marlborough area and Wellington, the nation's capital city 55 kilometres north of the epicentre. The Cook Strait earthquake is considered the first of an earthquake doublet, with a second earthquake of similar magnitude at Lake Grassmere. The Lake Grassmere earthquake had a magnitude of 6.6. It occurred just after 2:30 pm on 16 August 2013, and was centred 8 km under the north-east of the South Island. The focal mechanism shows it to be a strike-slip earthquake, similar to the M6.5 earthquake in Cook Strait.

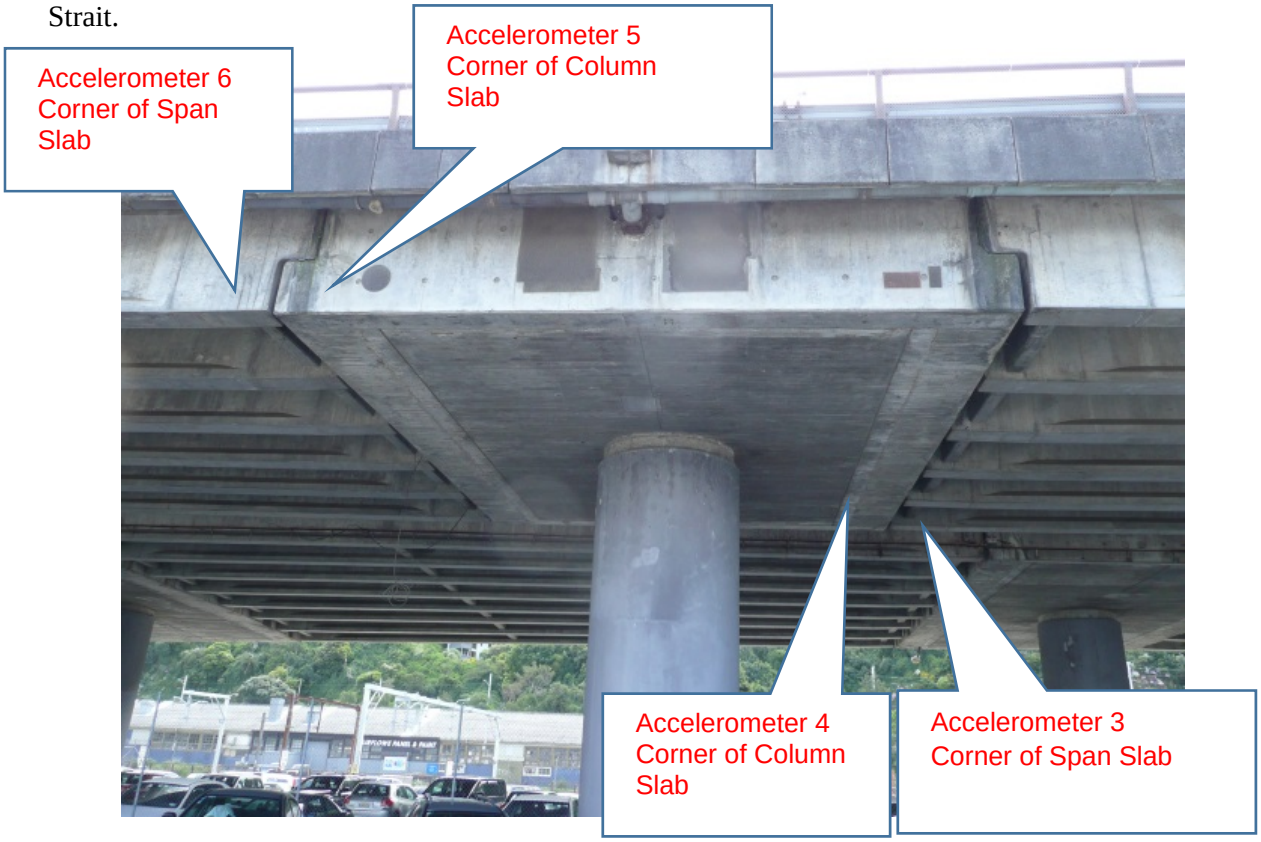

Figure 2: Sensor locations on Thorndon Overbridge

Table 1. Summary of accelerometer locations

Description	Latitude		Longitude		Height
Accelerometer 1	-41.26338902	S	174.78738629	E	-6.90
Accelerometer 2	-41.26350349	S	174.78727889	E	-8.75
Accelerometer 3	-41.26322082	S	174.78747097	E	-7.47
Accelerometer 4	-41.26330165	S	174.78739514	E	-7.40
Accelerometer 5	-41.26369325	S	174.78718130	E	-7.08
Accelerometer 6	-41.26370134	S	174.78717371	E	-7.15
Accelerometer 7	-41.26377308	S	174.78702599	E	-9.00
Accelerometer 8	-41.26361797	S	174.78717150	E	0.00

4 RESULTS

4.1 Dynamic characteristics

The toolbox also performs automated frequency-domain analysis of acquired data, evaluating the power spectral density (PSD) spectra at different sensors. By plotting sequences of the PSD spectral estimates of every hour of data, spectrogram plots are obtained, as shown in Figure 3. From spectrogram plots, the frequency component distribution is easily captured, allowing the observation of the time variation of natural frequencies, as well as the identification of different intensity periods. Figure 3 depicts the PSD distribution of vertical acceleration data obtained from accelerometer 2, which is located in the mid span of the bridge deck, in the period between 1st of May to 1st of October 2013. A drop of 0.05 Hz in the natural frequency of the first vertical mode has been observed immediately after the Cook Strait earthquake (21 July 2013) indicating a very minor but permanent alteration of the bridge dynamic performance due to this earthquake. No further drop or change in the natural frequency was noticed after the second major earthquake; Lake Grassmere earthquake which occurred on 16 August 2013.

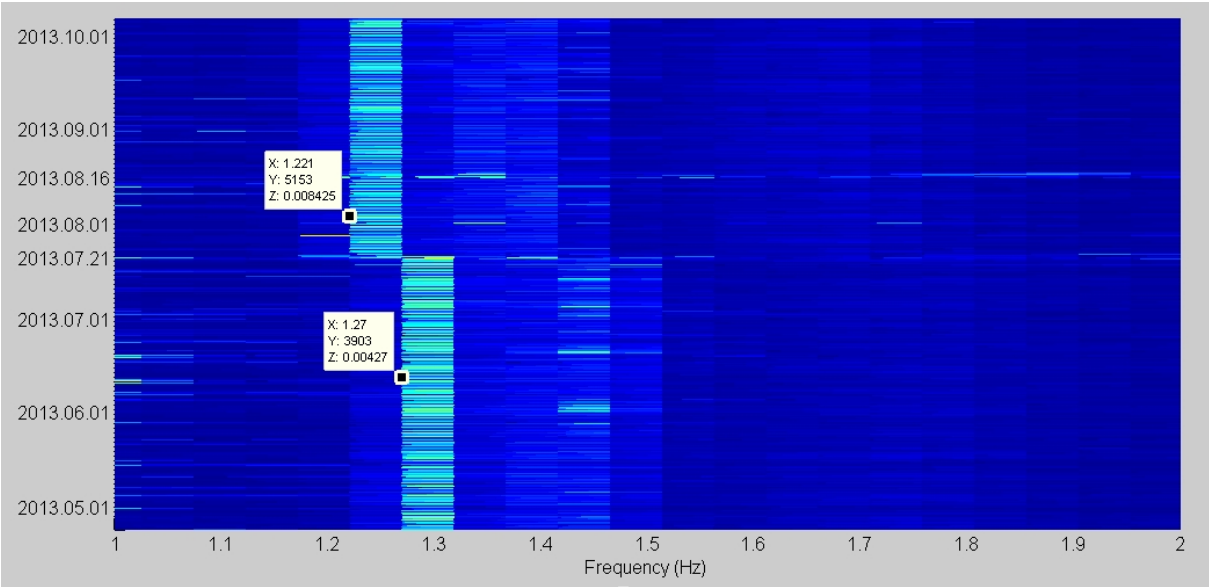

Figure 3: PSD of vertical acceleration from 1 May to 1 October 2013 measured by accelerometer 2

4.2 Vibration intensity

The vibration intensity is a good indicator for the stress level of a structure subjected to dynamic loads. Increasing vibration intensities of individual structural members under similar operational loads can be an indicator of fatigue-relevant damage mechanisms. Acceleration data from the tested bridge in this study has been recorded continuously at a rate of 50 samples per second since August 2012. Raw data was divided to hourly intervals and peak acceleration and RMS values were determined for every hour interval. Figures 4 and 5 show a histogram of the peak acceleration values reported at accelerometer 6 in the vertical direction for the monitoring periods between January-June 2013 and July-December 2013, respectively. The July-December 2013 period includes data during and after the two major earthquakes; Cook Strait and Lake Grassmere. The intention here is to compare the vibration intensities before and after the two major earthquakes including several strong aftershocks. As clearly indicated in Figures 4 and 5, no significant change in the peak acceleration distribution was observed before and after the earthquakes. The acceleration peaks histogram comprises two close to normal distribution sections. The peak acceleration in the first section ranges from 0 to 0.15 m/s^2 and is centred around 0.08 m/s^2 which indicates very light traffic volume, likely during night hours and outside rush hours. In the second section, peak acceleration values are higher compared to the first part indicating heavier traffic loads during rush hours. Very similar distribution is observed for the two monitoring periods. RMS data before and after the earthquakes are shown in Figures 6 and 7, respectively. Similar distribution and amplitudes of RMS data can be clearly observed in the two

monitoring periods. Similarity in the peak and RMS acceleration data indicates with good confidence that the bridge performance has not been altered after the earthquakes. The sensitivity of vibration intensity indicator such as peak acceleration and RMS to small damage levels needs further investigation.

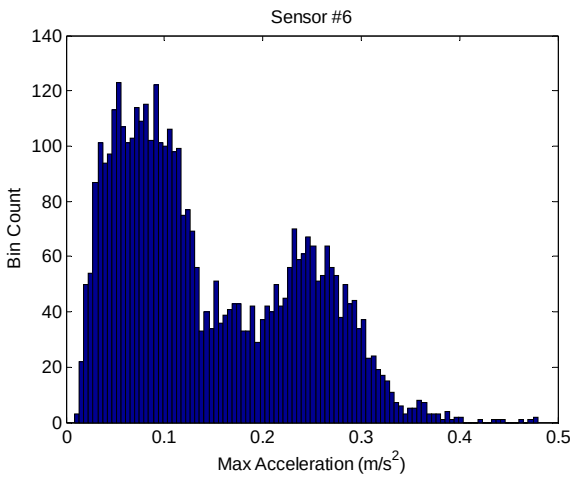

Figure 4: Histogram of maximum vertical acceleration from 1 January to 30 June 2013 measured by accelerometer 6

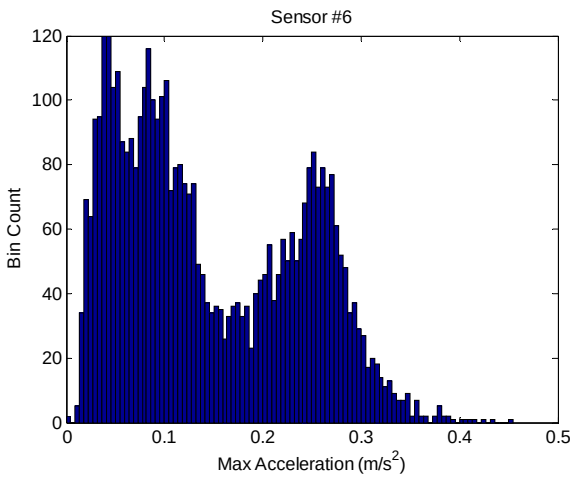

Figure 5: Histogram of maximum vertical acceleration from 1 July to 31 December 2013 measured by accelerometer 6

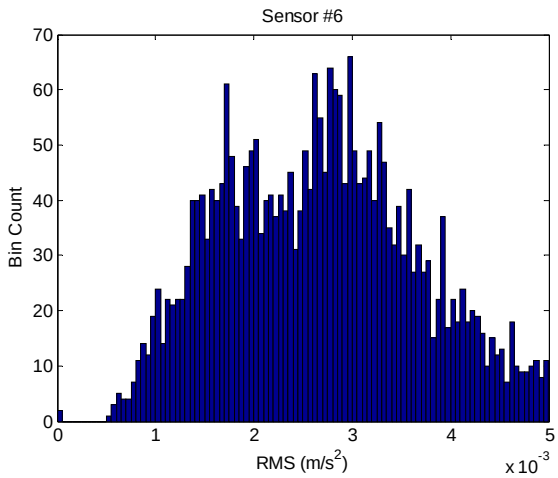

Figure 6: Histogram of RMS of vertical acceleration from 1 January to 30 June 2013 measured by accelerometer 6

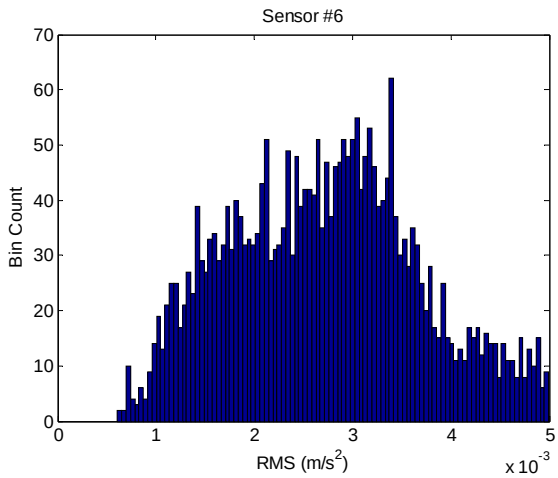

Figure 7: Histogram of RMS of vertical acceleration from 1 July to 31 December 2013 measured by accelerometer 6

5 CONCLUSION

This paper is focused on the development of computational tools for monitoring and damage assessment of structures. The toolkits provide functions for automated dynamic parameters and response amplitudes monitoring and it has been developed to integrate long term continuous structural monitoring systems. The use of this toolkit in the context of long-term monitoring has been demonstrated using acceleration data recorded over one year from a full scale concrete bridge located in Wellington, New Zealand. The test bridge was subjected to two major earthquakes of magnitude

M6.5 during the monitoring period. The dynamic performance of the bridge was evaluated before and after the earthquakes utilising the developed toolkit. A very small drop in the natural frequency of the first vertical mode was observed after the first earthquake but with no major change in the overall dynamic performance of the bridge. This investigation illustrates the potential of this package in terms of automated processing of large amount of data enabling the accurate characterisation of the time variation of natural frequencies and dynamic performance indicators over long periods of continuous monitoring.

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