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MA, Q. T., Beskhyroun, S., Simkin, G. B., Wotherspoon, L. W., Ingham, J. M., Cole, G., . . . Sharpe, R. (2014). Experimental evaluation of inter-storey drifts during the Cook Strait earthquake sequence. In *Towards Integrated Seismic Design*. Auckland. Retrieved from http://db.nzsee.org.nz/2014/Orals.htm

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Experimental evaluation of inter-storey drifts during the Cook Strait earthquake sequence

2014 NZSEE
Conference

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ABSTRACT: Building interstorey drifts remain to be the most direct and accurate indicator of damage potential during earthquakes. However, interstorey drifts are often difficult to measure due to the lack of an absolute frame of reference. Currently, numerical integration of acceleration data is the most commonly used technique to experimentally determine interstorey drifts in real buildings. This technique is very sensitive to low frequency errors and requires high quality acceleration data. Traditionally, buildings are rarely instrumented and consequently actual building acceleration and displacement data are rare. With recent advances in computing processing power, sensor and data transmission technologies, it has now become accessible for buildings to be densely instrumented and continuously monitored for vibration.

This paper presents interstorey drift estimates of a midrise building in Wellington during the Cook Strait earthquake sequence. A number of different interstorey drift estimation algorithms were applied carefully. They produced very similar predictions and enabled displacement profiles to be predicted.

1 INTRODUCTION

In the past five decades, data from instrumented structures have led to improved understanding of structural response during earthquakes. This has enabled engineers to critically evaluate and identify weaknesses of current design and construction methods, and to recommend changes to minimise future seismic vulnerability. Many of the seismically instrumented buildings worldwide were instrumented with this as the primary objective and were funded through national public good science programmes (Benz 1999; Shakal et al. 1988; Tsai and Lee 2005; Uma et al. 2011).

In addition to improving general predictive models in the long term following shaking events, seismic instrumentation can also quantitatively inform building stakeholders on a building's structural integrity and habitability immediately following an event. This has the potential to minimise potential loss of lives, unnecessary building evacuations and business downtime.

A paper by Deam and Cousins (2002) outlined a sample list of information requirements for achieving different objectives with building instrumentation. In current practice, this information is delivered primarily via acceleration measurements at various locations within a building. It was highlighted that the most desirable predictor for building damage is interstorey drift. The direct monitoring of interstorey drifts in building remains elusive due to the difficulties in obtaining an absolute frame of reference for displacement measurements.

In the past decade, there have been exponential advances in computing capability, sensor technologies and digital data transmission technologies. The combined effect of these advances is that it is now more affordable than ever for private enterprises to provide seismic instrumentation for damage detection purposes. It has also now become practical to densely instrument a structure and process the large volume of instrument data rapidly to provide real-time data interpretation (Ulusoy et al. 2013).

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Whilst there are interesting developments in optical sensors and Global Positioning Systems for measuring interstorey drifts directly, the current practice still relies heavily on the use of accelerometer measurements (Bennett and Batroney 1997; Çelebi and Sanli 2002).

This paper presents a brief review of a number of interstorey drift estimation strategies using accelerometer data. Indicative effectiveness of the approaches is presented via a case study on a 14 storey concrete building instrumented during a M5.4 shaking event of the 2013 Cook Strait aftershock sequence (GeoNet 2013a).

2 ESTIMATING BUILDING DISPLACEMENTS FROM ACCELERATIONS

2.1 Double integration of acceleration data

Double integration with respect of time is the prevalent technique in converting building acceleration data into dynamic displacement data. For this technique to be effective, a number of oftentimes subjective steps are required to minimise the effects of low and high frequency errors.

Mathematically, the double integration process is summarised as Equation 1.

$$u(t) = \int\int \ddot{u}(t)\,dt^2 = \int \dot{u}(t)\,dt + At + B \qquad (1)$$

where $u, \dot{u}, \ddot{u}$ are displacement, velocity and acceleration respectively; and
A, B are constants of integration

Equation 1 provides the blueprint to convert acceleration time history data to displacement time history data. Equation 1 can be solved by utilising any numerical integration technique such as the trapezium rule or the Simpsons rule. Integration schemes should be selected carefully to balance the stability requirements and error propagation characteristics of different frequencies (Worden 1990). Regardless of the integration scheme selected, numerical integration will produce a shift of the reference baseline. One approach in correcting this is to apply baseline correction, where by one or more piecewise baselines are subtracted from the integrated results. A common strategy is to assume building velocity is a zero-mean signal. Thus, a reference linear or low-order polynomial baseline can be fitted using least square technique between two subjectively selected points in time where the velocity is assumed to be zero.

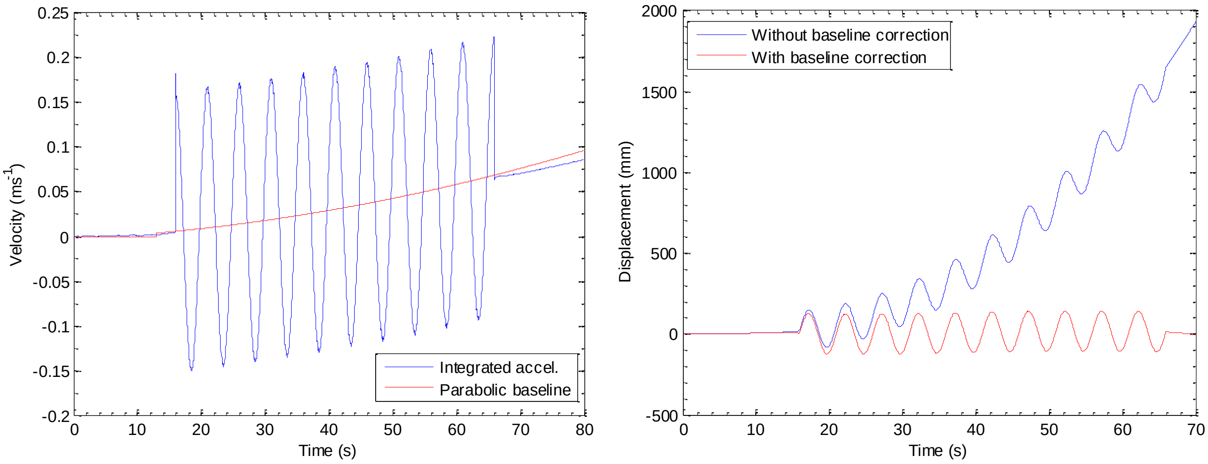

Figure 1. (Left): An illustrative example of baseline fitting; (Right): the integrated displacement with and without baseline correction.

Figure 1 presents an example application of baseline fitting and the effect of baseline correction on the integrated displacements. It should be noted that applying baseline correction is in effect applying a high-pass filter with unknown frequency response characteristic, for the primary purpose of removing errors from the integration process (Boore and Bommer 2005).

2.2 **Filtering strategies**

In conjunction or separately from baseline correction, filtering can be applied to improve signal quality. There is no universal rule or specific guidance in the exact sequence, extent and parameters of filtering for building acceleration data. Operators usually apply filtering subjectively in order to recover physically plausible integrated displacements. Whilst filtering can minimise some sources of errors, it is still ineffective to overcome problems such as sensors misalignment, titling and rotation of sensors and poor instrument accuracy.

The sections below examine the use of low- and high- pass filtering. This study used acasual digital filters on recorded accelerations which produced no phase distortion. This is important for interstorey drift calculations.

2.2.1 *Low- and high- pass digital filters*

Low-pass digital filters remove short period noise in the building acceleration data. Short period noise may stem from a number of sources including fluctuation in sensor sensitivity, temperature fluctuation or instrument hysteresis. These generally have little effect on the displacement predictions compared to that caused by long period noise. Conducting low-pass filtering to remove short period noise increases the signal-to-noise ratio and decreases the signal amplitude and displacement prediction. The low-pass filter cut-off frequency (f_c) is typically selected to be sufficiently high to ensure all possible structural behaviours are captured. Integrated displacements are generally insensitive to the selection of low-pass cut-off frequencies. With modern digital accelerometers, it is common practice to avoid low-pass filtering altogether.

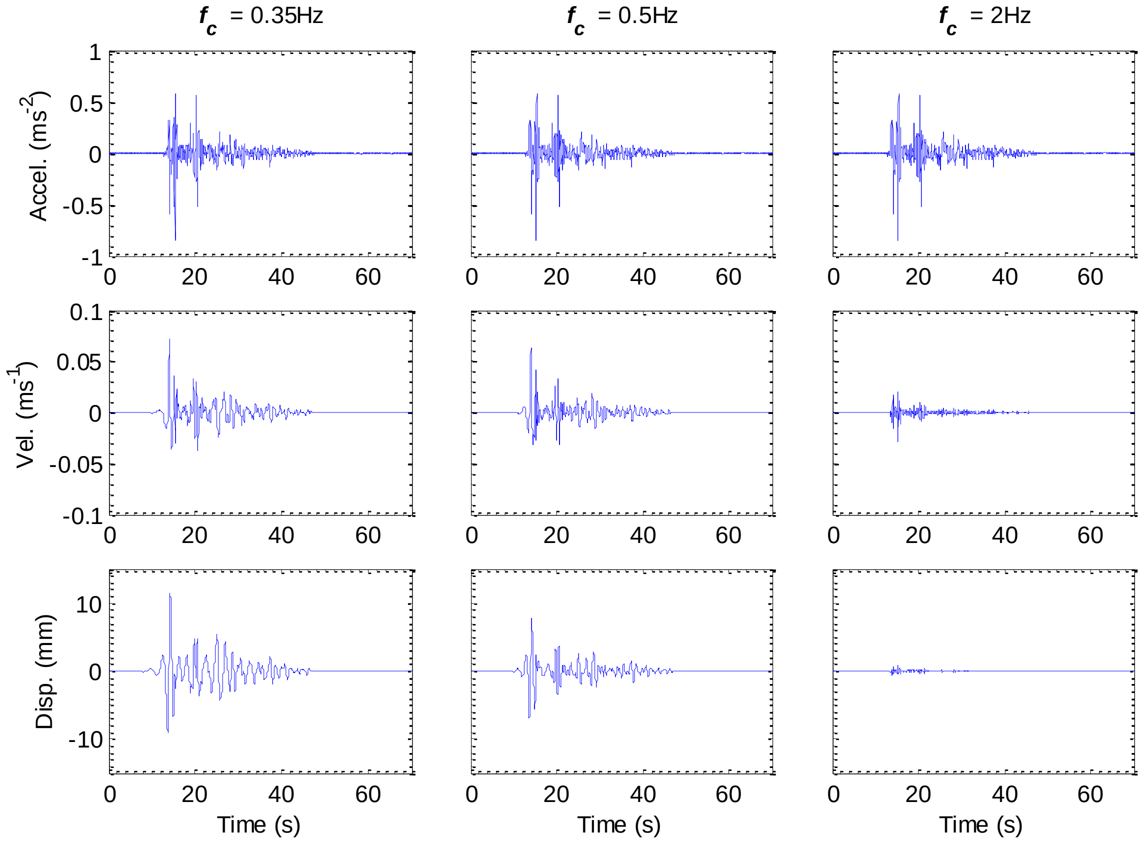

Figure 2. Displacement time-histories based on double integration of building accelerations with varying high-pass filtering corrections.

High-pass digital filters are the most widely used tool for removing long period noise and erroneous long period drifts from the integration process. When utilising high-pass filtering, the results are highly sensitive to the selection of the filter cut-off frequency. Boore and Bommer (2005) summarised a number of considerations for selecting cut-off frequencies for strong-motion applications, ultimately the selection of filter cut-off is subjective to the user. A weakness in this approach is that filtering is indiscriminate and that it will also incorrectly remove displacements arising from true long period structural behaviour. This may be significant for structures experiencing plastic deformations or for special structures with long natural periods. Figure 2 presents a series of examples illustrating the effect of high-pass filtering cut-off selection.

2.3 **Laboratory calibration**

To examine the real-world effectiveness of the double integration approach, a set of five accelerometers were mounted on a shaking table and subjected to a range of sinusoidal and earthquake motions. Figure 3 presents a photograph of the test setup and the properties of the table motion are summarised in Table 1. The accelerometers used in these tests are the same ones described in a paper by Beskhyroun and Ma (2012). During the shake table testing, a linear-variable differential transformer (LVDT) recorded the table displacements at 100Hz, and the accelerometers recorded the shake table's acceleration at 40Hz. A low accelerometer sampling rate was deliberately selected to replicate a non-ideal real-world application.

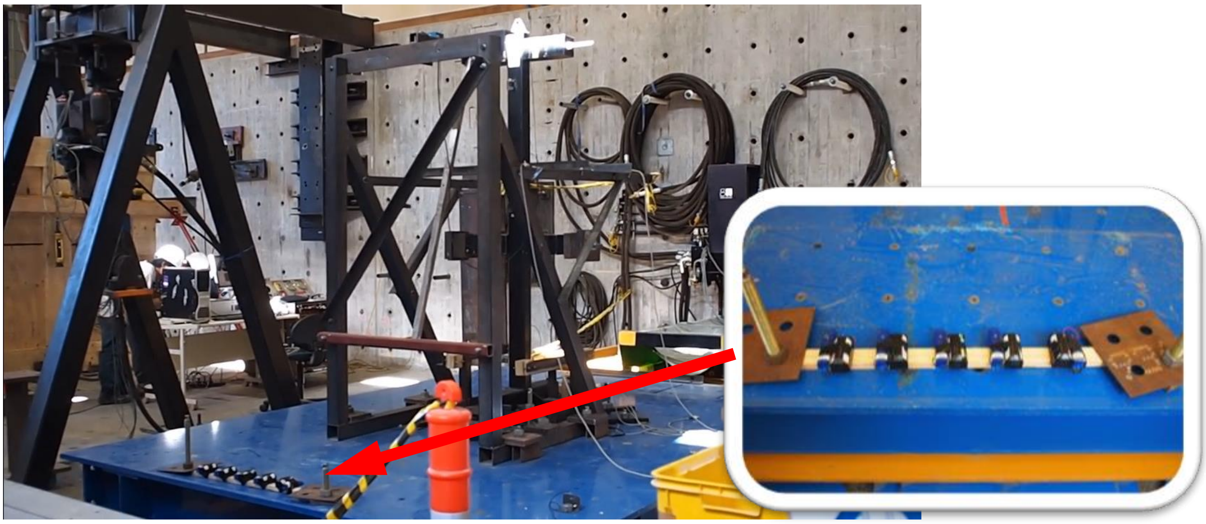

Figure 3. Shake table calibration setup.

A double integration approach with linear baseline correction and 0.35Hz high-pass filtering was applied to the acceleration to derived shaking table estimate. Analysis of the sinusoidal ground motion demonstrated that accurate displacement estimates are possible for frequencies greater than 0.5 Hz. Figure 4 presents examples for illustrative comparisons, and Figure 5 compares the peak-to-peak accuracy against the input motion frequency and the choice of f_c. It should be noted that the results can be further improved by conducting a synchronisation exercise outlined in Beskhyroun et al. (2012).

For sinusoidal motion less than 0.5 Hz and earthquake type motions, best fit velocity baseline correction followed by a 0.1-0.2 Hz high-pass filter of the integrated displacement was the most effective. Figure 6 presents two illustrative comparisons of indicative performance from the shake table calibration exercise.

Table 1. Summary of shake table motions

ID	Motion type	Start freq. (Hz)	End freq. (Hz)	No. cycles	Amplitude (mm)	Duration (s)
1	Uniform sine	0.1	0.1	5	120	50
2	Uniform sine	0.2	0.2	10	120	50
3	Uniform sine	0.3	0.3	10	100	33
4	Uniform sine	0.5	0.5	25	50	50
5	Uniform sine	0.75	0.75	40	40	53
6	Uniform sine	1	1	50	30	50
7	Uniform sine	2	2	70	15	35
8	Uniform sine	3	3	105	10	35
9	Uniform sine	4	4	140	5	35
10	Uniform sine	6	6	210	1.5	35
11	Uniform sine	8	8	280	3.5	35
12	Uniform sine	10	10	350	3	35
13	Sweep Forward	0.1	10		20	60
14	Sweep Forward	0.1	10		35	60
15	Earthquake					

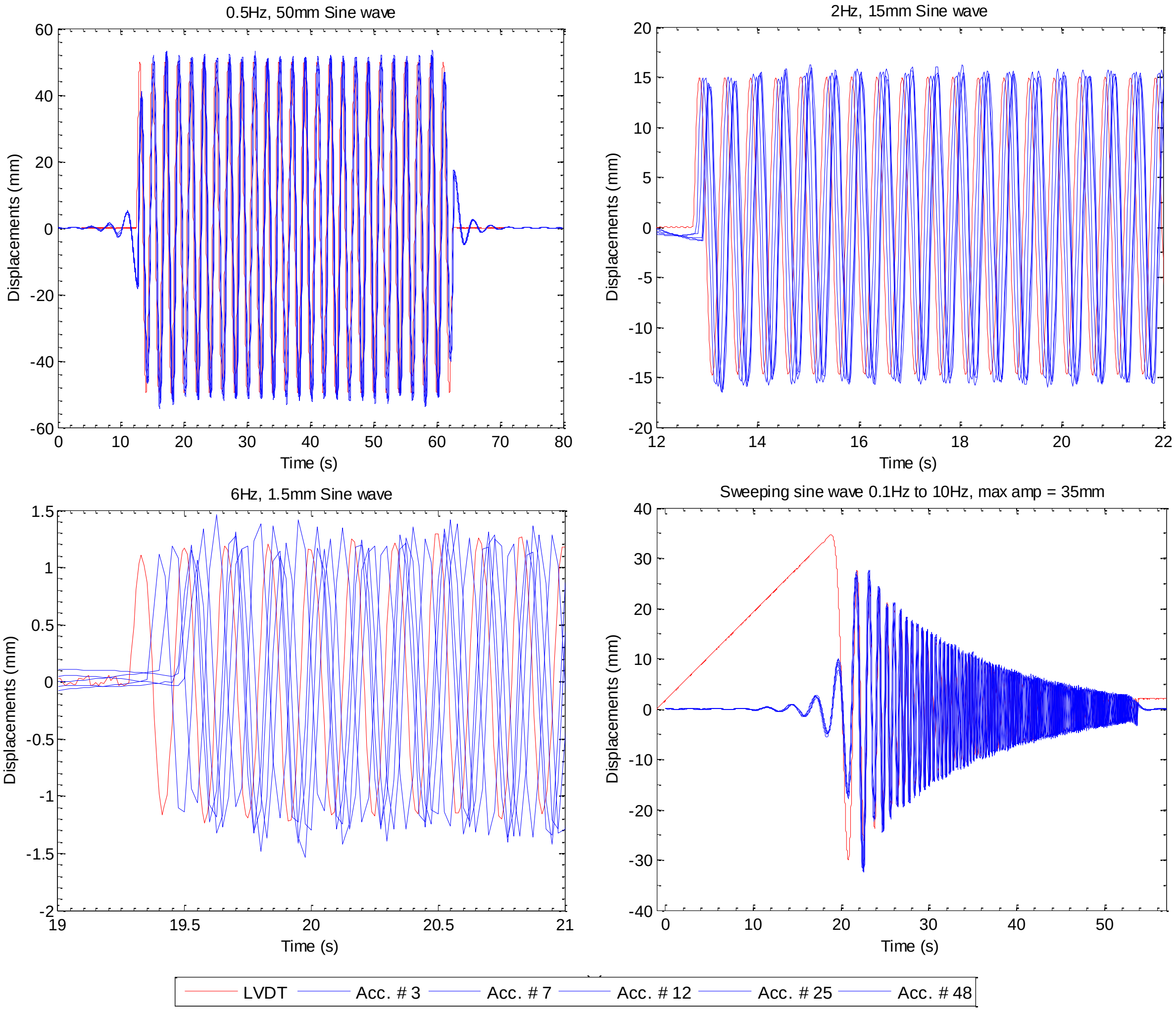

Figure 4. Illustrative comparison of measured shake table displacements versus estimated displacement.

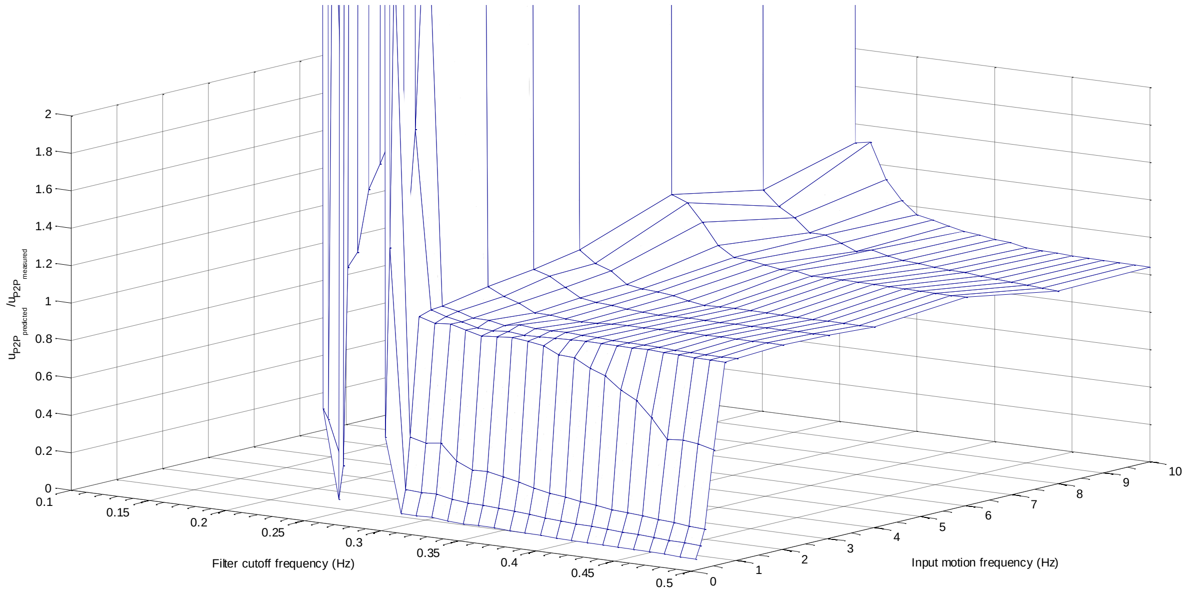

Figure 5. Estimated peak-to-peak displacement against recorded displacements using a high-pass filter technique, for sinusoidal motion with varying frequencies and varying high-pass filter cut-offs.

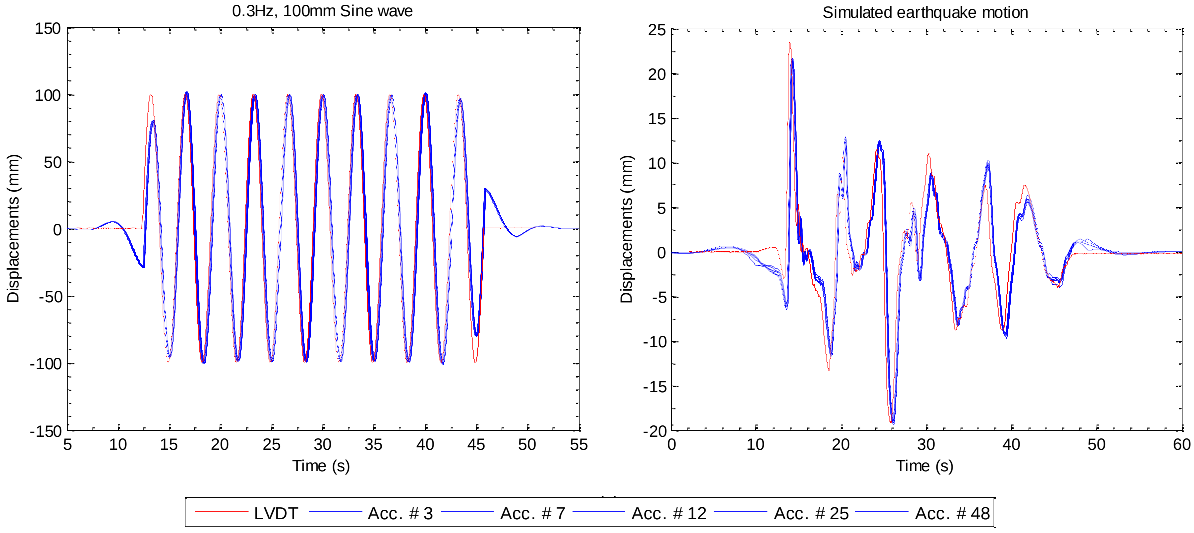

Figure 6. Comparison of measured shake table displacements versus estimated displacement processed by baseline correction; (Left): 100 mm uniform sine wave at 0.3Hz, (right) simulated earthquake motion.

3 TEST BUILDING

Following the 2013 Seddon earthquake (GeoNet 2013b), the authors with the assistance of engineers from the Beca group instrumented a twelve-storey 1970s concrete building with temporary instrumentation. Ten accelerometers were installed at six floor levels. These were located in the corners of the building wherever possible and they recorded building accelerations from 24 July to 12 August 2013. During this period the largest recorded earthquake was a M5.4 aftershock. Figure 7 and Table 2 summarise the accelerometer placement. The accelerometers were either secured to the floor or the wall, and they were aligned with principle axis of the building. Modal analysis and detailed finite element analysis estimated that the building has a first mode period of 0.61 s.

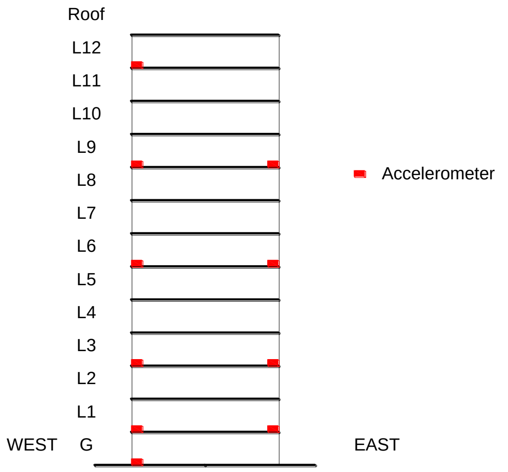

Figure 7. Vertical distribution of accelerometers.

Table 2. Summary of accelerometer placement

Level	Accelerometer ID			
	NE	SE	SW	NW
Roof				
L12			015	
L11				
L10				
L9		022		013
L8				
L7				
L6		055		031
L5				
L4				
L3		033		035
L2				
L1		057		016
G			051	

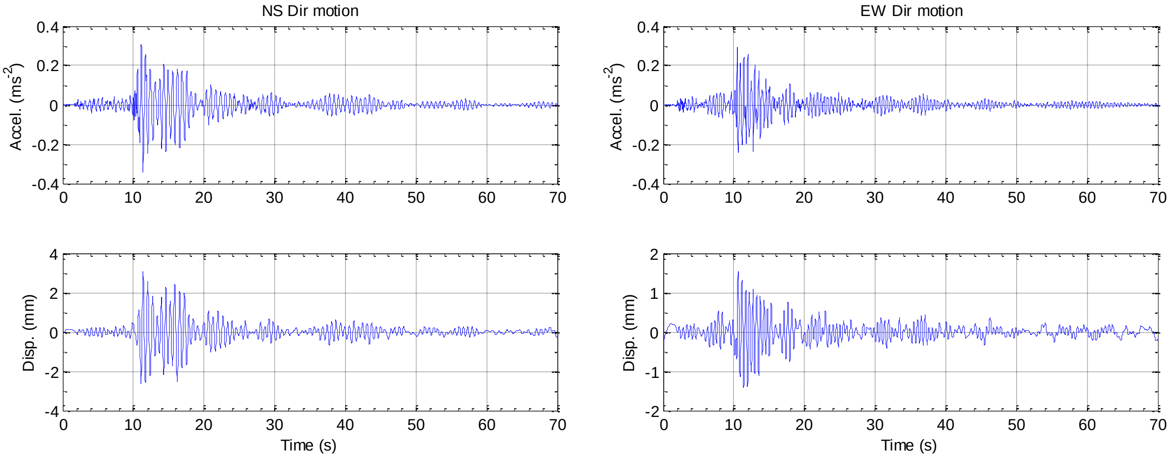

Figure 8. Measured accelerations and estimated displacement histories on the 12th floor of the instrumented building during a M5.4 aftershock.

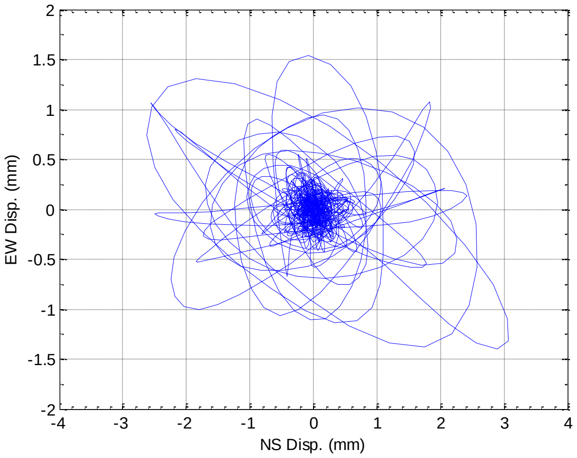

Figure 9. Estimated displacement trajectory of the 12th floor

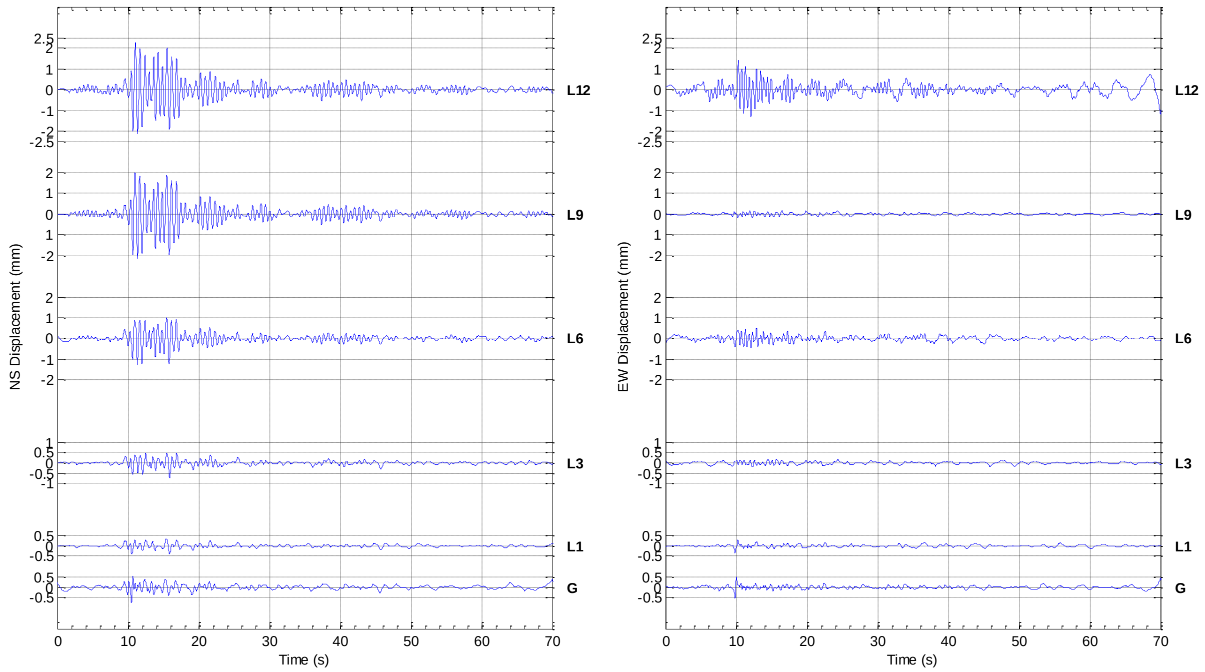

Figure 10. Estimated displacement history of the instrumented floors during a M5.4 aftershock.

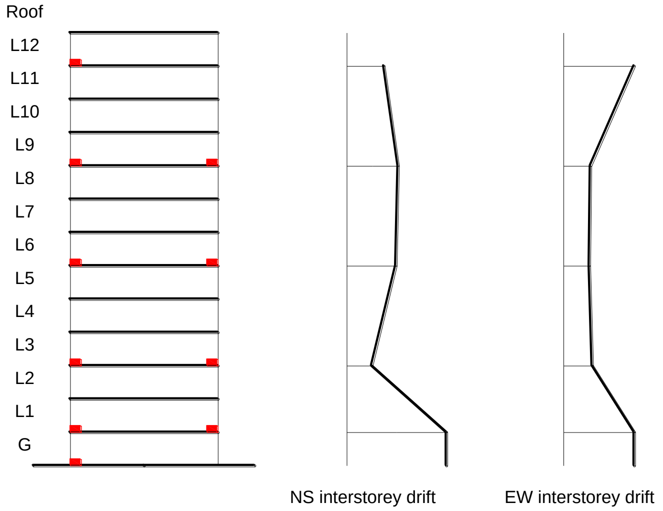

Figure 11. Graphical representation of the maximum interstorey drifts.

Table 3. Maximum average interstorey drift

Level	NS (mm)	EW
L12	0.28	0.53
L9	0.39	0.20
L6	0.37	0.19
L3	0.19	0.22
L1	0.75	0.53

Following procedures outlined in section 2, recorded building accelerations were converted into three dimensional building displacements for the single M5.4 aftershock. Figure 8 and 10 present the estimated displacement time history trace for the SW corner of level 12. Figure 10 presents the estimated displacement time history for all instrumented floors at their geometric centres during the considered event. Accordingly, Table 3 presents the maximum average floor-to-floor interstory drift estimates at the centre of each instrumented floor. These are plotted graphically in Figure 11.

4 CONCLUSION

Through advances in sensors and computing technologies, it has now become practical for private building owners to seismically instrument their buildings and obtain insightful information on the structure performance rapidly following strong ground motion. This paper has demonstrated through case studies, strategies for developing building displacement estimates from acceleration measurements. The case study and the laboratory validation exercise have demonstrated that robust interstorey drift estimates can be obtained via inexpensive equipment and careful data processing.

5 ACKNOWLEDGEMENTS

The authors would like to thank the many professional engineers and building owners who facilitated access and provided permission to instrument buildings during the 2013 Cook Strait Earthquake sequence.

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